On the accuracy of HF radar surface current measurements: Intercomparisons with ship-based sensors


Abstract. High-frequency (HF) radar systems can provide periodic, two-dimensional, vector current estimates over an area approaching 1000 km². As the use of these HF systems has gained wider acceptance, a number of attempts have been made to estimate the accuracy of such systems. However, comparisons of HF radar current estimates with in situ sensors are difficult to interpret since HF systems measure currents averaged over an area of ~1 km² and to a depth of only ~50 cm while in situ sensors measure currents at a point and somewhat greater depths (~1 to 10 m). Previous studies of the accuracy of HF radar technology have thus attributed the differences observed between HF radar and in situ sensors to an unknown combination of vertical shear, horizontal inhomogeneity, in situ instrument errors, and HF radar system errors. This study examines the accuracy of HF radar current measurements using data from the 1993 High Resolution Remote Sensing Experiment, conducted off Cape Hatteras, North Carolina. Data from four shipborne in situ current meters are compared with data from an Ocean Surface Current Radar (OSCR), a commercial current-measuring radar. We attempt to discern the predominant sources of error in these data by using multiple simultaneous measurements from different sensors and by examining the variation of observed current differences as a function of location. The results suggest an upper bound on the accuracy of the OSCR-derived radial currents of 7 to 8 cm/s.

1. Introduction

Near-surface ocean currents play a variety of roles in coastal environments. Physically, wind stress is imparted through an upper surface boundary layer. These upper layer stresses play an important role in the development and maintenance of the mixed layer. Biologically, near-surface currents distribute and disperse both plankton and fish eggs. Ecologically, many pollutants, such as oil, are surface borne. The dispersion of such pollutants depends critically on the near-surface current structure. Thus, from multiple viewpoints, the measurement of near-surface currents in the coastal environment is an important problem.

Unfortunately, conventional methods for measuring near-surface currents (depths ~1 m) are somewhat problematic. While careful design of surface drifters can minimize problems due to windage and wave interaction, single drifters are limited and uncontrollable in their spatial and temporal coverage, especially in convergent and divergent flow regimes. Multiple drifters can be prohibitively expensive when used in sufficient quantities to adequately characterize the current within a large region over a significant period of time. Moored instruments can be used to obtain long time series, but they usually suffer from motions of the moored body. Furthermore, the instruments are typically suspended below a surface float, which physically restricts the minimum depth of the current measurement to a few meters. Currents measured from ship-mounted acoustic Doppler current profilers (ADCPs) can be useful, but the first measurement bins are necessarily below the draft of the ship and ship time is expensive. For these reasons, a land-based method for continuously measuring surface currents in the coastal region has considerable merit.

The measurement of near-surface ocean currents using electromagnetic backscatter measured from a high-frequency radar was first demonstrated over 20 years ago [Stewart and Joy, 1974; Barrick et al., 1974]. (Generally, the term high-frequency, or HF, refers to systems with carrier frequencies between 3 and 30 MHz.) This technique, based on the results of Crombie [1972], utilizes the fact that HF backscatter from the ocean at near-grazing angles is predominantly due to Bragg scattering. Thus the Doppler spectrum of the HF radar return contains sharp peaks associated with those surface gravity waves with a wavelength that are either approaching toward, or receding from, the radar site [Crombie, 1955]. The frequency of these Doppler peaks reflects the phase velocity of the scattering waves. By subtracting the known phase velocity of the scattering wave in the absence of current, \( c_p = \sqrt{g/k} \), from the measured phase velocity, an estimate of the component of the surface current in the look direction of the radar can be obtained. Two or more stations, viewing a particular measurement point from different directions, can then be used to estimate surface current vectors.

Several practical radar systems for measuring ocean currents in the near-coastal environment have been developed and commercialized. At least two such systems are currently available: the...
Coastal Ocean Dynamics Application Radar (CODAR), manufactured by CODAR Ocean Sensors, Ltd., and the Ocean Surface Current Radar (OSCR), manufactured by Marconi, Inc. While we utilize an OSCR system, owned and operated by the University of Miami, for this study, we believe that the results presented here would, in principle, be the same for a CODAR system. The two systems differ in beam-forming technology but rely on fundamentally similar physics and Doppler-processing algorithms for their operation. An informative side-by-side comparison of an OSCR and several CODAR systems has just been published by Fernandez and Paduan [1996].

These commercial systems are limited to near-coastal environments because of their design and the nature of ground wave HF radio propagation. (Attempts have been made to operate OSCR from both an anchored and a moving ship [cf. Skop et al., 1994; Peters and Skop, 1995].) Most HF communication systems rely on reflections off the ionosphere to achieve over-the-horizon operation. Unfortunately, motions in the ionosphere, which are responsible for the fading typically observed in HF communications, act to blur the Doppler signature of the Bragg scatterers. While some encouraging progress has been made on long-range current estimates using HF radars [Trizna, 1982; Georges and Harlan, 1995], the most common HF current-measuring systems utilize ground wave propagation to eliminate ionospheric effects. Losses in ground wave propagation subsequently limit CODAR and OSCR systems to effective ranges of less than 100 km, although we note that additional power could be combined with higher gain antennas to extend this range to several hundred kilometers.

