OFF-SHORE WIND MEASUREMENTS BY HF DOPPLER GROUND-WAVE RADAR

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Abstract. Remote measurements of wind velocity are performed, up to 100 km away from the shore, by using some features of the Doppler spectrum of HF radio waves backscattered by the sea. The variation with radio-frequency of the ratio of the amplitudes of the two Bragg lines in this spectrum shows a discontinuity occurring at a value simply related to the wind velocity. The validity of these measurements is discussed by comparison with meteorological data obtained by conventional methods.

1. Introduction

In the last 10 years, coherent decametric radar has been shown to be a powerful tool for the remote sensing of the sea surface (Crombie, 1971; Hasselmann, 1971; Teague *et al.*, 1973; Barrick *et al.*, 1974; Tyler *et al.*, 1974). Recently, oceanic winds have been measured with good accuracy at long range, up to 3000 km, by skywave radar (Long and Trizna, 1973; Stewart and Barnum, 1975). In the following, the possibility of measuring winds at shorter range (< 150 km) by ground wave radar is discussed and an example is given of the results of such an experiment performed in the western Mediterranean sea.

2. Theoretical Considerations

Crombie (1955) was the first to show that the Doppler spectrum of a radio wave backscattered by an element of the sea surface contains two components, corresponding to the surface gravity waves propagating in two opposite directions (towards and away from the receiver) and selected by the Bragg diffraction condition (ocean wavelength equal to half the radio wavelength). Following the theoretical works of Hasselmann (1971) and Barrick (1972), non-linear interactions have been shown to cause so-called second-order effects, by which the omnidirectional spectrum of the sea surface "modulates" the spectrum of the backscattered electromagnetic wave on both sides of the Bragg lines. For a particular operating frequency, the Doppler spectrum contains sufficient information for the measurement of oceanic winds:

– Assuming that the Bragg components of the sea spectrum are saturated, the amplitude of the second-order echoes with respect to the first-order peaks provides an absolute measurement of the significant wave height (Barrick *et al.*, 1974), which is related to the wind velocity.

– The ratio R of the amplitudes A_- and A_+ of the two Bragg lines (A_- corresponding to the receding ocean wave, A_+ to the approaching one) is, at a particular frequency, and for a particular wind velocity, dependent on the angle θ between the direction of the wind and the radar beam direction (Stewart and Barnum, 1975).

Without using second-order echoes, it can be shown that the ratio R presents strong variations with radio-frequency, in a way depending on the wind velocity which can, in turn, be evaluated by this means. The wind direction is then estimated as described above.

The ratio R, describing the anisotropy of the directional sea spectrum, is defined as

$$R = \frac{g(\theta)}{g(\theta+\pi)}$$

where $g(\theta)$ is the angular distribution of the energy in the sea spectrum, and θ is the direction of the wind evaluated from the direction of the radar beam. As suggested by Longuet-Higgins *et al.* (1963), the directional pattern, for a fully developed sea, can be represented by $g(\theta) = \cos^s(\frac{1}{2}\theta)$, where s is a function of both the ocean wave frequency, $f = \omega/2\pi$, and the wind velocity $\mathcal{V}$.

From experimental results, a variation of the s parameter has been proposed (Tyler *et al.*, 1974):

$$\begin{aligned} s &= 0.4(\mu-\mu_0)^{-1} \quad &&\text{for } \mu > \mu_0 \simeq 0.1 \\ s &= 4 &&\text{for } \mu < \mu_0 \end{aligned} \tag{1}$$

with $\mu = \mathcal{V}_*/KV_p$.

$\mathcal{V}_*$ is the 'friction velocity', related to the wind velocity $\mathcal{V}$ through a drag coefficient C_D: $U_* = (C_D)^{1/2}\mathcal{V}$, K is the Von Karman's constant (=0.4), V_p is the phase velocity of the ocean wave: $V_p = g/\omega$ (g is gravity).

There is little information about the actual value of s near the cut-off occurring at $\mu = \mu_0$, where equation (1) would give $s = \infty$ but the largest measured values are less than 15. For a particular wind velocity, the cut-off occurs at the frequency ω_0 defined as:

$$\omega_0 = \mu_0 \frac{Kg}{(C_D)^{1/2}\mathcal{V}}. \tag{2}$$

The variations of R as a function of the dimensionless parameter $x = \omega/\omega_0$ are plotted in Figure 1, for various θ. They exhibit a discontinuity for $\omega = \omega_0$ ($x = 1$). Using this feature, we can expect to measure the cut-off frequency by soundings at a number of frequencies, and then evaluate wind velocity by equation (2).

