Polarized Microwave Scattering by Surface Water Waves and Turbulence

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Abstract Measurements of the fine space-time structure of short gravity-capillary waves in the presence of turbulence, as well as Ku-band scattering at grazing and moderate incidence from mechanically-generated waves in a wave channel are presented. This study was stimulated by the need to investigate the influence of nonlinear features of the scattering surface, which contribute to scattering at grazing incidence. Mechanically generated steep periodic (3 to 6 Hz) waves were used as a source of bound parasitic capillary waves. An oscillating (2 to 7 Hz) grid was used as a source of subsurface turbulence. A scanning laser slope gauge (SLSG) and an imaging slope gauge were used to measure short waves of length 0.2-20 cm, and frequencies up to 150 Hz. A dual polarized (VV, HH) coherent pulsed Ku-band scatterometer with 3ns temporal resolution was used to obtain Doppler spectra of the scattered signals for grazing angles from 12 to 30 degrees. Simultaneous time series of wave slopes and microwave scattering and their frequency spectra permitted a comparison of these parameters both with and without turbulence.

It was found that the energy of bound short waves increased substantially (by 10-40%) on interaction with the turbulence. Measurements of the Doppler frequency shift and amplitude of the scattered signal are consistent with this change in the wave field, and reveal Bragg scattering by the bound waves.

INTRODUCTION

Bound gravity-capillary waves (Fedorov and Melville, 1998; Fedorov, Melville & Rozenberg, 1998) [1,2] are widely present in nonlinear sea-surface wave fields and may strongly affect microwave scattering, air-sea and wave-current interaction. Recent laboratory measurements of Ku-band scattering at grazing incidence from wind waves (Rozenberg et al., 1995) [3] showed that the Doppler spectra of a scattered signal have a bimodal structure. While the first low-frequency part of the spectrum corresponds to the Bragg scattering from free capillary waves, the high-frequency part is associated with scattering from the bound capillary waves at the crests of the dominant waves. To verify this interpretation and separate bound waves from free waves, laboratory measurements of the Ku-band scattering at grazing incidence from a steep periodic and wind short waves was conducted (Melville et al., 1997) [4]. It was shown that the steep periodic waves are a source of Bragg scattering from bound waves only. The present study is an extension of this experiment to include wave-turbulence interaction. Subsurface turbulence may strongly affect the short bound waves and, consequently, the scattered signals. An understanding of the fine space-time structure of the waves and its modulation due to turbulence is very important.

EXPERIMENTAL METHODS

The experiments were conducted in a glass-walled channel in the Hydraulics Laboratory at the Scripps Institution of Oceanography. The channel is 30m long, 0.5m wide, and filled to a depth of 0.6m with fresh water. The steep periodic waves in the frequency range from 3.0 to 7 Hz and steepness $ak = 0.1 - 0.35$ were generated by the piston-type wavemaker. The scanning laser slope gauge (SLSG) and imaging slope gauge (ISG) were built and used for measuring short waves with wavelengths from 0.1 to 20 cm and frequencies up to 150Hz. Turbulence was created by an oscillating grid (frequency of oscillation 3-7Hz, stroke 1-3 cm), which was placed 6-10cm beneath the water surface and 30cm upstream of the field of view of the SLSG. Digital Particle Imaging Velocimetry (DPIV) was used to measure the turbulent velocity field.

The microwave scattering was evaluated by the amplitude and frequency of the scattered signal, measured by a coherent, 14Ghz (λ=2.1cm), dual polarized, pulsed (3ns width) scatterometer (described in detail in Rozenberg et al., 1995) [3]. The scatterometer antennas were fixed at 40 - 140 cm above the water surface, with the grazing angle varying from 12 to 35 degrees. The scatterometer was aimed in the upstream direction to have a common footprint with the SLSG.

RESULTS

Microwave scattering measurements were carried out for both VV and HH polarizations and upstream direction of illumination at grazing incidence angles from 12 to 30 degrees and 4, 5, and 6Hz periodic waves with steepness ak up to 0.35 both with and without turbulence.

