Using Multifrequency HF Radar to Estimate Ocean Wind Fields

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Abstract- As indicated by growing deployments world wide, HF radar is an increasingly important tool for mapping coastal surface currents. It has been used to determine wind direction. We report further on the ability of multifrequency HF radar to measure the vector wind field and the impact that such measurements have on the measurement of wind fields over coastal land and sea. In this study we use a yearlong 2000-2001 data set collected over Monterey Bay, California. Our Multifrequency Coastal Radars (MCR's) operated at 4.8, 6.8, 13.4 and 21.8 MHz, measuring currents at effective depths of about 2.5, 1.8, 0.9 and 0.6 m respectively. For training and validation we use the M-1 buoy deployed by Francisco Chavez at the Monterey Bay Aquarium Research Institute. Validation results over the year time span indicate standard errors of prediction of 1.7 m/s for wind speed and 25° for direction with biases of 0.1 m/s and 0.3° respectively. We discuss limitations of this technique at low wind speeds. Finally we present a regional wind field assimilating HF radar estimates and demonstrate the beneficial impact of multifrequency HF radar, wind field measurements, on estimation of the coastal wind field over both land and sea.

I. Introduction

HF (decameter wavelength) surface-wave radar is an increasingly useful tool for observing near-surface currents in the coastal ocean (Fig. 1) as part of the Coastal Ocean Observing System (COOS). We point out that such radars, if equipped for multifrequency operation with real aperture antennas, can produce maps of surface wind field, surface wind stress and surface waves, plus ship detection and monitoring. Here we discuss experiments in mapping the km-scale, vector wind field over the ocean. Further, we demonstrate how HF radar wind field measurements can be combined with shore-based anemometers to produce a wind field estimate over both land and sea. Although most HF radar systems operate at a single frequency, we focus on Multifrequency Coastal Radar (MCR) that measures currents at four depths in the top few meters. MCR's use a 50 m long, physical array receive antenna near the coastline. MCR systems are research instru-

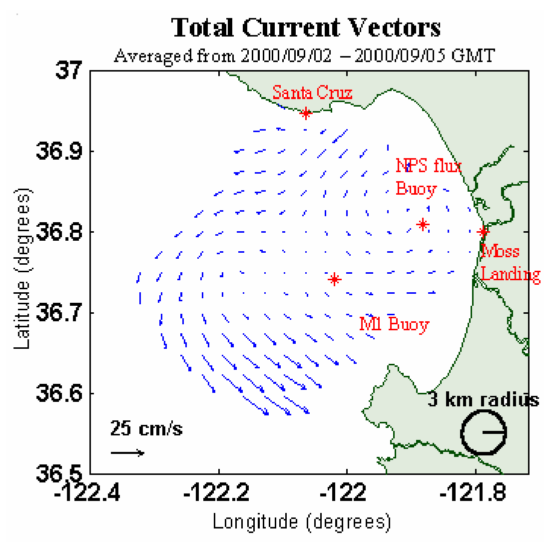

Fig. 1. Monterey Bay, California site diagram showing the HF MCR's at Long Marine Lab. (near Santa Cruz CA) and Moss Landing Marine Lab. (near Moss Landing CA) and the M1and NPS air-sea flux measurement buoys (for wind speed and direction).

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ments operating at 4.8, 6.8, 13.4 and 21.8 MHz, measuring currents at effective depths of 2.5, 1.8, 0.9 and 0.6 m respectively.

The ratio of the HF echo power in the approaching and receding Bragg lines of the Doppler spectrum can be used to estimate wind direction [1, 2, 3]. We have successfully used MCR currents at all effective depths as well as the Bragg line ratios to estimate the vector wind [4]. We use a nonlinear Partial Least Squares (PLS) method to build a predictive model, based on regressions from a training data set. Applying this method to an annual data set we find standard errors of prediction (SEP's) of 1.7 m/s for wind speed and 25° for direction with biases of 0.1 m/s and 0.3° respectively. Such wind field maps have applications in data assimilation into high-resolution coupled air-sea meteorological models (e.g. COAMPS), recreation, air-sea rescue and forest fire control.

II. Data sources and collection

The observational geometry is shown in Fig. 1 with MCR's located at the Long Marine Lab. of the University of California at Santa Cruz and at the Moss Landing Marine Lab. of the California State University System. The surface currents shown were averaged over a three-day period. Data on wind speed and direction were collected from the M1 buoy, operated by the Monterey Bay Aquarium Research Institute (MBARI).

