Mapping Wind Direction with HF Radar

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Besides the measurement of ocean surface currents, high-frequency (HF) radar has also been demonstrated to be effective at measuring the wind direction at scales on the order of one to several kilometers and over areas of millions of square kilometers in the case of sky-wave HF radars (Georges *et al.*, 1993) and many hundreds of square kilometers in the case of groundwave HF radars. The capability to estimate the wind direction at high resolution over large areas makes HF radar unique in that it is ground based, yet is capable of collecting remotely sensed measurements of the oceanic wind field that could prove beneficial to mariners, weather forecasters, ocean and atmospheric modelers, offshore operators, and recreational users. Not only are such measurements useful to a variety of people, but they would be expensive and difficult, if not impossible, to obtain through other means, such as through the use of buoys at this resolution.

Background

Some of the first work that involves measurements of wind parameters using HF backscatter dates back to Long and Trizna (1973), where a sky-wave HF radar at the U.S. Naval Research Laboratory in Maryland was used to obtain measurements of wind direction over large areas of the Atlantic. Sky-wave radars offer wind direction coverage of huge areas of the ocean; however, their spatial resolution (~10 km) does not approach that of ground-wave systems (~1 km).

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Since the early sky-wave work, many studies have been conducted by a number of different groups for the purpose of measuring wind direction over both large areas of the ocean using sky-wave radars and in coastal regions using groundwave radars. A few examples of groundwave measurements include Heron *et al.* (1985) and Heron and Rose (1986), who used HF radar measurements to obtain estimates of both wind direction and the variability in the winds near the coast.

How Wind Measurements Are Made

HF radar measurements are unique in the sense that radar backscatter is received from Bragg-resonant waves propagating both away from the radar location and toward the radar location. Furthermore, ocean gravity waves in the Bragg-resonant regime have wavelengths such that they may reasonably be assumed to be locally generated by the wind. If the wind has been blowing for a long enough time and over sufficiently long fetch, the two-dimensional distribution of surface wave energy in equilibrium with the wind can be modeled as a cardioid distribution as a function of angle with respect to the wind direction. The form of this distribution was suggested by Longuet-Higgins *et al.* (1963) to be:

$$G(\theta) = A\cos^{s}(\theta/2) \tag{1}$$

where $G(\theta)$ represents the angular distribution of wave energy, A is a constant, θ is the angle from the direction of maximum wave energy (i.e., the angle to the wind), and s is a spreading parameter. Plots of this cardioid function are shown in Figure 1 along with backscatter spectra corresponding to different radar look directions relative to the wind direction. Positive Bragg peaks in these spectra are associated with waves approaching the radar site, whereas negative Bragg peaks are associated with waves receding from the radar site. The "height" of these peaks is directly related to the energy within the approaching and receding wave components. It is the relative height (i.e., ratio) of the two Bragg peaks that contains information on the wind direction.

The relationship between the Bragg peaks and wind direction may best be understood through examples with reference to Figure 1, and to the Bragg ratio (in dB), which is defined as:

$$\zeta = 10\log(B^{+}/B^{-}) \tag{2}$$

where B^+ and B^- are the positive and negative Bragg peak levels, respectively. If, for example, waves propagating toward the radar are much stronger than waves propagating away from the radar, then the Bragg ratio is large and positive, and the wind is assumed to be directed toward the radar (e.g., left panel of Fig. 1). The opposite condition occurs when the wind is directed away from the radar. If the wind is blowing at right angles to the radar direction, then $B^+ \approx B^-$ and the Bragg ratio is near zero (e.g., center panel of Fig. 1).

If one defines both approaching and receding radar look directions relative to the wind (e.g., Fig. 1), then the Bragg ratio, using (1) and (2), is related to the wind direction by:

$$\zeta = 10\log\left[\frac{\cos^{s}\left(\frac{\theta^{-}-180^{\circ}}{2}\right)}{\cos^{s}\left(\frac{\theta^{-}}{2}\right)}\right] = \log\left[\tan^{s}\left(\frac{\theta^{-}}{2}\right)\right] \tag{3}$$

where θ^- is the angle between the wind direction and the receding Bragg waves. Equation (3) can be inverted for θ^- and, hence, the wind direction if a value for the spreading parameter, s, is assumed. (Commonly a value of s = 4 is used.) There is, however, a left-right ($\pm\theta$) am-

