REMOTE SENSING OF DIRECTIONAL GRAVITY WAVE SPECTRA AND SURFACE CURRENTS USING A MICROWAVE DUAL-FREQUENCY RADAR

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ABSTRACT

The modulation of small-scale water waves induced by larger-scale 2 to 25 meter gravity waves has been studied by using a coherent, dual-frequency radar technique. The gravity wave modulation manifests itself as a narrow, Doppler-shifted, resonance peak in the product power spectrum of the backscattered returns. The dispersion relation (for both deep and shallow water) of the modulation pattern matches that of gravity waves. Modulation amplitude spectra have been experimentally obtained which, after sufficient averaging, closely resemble directional gravity wave slope spectra and reveal the presence of water surface surface currents.

Introduction

An effort has been made to develop a compact, active, remote sensing instrument[1-2] capable of making area-extensive measurements of the properties of wind-generated surface water waves. This effort has led to the design, building, and testing of 1) a prototype CW dual-frequency coherent X-band radar and, 2) subsequent development of a pulsed dual-frequency radar operating at L-band. These radars were designed specifically to measure 1) directional gravity wave spectra, 2) ocean surface currents, 3) shallow water gravity wave dispersion effects, and 4) the modulation of capillary or short-gravity waves by larger, longer, gravity waves.

The system output is similar to that of a conventional single frequency radar operating at HF frequencies. The dual-frequency system, however, provides 1) simultaneous information on capillary and gravity waves (useful for wave-growth and wave-wave interaction studies), 2) employs a much more compact, directional antenna, and 3) is easily swept in frequency over the entire band of interest, and does not transmit in the broadcast band. The dual-frequency radar system responds primarily a wave system characterized by a single pair of capillary and gravity wave wave-numbers $[\vec{k}_c, \vec{k}_g]$ and modulation effects which are, in general, quite complex may be more easily sorted out and understood. The radar technique reported here makes use of the propagating spatial modulation pattern impressed on the small-scale waves to detect the longer, underlying, gravity waves.

Experimental Instrumentation and Environment

The experiments reported here were carried out on a cliff site 32 meters above the Chesapeake Bay, at the Chesapeake Bay Division of the Naval Research Laboratory. Two radar systems were ultimately installed at the site. The first system, CW 10W X-band dual-frequency radar, was quite successful for demonstrating the feasibility of the concept but was later abandoned because of its extreme sensitivity to local surface winds.

The second dual-frequency radar was a pulsed 5KW (peak) L-band (1230 MHz) radar and was used to make the measurements reported on. The coherently related dual-frequencies $[f_1, f_2]$ were transmitted with a PRF of 5000 on alternate pulses. The difference frequency $\Delta f (= f_2 - f_1)$ could be varied from 500 KHz to 100 MHz. This method allowed excellent channel separation and noise suppression (via temporal decorrelation). A pulse compression network was used for both channels so that the transmitted 5 μs pulses were compressed to 600 ns in the receiver. This compression allowed adequate resolution cell range extent on the sea surface (~90m) while further suppressing noise. The large peak power allowed measurements on sea backscatter to be carried out to greater than 5 km. The position of the resolution cell was determined by a range gate whose position could be changed continuously. Spectral fold-over was prevented by means of a frequency-shifter cavity designed to shift the spectrum by an amount (40 Hz) which was adequate for the L-band spectra. The backscattered sea return at f_1 and f_2 was separated using paralleled sample and hold amplifiers. Timing control pulses for these amplifiers determined both the channel being sampled and the position of the resolution cell on the sea surface. The block diagram for the L-band system is shown in Figure 1. The back-