HF radar data from the radar sites of Fig. 1 were processed using beamforming techniques to yield Doppler spectra. These spectra were then processed to yield radial currents and the Bragg line power ratio [4]. The radial currents from the two sites were combined to form surface current maps, see Fig. 1. Data derived from MCR radar measurements, used here as observables, are as summarized follows:

1. U and V components of the radial currents at all four radar frequencies, corresponding to four effective depths in the top 3 m of the water column. One set for each MCR site.
2. Current vector components U & V, speed and direction at all four radar frequencies, i.e. at four effective depths
3. Bragg-line ratios observed at both observational sites
4. Wind direction estimated from Bragg-line ratios. (as determined by an empirical model [1])

Analysis required data from both radar sites and from the M1 buoy (for training and assessment). In spite of instrument outages some 724 hourly data sets were collected in 2000-01.

III. Estimation of wind vector using partial least squares and comparison with buoy measurements

Partial Least Squares (PLS) was used to derive empirical predictive models for wind speed and direction that utilized multifrequency HF radar data as discusssed above. PLS is a linear regression technique developed in the 1960s that is similar to Principal Components Regression (PCR) [5]. However, PCR first decomposes the matrix of observed values and regresses the scores against the wind, while PLS uses both the observed data as well as the wind data in the decomposition. PLS is well suited to situations with many input variables conveying similar information, but having poorly defined relationships with the parameters we desire to estimate, namely wind vector (U & V) components [6].

All the 52 variables (summarized above) from radar observations at the two sites were used in the PLS training process. Note that some of these 52 variables can be derived from others, e.g. the current speed and dirction can be derived from the U (eastward) and V (northward) current components, but have non-linear relationships. Bragg line ratios are translated into wind directions with respect to the radar look direction using the method of Georges et al. [1]. This is done so that known nonlinear effects, e.g. rectangular to polar conversion, are reduced to a minimum. There is a lot redundant information in this set of input variables and we rely on PLS to sort out the most important variables and weight them most heavily in the prediction algorithm dervived from the 'training' data set. In this case we used about 2/3 of the data set as the training set and then applied the resulting PLS prediction algorithm to the remaining 1/3 of the data set to evaluate the algorithm. The year long 2000-2001-experiment period allowed testing over a long time period with varied environmental conditions.

PLS model results using the 2000-2001 data set are quite encouraging, shown by the wind speed validation in Fig. 2, below -- direction errors are discussed later. The standard error of prediction (SEP) when compared to M1 buoy measurements was 1.7 m/s with a bias of –0.1 m/s (regression slope of 0.64 and R^2 = 0.47) for wind speed and 25.4° with a bas of 0.3° for wind direction (slope = 1.03 and R^2 = 0.89).

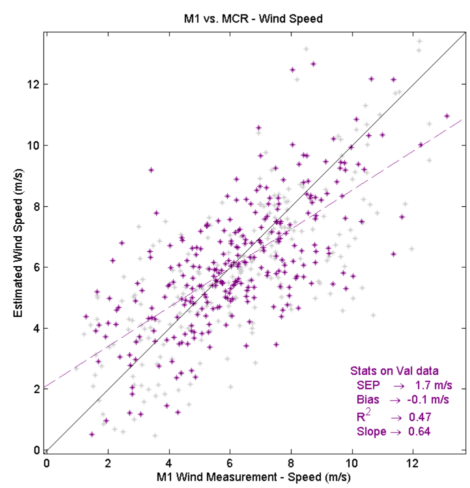

Fig. 2. Validation scatter plot for HF radar estimates of wind speed as compared to M1 buoy measurements. The grey data points are the validation data set shown to give a complete picture of the data set. The solid line fits are for perfect estimates; the dashed lines for relationships estimated by PLS.

In Fig. 3 below we show a wind field map over Monterey Bay created using the multifrequency HF radar PLS technique. Winds compare well with the buoy measurements (red arrows) and in this case winds are away from the prevailing wind direction (WNW) due to the passage of a low-pressure system.

It is likely that some of the difficultly of using measured ocean currents to estimate wind comes from the lag between the change in wind and the resulting change in ocean currents. Therefore, additional PLS models were built that included time history (a form of Kalman filtering). We compared a model built on single hour of MCR data per wind estimate with a model that also included the previous hour of MCR data. The results showed lower biases due to the inclusion of more data, but the SEP did not improve.