Since the development of HF radar for current measurement, there have been a number of experiments to evaluate the accuracy of this technology. The first experiments [Stewart and Joy, 1974; Barrick et al., 1977; Frisch and Weber, 1980] compared HF radar estimates of current to those derived from drifting buoys. These studies reported differences between the radar- and drifter-derived currents of 15 to 27 cm/s. Paduan and Rosenfield [1996] present a more recent study using the same technique, reporting 13 cm/s rms differences in current magnitude. Later studies, comparing HF data with current measurements from moorings or bottom-mounted ADCPs [Holbrook and Frisch, 1981; Leise, 1984; Porter et al., 1986; Matthews et al., 1988], reported differences ranging from 9 to 17 cm/s. While the level of agreement found in these studies is encouraging, all acknowledged the difficulties in comparing HF radar-derived currents, which are area-averaged estimates made at the surface, with in situ measurements, which are essentially point measurements made at some finite depth. Prandle [1991] includes an overview of a series of studies comparing tidal ellipses determined from HF radar and conventional current meters. Using HF-radar-derived surface currents from the High Resolution Remote Sensing Experiment, Shay et al. [1995] found rms differences of 12–15 cm/s between surface and moored subsurface current measurements. This study focused on understanding these differences within the context of bulk vertical current shears of about 1–2 cm/s per meter by decomposing the observations into various frequency bands. More recently, Paduan and Rosenfield [1996] reported on extensive intercomparisons of HF radar data with in situ sensors in Monterey Bay, including a rather complete discussion of the difficulties and uncertainties in such a comparison.

This study is an attempt to better estimate the accuracy of current estimates made by an HF radar system. Our approach is to compare shipborne surface current measurements to those obtained by HF radar over the 2 weeks of the High Resolution Remote Sensing Experiment. We utilize two techniques in an attempt to apportion the observed current estimate differences to physical differences and instrument errors. The first technique involves the simultaneous comparison of estimates derived from multiple instruments, including the HF radar. We hoped that the relative magnitude of the observed differences would lead to an apportionment of the errors. The second technique examines the dependence of the observed current estimate differences with location. By combining the data with a simple model of the spatial dependence of errors in the HF radar system, we estimate upper bounds on the accuracy of that system.

2. Data Sources

The data used in this study were obtained during the High Resolution Remote Sensing Experiment [Herr et al., 1991]. This experiment, jointly supported by the Office of Naval Research and the Naval Research Laboratory, was designed to investigate the detailed processes involved in radar imaging of submesoscale features. The experiment took place 10 to 50 km offshore from Cape Hatteras, North Carolina, from June 10 through June 26, 1993. The reader is referred to Shay et al. [1995] for a description of the oceanography of the region during the period of the experiment.

The experiment was supported by a wide variety of research platforms, including two research vessels holding in situ sensors, several aircraft with real and synthetic aperture radars, the ERS-1 satellite, and a land-based Ocean Surface Current Radar (OSCR). Both of the research vessels, USNS Bartlett and R/V Columbus Iselin, also deployed small towed platforms containing current sensors as well as other instrumentation. Our study compares data from four separate current sensors on the research vessels and towed platforms to those obtained from the OSCR in order to evaluate the accuracy and limitations of OSCR. Each of the systems involved in the comparison is described in the paragraphs below.

2.1. OSCR

OSCR is a dual-site pulse-Doppler radar operating at a frequency of 25.4 MHz. The transmit antenna for this system is a four-element Yagi configuration with a front-to-back power ratio of 6 dB and a 90° wide beam pattern. A phased-array receiving antenna, with a beam width of approximately 6°, is used to azimuthally scan the ocean region illuminated by the transmitted beam. The radar estimates near-surface currents within each range and azimuth cell by identifying and tracking frequency shifts in the peaks of the Doppler spectra of the ocean backscatter corresponding to the advection of the Bragg wave. Since an individual station is only sensitive to radial Doppler velocities, two separate stations are used in the system to obtain vector current estimates. During the High Resolution Remote Sensing Experiment the two stations of the OSCR system were deployed on the shore in the towns of Avon and Waves, North Carolina. These two sites were separated by a distance of 24 km [Shay et al., 1995].

While intermediate data products were recorded from the OSCR system, the final data products, used in this study, were maps of surface current estimates. These maps display estimates of the near-surface current everywhere within a circle of about 35-km diameter centered about 25 km off shore and with a mean horizontal resolution of approximately 1.2 km. Such maps were produced every 20 min during nearly the entire period of the experiment. One such map is shown in Figure 1.

Several aspects of the OSCR system, some of which are important for this analysis, are worth noting.

1. In contrast to the in situ sensors, which essentially measure currents at a point, the OSCR current estimates are based on averages taken over an area of between 2.5 and 5.6 km². More precisely,
the OSCR current estimates are based upon all of the spectral information obtained within the resolved area. Horizontal variations in the current field with scale lengths less than 1 km will result in broadened or multiple Doppler spectral peaks. The software must then choose between valid Bragg pairs. Thus there will be times when the OSCR-estimated current, though valid, will differ from an in situ measurement. Due to the complexity of the current regime off Cape Hatteras, these averaging effects may contribute substantially to the observed rms differences.

2. The wavelength of the Bragg scatterers for OSCR is 5.9 m. As such, OSCR responds to surface currents integrated over approximately the upper 0.5 m (= $\lambda_r/8\pi$, where $\lambda_r$ is the radar wavelength) of the water column [Stewart and Joy, 1974]. The in situ data used in this study were obtained at depths of 1 to 10 m. Vertical inhomogeneity in the near-surface current over these scales contributes to differences in the current estimates.

3. The OSCR system utilizes simple criteria to eliminate bad data. These criteria are based on the strength of the backscatter and the form of the resulting Doppler spectra. In particular, current estimates are not recorded for those points and times where neither the approaching nor the receding Bragg peaks are greater than 6 dB above the background noise floor. Thus the current maps produced by OSCR have some gaps in them. This explains some of the holes in the measurement domain.

4. The data quality criteria used by OSCR are not perfect, and some current estimates that are wildly erroneous can still be found in the data. Such wild points were observed to occur less than 1% of the time within the data.

5. To avoid interference with each other, the OSCR master and slave sites are not operated simultaneously but are instead operated sequentially. The sequence begins with the master site operating for a period of 5 min. Both sites are then silent for the remainder of the 20-min cycle during which time data are exchanged between the sites and processing is performed. This sequencing of measurements means that the two radial measurements used for each vector estimate are not taken simultaneously. Errors due to this temporal undersampling are unlikely, as this would require a feature with a phase velocity of the order of 4 m/s (= 1.2 km/5 min).