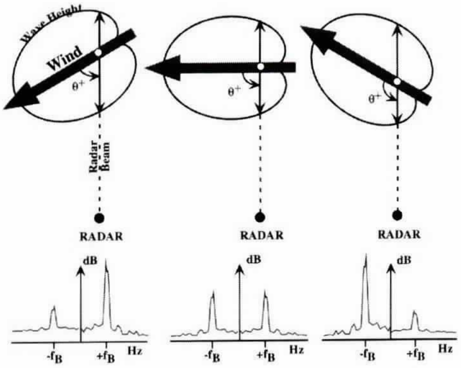

*Fig. 1: Sample distributions of surface wave energy as a function of angle relative to the wind direction for cases with wind blowing toward (**left**), at right angles to (**middle**), and away from (**right**) the radar look direction. Sample backscatter spectra below show relative heights of the approaching (+) and receding (−) Bragg peaks for each case and θ^+ denotes the angle between the wind and the approaching wave directions.*

biguity in the solution that must be resolved using independent observations, assumptions about time continuity, or (preferably) estimates from a second radar site viewing the ocean from a different angle.

Results from a Phased-Array System

In Wyatt's paper (Wyatt 1997) on directional wave mapping using the Ocean Surface Current Radar (OSCR) system, wind direction maps are also included (see Wyatt 1997, Fig. 4, this issue) that show the effect of a low pressure system moving past the radar sites. Here we present a similar result from an OSCR deployment off Duck, North Carolina in October 1994. Surface current data from this experiment are described by Haus et al. (1995) and Shay et al. (1997). Importantly, the experiment included offshore moored wind measurements within range of the OSCR sites. In addition, the Army Corps of Engineer's research pier at Duck collected wind measurements at the nearshore boundary of the radar field.

Wind direction estimates from the OSCR cell closest to the offshore mooring are shown in Figure 2, together with observed wind directions, for a 2-day period that included the passage of a sharp front on 9 October. The remotely sensed direction estimates agree very well with those measured at the mooring. In this case, data from only one of the two OSCR sites (the master site) were used, and the directional ambiguity in the Bragg ratio was resolved by minimizing the differences with the mooring data. Hence the OSCR estimates are not independent of the mooring data in this example, but the results are still very encouraging. (During this experiment, the noise level of the OSCR slave site was such that useable Bragg ratios were unavailable most of the time.)

The important potential of HF radar data with regard to the wind field is in their ability to map wind direction and detect frontal boundaries (sudden changes in direction) and small-scale storms (e.g., waterspouts, thunderstorms). High resolution wind direction maps from before and after the frontal passage of 9 October are shown in Figure 3, together with observed directions at the mooring and on the research pier. Again, these estimates were made without the benefit of the second radar site. They are, nonetheless, remarkable in terms of the two-dimensional views they provide. Primarily onshore winds throughout the region shifted to alongshore with the passage of the front. In addition, the radar maps show variations in wind direction over horizontal scales of just a few kilometers. Wind stress divergences and curls over these scales, and their impact on coastal mixing and circulation, can only be investigated using HF radar systems.

Results from a Direction-Finding System

The wind direction mapping described above was accomplished using

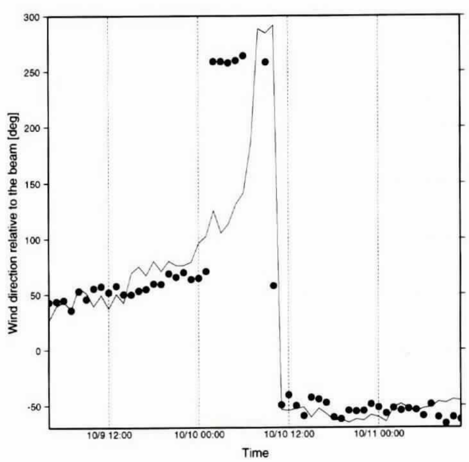

Fig. 2: Wind direction relative to the master radar site measured at a wave buoy off Duck, North Carolina in October 1994 (solid) together with estimates from the HF radar (symbols).

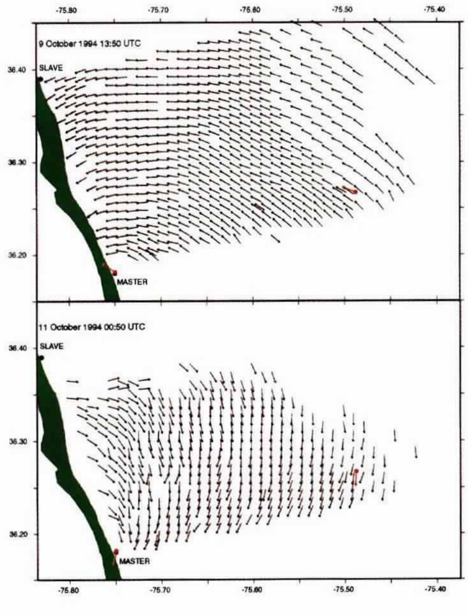

Fig. 3: Wind direction maps from 9 and 11 October 1994 off Duck, North Carolina from OSCR measurements at the master HF radar site. The measured directions at an offshore mooring and from a research pier are also shown in red.