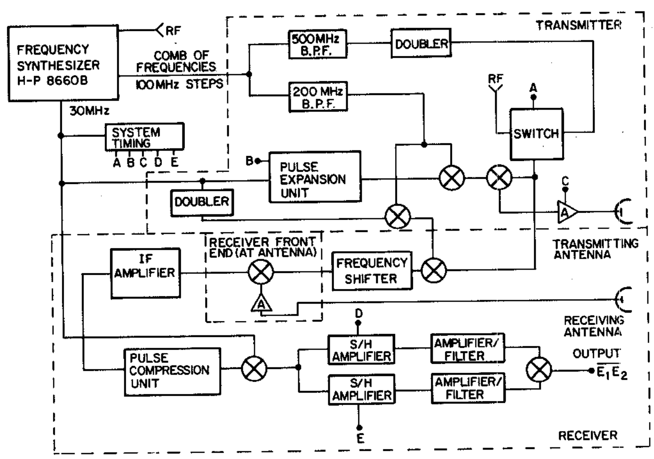

Figure 1: The L-band pulsed dual-frequency ocean wave spectrometer system.

scattered microwave fields E_1 and E_2 associated with f_1 and f_2 are mixed down, linearly detected, and multiplied together in the receiver. Only components of the wave modulation pattern which are in Bragg resonance with the beat frequency Δf ($= f_2 - f_1$) will produce a significant backscatter cross section. This resonant return will appear as a sharp Doppler shifted spectral line in the product power spectrum $\mathfrak{F}[E_1 E_2^* \otimes E_1^* E_2]$ of the returns. The frequency f_p of this line, in the absence of surface currents, will equal the frequency of the modulating wave k_g, whereas, the amplitude of the line will be related by some coupling coefficient to the actual long wave amplitude.

Experimental Measurements

Dispersion Measurements

The first physical proof that the X and L-band radars were capable of measuring the modulation of capillary waves caused by gravity waves was obtained when it was found that the position of the resonant peak in the Doppler spectrum obeyed the gravity wave dispersion relation for the shallow water conditions prevailing at the experimental site. These measurements were followed by attempts to measure complete directional modulation spectra of gravity waves.

Directional Gravity Wave Measurements

Figure 2 shows two examples of direction modulation power spectra measured with the L-band system. The spectra were compared with spectra simultaneously obtained from a capacitance waveprobe, and from Sea Photo Analysis[3] of photographs. The position of the peaks obtained from the radar data agreed well with the positions obtained by the other sensors and theory. The shape of the spectrum, which could only be accurately compared with the sea photograph data, was also in good agreement with the sea photograph spectrum when sufficient spectral averaging was performed.

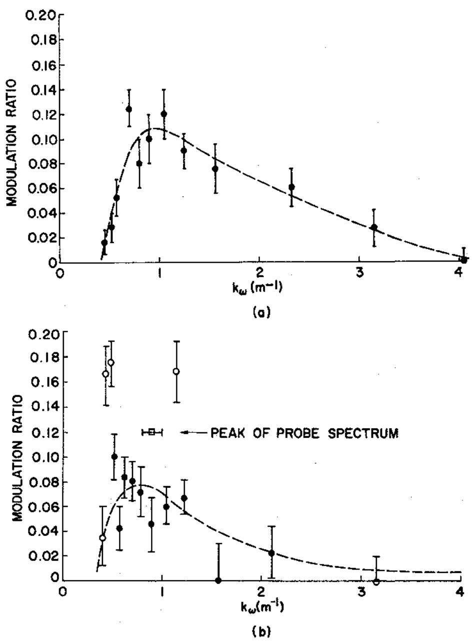

Figure 2: Directional gravity wave modulation spectra obtained using the X-band radar.

The modulation spectra sensed by the radar and the actual gravity wave spectra appear to be closely related.

Measurements of directional gravity wave spectra have not been totally satisfactory because of the long data-acquisition time required for both Doppler processing and signal averaging. Measurements have been made recently using a more highly evolved L-band radar system which is capable of making multiplexed measurements on 50 transmitted frequency pairs in only 5 ms. Multiplexing of the radar data makes possible 1) more accurate measurements of gravity wave spectra since the data is interleaved throughout the entire data acquisition period, and, 2) allows more averaging to be performed during the time interval for which the wave system may reasonably be considered as being stationary. In particular, we have used a frequency synthesizer (capable of switching frequencies in 20 μs) programmed remotely by a set of frequencies stored by an EPROM, to provide a multiplexed output which is then upconverted to L-band. The decoding of the multiplexed output is performed by using appropriately timed sample and hold circuits.