6. The phase velocity of the Bragg waves is altered in shallow water, which directly affects the surface current estimates. Fortunately, at the wavelength at which OSCR operates, this effect only becomes significant for water depths less than 3 m, and no depths this shallow were encountered in this study.

7. The expected precision of a radial current estimate made by OSCR is 2.2 cm/s. This figure is based on the length of the analysis record for the specific setup utilized during this experiment and represents a limit in the system's ability to locate a particular Doppler peak.

2.2. R/V Columbus Iselin

R/V Columbus Iselin was equipped with a hull-mounted 300-kHz narrowband ADCP. This ADCP produced current estimates starting at a depth of 4.6 m. In the shallower waters, from the center of the OSCR measurement domain to near shore, bottom tracking and the ship's gyrocompass were used to estimate true near-surface currents. In less than 5% of the data, the bottom track signal became too weak to use, so the ADCP and gyrocompass data were combined with data from the ship's standard Global Positioning System (GPS) to estimate currents.

In bottom track mode, the theoretical standard deviation for horizontal current from a single ping from this ADCP is 5.7 cm/s (10-m bin, $\pm 30^\circ$ beam angles). With a ping every 1.5 s, 20 min of averaging should reduce this standard deviation to 2 mm/s. Unfortunately, this calculation fails to take into account longer-term biases caused by flow distortion about the vessel, the effect of bubbles entrained near the sensor head, compass errors, and variations in flow during the averaging interval. These other sources of errors, which are difficult to estimate, are likely to dominate in our measurements. Experience suggests though that the combined errors can be expected to be on the order of 1 to 5 cm/s. The same considerations hold true for the other ADCPs used in this study.

2.3. LADAS

LADAS was a towed catamaran system developed by Erik Bock at the Woods Hole Oceanographic Institution for measuring the structure of centimeter-scale surface waves and the modulations of these short waves by long waves. (We use the past tense here since LADAS was lost at sea during a recent experiment on the West Coast.) Its primary instruments were a scanning laser slope gauge [Bock and Hara, 1995], a suite of meteorological instruments, a differential GPS (DGPS) receiver, a six-degree-of-freedom, strapdown motion sensing package [Edson et al., 1996], and a three-axis ultrasonic current meter. Data from this current meter and the differential GPS (DGPS) receiver were utilized in this study.

The three-axis ultrasonic current meter was a UCM 40 Mk II, manufactured by NE Sensors, Inc. This instrument measures currents over a set of orthogonal 10-cm paths by measuring the time of flight of a series of high-frequency acoustic pulses. The instrument has a resolution of 1 mm/s and an accuracy of 3% of the measured value ± 5 mm/s with an integration period of 1 s. The instrument utilizes an internal three-axis flux gate compass and a two-axis tilt sensor to compensate the data for the instrument orientation. The system also includes built-in temperature, conduc-
tivity, and pressure sensors. This instrument was mounted forward on the body of the catamaran, between the two hulls. In this mounting position the sensors were outside the wakes of the pontoons when the catamaran was being towed forward. The current sensors were located at a mean depth of 1.0 m.

The data from the LADAS UCM were combined with the differential GPS data to estimate true currents. The predominant errors in this combined data set are likely due to biases and noise introduced by pitch and rolling motions of the catamaran in the wave field. While to lowest order, these high-frequency motions should average out, they may introduce biases into the estimate since the depth of the UCM measurements varied coherently with the surface waves as the platform pitched up and down.

2.4. USNS Bartlett

USNS Bartlett was equipped with a 300-kHz hull-mounted, narrowband ADCP. In the shallower waters, throughout most of the OSCR measurement domain, bottom tracking and the ship’s gyrocompass were used to estimate true currents. In approximately 3% of the data the bottom track signal became too weak to use, so the ADCP and gyrocompass data were combined with data from a real-time differential GPS system to estimate currents.

2.5. TOAD

The Towed Acoustic Doppler (TOAD) platform is a small tube with stabilizing fins that is designed to hold an ADCP as it is towed on the surface, outboard of a vessel [Marmorino and Trump, 1996]. This system, developed by the Naval Research Laboratory, was designed to keep the ADCP away from the influences of the ship while still providing a relatively stable platform for making current measurements. During the High Resolution Remote Sensing Experiment, a 600-kHz broadband ADCP was deployed from TOAD. The TOAD platform was deployed periodcally from USNS Bartlett throughout the experiment to track near-surface current features.

Because of its small size, the TOAD platform experiences more transient accelerations than the towing ship. These accelerations adversely affected the onboard attitude sensors, making the absolute water velocities measured from TOAD noisier than those from the shipboard system. To minimize this problem the shipboard data were merged into the TOAD data by offsetting the TOAD data so that the average absolute water velocity between 10 and 20 m measured by TOAD was identical to the value measured by the shipboard system. The result of this merging process is that the absolute water velocities reported by both systems between 10 and 20 m will be virtually identical. The advantage of the TOAD data lies in its smaller bins (0.5 m versus 1.0 m) that measure closer to the surface (1.6 m versus 8.8 m) than the Bartlett ADCP.

3. Methodology

This study compares the OSCR current maps with the near-surface current measurements made from three separate ADCPs (Iselin, Bartlett, and TOAD) as well as data from the three-axis current meter mounted at 1-m depth on LADAS. The methodology used to compare these data is relatively straightforward. Data from the in situ sensors were combined with the bottom track velocities, or the differential GPS navigation data where the depth of the water precluded bottom tracking, and platform orientation data to obtain estimates of the Earth-fixed currents at the platform location. These time series were reduced to a sample every 20 min by averaging those values corresponding to each OSCR observation period. We estimate that the errors in alignment of these data-averaging periods are less than a few seconds, since all of the data streams included timing information traceable to GPS time. An equivalent series of surface current data were then constructed by selecting the OSCR data closest to the in situ data in time and space.

