VALIDATION OF HF RADAR MEASUREMENTS

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HF radars are a unique and powerful tool for measuring surface currents. They provide an unparalleled window into the spatial variations of near-surface currents. But oceanographers who are more accustomed to measuring currents with instruments that actually get wet, may reasonably ask how accurate can such remote measurements be made? And while this is an easy and obvious question to ask, it is an interestingly difficult question to answer.

We have been studying the accuracy of the OSCR HF radar system through analysis of data from the ONR-sponsored High-Resolution Remote-Sensing Experiment that was conducted off Cape Hatteras, North Carolina during the summer of 1993. This experiment provided a unique opportunity to examine the complex questions of HF radar accuracy. Along with several weeks of HF radar data, we had access to multiple *in situ* measurements of current from both moored and ship-based devices. In a series of analyses we have attempted to validate the HF current measurements through comparison with the *in situ* data. The key has been to examine the temporal and spatial variations within these data in order to distinguish the sources of the underlying differences between the systems we compare.

Comparisons with *In Situ* Instruments

When evaluating the accuracy of a new instrument, the typical procedure is to compare side-by-side measurements made with both the new instrument and an older instrument of known accuracy. It is important in such a comparison that the two instruments are measuring the same physical quantities, but this is a problem in evaluating the accuracy of an HF radar. The canonical HF radar measures near surface currents integrated over the upper 50 cm, averaged over a 1 km square and averaged over a 10 minute period. Typical *in situ* current meters measure currents at fixed depths which are typically greater than the HF radar's effective depth, at essentially a single point in space and offer fast response. The differences observed when these systems are compared are a result of differences in the measured quantity combined with the sampling techniques and inaccuracies of the instruments themselves. This makes it difficult to isolate the accuracy of the HF radar from other sources of observed difference.

The first pioneers in this field compared HF radar measurements with drifters [*Stewart and Joy*, 1974; *Barrick et al.*, 1977; *Frisch and Weber*, 1980]. These comparisons were limited by the paucity of data and limits on the spatial and temporal coverage of the drifters, but they served to provide an upper bound on the errors of the HF system of 15-27 cm/s. Some later investigations compared the HF radar data with bottom-mounted ADCPs or moored instruments [*Holbrook and Frisch*, 1981; *Leise*, 1984; *Porter et al.*, 1986; *Matthews et al.*, 1988; *Shay et al.*, 1995], finding differences ranging from 9 to 17 cm/s. *Prandle* [1991] performed a similar study, but limited the comparisons to tidal and lower frequencies. The argument was made that these low temporal frequencies imply low spatial frequencies, making the *in situ* measurements made at a point more comparable to the area- and time-averaged HF radar measurements.

In our initial study (*Chapman et al.*, 1997) we compared *in situ* measurements from ship-mounted and towed ADCPs with HF radar measurements. We began by averaging the *in situ* data into 20 minute samples, corresponding to the OSCR sampling period. A pseudo time-series was then constructed from the time series of OSCR current maps, by tracking the movement of the ship through the OSCR measurement domain. Thus we constructed a subset of the OSCR data that was directly comparable to the *in situ* data set.

The direct comparisons of HF and *in situ* current measurements made in this way, an example of which is shown in Figure 1, indicate differences of 8-15 cm/s. But from this limited form of comparison it is impossible to determine how these differences are apportioned between errors in the HF radar, errors in the *in situ* sensors, or differences in the measured quantities.

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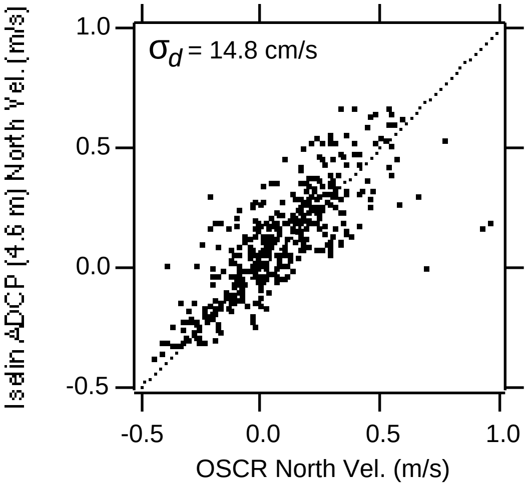

Fig. 1: Comparison of north component of near-surface current as determined by a ship-mounted ADCP at 4.6 m depth and OSCR. The rms difference between the estimates is 14.8 cm/s. The dotted line is a line of equal velocity.

We have improved on these analyses by creating a model of the errors in the HF radar, and examining how these errors differ from those of the *in situ* sensors. This simple model allows us to separate out the various sources of difference. We began by considering geometric dependence of errors in the HF radar.

