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# Communiqué on Veering Wind Effects On Scatterometry From The Sea-Surface

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## ABSTRACT

To characterize scatterometer returns from the sea-surface near meteorological fronts, we investigated microwave scattering from seas in which long-waves are at oblique angles to short-waves. We simulate the effects of veering winds on a C-band scatterometer by using models in which the short-waves align with the wind-friction velocity  $u_*$ , but the long-waves are at oblique angles to the  $u_*$  direction. As the oblique angle increases, tilt effects due to the long-waves led to unusual scan patterns with reduced azimuthally-averaged radar cross-sections  $a_0$ .

Keywords: fronts, wind and scatterometry.

## INTRODUCTION

Scatterometer backscattered power data are typically useful to infer wind vectors by analysis of normalized radar-cross-section scans  $\sigma^0(\phi)$ , where  $\phi$  is the azimuthal viewing angle. For suitable steady conditions, wind-wave distributions of the sea-surface are symmetric with respect to the average wind-direction, so azimuthal scans of  $\sigma^0$  are well described by three-term Fourier cosine models. Steady winds, however, do not persist indefinitely because weather conditions are nonstationary, with notable gradients near meteorological fronts and major cyclones. Short waves rapidly adjust to the local wind conditions but the relaxation-time for long-waves is prolonged; consequently, wave-distributions are not always symmetric with respect to the local wind direction. Thus for veering winds, the energy-containing long-waves are not aligned with the wind vector and unfortunately there is a dearth of field measurements to characterize  $\sigma^0(\phi)$ . If operational scatterometer algorithms do not account for these circumstances, there is a possibility of increased errors in wind vector estimates in regions where the weather is changing. Fronts are of considerable meteorological and oceanic interest, so it is important to understand and to monitor air-sea interaction processes in these areas. The objective of this paper is to present results of numerical simulations that we conducted to assess the likely effects of veering winds.

Remote sensing studies have not addressed how these factors affect wind estimates, so we conducted a numerical experiment with a C-band scatterometer. Sea-surface models and scattering computations are reviewed prior to reporting the findings. This

analysis reveals that long-waves at oblique angles to short wind-generated waves may contribute to considerable errors in wind vectors inferred from scatterometer data.

## FORMULATION

By examination of data and numerical models (Hasselmann *et al.* 1980, Günther *et al.* 1981, Allender *et al.* 1983, Holthuijsen *et al.* 1987, Young *et al.* 1987, Van Vledder and Holthuijsen 1993, Quandoo and Komen 1993), we find that a congruous description emerges. Assume that homogeneous steady winds are the existing conditions, when suddenly the wind shifts, without changing speed, to a different direction. High frequency waves are closely coupled to the air-boundary layer and they adjust quickly, order of minutes, to new conditions; however the relaxation time for low frequency waves is on the order of hours. So by 'veering' or 'rapidly turning' winds, we mean that the wind direction changes by a significant amount in an interval that is short compared to that required for complete angular relaxation of the entire wave-field. Two regimes are observed: a small shift regime and a large shift regime. In the large shift regime, the wind direction rotates by more than  $\sim 60$  to  $90^\circ$  and a new independent wave system is generated following classical trends, while the preexisting wave system dissipates. This study considers just the small shift regime, in which the wind rotates by less than  $\sim 60$  to  $90^\circ$  and the existing long-wave spectrum slowly rotates to the new wind direction. High-frequency waves quickly align with the effective wind stress; nonlinear interactions siphon energy away from the new wave system (therefore retarding development of a secondary peak) and transfer energy to the preexisting long-wave system; and long-waves lose energy through whitecapping. Due to the asymmetric energy gains by radiative effects and energy losses due to dissipation, the long-wave system slowly rotates toward the new wind direction. The rotational relaxation time is approximately equal to the development time for fully-developed seas by comparable winds; the rotational relaxation-time, however, is sensitive to wave-age (shorter for fresher seas). Therefore in small shift cases, spectral evolution due to veering winds is rapid adjustment of short waves to the new wind direction and subsequent turning of long-waves.

The UCL simulator was used in this study to compute backscattered microwave power values for a C-band (5.3 GHz) scatterometer. This software was developed to aid in altimeter

and scatterometer investigations and it is thoroughly documented by Sobieski *et al.* (1986); concisely reviewed by Guissard *et al.* (1994) and Sobieski *et al.* (1994); and particular features reported by Baufays *et al.* (1988 a&b), Guissard *et al.* (1986, 1987, 1989) and Sobieski *et al.* (1991, 1993). Maxwell's equations are the fundamental equations of electromagnetic theory, which is the basis for these estimates of backscattered microwave power from wind-generated surface waves. As usual, the UCL simulator uses composite surface theory, which was developed to deal with the large surface displacements found in ocean waves. A thorough review of this approach is presented by Plant (1990). Although various approximations are required, an important one is that for incidence angles between  $\sim 20$  and  $70^\circ$ , the primary effect of the large-scale surface is simply to tilt the small-scale structure which backscatters according to first-order Bragg theory. Guissard (1993) clarified differences between sea-surface models used for wave propagation studies and models used for scattering studies. There is no sea-surface model that is universally accepted as the standard for naturally occurring winds and seas. We modified the Bjerkaas-Riedel (1979) model to account for veering winds.

