EXPERIMENTAL VERIFICATION OF THE THREE-FREQUENCY SCATTEROMETER CONCEPT

Dale L. Schuler and William J. Plant

Naval Research Laboratory
Washington, D.C.

H. Carl Miller

Coastal Engineering Research Center
Field Research Facility
Duck, N.C.

Abstract

A new three-frequency microwave scatterometer technique has been conceptualized from theory developed earlier for the parent dual-frequency instrument. The theory for this new instrument predicts a significant improvement in output signal quality and, ultimately, in the accuracy of directional measurements of ocean wave spectra. An attempt to experimentally verify this concept is reported here. The results of the studies indicate that the technique is both practical and effective.

1. Introduction

There is considerable interest within the Navy as well as the oceanographic and remote sensing communities in the building of an instrument which can measure directional sea surface wave spectra. An ideal instrument should be sensitive enough to allow accurate measurements to be made on virtually the entire ocean wave spectrum, even down to wavelengths as short as one meter. In addition, the directivity of such a system should far exceed that obtainable from buoy measurements and should be comparable with the directivity of currently available in-situ buoy/pressure sensor arrays. Finally, the system should be compatible with airborne and spaceborne platforms for large-scale remote sensing of the seas.

2. Genesis of the New Technique

The three-frequency scatterometer is a recently conceived microwave remote sensing technique which theoretically has the ability to meet these performance criteria. The three-frequency technique was developed through a re-examination of the theory behind the related dual-frequency scatterometer. Both of these techniques involve scattering areas which are so large that wave features are not resolved. Wave properties are studied instead by spatially resonating with selected waves over the entire area. A non-resonant, clutter background return forms a significant and undesirable part of the dual-frequency scatterometer output. This unwanted contribution severely limits the minimum signal detectability. The new three-frequency technique actually converts this background term into a part of the wave modulated signal, thus creating a system whose detectable signal range is limited only by system thermal noise. The most obvious benefit from the improved signal quality and dynamic range is that accurate measurements can

be made on the weaker, low-amplitude wave systems that occur at both ends of the spectrum. Detection of long-wave phenomena (fully-developed wind waves and swell) is important because of the damage caused by these systems to coastal installations as they steepen in shallow water. A knowledge of the short wavelength (15 m or less) waves is important to the planning of small-craft operations, underwater acoustic-system performance, and to studies of the early stages of growth of wind-wave systems.

The three-frequency scatterometer concept is closely related to the well-developed dual-frequency technique which has been used to measure both directional wave spectra and surface current flows. Both types of scatterometers operate coherently in the microwave band and transmit carrier signals separated in frequency by some Δf which is in the Megahertz range. Return signals due to each of the transmitted signals are separately received and then beat together. The power spectrum of the resultant output when any pair of signals is beat together appears as shown schematically in Figure 1. The formation of a power

DUAL-FREQUENCY DOPPLER SEA SPECTRA

Figure 1. Power spectrum of the output of a dual-frequency scatterometer.

spectrum is only necessary for the two-frequency technique but it is a useful way to introduce the

three-frequency concept. It consists of the sum of a broad background spectrum and a sharp resonance line. The background spectrum is the result of a convolution of the Doppler spectra of the two received microwave signals and consequently has a width of a few tens to a few hundred Hertz. The sharp " Δk " line, on the other hand, is the result of a resonance between the beat pattern of the two electromagnetic signals and the modulation pattern of the short ocean surface waves (centimetric "Bragg waves") responsible for the backscatter. It has a width of a few tenths to a few Hertz depending on the relative speed of the microwave antenna and the ocean surface (Plant, 1977; Alpers and Hasselmann, 1978; Jackson, 1981).

The frequency of the center of the Δk line is exactly equal to the frequency of the ocean surface wave which travels along the horizontal radar look direction and whose wavenumber, K_w , is $2\Delta k \cos \theta$ where Δk is the wavenumber separation of the transmitted microwave signals and θ is the grazing angle (Plant, 1977). If a current exists on the surface, the wave of wavenumber K_w will be advected by the current and its frequency in the antenna's frame of reference will change. By this means surface currents along the horizontal radar look direction can be measured using dual-frequency scatterometers (Schuler, 1978; Alpers, et al., 1980). By varying Δk , vertical profiles of horizontal currents along the radar look direction can also be determined (Schuler, et al., 1981). One requirement for such measurements is, of course, that the Δk -line can be easily distinguished from random variance in the background level. This requirement is frequently not well satisfied and therefore severely limits applicability of the technique (Schuler, 1978).