Note that while the data were in the form of a time series, this time series was obtained at the time-varying position of the platforms as they moved about the experimental area. Thus conventional time series analyses cannot be usefully applied to these data. Instead, we restrict ourselves to nontemporal statistical comparisons.

Our initial analysis is based on simple scatterplots between pairs of related estimates of the north and east components of the surface velocity. The rms difference in the velocity estimates, which we refer to as \( \sigma_v \), is used to characterize the comparisons. This is the most commonly used statistic in previous intercomparison studies, making our results directly comparable to those studies. The reader is cautioned though not to attribute all of the rms difference to errors in the HF radar current estimate.

The reader should note that throughout this paper we are careful to distinguish between the terms “differences” and “errors.” In our usage, subtracting two current estimates results in a current estimate “difference.” This current estimate difference is likely due to a combination of differences in the quantity measured due to physical processes and to noise in the instruments themselves. We refer to noise within an instrument, causing the instrument to read other than a true value, as an “error.” Thus we are trying to estimate HF radar errors by studying observed differences.

4. Results and Discussion

Before presenting the results, it is instructive to consider the possible causes of differences in surface current estimates made by the OSCR system, an ADCP, and the ultrasonic current meter. The first possible cause is the comparison of dissimilar quantities. The OSCR measures surface currents averaged over a 1.5-km² area and to an effective depth of about 50 cm. The ADCPs measure over an area of at most a few square meters in the bins nearest the surface and measure at an effective depth of several meters, depending on the system and how it is mounted. The ultrasonic current meter measures over a scale length of 10 cm at a depth of 1 m. One should not expect such measurements to agree for a variety of physical reasons. For example, differences could be due to horizontal inhomogeneity caused by local eddies and fronts. Likewise, vertical shear arising from the near-surface boundary layers or internal waves can also lead to differences [Shay et al., 1995]. Here, and elsewhere throughout the paper, by vertical shear we mean those bulk vertical shears remaining after 20 min of averaging.

The second possibility is temporal or spatial misalignments of the measurement data sets. Any misalignments of the data sets, either temporally or spatially, will cause a decorrelation of the results. Given the relatively high accuracy of the data set timing, we do not expect temporal decorrelation to be a problem. Likewise we believe that the spatial mismatch was also small. The in situ sensors utilized differential or standard GPS data for spatial positioning, systems with accuracies of better than 100 m. The other possible uncertainty was the positioning of the OSCR grid locations. In the radial direction, these positions are determined quite accurately by the system range gate timing. In the azimuthal direction, these positions are determined by the physical and electrical alignment of the OSCR phased-array antenna. The estimated physical accuracy of the antenna alignment was less than 0.5°, which would bound the errors in cell positioning to less than 1/3 of the cell size.

Electrical misalignment of the phased array, which could take the form of increased sidelobes in the antenna pattern, is a concern...
with this type of system. No significant correlation was observed between antenna look angle and radial current estimates differences made from each OSCR site and from the Bartlett and Iselin ADCPs. This suggests that phase misalignments of the antenna are at least uniformly varying across the antenna aperture, making substantial errors due to this source unlikely.

A third possibility is systematic biases or noise in the OSCR data. Any biases or noise within the estimates derived by OSCR will contribute to the differences in the comparison with other instruments. These are the errors we are trying to evaluate.

The fourth possibility is systematic biases or noise in the in situ data. Likewise, any biases or noise in the in situ data will also contribute to differences in the comparisons. Such errors could arise from errors in the sensors themselves or the platform motion and orientation corrections. Hence these data depend on the accuracies of the current sensors, bottom-tracking algorithms, or DGPS velocity estimates, as well as compass sensors.

An appreciation for the possible sources of differences led to our general approach of comparing these data streams. In this approach, to the extent that we could, we utilized multiple data comparisons in an attempt to apportion the observed differences to one of the above causes. This approach is explained in detail below.

4.1. OSCR Versus Columbus Iselin

Figure 2 presents the comparisons between OSCR and the Iselin ADCP data. The north and east current component comparisons are shown in the upper panels (Figures 2a, 2b, and 2c) and lower panels (Figures 2d, 2e, and 2f), respectively. The leftmost two panels (Figures 2a and 2d) compare OSCR and the shallowest ADCP bin at 4.6-m depth. The middle two panels (Figures 2b and 2e) compare OSCR and the next deepest ADCP bin at 5.6-m depth. The rightmost two panels (Figures 2c and 2f) compare the data from the two adjacent ADCP bins. The dotted line, which has been placed on each panel for visual comparisons only, indicates the line where the two current estimates are equal. This line does not represent a least squares fit to these data. The rms difference of each of the comparisons, $\sigma_d$, is given in the upper left corner of each panel.

In Figure 2a at least two erroneous points in the OSCR estimates are evident. These wild points can easily be associated with errors in the OSCR estimates since the OSCR-estimated current component value of 90 cm/s is beyond any others observed by either instrument. A third wild point is evident, although its source is not clear. Other than these three wild points, the remaining 401 points are nicely clustered about the line of equal velocity. The standard deviation of the difference is 14.8 cm/s for all 404 points. If these differences were drawn from a Gaussian distribution, the error bounds on this estimate of $\sigma_d$, to the 95% confidence level, are estimated to be ±1.0 cm/s.

Figure 2b shows a similar grouping of points about the equal velocity line, but with a slightly higher standard deviation of the difference of 15.1 cm/s. One point, which is not visible in this figure, has been excluded from the computation of $\sigma_d$ in Figures 2b and 2c because the OSCR velocity estimate was greater than 1.5 m/s. Given the error bars of ±1.0 cm/s at the 95% confidence level, the differences observed between the OSCR and ADCP data at 4.6-m and 5.6-m depth are on the border of statistical insignificance. At the same time, as should be expected, the agreement between the 4.6-m and 5.6-m ADCP bins (Figure 2c) is much better than the agreement between either ADCP bin and OSCR.