(a) Waves only First, the wave field and scattering were analyzed for a case without turbulence. Typical SLSG spectra for 4 Hz periodic waves and the HH and VV scattered signals at 12 degrees grazing angle are presented in Fig.1a, b, and c, respectively, by solid lines. Note the presence of parasitic capillary waves in the slope time series (Figure 2a) at every crest of the dominant 4 Hz waves (Fedorov and

Melville,1998) [1]. The presence of significant harmonics (up to the 30th) is typical for the slope spectra for such waves (see Fig.1a). The presence of harmonics is noticeable also on HH and VV spectra (Fig.1b, c), but the difference is obvious. The Bragg component (n=8-10, λ_B =1.25 cm.) for scattered signal spectra for both HH and VV is prominent. The wavelength of the Bragg-resonant component and its Doppler shift can be determined from the equations:

$$\lambda_o = 2\lambda_B \cos\psi , \qquad F_D = \frac{2C}{\lambda_o}\cos\psi = F_B ,$$

where λ_o is the microwave length, λ_B is the Bragg-resonant wavelength, ψ is the grazing angle, F_D is the Doppler shift, and C and F_B are the phase velocity and frequency of the Bragg-resonant waves. For all cases measured, both HH and VV scattering by parasitic bound waves is consistent with the Bragg mechanism. Note that bound waves are the only source of the scattering from the 4 Hz periodic waves.

(b) Waves with turbulence Let us now compare similar scattered signal and slope field parameters, but measured with both waves and turbulence. A grid oscillating with frequency of 7 Hz and stroke of 3 cm, placed at 8 cm beneath the water surface generated the turbulent velocity field with an RMS velocity of 1.0 -1.2 cm/s and a local Reynolds number of order $Re \sim 800$. Here, slope time series exhibit a sharp increase in the bound waves (Fig.2b). The spectra for both surface slope field and scattered signals (dashed lines in Fig.1a, b, c), confirm this feature. In the presence of turbulence the intensity of the bound waves is increased by 3-5 dB. Note the substantial broadening of the spectral peaks for all signals due to the turbulence: it is impossible now to distinguish between the harmonics exactly. To understand better the physical nature of the wave-turbulence interaction, a detailed study of the fine space-time structure of the short waves in the presence of turbulence was provided. It was found that turbulence can both influence the direction of propagation of periodic surface waves and slow down periodic surface waves (decrease the phase velocity). The latter effect can result in an increase in the wave steepness and, consequently, intensify the bound waves. As an example of the observed features of wave-turbulence interaction, the images of the periodic 7 Hz waves with and without turbulence are presented in Fig.3. The left and right plates of this figure show instantaneous slope images without and with turbulence, respectively, and the middle plate is a snapshot of the turbulent velocity field measured at 1.5 cm beneath the water surface. The periodic 7Hz waves are traveling from right to left; the distortion of the fronts of the waves due to turbulence is remarkable. Note also the increased slope of the bound waves in the presence of turbulence.

It should be noted, meanwhile, that a further increase of the turbulence intensity ($Re > 2000$) may change the surface wave field dramatically, resulting in significant damping of the waves and a great reduction in the scattered signal.

SUMMARY & CONCLUSIONS

1. Laboratory measurements of Ku-band scattering at grazing incidence, as well as the fine space-time structure of short periodic surface waves are presented.

2. Mechanically generated periodic steep surface waves were studied as a source of microwave scattering in both the presence and absence of grid-generated turbulence.

3. Turbulence is found to affect surface wave fields, modulating the direction of propagation and the phase velocity of the short periodic waves. For weaker turbulence, ($Re < 1000$) the reduction in phase velocity of the steep short waves caused an increase in the wave steepness and, consequently, the strength of the bound parasitic waves. A further increase in the intensity of turbulence may change the wave field dramatically, effectively damping the waves.

4. Measurements of the Doppler frequency and amplitude of a scattered signal reveal Bragg scattering from the bound waves, which is reflected in all observed features of the wave-turbulence interaction.