Geometric Model of HF Radar Errors

As described elsewhere in this issue, the HF radar estimates vector currents by measuring the radial currents from two separate stations. These two radial estimates are then combined to form estimates of the vector current at each point in the measurement domain. It is reasonable to assume that each of the stations measures the radial velocity to the same levels of accuracy. We will further assume that with proper installation of the HF radar systems (in particular the proper physical and electrical alignment of the phased array antennas) that these radial velocity errors are relatively position independent, at least for those ranges where the signal-to-noise ratio is sufficiently high. It then turns out that combining these two radial velocity measurements into a vector current measurement imposes a position dependent error on the vector components.

This is most easily seen by considering Figure 2, which indicates the station locations and coverage area of the OSCR system for the High-Res experiment. Assume that each radial velocity measurement has an associated rms error of σ_r. Consider the errors in the North and East current components determined at a point at the far extreme of the map, due East of the stations. As the range increases, the East component of the velocity takes the form of the average of the two radial components, and thus the rms error in the east component approaches $\sigma_r / \sqrt{2}$. In contrast, the North component of the current is related to the difference of the radial components, a difference of large numbers, and so we would expect the errors to be significantly larger than σ_r.

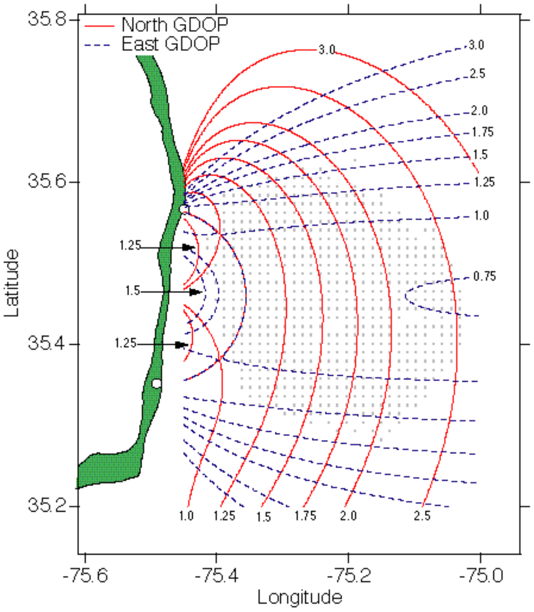

Fig. 2: Map of the North (solid red lines) and East (dashed blue lines) Geometric Dilution of Precision (GDOP) for the OSCR measurement domain. The circles along the coast designate the OSCR sites, and the gray dots indicate the OSCR measurement locations.

We in fact have worked out a model for the positional dependency of the rms errors in the current components, the results of which are shown by the contours in Figure 2. We write that the errors in a current component are given by

$$\sigma_n = GDOP_n \ \sigma_r , \quad \sigma_e = GDOP_e \ \sigma_r$$

where σ_n and σ_e are the rms errors in the north or east directions, σ_r is the radial velocity error from a single station, and $GDOP_n$ and $GDOP_e$ are the Geometric Dilution of Precisions, factors determined by our model. (The GDOP terminology was borrowed from the GPS community, e.g. see *Wells*, 1986)

The contours of constant GDOP in Figure 2 indicate that the errors in the north component of the HF radar current measurements will be larger than in the eastern component. Furthermore, the errors in the HF radar determination of the north component of the current vary significantly with location within the measurement footprint.

As mentioned above, the differences between the HF radar and *in situ* data can be attributed to three terms:

$$\sigma^2_{diff} = \sigma^2_{HF} + \sigma^2_{insitu} + \sigma^2_{physics}$$

where σ_{diff} is the rms difference between the measurements, σ_{HF} is the rms error in the HF radar measurement, σ_{insitu} is the rms error in the *in situ* measurement, and $\sigma_{physics}$ is the rms difference in the physical parameters measured by the HF radar and *in situ* instruments. We have assumed here that the errors in the *in situ* measurements and the rms differences in the physical parameters are uncorrelated with the rms errors in the HF radar measurements, an assumption that we have verified by statistical analysis of our data sets.

Our problem is thus reduced to finding σ^2_{HF} given the observed σ^2_{diff}. Our model suggests that the observed errors should be expressible as

$$\sigma^2_{diff} = \sigma^2_r \; GDOP^2 + \sigma^2_{other}$$

Figure 3 is a plot of the squares of the observed differences in the north current component versus the square of $GDOP_n$ as determined by the model and the *in situ* measurement location. While these data are obviously noisy, a least squares linear fit does suggest that σ_r is of the order of 7-8 cm/s, a value comparable to the rms noise in the *in situ* sensors. While all of this might seem a bit round about, we know of no other way of separating the accuracy of the HF radar from the other sources of differences.