phased-array systems where the beam is electronically "steered" to a particular direction and the entire Bragg peak energy ratio is measured. It is likewise possible to use backscatter data from direction-finding systems, such as the CODAR SeaSonde, to map wind direction using compact colocated antennas. This can be done by extending the surface current algorithms (e.g., Lipa and Barrick, 1983; Barrick and Lipa, 1997) to provide the Bragg power ratio for the extracted bearing angles corresponding to the particular Doppler frequency bin (or radial velocity). The estimation of wind direction is, therefore, more restrictive than surface current estimates, because both Bragg peaks must produce a similar bearing estimate for each radial velocity bin. Like the phased array, wind direction estimates for a particular grid location must be available from both radar sites if two-site data are to be used to resolve the direction ambiguity.

An intitial attempt at wind direction mapping using two SeaSonde systems off the Oregon coast is shown in Figure 4. A reversal of alongshore wind direction from downwelling-favorable to upwelling-favorable between 20 May and 21 May 1996 is clear in the figure, along with the suggestion of small-scale structure similar to that observed off North Carolina by the OSCR system.

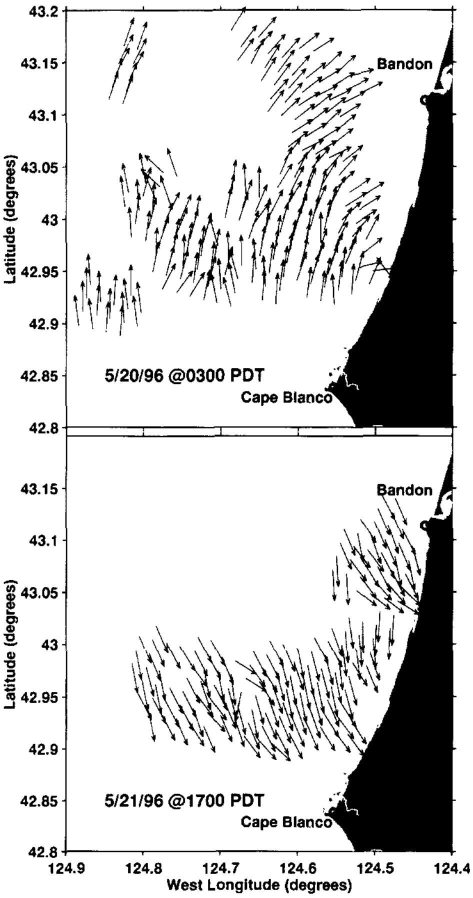

Fig. 4: Wind direction maps from 20 and 21 May 1996 off Bandon, Oregon from two-site SeaSonde measurements at Bandon and Cape Blanco.

Conclusions

Mapping marine surface wind direction is another unique capability of HF radar systems. Although still in the preliminary stages, this technique may yield synoptic measurements of coastal wind variations with resolutions of only a few kilometers. New systems under development, such as the multifrequency, phased-array system mentioned in Teague *et al.* (1997) should have better sensitivity for both wind and wave calculations because their computer-controlled design will allow rapid changes in the transmit and receive parameters. The multifrequency aspect of these systems will also allow for comparisons of wind direction estimates from a range of frequencies and, hence, a range of Bragg wavelengths that may help to assess the fundamental assumptions made about equilibrium conditions. Since ocean waves at different wavelengths respond differently (directional relaxation) to changes in wind speed and direction, the methodology described here could also be applied to infer the directional distribution of ocean waves.

Mapping of wind direction is possible from both phased-array and direction-finding HF radar systems. Results from the latter presently can have less spatial resolution due to the need to obtain simultaneous direction solutions from both positive and negative Bragg peaks.

It should be pointed out that the measurements described here yield maps of wind direction only. They do not provide estimates of wind speed. Thus it is not possible to obtain a true vector wind field in this way. Nonetheless, the ability to map an important wind parameter such as wind direction, and to document its hour-to-hour evolution, is unique. For example, real-time observations of approaching atmospheric fronts and thunderstorms are helpful in the safe passage of commercial and recreational vessel traffic inside and outside of ports and harbors. These measurements could be combined with other wind measurements from moorings and the shoreline, and with simultaneous maps of surface current velocities and surface wave heights, to begin to study interaction of the coastal atmosphere and ocean on short time and space scales.

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