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APPLICATION OF RADAR AND MICROWAVE SCATTERING TO OCEAN WAVE RESEARCH

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ABSTRACT

The high data rate and advanced technology of modern radar systems make them attractive instruments for measuring the properties of random wave fields. When the objective is wave research, it is particularly important that the relation between wave field properties and radar output be clear and unequivocal. This is generally the case in the measurement of radar range (altimetry), the measurement of line-of-sight speeds (Doppler shift) and under those conditions where the scattered electromagnetic field is proportional to the surface displacement. The latter situation is that of first order Bragg scattering, in which case the influence of all waves outside a narrow window at the Bragg resonance condition is strongly filtered out. In this case, it has proved possible to measure such wave properties as temporal growth and approach to equilibrium in wind-wave tanks and spectral energy transport in wave tanks or at sea. Furthermore, the Doppler shift is accurately the frequency of the Bragg wave in first order scattering. Thus phase speeds may be determined not only for their intrinsic interest but as a means of measuring surface currents and probing the profile of the mean flow on both sides of the air-water interface. Results of all these techniques are now available in the case of wind-wave tanks and numerous examples are presented. The techniques have so far been less fully exploited at sea, but some examples from HF groundwave scatter and dual frequency microwave radar returns from wind-generated seas are available. Finally, opportunities for exploiting second order Bragg and two-scale scattering results for wave research are also discussed.

INTRODUCTION

Most of the instruments used to measure ocean surface waves sample the surface over a limited spatial region. They are essentially point probes. In consequence, it is necessary to use large, often cumbersome, arrays of probes or to record over an impractically long time in order to obtain reliable, detailed information about the random wave field. In contrast, a radar, in addition to being a remote sensor, is inherently an area-extensive probe which can automatically, and nearly instantaneously, average over a large surface region. It is worth pointing out that, in what is probably the earliest application of radar to ocean wave research, the airborne radar wave profiler of Barnett and Wilkerson (1), the radar was used as a point probe. It appears to have been largely superseded in profiling application by the laser.

Two modes of radar operation are discussed here. The first takes advantage of the close match between ocean wavelengths and available radio and microwavelengths. The scattering is like that of x-rays from periodic crystal lattices--Bragg scattering. The surface displacement spectrum is obtained directly, but only at a single ocean wavelength--the Bragg wavelength--which is uniquely related to the radar or radio wavelength. It is thus necessary to use a range of radio wavelengths or vary the scattering geometry, in order to cover the wave spectrum. In the second mode the precise nature of the scattering mechanism is less important. It is only necessary that the scatterers, short Bragg waves, specular points, or whatever, be modulated by the larger ocean waves. It is the modulation which is detected and utilized although this may be only indirectly related to wave amplitude. However in this case only a narrow band of radar wavelengths is required, which is a great practical convenience.

BRAGG SCATTERING

Suppose a transmitting antenna is oriented (Fig. 1) at depression angle θ_1 and a receiving antenna at angle θ_2 to the plane in which a wave system is propagating. If the wave is not too large in amplitude compared to the radar wavelength the scattered power is proportional to the surface displacement spectral amplitude of the wave component at the Bragg wavevector $\underset{\sim}{k}_B$ where:

$$\underset{\sim}{k}_B = [\, k_o (\cos\theta_1 + \cos\theta_2)\, , 0\,] \qquad (1)$$

and k_o is the microwavenumber. Note that this is a vector equation. In first order Bragg scattering the radar strongly filters out all other wavevectors. Since the wave is moving the scattered energy is Doppler shifted. The Doppler shift is just that associated with the line-of-sight components of the phase speed of the wave, and this proves to be identically the frequency of the Bragg wave. Let us denote the ordinary power spectrum of the scattered and linearly detected microwave field as the Doppler spectrum. In first order Bragg scatter the Doppler spectrum is proportional to $\Psi(k_B, 0, \omega)$, the complete surface displacement spectrum.

There have been numerous measurements of such Doppler spectra of wind-generated waves beginning with Crombie. The character of these spectra is easily illustrated with wavetank measurements. At a fixed fetch in a linear wavetank, the rms height and wave period increase with increasing windspeed. The development of Doppler spectra measured at a fetch of 8 meters using a microwavelength of 7 cm and $\theta_1 = 25^o$, $\theta_2 = 120^o$ is shown in Fig. 2. For these conditions, the Bragg wave is 16.5 cm in length and in the absence of wind, 3.05 Hz in frequency. Thus at the lowest wind the dominant wave is much shorter than the Bragg wave which is very small--less than 10 microns in amplitude. As the wind increases from its lowest value the predominant feature of the Doppler spectra is the rapid growth of the narrow first order Bragg peak which continues until the Bragg wave is the dominant wave ($u_* = 34$ cm/sec, Fig. 2). With further increase in wind the dominant wave becomes longer than the Bragg wave. The first order Bragg peak is then substantially diminished while, simultaneously, higher order peaks appear which eventually quite dominate the Doppler spectra.

