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Interpretation of Backscattered HF Radio Waves from the Sea

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Abstract

Radar oceanographers have long relied upon a simple diffraction grating model of the sea surface to explain the predominant features in the backscattered Doppler frequency spectrum. It is argued in this paper, however, that the ruled diffraction grating model with scattering localized to wave crests is incorrect and that a sinusoidal grating of period one-half the radio wavelength, with scattering from the entire surface, is the simplest representation of the sea surface which is consistent with both rigorous theory and experimental observation.

1. Introduction

Backscatter of HF radio waves has been used for many years as a remote probe of the sea surface (Crombie 1955; Ward 1969; Long and Trizna 1973; Valenzuela 1974; Barrick *et al.* 1974; Barrick 1977; Lipa 1977; Barrick *et al.* 1977; Trizna *et al.* 1977; Teague *et al.* 1977; Lipa and Barrick 1980; Maresca and Carlson 1980; Dexter *et al.* 1982). It has been shown theoretically and confirmed experimentally that to a first approximation only water waves of wavelength half that of the incident radio wave contribute to the Doppler shifted spectrum leading to *two* dominant peaks in the echo (see above references and Barrick 1972*a*; Johnstone 1975; Robson 1984; we focus here on the so-called first-order effects and do *not* consider either multiple scattering or nonlinear hydrodynamic effects, which produce other distinctive features in the spectrum). On the other hand, the physical model most often cited in the above literature is the simple ruled diffraction grating model of the sea surface, with the 'lines' corresponding to crests (Crombie 1955; Dexter *et al.* 1982) or some other unspecified feature of the waves. Such a model leads to *multiple* first-order peaks, arising from constructive interference of waves whose wavelengths are any positive integral multiple of $\frac{1}{2}\lambda_0$ where λ_0 is the radio wavelength, as is recognized by some (Dexter *et al.* 1982) and is shown below in equation (5). Thus Crombie (1955) was not even qualitatively correct. It is of interest that Crombie (1971), perhaps aware of the shortcomings of his earlier paper, proposed a scattering model based upon work by Wait (1966). While Crombie eventually arrived at essentially the correct result, there is an internal inconsistency between the initial descriptive portrayal of localized scattering from crests, together with the usual arguments on ruled diffraction gratings, and the subsequent mathematical treatment, which (correctly) considers scattering from the entire surface.

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Thus there remains a problem of logic and basic physical understanding, particularly in the outlook of many radar oceanographers, who prefer to quote Crombie's 1955 model. Our paper aims to settle this difficulty by proposing a *sinusoidal diffraction grating* as a model of the surface and we show, through standard physical optics how this overcomes the above difficulties.

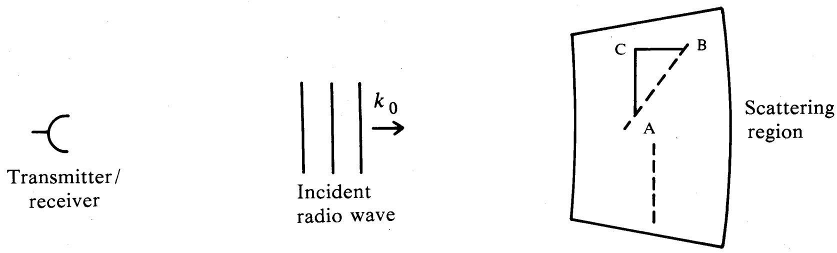

Fig. 1. Diagram showing the physical situation with a stationary transmitter and receiver probing an area of the sea surface; k_0 is the wavevector for the incident radio wave moving in the x direction. In the scattering region two different water waves are shown schematically by dashed lines, one moving parallel to k_0 and one moving obliquely to k_0. For any point A on the oblique wave we can find another point B such that the path difference 2BC in the backscattered signal is an odd multiple of half the wavelength, resulting in destructive interference; that is, such waves do not contribute to the backscattered spectrum.

2. Theory

Fig. 1 is a common physical situation, where the transmitter and receiver are co-located in a monostatic arrangement. A typical backscattered HF frequency spectrum contains two dominant peaks, Doppler shifted with respect to the original frequency in the absence of surface currents by $\Delta f = \pm(g/\pi\lambda_0)^{\frac{1}{2}}$, corresponding to water waves moving towards and away from the receiver respectively, superimposed upon less intense features (typically 10–20 dB lower), which are due to multiple scattering and nonlinear hydrodynamic effects (Barrick 1972*b*; Johnstone 1975; Robson 1984). We focus our attention here on the dominant peaks only. The scattering region is sufficiently far from the source that the incident radiation is effectively a plane wave. Moreover, the dimensions of the scattering region are large compared with λ_0 and, while effects due to finite area of illumination are easily accounted for (Crombie 1971), we shall neglect them here. Elementary considerations indicate that only sea surface motion parallel to the transmission direction need be considered under these conditions, for backscattering from obliquely directed components results only in destructive interference (see Fig. 1).