Detection of Surface Currents

Stewart and Joy[4] as well as Teague, Tyler, and Stewart[5] have demonstrated that ocean currents could be remotely sensed using an HF radar which measured the superposition of the gravity wave propagation velocity and the surface current velocity, The current sensed was actually an average of approximately k_g^{-1} meters (where $k_g = 2\pi\lambda_g^{-1}$ is the gravity wave wavenumber and λ_g is its wavelength). Water currents at the experimental site are relatively small (<50 cm/sec) but a successful attempt was made to monitor a tidal cycle from maximum ebb flow and back to slack flow (a period of greater than four hours).

The measurement technique only requires the existence of one resonance peak incrementally shifted away from a known quiescent, or zero current, position in the Doppler spectrum. Figure 3 shows a plot of the tidal current speed measured by the radar as a function of time. Although an in-situ current meter was not available, a tide measurement station was located two miles away at Holland Point.

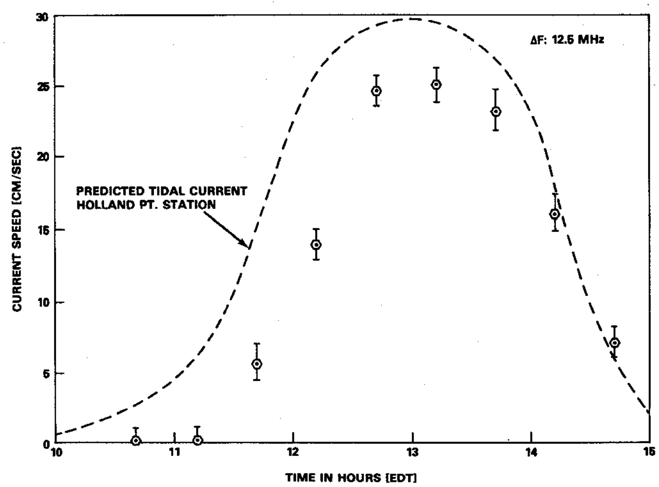

Figure 3: Tidal surface current sensed by the CW-X band radar as a function of time.

The dashed curve of Figure 3 represents the magnitude of the predominantly North-South current flow predicted for the Holland Point station at the date and time of our experiment. The current values measured by the radar, although consistently lower than the predicted values, do indicate clearly that a portion of a tidal current cycle was being sensed.

Conclusions

The dual-frequency radar technique reported here appears to be the basis for a practical instrument to remotely sense the properties of, and interactions between, capillary-gravity or short-gravity-gravity two-scale wave systems. It has the capability of measuring 1) the gravity wave dispersion relation for deep and shallow water, 2) directional gravity wave modulation spectra, 3) surface currents, and 4) selected two-scale wave-wave interactions.

Both the X-band or the L-band dual-frequency radar systems are small enough to be mounted in an aircraft for use as an oceanographic research tool or as a means of monitoring gravity wave systems and currents on the open oceans.

References

1. Schuler, D. L., Remote Sensing of Directional Gravity Wave Spectra and Surface Currents using a Microwave Dual-Frequency Radar, Radio Science, vol. 13, no. 2, 321-32, March, 1978.

2. Plant, W. J., Studies of Backscattered Sea Return with a CW Dual-Frequency X-Band Radar, IEEE Trans. Antennas Propagat., AP-25, 28-36, January, 1978.

3. Stilwell, D., Directional Energy Spectra of the Sea from Photographs, J. Geophys. Res., 74, 1974-1986, April, 1969.

4. Stewart, R. H. and Joy, J. W., HF Radio Measurements of Surface Currents, Deep Sea Research, 21, 1039-1046, 1974.

5. Teague, C. C., Tyler, G. L. and Stewart, R. H., Studies of the Sea using HF Radio Scatter, IEEE Trans. Antennas Propagat., AP-25, 12-19, January, 1978.