Doppler spectra observed at sea (2,3) differ in important detail but not in qualitative substance from these spectra. It would, of course, be highly unusual to be able to observe the development of wave systems with increasing wind at sea but the development with fetch is very similar. The use of HF radar in the groundwave mode to measure this development is particularly apt since fetch can be varied simply by ranging the radar in the usual way. The feasibility of this approach has been demonstrated by Crombie (4), and its application to wave-wave interaction studies similar to those carried out by Hasselmann et al (5) is obvious. Tyler et al (6) have made an ingenious application of synthetic aperture radio scatter to measure directional wave spectra.

A pervasive feature of the spectra in Figure 2, as of Doppler spectra at sea, is the existence of upwind traveling waves. In the directly upwind direction these are, in the tank, as at sea, about 30 dB lower than the downwind wave. However the advancing and receding Bragg peaks become more nearly equal as the direction of radar look is rotated toward the crosswind direction. The ratio of the magnitudes of the advancing and receding Bragg peaks can be used to determine wind direction (2,7). Finally, close perusal of Figure 2 will show that the advancing and receding Bragg lines are not symmetrically placed about zero Doppler shift. This is the result of the advection of waves by currents and the magnitude of the line-of-sight component of current can be determined from the difference (i.e. algebraic sum) of the Doppler shifts.

We are unaware of cases of HF scatter from ocean waves in which the higher order Doppler peaks overwhelm the first order scatter as in Figure 2. These higher order effects may nonetheless be useful because there are practical constraints, including encroachment on the radio broadcast bands, against the use of radio waves long enough to be scattered at first order by the ocean waves of most interest--those aroused by storms. Unfortunately these higher order Doppler peaks have twin origins--electromagnetic and hydrodynamic--which are about equally effective in producing them. Theoretical studies aimed at interpreting these effects are an area of active current research.

TWO SCALE SCATTERING

When the dominant wave is long compared to the Bragg wave, and the rms wave height of the order of or larger than the radio wavelength, the interpretation of Doppler spectra again becomes qualitatively simple. In this case the smaller scale scatterers are advected about by the orbital motions of the large wave, distinct Doppler splittings are obliterated, and the width of the Doppler spectrum is approximately the rms orbital speed of the wave system. For fully developed seas this orbital speed is a function only of the wind responsible for the wave system. In this sense the Doppler bandwidths can be used as a remotely sensed measure of windspeed (7).

It has long been known (6,9) that the local scattering cross-section, sensed by radar with pulse length short compared to the ocean wavelength, is correlated with the large scale structure of the ocean surface. In a two-scale scattering model we can think of this as modulation of the small scale scatterers by the large waves. We recently reported results of a laboratory study (10,11) of these modulations in a case where the small scale scatterers were centimetric wind generated and the large scale waves plunger generated, nearly monochromatic waves. We found that there were two major sources of modulation of scattering cross-section. Firstly, the scattering cross-section per unit area depends on the local angle of incidence θ' (Figure 3). Since the small waves are tilted by the large wave this angle depends on the position with respect to the large waves. Secondly, the amplitude of the small waves is actually changed due to straining of the small waves by the horizontal component of orbital motion of the large wave. The modulation due to tilting is, in the first approximation, independent of the wind. That due to straining is wind speed dependent because the small waves are more strongly coupled to the wind at higher windspeeds and so respond less to the straining. The two modulating effects, moreover, are in phase when the radar looks upwind but out of phase looking downwind. The result is that the modulation depends markedly on the direction of radar look with respect to the wind as well as upon the magnitude of the wind (Figure 4).

Plant's (12) study of sea return with a dual frequency coherent radar at 9.3 GHz is a particularly perspicuous investigation of these modulations on Chesapeake Bay. The power spectra of the signal from this radar (Figure 5) is superficially very much like that from an HF radar in first order Bragg scattering. The spectrum is sharply peaked at a frequency corresponding to the ocean wave with wavenumber equal to the difference between the wavenumbers of the two transmitted CW signals. The radar responds to the wave with wave vector given by equation (1) but with k_o replaced by Δk the difference in transmitted wavenumbers. The amplitude of the Doppler peaks, when plotted vs Δk (Figure 6) exhibits a wave-spectrum like form provided the wind is steady.