Figure 2. Comparisons of the surface current component estimates made from the Iselin ADCP and OSCR. The dotted line indicates the line of equal currents. It does not represent a fit to the data. The rms difference between the estimates, $\sigma_d$, is given in the upper left corner.
4.2. OSCR Versus LADAS

Comparisons of the OSCR, UCM, and ADCP data from LADAS are shown in the six panels in Figure 3. While the total number of points is much smaller for these comparisons because of the limited amount of time that LADAS was deployed during the experiment, all of the comparisons show a similar trend about the line of equal current. The rms differences for these comparisons range from 11 to 16 cm/s.

The LADAS comparisons are particularly interesting due to the presence of three distinct types of sensors. If the differences in the OSCR comparisons were predominantly due to mean vertical shear, we would expect to find that the agreement between OSCR and the LADAS UCM would be substantially better than the agreement of either instrument with the deeper ADCP. This does not appear to be the case. If, on the other hand, the differences were predominantly due to the differences between point measurements and area-averaged measurements, we would expect that the agreement between the LADAS UCM and Iselin ADCP would be superior to either in situ sensor compared to OSCR. Again, this does not appear to be the case.

4.3. OSCR Versus USNS Bartlett

Figure 4 contains the data comparisons between OSCR and the Bartlett ADCP. Note that a single wild point, with a current estimate exceeding 1.5 m/s, was deleted from the OSCR north component data set prior to estimating the rms difference.

4.4. OSCR Versus TOAD

Our final set of data, containing comparisons between OSCR and the TOAD ADCP, is shown in Figure 5. Again, the comparisons show good agreement between the data sets, with rms differences ranging from 9 to 16 cm/s.

4.5. Comparison Summary

The results of these comparisons are summarized in Table 1. The second and third columns present the number of points used in the comparison and the linear correlation coefficient for those comparisons. The rms differences for each comparison are given in the fourth column, along with error bounds for these estimates. These bounds were computed at the 95% confidence level, assuming that the component differences are Gaussian-distributed random variables. The estimates of the variance from a given sample size are thus assumed to be \( \chi^2 \) distributed, and the error bounds are easily computed. The last two columns contain depth corrections as described below.

Several interesting observations can be made from this data summary.

1. All of the comparisons with OSCR show roughly comparable differences of between 9 and 16 cm/s. This places an absolute upper bound on the errors of the OSCR estimates, which is comparable to that reported in previous studies [Shay et al., 1995].

2. There is a statistically significant difference between the north and east rms differences for only two cases, the LADAS UCM and the TOAD 2-m ADCP. These are also the two shallowest instruments. More will be made of this point in the following section.

3. The lowest correlation coefficients are associated with the comparisons of OSCR with the deepest instruments. This suggests that near-surface vertical shear is an important, but not dominant, component in the differences observed between OSCR and the in situ sensors.
between the in situ and OSCR data in the same manner as fluctuating differences or noise.

Figure 6 indicates that the rms differences grow quickly in the upper 4 to 5 m, and then more slowly below that depth. The last column in Table 1, labeled “TOAD rms Shear,” contains estimated rms differences taken from Figure 6 at the depths of the instruments being compared. In making these estimates we assumed that there was no vertical shear in the near-surface layer above the bins sampled by the TOAD ADCP. The reader is cautioned that these results cannot be directly applied to compensate for shear in Table 1, because many of the measurements were taken at different locations and because the analysis does not separate the shear effects from depth-dependent noise in the TOAD ADCP. We have included these values solely for the purpose of comparison. Despite these caveats, the data do suggest that the effects of vertical shear are largest on the differences observed between the deepest and shallowest instruments. Furthermore, it appears that the differences due to shear are probably comparable to the differences due to other sources.

4.7. Calculation of Geometric Dilution of Precision for OSCR

The comparisons we have presented to this point have been limited to scatterplots and first-order statistics. The next step in this analysis is to examine the spatial dependence of the observed differences. During the 2 weeks of the experiment, the two research vessels traversed most of the OSCR measurement domain numerous times. Figure 7 is a map of the locations of the research vessels during the experiment. This wide range of measurement locations, combined with a simple theoretical model predicting the response of OSCR, can be used to examine the spatial dependencies of errors in the OSCR estimates.

Simple figures of merit for OSCR’s ability to estimate surface current components can be derived. (The reader is referred to Lipa and Barrick [1983] for an alternative derivation.) Figure 8 presents a sketch of the geometry pertinent to current component determination with OSCR. Within this diagram, site 1 and site 2 are the locations of the OSCR master and slave sites, respectively. At each point in the OSCR measurement domain, the radial velocities, \( V_1 \) and \( V_2 \), are estimated.

The in-line and orthogonal velocities, \( V_i \) and \( V_o \), can be estimated in terms of the sums and differences of the radial velocities:

\[
\begin{align*}
V_i &= (V_1 + V_2)/2\cos\theta, \\
V_o &= (V_1 - V_2)/2\sin\theta,
\end{align*}
\]  

where \( \theta \) is half of the angle between the intersecting beams. The in-line and orthogonal velocities can then be rotated to obtain estimates of the north and east velocity components:

\[
\begin{align*}
V_n &= V_i \sin\alpha + V_o \cos\alpha, \\
V_e &= V_i \cos\alpha - V_o \sin\alpha,
\end{align*}
\]  

where \( \alpha \) is the mean look angle as defined in Figure 8. Substitution yields

\[
\begin{align*}
V_n &= \left(\frac{\sin\alpha}{2\cos\theta} + \frac{\cos\alpha}{2\sin\theta}\right)V_1 + \left(\frac{\sin\alpha}{2\cos\theta} + \frac{\cos\alpha}{2\sin\theta}\right)V_2, \\
V_e &= \left(\frac{\cos\alpha}{2\cos\theta} - \frac{\sin\alpha}{2\sin\theta}\right)V_1 + \left(\frac{\cos\alpha}{2\cos\theta} + \frac{\sin\alpha}{2\sin\theta}\right)V_2.
\end{align*}
\]  