In our view the performance of our algorithm can be improved by both editing out estimates that are likely to be wrong and improving the estimates we retain. In the former category are wind direction estimates when the winds are < 3 m/s. Since the phase speed of the shortest (6.6 m) ocean waves that we sense with our system is 3.2 m/s, we would not expect radar echoes from wind driven waves when the wind

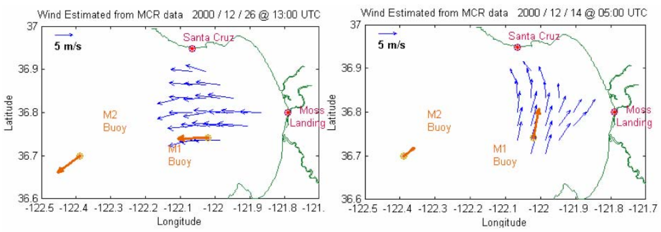

Fig. 3. Example wind field maps over Monterey Bay showing winds from the east and south (away from the prevailing wind direction WNW) during the passage of low-pressure systems in December 2000.

speed is < 3 m/s for some tens of minutes. Hence, for wind speeds < 3 m/s we should discard wind direction estimates because the waves we sense are not wind driven. Fig. 4 confirms this idea, as all the large outliers are for wind speeds is ≤ 3 m/s. We plan to include this effect in future algorithms.

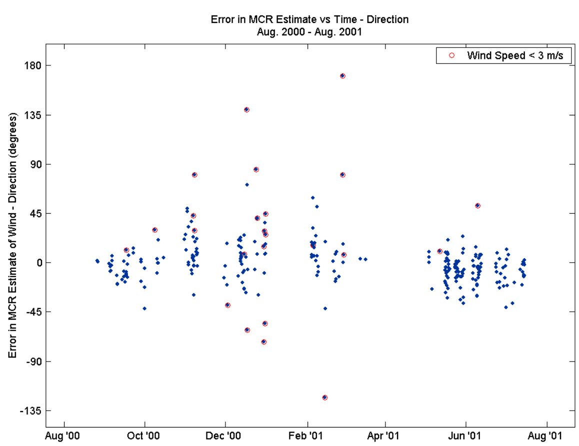

Fig. 4. Error in MCR estimates of wind direction over a year period in 2000-2001. Note that outliers are for wind speeds < 3 m/s.

IV. Objective Analysis of Regional Wind Fields over Land and Sea Using HF Radar Measurements and Land-Based Anemometers

To show the usefulness of HF wind field mapping capability we assimilate our HF wind measurements into a retional wind field analysis over both land and sea. We compare the regional wind field with and without the HF measurements with a meteorological buoy in the HF radar footprint and other surface wind measurements by land-based anemometers. The test bed for this demonstration is shown in Fig. 5 below. We use the WOCSS (Winds on Critical Streamline Surfaces) methodology [7] to construct an objective analyses of wind observations that account for the fact that stable layers in the atmosphere suppress vertical motions and force air flow around hills and ridges, rather than over them. The WOCSS code defines surfaces where flow should take place, given that there is a maximum height to which the kinetic energy of the wind can lift a parcel of air in a stable atmosphere. Maximum height is based on the premise that an air parcel's vertical displacement balances the original kinetic energy of the flow at low altitudes with the energy required to change altitude in the presence of a buoyant restoring force.

The relationship above determines the maximum height for each of a number of flow-following surfaces, which may intersect the terrain when the atmosphere is stable. A second interpolation defines winds on the new surfaces. Then, these "first guess" winds are iteratively adjusted to reduce two-dimensional divergence on the flow surfaces. Winds are set to zero where the flow surfaces intersect the terrain so the iterative adjustments force flow around terrain obstacles. The method performs well when there is adequate input data [8]. Further information is in Ref. [9]. The stations within the domain used for WOCSS analyses are marked (×) in Fig. 5; stations outside the area were used, but were weighted less heavily.

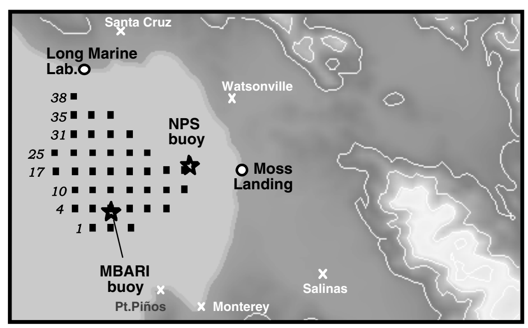

Fig. 5. Locations of MBARI (❍), M1 and NPS buoys (✩), land stations (**X**), locations used for wind estimates (■); 200 m contours.