3. Experimental Conditions

The radar essentially consists of a coherent, wide-band (2–30 MHz) system (de Maistre *et al.*, 1975), located on a beach, 30 km from Toulon, on the French

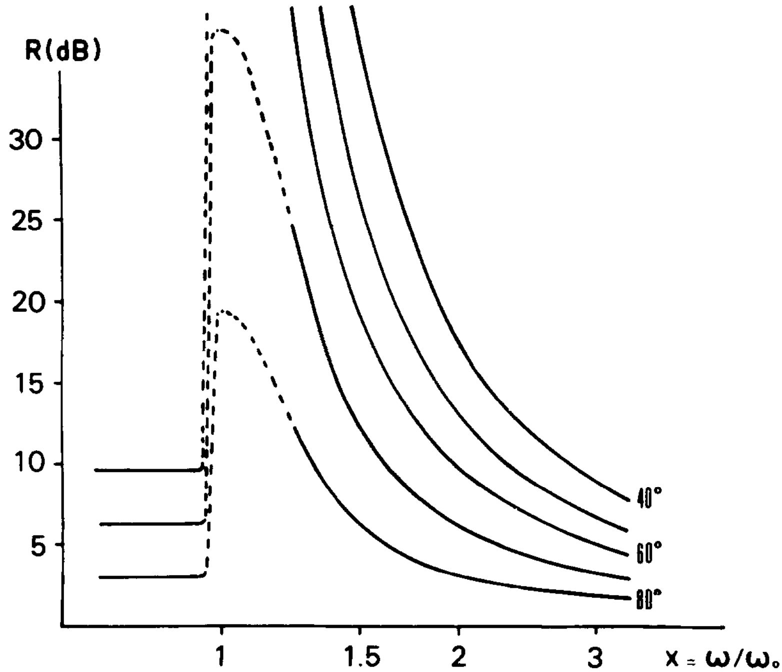

Fig. 1. Theoretical variations of R as a function of the dimensionless parameter $x = \omega/\omega_0$ (ω is the ocean wave angular frequency, and ω_0 the angular cut-off frequency of the spectrum).

Mediterranean coast. The transmitting antenna operates conveniently in the range 4–20 MHz. A directive monopoles array was used for receiving, which had a theoretical azimuthal beam width of 10° at 15 MHz and almost 30° at 5 MHz (Figure 2). Though this broad-band system was planned to use several radio-frequencies simultaneously, in the present experiment, the whole band was scanned sequentially.

In relation to the power of the transmitter (1 kW), returns have been obtained out to 150 km. The radial extension of the sea surface studied is 15 km (pulse width: 100 μs).

The power spectrum is calculated by a minicomputer giving as a best frequency resolution 0.015 Hz. Real-time analysis gives spectra for one particular distance, while recorded data allow us to obtain spectra at any distance.

4. Experimental Results

An example of a multifrequency sounding is shown in Figure 3, where R is plotted as a function of the ocean wave frequency f for three distances: 20, 50, and 80 km. The duration of the sounding was about 45 min.

At that time, the wind, measured at a meteorological station (M, Figure 2) on an island, had a speed (10 m s^{-1}) and a direction (280°) constant for at least four hours.