These equations are of the form \( z = aV_1 + bV_2 \), where \( V_1 \) and \( V_2 \) are random variables representing the radial current measure-
ments. If we assume that the noise in each radial measurement, \( \sigma \), is identical, then the noise of the scaled sum is given by \( \sigma_z = \sigma \sqrt{a^2 + b^2} \). Applying the relationship \((u + v)^2 + (u - v)^2 = 2(u^2 + v^2)\) to (3) yields estimates for the errors in the north and east components:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Number</th>
<th>rms Difference, Shear, ((\text{cm/s}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iselin 4.6-m ADCP</td>
<td>404</td>
<td>0.79, 14.8 ± 1.0, 6.2</td>
</tr>
<tr>
<td>versus OSCR</td>
<td></td>
<td>0.73, 14.5 ± 1.0, 6.2</td>
</tr>
<tr>
<td>Iselin 5.6-m ADCP</td>
<td>404</td>
<td>0.79, 15.1 ± 1.0, 8.1</td>
</tr>
<tr>
<td>versus OSCR</td>
<td></td>
<td>0.70, 15.3 ± 1.0, 8.1</td>
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<td>Iselin 4.6-m ADCP</td>
<td>404</td>
<td>0.99, 3.2 ± 0.2, 1.4</td>
</tr>
<tr>
<td>versus Iselin 5.6-m ADCP</td>
<td>404</td>
<td>0.99, 3.0 ± 0.2, 1.4</td>
</tr>
<tr>
<td>LADAS 1-m UCM</td>
<td>86</td>
<td>0.75, 15.7 ± 2.2, 0.0</td>
</tr>
<tr>
<td>versus OSCR</td>
<td></td>
<td>0.90, 11.2 ± 1.6, 0.0</td>
</tr>
<tr>
<td>Iselin 5.6-m ADCP</td>
<td>404</td>
<td>0.85, 11.0 ± 1.5, 7.7</td>
</tr>
<tr>
<td>versus OSCR (only during LADAS deployment)</td>
<td>86</td>
<td>0.88, 12.6 ± 1.8, 9.1</td>
</tr>
<tr>
<td>LADAS 1-m UCM</td>
<td>86</td>
<td>0.80, 14.4 ± 2.0, 8.3</td>
</tr>
<tr>
<td>versus Iselin 5.6-m ADCP</td>
<td>86</td>
<td>0.84, 13.5 ± 1.9, 10.3</td>
</tr>
<tr>
<td>Bartlett 10-m ADCP</td>
<td>465</td>
<td>0.71, 16.2 ± 0.9, 11.6</td>
</tr>
<tr>
<td>versus OSCR</td>
<td></td>
<td>0.48, 15.3 ± 0.8, 15.4</td>
</tr>
<tr>
<td>TOAD 2-m ADCP</td>
<td>130</td>
<td>0.75, 12.5 ± 1.4, 0.0</td>
</tr>
<tr>
<td>versus OSCR</td>
<td></td>
<td>0.85, 8.6 ± 1.0, 0.0</td>
</tr>
<tr>
<td>TOAD 10-m ADCP</td>
<td>130</td>
<td>0.66, 14.8 ± 1.7, 11.6</td>
</tr>
<tr>
<td>versus OSCR</td>
<td></td>
<td>0.39, 15.9 ± 1.8, 15.4</td>
</tr>
<tr>
<td>TOAD 2-m ADCP</td>
<td>130</td>
<td>0.80, 11.6 ± 1.3, 10.6</td>
</tr>
<tr>
<td>versus TOAD 10-m ADCP</td>
<td>130</td>
<td>0.46, 15.5 ± 1.8, 14.6</td>
</tr>
<tr>
<td>TOAD 2-m ADCP</td>
<td>130</td>
<td>0.78, 12.2 ± 1.4, 10.6</td>
</tr>
<tr>
<td>versus Bartlett ADCP</td>
<td>130</td>
<td>0.43, 15.9 ± 1.8, 14.6</td>
</tr>
</tbody>
</table>

The upper and lower values on each line are the north and east current component statistics, respectively. The last column, representing the magnitude of the vertical shear observed by the TOAD ADCP during the experiment, is based on an analysis of Figure 6.

Figure 5. Comparisons of the surface current component estimates made from the TOAD ADCP and OSCR.

Table 1. Summary of the rms Differences Obtained from Comparisons of Differing Estimates of Surface Current Component Estimates.

Figure 6. The rms differences observed in the TOAD ADCP data between current measurements made at various depths and those made at 1.6-m depth.
Figure 7. Map of research vessel locations during the experiment relative to the OSCR measurement domain.

Figure 9. Map of the north (solid lines) and east (dashed lines) geometric dilution of precision (GDOP) for the OSCR measurement domain.

\[
\sigma_n = \left[ 2 \left( \frac{\sin^2 \alpha \sin^2 \theta + \cos^2 \alpha \cos^2 \theta}{\sin^2 (2\theta)} \right) \right]^{1/2} \sigma, \\
\sigma_e = \left[ 2 \left( \frac{\cos^2 \alpha \sin^2 \theta + \sin^2 \alpha \cos^2 \theta}{\sin^2 (2\theta)} \right) \right]^{1/2} \sigma. \tag{4}
\]

Borrowing from the terminology of the GPS navigation system [Wells et al., 1986], we will refer to the ratios \(\sigma_n/\sigma\) and \(\sigma_e/\sigma\) as the north and east geometric dilution of precisions or GDOPs. These GDOPs can be thought of as multipliers of the noise associated with the geometry of the HF radar measurement. Applying these formulae, we can derive the map of the north and east GDOPs for the OSCR measurement domain shown in Figure 9.