The ratio of integrated intensities of the Δk -line and the background spectrum, χ , has been shown to be related to the surface wave slope spectral density $S(K_w)$ by the equation

$$\chi = \frac{2\pi^2 |m|^2 S(K_w) \coth^2(K_w d)}{A} \quad (1)$$

where d is water depth, A is illuminated area, and m is the modulation transfer function relating the received power modulation to the slope of the long surface wave (Alpers and Hasselmann, 1978; Plant and Schuler, 1980). The inverse dependence of χ on A has been observed experimentally (Plant and Schuler, 1978; Johnson, et al., 1982) and the equation has been shown to account well for observed values of χ (Schuler, et al., 1982; Johnson and Weissman, 1983). Alpers and Hasselmann (1978) pointed out that this signal to background ratio can be increased by low pass filtering but their best estimate of such a ratio was only 1.8 for measurements from satellite altitudes. Thus, once again, the background clutter spectrum was the predominant factor limiting system performance. The three-frequency scatterometer was conceived of as a solution to the problem of inferior signal to background performance. In fact, a calculation using parameters similar to those used by Alpers and Hasselmann (1978) yields a ratio of 71 for the

signal-to-noise ratio of the three-frequency instrument. This indicates that the three-frequency technique will produce signal-to-background ratios 16 dB better than the dual-frequency technique operating from a spaceborne platform.

3. Theory of the Technique

The three-frequency scatterometer concept is most easily understood by considering a microwave system transmitting four carrier frequencies (Figure 2) either simultaneously, or in rapid time sequence. Each of the pairs of signals separated by Δf could be processed to obtain a conventional dual-frequency scatterometer output. If, however, we allow the separation δf between these two pairs to become equal to Δf then high signal quality three-frequency scatterometer measurements can be made.

Figure 2. Frequencies of transmitted signals for a frequency-agile dual-frequency scatterometer. For the three-frequency scatterometer $\delta f = \Delta f$.

The processing of the three-frequency output signals can be carried out quite simply in the time domain as shown in Figure 3. Returns due to the

Figure 3. Method of processing three-frequency scatterometer returns in the time domain. Output P_{nk} is proportional to the ocean wave slope spectral density.

three equally-spaced transmitted frequencies, E_1 , E_2 , and E_3 , are first multiplied in pairs and low-pass filtered to yield $E_1E_2^*$ and $E_2E_3^*$ (called $P_{n\lambda}$ and $P_{n\lambda}$). These resultant products are then multiplied together and low pass filtered to yield $P_{n\lambda}$, the desired mean value. Thus, the Fourier transforming techniques employed above to obtain frequency spectra are, in fact, not really required to process three-frequency data to obtain ocean wavenumber spectra. The value $P_{n\lambda}$ is important because it is a quantity which, as we will see, can be directly related to wave slope (or height) spectral density for a water wavenumber $K_w = 2\Delta k \cos\theta$. It can be shown (Schuler, et al., 1984) that an expression from a normalized value of $P_{n\lambda}$ may be given by,

$$\frac{P_{n\lambda}}{P} = \frac{2\pi^2 |m(\Delta k)|^2 S(\Delta k) \coth^2(\Delta k d)}{A} \quad (2)$$

where $\Delta k = \frac{2\pi \Delta f}{c}$ (c is the speed of light),

$m(\Delta k)$ = modulation transfer function,
 $S(\Delta k)$ = wave slope spectral density,
 A = scattering cell area,
 d = water depth,
 P = system output when $\delta f = \Delta f = 0$.

Equation (2) indicates that the system output is proportional to wave slope, Wave slope and wave height spectra $F(\Delta k)$ are, however, related by

$$S(\Delta k) = (\Delta k)^2 \cdot F(\Delta k) \quad (3)$$

Combining Equations (2) and (3) we may solve for the ocean wave height spectra $F(\Delta k)$,

$$F(\Delta k) = \frac{A}{2\pi^2 (\Delta k)^2 |m(\Delta k)|^2 \coth^2(\Delta k d)} \frac{P_{n\lambda}}{P} \quad (4)$$

The value of $m(\Delta k)$ is, in reality, a complicated function of both geophysical and microwave parameters. Its value, however, has been experimentally determined for many cases (particularly at L-Band) and Equation (4) may then be used to determine $F(\Delta k)$ from the three-frequency scatterometer outputs.