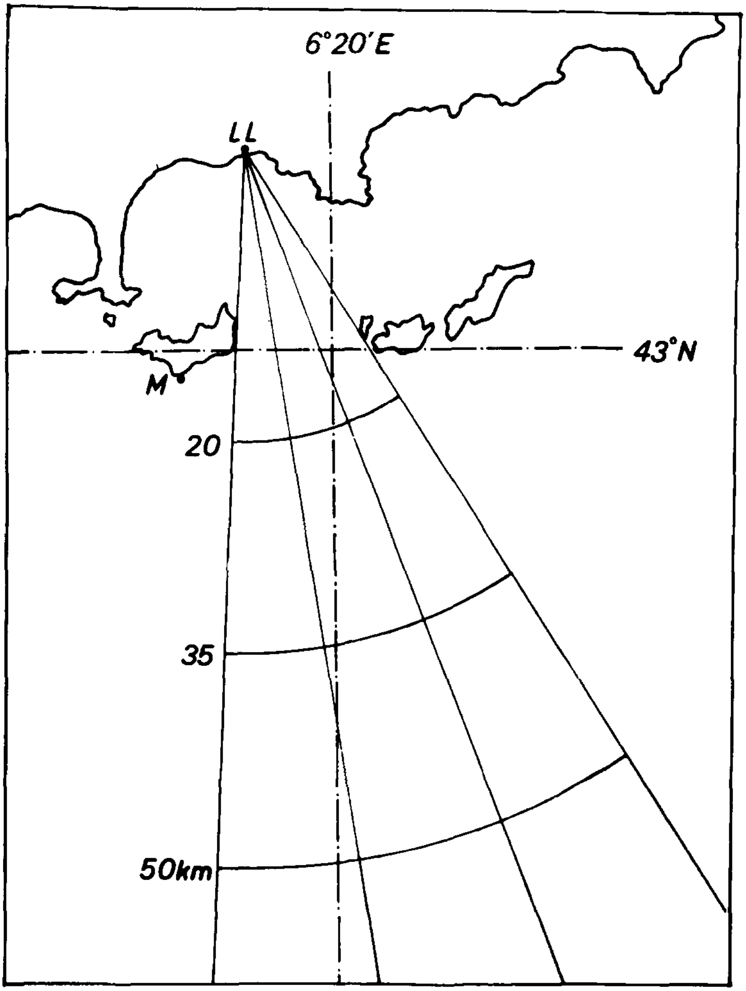

Fig. 2. Geographical conditions. The location of the radar is indicated as LL (La Londe). The location of the meteorological station is indicated as M.

The assumption of a sea in equilibrium with the wind, necessary in equations (1) and (2) was then satisfied.

At greater ranges, the discontinuity occurs approximately at $f_0 = 0.22$ Hz. The corresponding friction velocity is $U_* = 0.28$ m s^{-1} and the wind velocity is $U \simeq 8$ m s^{-1}. With this value of the wind velocity, the value of s may be deduced from (1) and the wind direction is then given by:

$$\theta = 2 \arctan \left(\frac{1}{R}\right)^{1/s}.$$

In the present experiment, the poor directivity of the receiving array does not allow good accuracy for θ, which is estimated (by this method) to be near 80°.

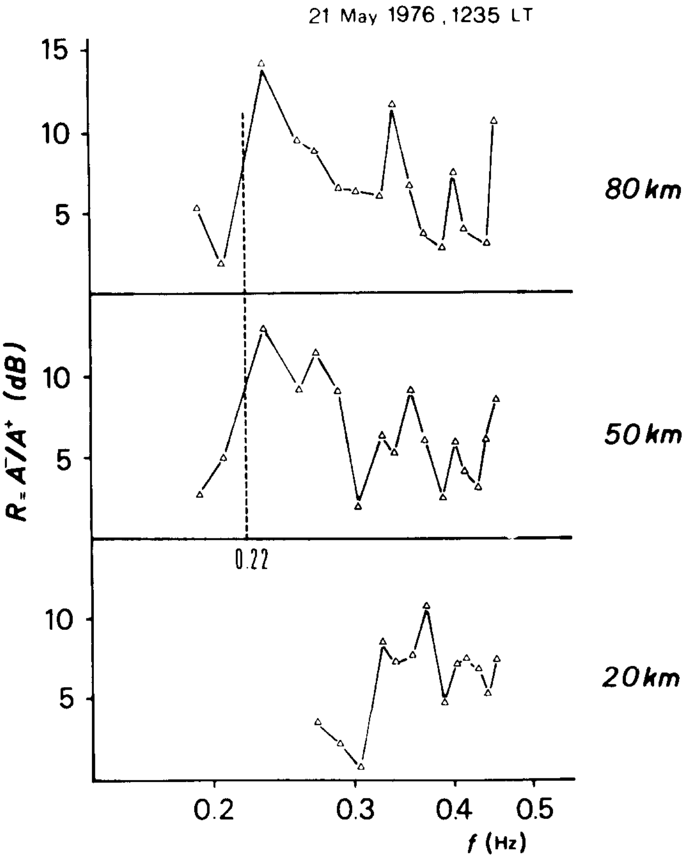

Fig. 3. Variations of R with ocean wave frequency f, for three distances (20, 50, 80 km) from the receiver. The dashed line indicates the approximative cut-off frequency.

All these results are consistent with the meteorological data and they agree with the data of a buoy located near the illuminated area, which measured a dominant period of the sea spectrum between 4 and 5 s.

The different behaviour observed at 20 km may be due to the short fetch in this area with the particular direction of the wind.

5. Conclusion

An example of a sounding of the sea surface at various radio frequencies by an HF Doppler ground wave radar was given. It showed a discontinuity in the variations of the anisotropy of the sea-state spectrum with frequency. The wind velocity is deduced from this cut-off frequency in the spectrum, and the wind direction is estimated.

This interpretation is valid only if the sea is in equilibrium with the wind, and this condition is expected to be generally fulfilled after a few hours in the Mediterranean sea, where the waves tend to be shorter than those found in the oceans.

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