## RESULTS

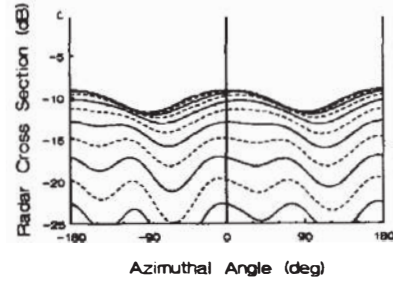
Let's appraise situations in which the wind changes direction, with speed unchanged. Due to geometrical symmetry, clockwise and counterclockwise veering winds yield scatterometric scans that are mirror images, so we present only counterclockwise wind-shifts. Figures 1 and 2 are for C-SCATT at  $30^\circ$  incidence angle and VV polarization.

For  $u^*$  ranging from 15 to  $75 \text{ cm s}^{-1}$ , we computed azimuthal scans with the oblique angle  $\Omega$  ranging from  $0$  to  $55^\circ$ , by  $5^\circ$ . Figure 1 presents a typical example for  $u^* = 30 \text{ cm s}^{-1}$ , which corresponds to moderate surface winds of  $\sim 8 \text{ m s}^{-1}$ . The scatterometer points upwind for  $\phi = 0^\circ$  and counterclockwise veering winds appear as clockwise rotations of long-waves. The scans show that (a)  $\sigma^0$  decreases as the veering angle increases, (b) maxima are rotated away from the wind axis and toward the long-wave axis and (c) at large veering angles, a regime exists with more than two maxima per scan.

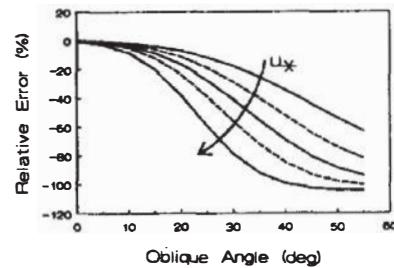
To assess the size of wind speed biases that could occur if an algorithm for fully-developed seas is employed for veering-winds conditions, we computed the relative error of wind speed estimates due to veering-winds as

$$\Delta = \frac{u_*(\Omega) - u_*}{u_*}, \quad (1)$$

where  $u_*(\Omega)$  is the friction velocity inferred by using a baseline algorithm developed for  $\Omega = 0^\circ$ , and input  $a_0$  from a veering-wind azimuthal scan. We summarize typical results in figure 2, which shows the relative error increases more rapidly for higher winds. Typical design specifications call for  $< 10\%$  error in wind estimates, consequently these errors are usually less than design objectives for  $\Omega < \sim 15^\circ$ . On the other hand, at larger angles the friction velocity estimates are grossly underestimated. Notice the reduction of  $a_0$  can be large enough that a scan might be interpreted as representing calm wind or instrumental noise.



**Figure 1.** Anomalous effects due to veering winds on C-SCATT scans: reduced power levels and misalignment of maxima.



**Figure 2.** Biases of wind speed estimates due to veering winds.

## SUMMARY

This study provides an assessment of veering wind effects on wind estimates from scatterometry of the sea-surface. Results from the numerical experiment with a C-band scatterometer reveal that veering winds reduce backscattered power levels and alter the shape of azimuthal scans. Fortunately if the veering angle is less than  $\sim \pm 15^\circ$ , the errors due to veering winds should be within typical design specifications ( $\pm 10\%$  for magnitude). If on the other hand  $\pm 15^\circ < \Omega < \pm 55^\circ$ , the effects of veering winds are dramatic and non-negligible because the backscattered power is significantly reduced and there is likely to be more uncertainty in deriving the stress direction. Moreover, power levels may be

so low in some extreme cases, that inversion algorithms will indicate data drop-out. This serendipitous effect might actually be useful for locating fronts. The general trends appear regardless of long-wave steepness or wind speed, so when weather patterns cause a shift in wind direction greater than  $\sim \pm 15^\circ$  (on a time scale that is short compared to the long-wave relaxation-time), results from standard scatterometer data reduction algorithms should be used with prudence.

These findings are dependent upon model assumptions, as is always the case for numerical experiments. Although we used sea-surface models that are in accord with present qualitative descriptions, more detailed measurements of sea-surface morphology for veering winds would certainly be helpful to guide and validate further numerical model development. Refinement of scattering calculations and data inversion techniques will be dependent upon a better understanding of (a) air-sea coupling processes (b) long-wave slope probability density distributions and (c) wave-wave interaction mechanisms. In this vein, a recent study by Geernaert *et al.* (1993) presents progress toward understanding the directional attributes of the ocean surface wind stress vector because it provides *in situ* measurements which are evidence that the stress vector direction is altered (stress vector and wind vector are non-aligned) due to long-wave effects pursuant to veering-winds. The role of various physical mechanisms that might contribute to this deviation is, however, still unsettled; so further research is needed to model momentum flux at the air-sea interface with respect to the wind-profile and sea-surface characteristics. It is suggested that veering-wind studies also include microwave scattering measurements so that weather fronts can be accurately monitored globally.

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