The map in Figure 9 indicates that the north GDOP varies from 1 to 2.5 in the OSCR domain, with the largest errors occurring at the farthest range cells. The east GDOP varies from 0.75 to 1.5, with the largest errors occurring at the northern and southern extremes of the domain. That the east GDOP falls below 1.0 at the farthest

Figure 8. Geometry of OSCR current determination.
range cells should cause no surprise. At these locations, the radial velocity estimates are nearly parallel and so the estimate of the east component of velocity is nearly the average of the two radial velocity estimates. In the limiting case of a point infinitely distant toward the east, the error in the east velocity estimate would go to \( \frac{\sigma_Y}{2} \) due to the averaging of two, like random variables. The apparent lack of symmetry in the map in Figure 9 is due to the fact that the sites are not aligned along a north-south axis.

It is important to note that the GDOP does not take into account the effects of reduced signal to noise that might be expected to decrease the accuracy of the current estimates in the farthest range bins. Its sole purpose is to predict the purely geometric component of the errors expected in the OSCR current estimates. We also note that the expressions in (4) are apparently not consistent with the similar but more general expressions derived by Lipa and Barrick [1983, equations (41) and (42)]. We attribute these differences to minor typographical errors in the paper by Lipa and Barrick. A re-analysis of their least squares approach to current determination in overdetermined systems shows that their corrected expressions reduce to our formula in the case of two sites.

Finally, our results are in disagreement with those of Prandle [1991, equation (2) and Figure 3]. We find that there is a typographical error in equation (2): the terms should be subtracted, not added. Furthermore, Figure 3 was apparently obtained by taking the absolute value of each of the terms in equation (2). This approach cannot be reconciled with our results, which correspond to adding the two terms of his equation (2) in quadrature. (Strictly speaking, this result only holds in the limit of large mean current magnitude. In general, the standard deviation of current magnitude depends on true mean current magnitude in a complex fashion, making it in an inappropriate method for comparison of current measuring devices.)

### 4.8. Apportionment of Errors

The theory of the previous section shows that the OSCR-dependent errors are position dependent. It is reasonable to assume that the errors due to other sources will not be position dependent. This distinction can be used to apportion the errors between the two sources.

The GDOP predictions suggest that the north component errors in our OSCR data should be larger than the east component errors. As we noted previously, there are only two cases where the differences between the north and east errors are statistically significant, and these are for the two shallowest in situ measurements, made by the LADAS UCM at 1-m depth and the TOAD ADCP at 2-m depth.

These observed differences can be used to apportion the observed errors through the observation that the total current difference variance for each component can be split into the sum of the variances of two terms:

\[
\sigma_i^2 = \text{GDOP}_i^2 \sigma_{\text{OSCR}}^2 + \sigma_{\text{other}}^2,
\]

where \( \sigma_{\text{OSCR}} \) is the effective radial velocity variance for OSCR and \( \sigma_{\text{other}} \) represents the variance from all other sources including the in situ measurement errors and the true differences in the measured quantities.

Given a pair of data sets with differing mean GDOP and assuming that the variances \( \sigma_{\text{OSCR}}^2 \) and \( \sigma_{\text{other}}^2 \) are independent of direction or location, we can solve these equations for \( \sigma_{\text{OSCR}}^2 \) and \( \sigma_{\text{other}}^2 \) using the observed mean \( \sigma_i \) for the data sets. The results of such an analysis are shown in the first two lines of Table 2. Note that the average north and east GDOPs for both the LADAS and TOAD data sets are 1.6 and 0.9, respectively. These average GDOP values are determined by the distribution of locations of the LADAS and TOAD during the experiment. The fact that they are the same for LADAS and TOAD is somewhat coincidental.

An alternative approach is to examine the dependence of differences on GDOP within a given data set. Figure 10 contains plots of the square of current estimate differences from both the LADAS and TOAD ADCP/OSCR comparisons as a function of the square of GDOP. (The reasons for this particular choice of parameters will be made clear in the following discussion.) Similar plots for the TOAD and LADAS are not presented because of the limited number of points available from these platforms.

While an increase in the variance of the differences as a function of GDOP is difficult to see, a consistent trend is indeed present in the north component current data. A statistical method for estimating the GDOP-dependent and independent components of the variance is required to examine this trend. We began by assuming that for each point, the component difference is given by the two-dimensional stochastic equation

\[
z_i = \text{GDOP}_i \cdot x_i + y_i,
\]

where \( z_i \) is the observed component difference at the \( i \)-th point, \( \text{GDOP}_i \) is the GDOP at that location, \( x_i \) is the equivalent error in the OSCR radial velocities at point \( i \), and \( y_i \) is the error in the other instrument. Squaring and taking the expected value yields

\[
\langle z_i^2 \rangle = \langle \text{GDOP}_i^2 \rangle \langle x_i^2 \rangle + \langle y_i^2 \rangle + 2 \langle \text{GDOP}_i x_i y_i \rangle.
\]

Note that the expectation value is taken over the range of possible errors, which is, as in Figure 10, geometrically orthogonal to the GDOP axis. Thus we expect that \( \langle \text{GDOP}_i^2 \rangle \) is the GDOP at that location, \( x_i \) is the equivalent error in the OSCR radial velocities at point \( i \), and \( y_i \) is the error in the other instrument. Squaring and taking the expected value yields

\[
\langle z_i^2 \rangle = \text{GDOP}_i^2 \langle x_i^2 \rangle + \langle y_i^2 \rangle.
\]

With the proper substitutions, this is exactly equation (5).