The conditions described above clearly meet the requirements for a discussion in terms of Fraunhofer diffraction theory, where it is well known that the diffraction pattern of an object is the spatial Fourier transform of that object (Lipson and Lipson 1969). Thus, if we associate a scattering amplitude $f(x)$ with each point x of our scattering region, then it follows from standard physical optics theory that the backscattered diffracted amplitude is

$$\psi \propto \int_{-\infty}^{\infty} f(x)\exp(-2\mathrm{i}k_0 x)\,\mathrm{d}x, \tag{1}$$

where $k_0 = 2\pi/\lambda_0$.

The classical *mistake* is to assume that the surface behaves like a ruled diffraction grating or a crystal lattice, the rulings or lattice planes corresponding to crests in the waves, separated by the wavelength λ_w (Crombie 1955; Ward 1969; Crombie 1971; Long and Trizna 1973; Valenzuela 1974; Barrick *et al.* 1974; Barrick 1977; Lipa 1977; Barrick *et al.* 1977; Trizna *et al.* 1977; Teague *et al.* 1977; Lipa and Barrick 1980; Maresca and Carlson 1980; Dexter *et al.* 1982). In that case we have (Lipson and Lipson 1969)

$$f(x) = \sum_{m=0}^{\infty} \delta(x - m\lambda_w) \tag{2}$$

and substitution into (1) yields

$$\psi \propto \sum_{m=0}^{\infty} \exp(-2\mathrm{i}k_0 m\lambda_w)$$

$$= \{1 - \exp(-2\mathrm{i}k_0 \lambda_w)\}^{-1},$$

which consists of periodic delta functions at

$$k_0 \lambda_w = n\pi \qquad (n = 1, 2, ...),$$

that is

$$\lambda_w = \tfrac{1}{2} n\lambda_0 . \tag{3}$$

From this viewpoint, all sea waves whose wavelength is an integral multiple of one-half the radio wavelength will result in constructive interference. Since each sea wave moves with a velocity characterized by its wavelength (assuming deep water waves),

$$v_w = \pm(g\lambda_w/2\pi)^{\frac{1}{2}}, \tag{4}$$

there will be a whole series of Doppler shifted peaks,

$$\Delta f = 2\lambda_0^{-1} v_w = \pm(ng/\pi\lambda_0)^{\frac{1}{2}} \qquad (n = 1, 2, ...), \tag{5}$$

in the backscattered spectrum. This is the interpretation of Crombie (1955) and Ward (1969). Others, including the references cited above, endorse Crombie's model on the one hand but, on the other hand, are vague about its physical implications, as described above. Crombie's model is inconsistent with both observation and the rigorous theory of Barrick (1972*a*) and Johnstone (1975) and must be discarded. It should not be used even in the most elementary discussions.

A more appropriate physical picture is that the scattering amplitude is proportional to the wave height at all points, not only at the wave crests. Thus, considering only one Fourier component of the wave-height spectrum for simplicity, we postulate

$$f(x) = A(k_w) \exp(\mathrm{i}k_w x), \tag{6}$$

where $k_w = 2\pi/\lambda_w$ and $A(k_w)$ is the amplitude of the water wave. Substitution of (6) and (1) yields

$$\psi \propto 2\pi A(k_w)\, \delta(k_w - 2k_0), \tag{7}$$

that is, constructive interference occurs only for that Fourier component with wavelength

$$\lambda_w = \tfrac{1}{2}\lambda_0 . \tag{8}$$

This particular component therefore acts as a sinusoidal diffraction grating and the fact that such gratings have only a first-order pattern is well known in optics. Equation (8) is the same as the standard grating result (3), but with n limited to 1. The corresponding Doppler shifts in this case are

$$\Delta f = \pm(g/\pi\lambda_0)^{\frac{1}{2}}, \tag{9}$$

corresponding to $n = 1$ in (5). This is in agreement with the rigorously established result of Barrick (1972*a*).

3. Concluding Remarks

The misunderstanding described above led Ward (1969) to postulate that the continuum, which one observes in addition to the two Doppler peaks (9), is due to a superposition of higher order diffraction components (i.e. $n \geqslant 2$), but Hasselmann (1971) correctly pointed out that such a continuum is due to other quite different processes. The impression is still to be had, however, that contemporary users and analysts of ocean radars remain under the misapprehension that Crombie's model is valid and, logically, that the $n \geqslant 2$ peaks exist, in spite of observational and theoretical evidence to the contrary. We believe that the false physical picture described above is probably responsible and hope that this paper will serve to clarify matters.

Finally, we point out that a simplified but nevertheless sophisticated picture of both simple and multiple scattering now exists in the literature (Robson 1984), which is consistent with both the present discussion and the Barrick–Johnstone formulation, but which avoids much of the mathematical complication of the latter.

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