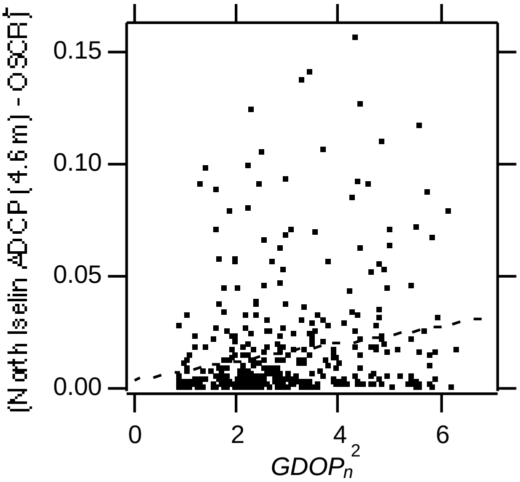

Fig. 3: Variations of the square of observed current component differences with $GDOP^2$. The dashed line represents a least-squares linear fit to these data, the slope of which indicates σ_r, the noise in the radial component of OSCR currents.

Error Budget

As a further check, the error budget above can be further expanded, with the individual terms $\sigma^2_{physics}$ each accounted for separately. This can be done either from the data or from geophysical models.

The data-centric approach examines the structure functions of the current, or the expected rms value associated from currents measured at two different locations, depths or times, as a function of distance, depth or lag. Figure 4 contains the spatial structure function of the expected differences as estimated from the OSCR data sets and several moored current meters.

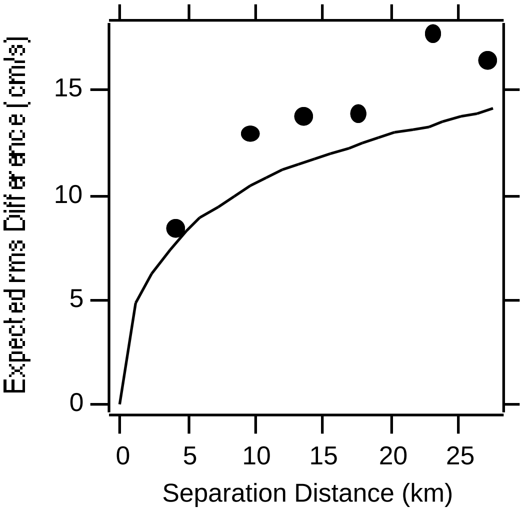

Fig. 4: Expected rms differences between near-surface observations as a function of cross-shelf separation. The solid line shows estimates of the rms differences for OSCR versus cross-shelf lag and the solid dots shows values for pairs of moored current meters.

While Figure 4 provides an estimate of the magnitude of the differences attributable to spatial inhomogenieties in the currents, these differences do in fact vary in a complex manner. This is shown in Figure 5, which plots contours of the rms differences (black), along with the magnitude of the complex correlation coefficient (red), for the OSCR currents referenced to a single OSCR cell near the middle of the measurement domain. The alignment of the mean differences with the Gulf Stream is evident, along with associated cross-stream decorrelation of the current fluctuations.

Alternatively, geophysical models can provide estimates of the expected differences, by modeling such physical processes as horizontal current variability, the Stokes drift, Ekman drift and current-induced baroclinicity.

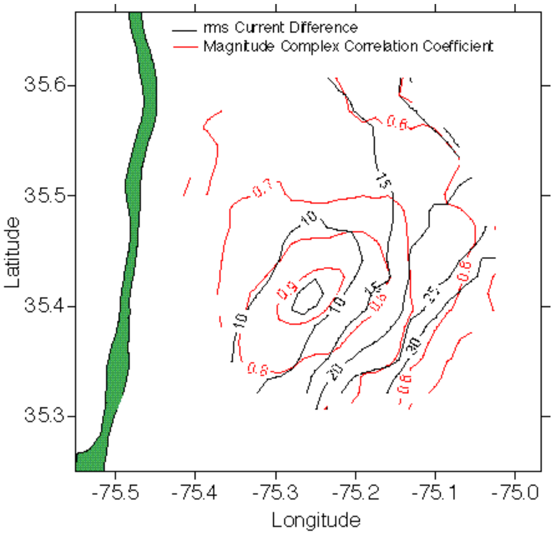

Fig 5: Spatial variability of OSCR surface currents calculated with respect to a single OSCR cell. The black contours are the rms difference for speed and the red contours are the magnitude of the complex correlation coefficient at zero temporal lag.

Graber et al. (1997) combined these approaches to examine how much of the total observed variance can be accounted for. They concluded that 40 to 60% of the observed rms differences between the radar-derived surface current and the near-surface current measurements can be explained. Their study indicated that differences due to spatial separation and baroclinicity appear to be comparable to the errors in the radar measurements themselves. However in strongly wind forced ocean conditions the Stokes and Ekman drift terms can easily dominate these differences.

Conclusion

Direct comparisons of HF radars with *in situ* instruments place an upper bound on the accuracy of the radar-derived current measurements of 10-15 cm/s. These estimates can be improved by examining the spatial dependence of the variability of observed current differences. This procedure suggests that the radar-derived radial velocity errors are more likely on the order of 7-8 cm/s. Further analysis of the underlying causes of differences suggests that most of the differences can be accounted for in terms of surface current variability in space, depth and time; as well as errors in the *in situ* and radar-derived currents. We conclude that when properly deployed, HF radars can accurately measure ocean surface currents, providing a unique tool for near-shore monitoring.

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