The mean error is very close to zero in these data, and more importantly, we a priori expect the errors to be zero mean, so the optimal estimator for variance is exactly the average of the variance \( \langle y_i^2 \rangle \). Thus each \( y_i^2 \) can individually be thought of as a single point estimate of the local variance. With this as background, we chose to perform a least squares fit of a line to the squared errors \( y_i^2 \) plotted against \( \text{GDOP}_i^2 \). In the above notation the slope and intercept then are \( \gamma_2 \) and \( \gamma_0 \), respectively.

This analysis depends on the independence of the radial errors in OSCR and GDOP. Possible reasons for such a dependence include reduced signal-to-noise ratio (SNR) with distance or an-

<table>
<thead>
<tr>
<th>Platform</th>
<th>Component</th>
<th>Mean GDOP</th>
<th>( \sigma_i ) cm/s</th>
<th>( \sigma_{\text{OSCR}} ) cm/s</th>
<th>( \sigma_{\text{other}} ) cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>LADAS UCM</td>
<td>north</td>
<td>1.6</td>
<td>15.7</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>LADAS UCM</td>
<td>east</td>
<td>0.9</td>
<td>11.2</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>TOAD 2 m</td>
<td>north</td>
<td>1.6</td>
<td>12.5</td>
<td>6.9</td>
<td>5.9</td>
</tr>
<tr>
<td>TOAD 2 m</td>
<td>east</td>
<td>0.9</td>
<td>8.6</td>
<td>6.9</td>
<td>5.9</td>
</tr>
<tr>
<td>Iselin</td>
<td>north</td>
<td>11.1</td>
<td>6.3</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>Bartlett</td>
<td>north</td>
<td>14.7</td>
<td>5.6</td>
<td>12.5</td>
<td></td>
</tr>
</tbody>
</table>
tenna pattern effects. Thus, before applying the technique to the Bartlett and Iselin north data, the correlation of the radial errors with GDOP was examined. This comparison was performed by computing the differences between the radial current estimates from each OSCR site and the in situ currents projected into these same radial directions. We were somewhat surprised to find a statistically significant correlation between these differences and the GDOP. This correlation appears to be due to SNR reduction with distance, as the differences also correlated with distance from the site, but not with the antenna look angle. We found that these correlations were driven by measurements made at distances greater than about 30 km and disappeared when the data sets were limited to points closer than 30 km.

Thus the least squares line fit technique was applied to the subset of the Bartlett and Iselin north data that fall within 30 km of the central point between the OSCR sites. This analysis is somewhat sensitive to wild points so we eliminated all data points from the calculation where the total error exceeded 50 cm/s. This eliminated only four points from the Iselin data set and two points from the Bartlett data set.

The results of this analysis, shown in the last two lines of Table 2, agree substantially with the previous estimates. These results indicate that the effective radial velocity errors in the OSCR system are no worse than 6 to 8 cm/s, values comparable to those of all of the other combined errors.

We refer to $\sigma_{\text{OSCR}}^2$ as the effective radial velocity variance in order to distinguish it from the simple radial velocity variance previously quoted as having a value of $$(2.2 \text{ cm/s})^2$$. We feel that this distinction is necessary since $\sigma_{\text{OSCR}}^2$ is the sum of the simple radial velocity variance plus any additional variance which is correlated with the GDOP. For example, any variance due to measurement field mismatch, such as that resulting from an azimuthal misalignment of the antenna, is directly correlated with location. Given a direct correlation with location, this variance will also be indirectly correlated with the GDOP. Thus the fact that we estimate an effective radial velocity error of 7 to 8 cm/s is not necessarily in contradiction with the manufacturer's assertion of radial velocity errors of 2.2 cm/s.

5. Summary

This study is an attempt to assess the accuracy of remote surface current measurements using HF radars. In this study we have compared coincident near-surface current data from four separate platforms with data from a commercial HF radar system. Intercomparisons of the data from the various systems exhibit rms differences ranging from 9 to 16 cm/s. At the very least, these comparisons provide an absolute upper bound on the errors associated with the current estimates from the HF radar system.

We recognize though that all of the observed differences are not attributable to errors in the remote current estimates. Some of the differences are undoubtedly due to errors in the in situ measurements. More importantly, some of the differences are likely due to physical processes associated with different effective depths at which the measurements are made (i.e., vertical shear), as well as the difference in temporal and areal averaging of the remote and in situ measurements. An improvement in the error estimate for the HF radar system can thus only be obtained by some apportionment of the differences between these possibilities.

In order to further this analysis, we developed a simple model of the effect of measurement location on the HF radar errors. We utilize the fact that HF radar errors vary over the deployment area of our experiment. This allows us to decompose the differences
observed between the HF radar data and those obtained from the in situ sensors. Four such decompositions suggest that the effective radial velocity errors in the HF radar system are no more than 7 to 8 cm/s, a value comparable to the total noise from all other sources of current differences.

Even given HF radar errors as large as 7 to 8 cm/s, such systems can still be extremely useful for a variety of research projects. It is important to note that due to the nature of our analysis we are unable to examine the temporal correlation of the noise. If, as we expect, the noise in the OSCR system is not temporally correlated, this noise will be spread over a broad range of temporal frequencies. The noise within any particular frequency band of interest, say a tidal band, would thus be a small fraction of the values quoted here. For example, the standard deviation within a single frequency bin of a spectral estimate obtained from an 1100-point time series would be \( (8 \text{ cm/s}) / \sqrt{550} = 0.34 \text{ cm/s} \). A realistic tidal surface current of 5 to 8 cm/s, as found by Shay et al. [1995], could be easily resolved above this noise level.

In summary, while HF radar systems have been promoted for remote surface current measurements for over a decade, we believe that their acceptance within the general oceanographic community has been slowed by a lack of validation studies. This study, along with the related studies of Shay et al. [1995] and Graber et al. [this issue], is our attempt to fill this void. These studies demonstrate that the remote sensing of surface currents in coastal areas using HF radar systems is an accurate technology suitable for wider use within the oceanographic community.

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References


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