The side-looking, synthetic aperture radar is potentially the most comprehensive radar sensor of the ocean surface. This radar utilizes the relative motion of the radar platform (aircraft or satellite) and the radar-illuminated terrain to provide a detailed image or map of the terrain. The mapping principle is simply that in the side-looking mode the Doppler shift in the signal reflected from a target in the terrain is proportional to the along-track position of the target with respect to the platform. The range of the target is obtained by more conventional techniques, usually linear frequency modulation or "chirping" in modern systems.

However, the surface of the sea is a terrain in motion. In the case of waves the scatterer motions which result in Doppler shifts are due to orbital speeds which, as we previously noted, are correlated with modulation of scattering cross-section. If the along-track resolution of the synthetic aperture radar is made sufficiently high to distinguish ocean waves, then for example the accelerations present in fully developed seas may result in refocussing or defocussing of the wave images. Spatial variation in scatterer velocity may, furthermore, result in wave images invisible to ordinary incoherent radar (13).

CONCLUSIONS

The high data rate and advanced technology of modern radar systems make them attractive instruments for measuring the properties of random wave fields. In fact radar technology is capable of providing more detailed measurements of surface velocities and displacements of the ocean surface than anyone currently appears to want to know, or pay for, or otherwise assimilate. The limitation on expanded application of radar to ocean wave problems is now ignorance of how to interpret measurements rather than undeveloped technology.

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SCATTERING GEOMETRY

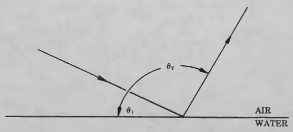

Figure 1 - Scattering geometry.

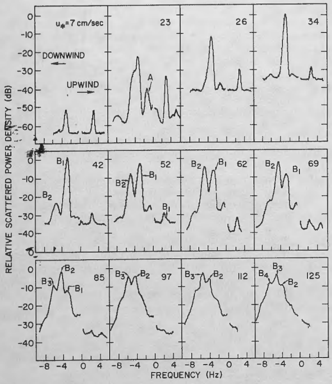

Figure 2 - Development of Doppler spectra with increasing wind at fixed fetch in a wave tank. The maximum windspeed is 15 m/s and the Bragg wavelength is 16.5 cm.

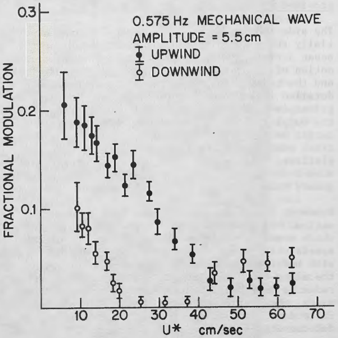

Figure 4 - Fractional modulation in backscattered power due to 0.575 Hz (4.2 meter) wave. Maximum wind is 10 m/sec. Microwave frequency = 9.375 GHz, $\theta = 45^{\circ}$.

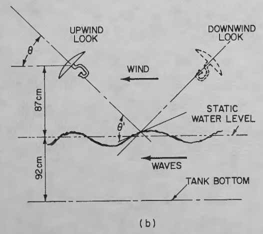

Figure 3 - Two-scale scattering geometry.

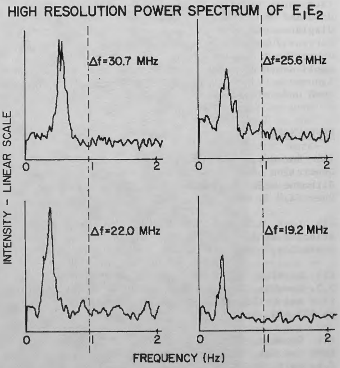

Figure 5 - Power spectra of dual frequency radar return from Chesapeake Bay. $\Delta k = 2\pi\Delta f$ x (velocity of light).

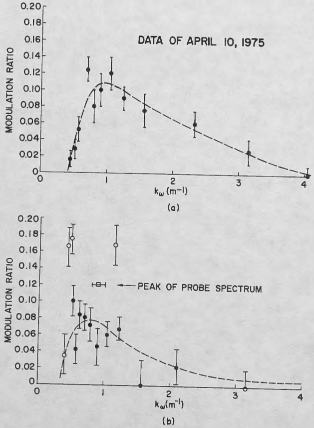

Figure 6 - Intensity of gravity wave line versus water wavenumber. (a) April 10, 1975
(b) June 11, 1975. The open circles were measured after a sudden drop and shift in the wind.