4. Experimental Verification of the Concept

A prototype version of the three-frequency scatterometer has been built and experimentally tested at the Army Coastal Engineering Research Center (CERC) Field Research Facility at Duck, North Carolina. Measurements of wave spectra were carried out during the period 5-9 December 1983 and 4-8 June 1984 from a site at the end of the pier 1840 feet out in the Atlantic ocean. The purpose of the December 1983 experiments was to test the three-frequency scatterometer concept by creating a system that would transmit an L-band carrier frequency f_0 as well as upper ($f_0 + \Delta f$) and lower ($f_0 - \Delta f$) sidebands on successive pulses. This triad of pulses was then repeated continuously. The returns from the sea due to the three frequencies

were sampled at appropriate times and held to form the three temporal signals E_1 , E_2 , E_3 shown in Figure 2. This system configuration only allowed data to be collected at one Δf (and thus, on only one long wavelength wave) at a time. Eight minute data records for each of a wide range of Δf values were taken serially to produce a spectrum. Data runs two hours in length were scheduled to straddle the twenty minute data acquisition periods used by CERC (Coastal Engineering Research Center) for the Baylor gauges mounted along the pier. These Baylor gauges yield a non-directional estimate of wave height (vs. wave frequency) and were used as a source of comparative data for the scatterometer.

The three-frequency scatterometer was operated at a high pulsing rate so that each triad of pulses was transmitted every 300 μs . The scattering cell that was used typically measured 300 m in the range dimension, 105 m in the azimuth dimension, and was centered 300 m from the radar site. Because the radar antenna was only 12.5 m above sea level, this meant that the measurements were done at a grazing angle of 2.5°. Normally, measurements are performed at higher grazing angles to avoid shadowing effects. The cell was positioned at long ranges to (1) minimize range-effects across the cell, and (2) show that the technique was capable of making directional area-extensive measurements even for the long wavelength waves that might be encountered as well at the Duck, NC (Outer-Banks) location. The antenna used was a 1.2 m parabolic disk whose vertical polarization radiation pattern had been modified through the use of L-band absorber to yield a pattern 20° (azimuth) by 13.5° (elevation). Wave spectra produced by this new instrument are consistent with simultaneous (non-directional) Baylor gauge wave measurements carried out by CERC personnel. The data were made comparable by converting the Baylor gauge data to a wavenumber spectrum and by correcting the three-frequency scatterometer data for (1) depth differences, (2) directionality, and by (3) assuming a value for the L-band modulation transfer function $m(\Delta k)$ which was correct for the environmental conditions that were present. A wave height spectrum of a 79 m swell system propagating toward shore from the northeast on 6 December is given in Figure 4. Figure 5 shows data on 7 December which contains the superposition of the swell system and a developing wind-wave system.

A second series of experiments (4-8 June 1984) was performed at the CERC Duck, NC pier to determine if multiplexing of the wave spectral information could be utilized to reduce the overall data acquisition period. If a complete wave height spectrum could be produced in twenty minutes (rather than two hours) then (1) more valid comparisons could be made with the Baylor gauges and (2) the assumption of stationarity of wave conditions would certainly be more justified.

A multiplexed three-frequency scatterometer was created by utilizing a fast-switching coherent frequency source which was controlled by a programmable EPROM. A block diagram of the new system is shown in Figure 6. The new multiplexed scatterometer is capable of transmitting up to twenty-five

Figure 4. Comparison of scatterometer and buoy-derived wave height spectra (vs. wavenumber for 6 December 1983).

Figure 5. Comparison of scatterometer and buoy-derived wave height spectra for 7 December 1983.

Δf triads differing by 1 MHz steps in 7.5 ms. This range of multiplexed channel frequency differences, Δf , allows measurements to be rapidly made for waves having wave lengths ranging from 6 to 150 meters. The data can be de-multiplexed in the field (for a first-look) or can be brought back to the laboratory to be separated out as individual computer files for further processing. Figure 7 gives an example of a de-multiplexed wave height spectra derived from data taken on 5 June 1984. The wind was from the southeast at 15 kts during the measurements and the significant wave height was 0.57 m. The scatterometer and the Baylor gauge spectra agree in both magnitude and general shape. The 9.75 second (77 meter) dominant wave was detected by both systems.

Figure 6. Diagram of the multiplexed three-frequency scatterometer system.

5. Conclusions

We have demonstrated through field-experimentation that ocean wave height spectra are measurable using the three-frequency scatterometer technique. The theory that was developed for the technique appears to be well founded and yields accurate estimates of wave heights. Furthermore, a multiplexed version of the basic three-frequency scatterometer has been shown to be a practical means of collecting data during acquisition times that are short enough so that naturally occurring dynamic, geophysical changes in the wave field may be studied.

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Figure 7. Example of de-multiplexed three-frequency scatterometer data.

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