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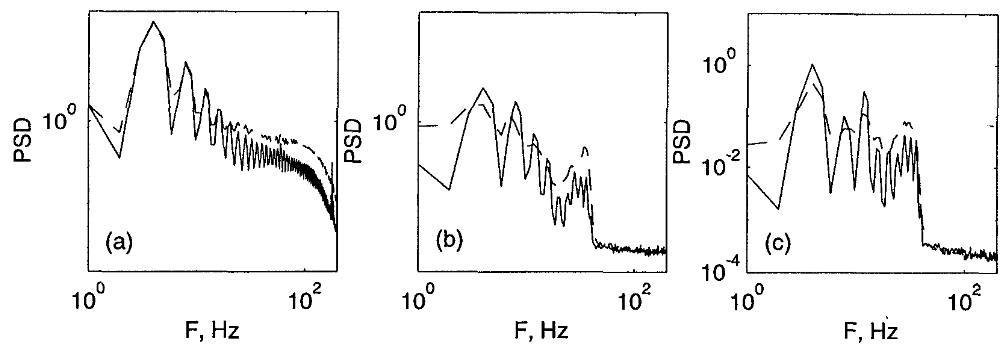

Fig.1. Slope spectra of steep 4Hz periodic waves (a), HH (b), and VV (c) scattered signals. Solid lines - waves only, dashed lines - waves + turbulence

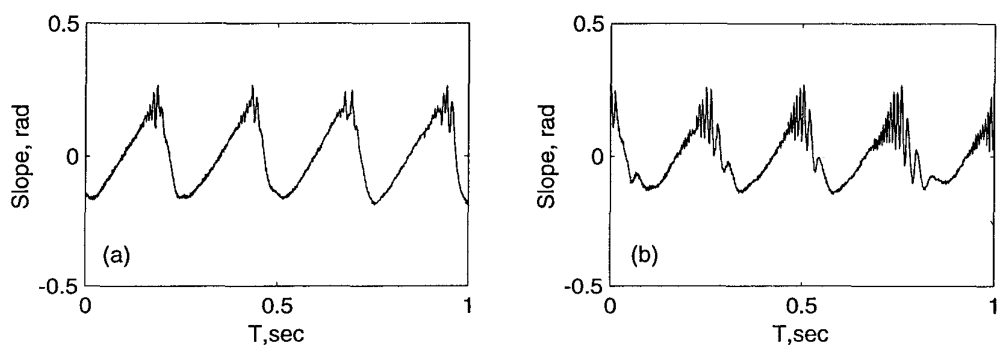

Fig.2. Time series for steep 4Hz periodic waves without (a) and with (b) grid-generated turbulence

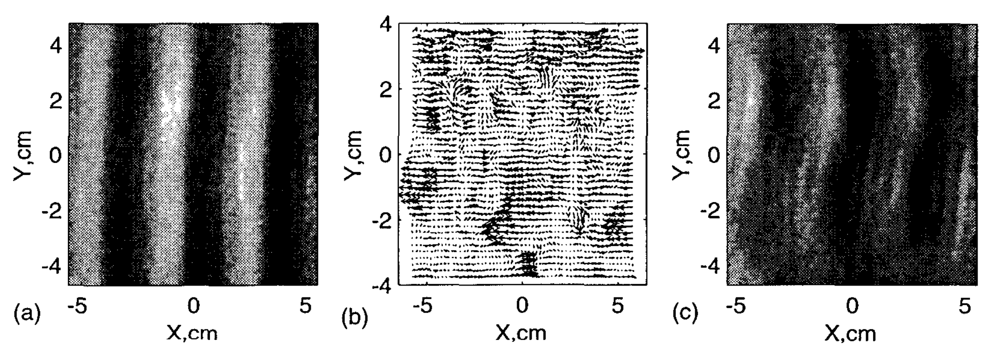

Fig.3. Images of: slope of 7Hz periodic wave without (a) and with (c) grid-generated turbulence, turbulence velocity field taken at 1.5 cm beneath the water surface (b)