Inputs required for WOCSS analysis are surface winds (HF winds and anemometers) and at least one temperature and wind sounding. Soundings are sparse and we were forced to use the 0000 UTC and 1200 UTC soundings from Oakland, about 100 km north of the center of Monterey Bay. The available surface observations were not ideal, having been collected for the purpose of estimating winds around San Francisco Bay, but there were usually at least a few sites to the south and east of Monterey Bay, as well as the more numerous sites inland and to the north. The dearth of available stations is an important reason for developing alternatives, especially in locations where no wind measurements are available over the water.

The crux of our experiment is to estimate winds over Monterey Bay with and without the wind data from our MCR HF radars and then compare these two estimates with winds measured in situ by the M1 meteorological buoy shown in Fig. 5. We have framed the results in the table below, in terms of regression plots with HF wind estimates on the x-axis and buoy measurements on the y-axis. Thus, the regression line on such a plot has a slope a and an intercept b.

It is obvious that the WOCSS objective analysis without MCR winds does not specify the wind at the M1 buoy very well. As expected, the estimates are improved when the HF radar wind values are included (WOCSS with MCR) among the inputs for the objective analysis. However, the WOCSS analyses with MCR winds are still not as good as those from MCR alone (Fig. 2). The reason for this is that the first guess fields used in the objective analyses are derived from inverse distance weighted interpolation, which results in considerable smoothing, and the wind at any point is heavily influenced by other nearby winds, which may differ from the actual wind at the point. With no terrain features in the bay, iterative adjustments do not significantly change the first guess winds. This artifact also explains the poor estimates at the buoy when WOCSS only uses onshore observations. The winds over land are weaker than over the Bay, resulting in pronounced underestimation of wind speed without HF sea winds.

Parameter at M1 buoy	Intercept, a	Slope, b	Correlation coefficient
WOCSS with MCR:			
u – m s^{-1}	–1.2	0.96	0.85
v – m s^{-1}	–0.7	0.77	0.46
Speed – m s^{-1}	1.3	0.93	0.59
Direction – °	21.1	0.90	0.89
WOCSS without MCR:			
u – m s^{-1}	–3.1	2.28	0.85
v – m s^{-1}	–1.0	1.42	0.37
Speed – m s^{-1}	4.4	0.25	0.08
Direction – °	23.7	0.97	0.80

In Fig. 6 below we show a wind field over the Monterey Bay region calculated using both HF wind measurements over the water and anemometer wind measurements over land as inputs to the WOCSS objective analysis scheme. Note the increased wind speeds in the center of the bay where the HF wind measurements make a helpful impact.

One of the questions we sought to answer was whether or not the WOCSS objective analyses would be changed much by the availability of MCR winds. The direction differences, on average are small, less than ±15° everywhere. However, the availability of MCR winds changes the speed estimates substantially over that part of the Bay covered by the radar and these estimates are more accurate. This effect is evident in the table above as well as Fig. 6. Throughout the domain, the average winds speeds are increased by the use of MCR winds. This is the result of the aforementioned artifact of inverse distance weighted interpolation. This argues that the WOCSS analysis needs to be tailored to the region and measurements available in order to obtain maximum accuracy.

We conclude that multifrequency HF radar measurements of the vector wind field are useful in estimating the km-scale, wind field on both land and sea in coastal regions. This leads to applications that must deal with km scale features in the surface wind, e.g. surface drift of toxins or debris, air-sea rescue, brush and forest fire control near the coast, recreation (sailing, surfing, fishing, etc.) and air-sea interaction.

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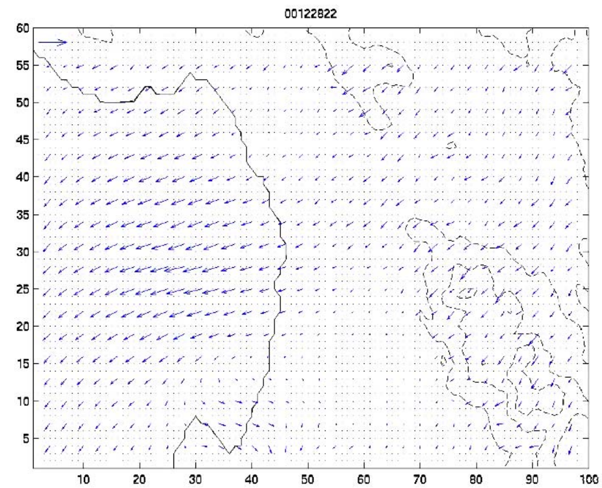

Fig. 6. Regional wind field merging HF and shore wind measurements. Note vorticity near Monterey Peninsula headland at bottom center.

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