A STUDY OF THE INFLUENCE OF NON-LINEAR WIND-WAVE-GROWTH PROCESSES ON SCATTEROMETRY

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ABSTRACT

From satellite altitudes, the only feasible way at present to globally monitor wind stress over the oceans is by the use of scatterometers. The principle of wind measurement by the scatterometer is simple. It has been established that for the scatterometer, Bragg scattering is the predominant scattering mechanism; the backscattering power is produced only from those water waves that satisfy the Bragg resonant condition. It has been assumed in the past that the resonant water waves grow monotonically with the wind stress; a simple empirical relationship between the wind stress and the backscattering power has been used until now as the algorithm for scatterometer data reduction.

Recent results from laboratory studies indicate that the growth of wind waves does not follow such a simple relationship. Furthermore, the relationship is not even monotonic. These complications can be attributed to the nonlinear nature of the wind-wave interaction processes. Specifically, the nonlinear relationship between the wind stress and the wave energy density is the consequence of the overshoot phenomenon. Although over-shoot as a function of fetch has been widely accepted, over-shoot as a function of wind stress has never been emphasized.

Published satellite scatterometer data from Skylab and Seasat and also aircraft results are examined to show that the radar backscattering does not vary smoothly with wind stress either as modeled by the empirical scatterometer algorithms. It is asserted that the nonlinearity exhibited in the satellite and aircraft radar results are the manifestation of the nonlinear, over-shoot wave growth phenomenon. To further supply proof of this hypothesis, preliminary results from a laboratory radar set are also presented that reinforce the satellite results. These findings raise questions about the scatterometer data reduction method employed at the present.

INTRODUCTION

Of all of the physical parameters that can influence the dynamics of the ocean, none is more important to the ocean current system and the major force for generating ocean waves (Phillips, 1977). Therefore, the demand for global wind data is strong for both meteorological and oceanographic applications. Since most of the earth's surface is covered by ocean and much of the sea surface is not easily instrumented for routine wind measurements by conventional means, the logical alternative is to use remote sensing techniques.

It is important to note at the outset that no remote wind measurement technique in existence can measure the actual movement of air. Instead, the wind's strength and direction must be inferred from other observables such as surface roughness, the ocean surface's brightness temperature, etc. The success of these implicit methods depends critically on two requirements. In the first place, the instrument must faithfully record the observables due to the wind. Then, a correct and unique inversion relationship between the observables and the wind must be known precisely. Both of these requirements depend upon our understanding of ocean dynamics, and satisfying them is a difficult task that has not as yet been accomplished in a definitive manner.

After considerable research and development, however, many instruments have been manufactured that provide remotely sensed wind speed and direction with acceptable accuracy. Wind speed has been inferred from the visible image of the sun glitter from satellite; ground-based HF radar; lidar; cloud motion from satellite images; altimeter; wind-wave radar; synthetic aperture radar; and, of course, the radiometer and the scatterometer. Among all these techniques, the scatterometer and radiometer have been proved to be the most versatile and reliable instruments. Consequently, they were designated as the primary instruments for wind measurement on the dedicated oceanographic satellite, Seasat, launched in 1978.

In this paper, the principles and potential problems associated with the scatterometer's measurement of wind speed will be discussed. Published analyses of Seasat and Skylab data and recently collected laboratory data will be used to document conclusions drawn in the discussion. A critical examination of our knowledge of the physical processes of wind-wave development and electromagnetic wave reflection by the ocean's surface is important in assessing the capability of the scatterometer technique for wind measurement.

THE PRINCIPLE OF SCATTEROMETER MEASUREMENT

Bragg's law is a well-known formula in optical diffraction and is frequently encountered and used in studies involving electromagnetic and water wave interactions. In fact, the design of the satellite scatterometer is based on the backscattering of off-nadir radar pulses by the selective Bragg scattering mechanism (Granatham et al., 1975). For constructive reinforcement of the scattered electromagnetic fields, the water wave spacing \( \lambda_W \) must be related to the electromagnetic wavelength \( \lambda_e \) by

\[ \lambda_e = 2\lambda_W \sin \theta / m \]  

where \( \theta \) is the radar signal incidence angle and \( m \) is the order of the scattering. For first order scattering, \( m = 1 \), and in terms of wavenumber

\[ k_W = 2k_e \sin \theta \]  

Analytical models of the sea return for radars looking at angles greater than 25° from the nadir have substantiated that Bragg scattering is the predominant ocean scattering mechanism (Peake, 1956; Wright, 1966; Wright, 1968). All of these used the classical perturbation theory results of Rice (1951) to describe electromagnetic scattering from a slightly rough dielectric surface. In the absence of large scale waves, the backscattering cross-section per unit area is given by

\[ \sigma_{pp} (0, \phi) = 8\pi \cdot 4\pi (k_W k_e) \rho_{pp} (0, 0) \]  

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measurements of the ocean's microwave backscattering of the capillary wave spectrum is essential. Windspeed RADSCAT is the aircraft instrument used by Jones et al. (1977). The data points displayed are aircraft data used to compute the WSCAT linear regression shown in the figure. The lines from Skylab 2 and 3 (Cardone et al., 1976) and Seasat (Schroeder et al., 1982) represent the empirical algorithms used for those two satellite scatterometer missions to relate \( \sigma^0 \) to windspeed. Whether these empirical formulas are appropriate for the remote sensing of wind speed is the subject of our discussion here.

**THE CAPILLARY WAVE SPECTRUM**

In concept, the empirical relationships described above are straightforward and are easily implemented. However, the need to constrain scatterometry to the use of algorithms of this sort is gone.

where \( \omega(k_x k_y) \) is the spectrum of the surface height undulations for wavenumbers \( k_x \) and \( k_y \) in the \( x \) and \( y \) directions, respectively, and \( \sigma^0(0,0) \) depends upon the incident and scattered field polarizations.

This basic perturbation theory model has been subsequently modified. The composite surface scattering model first proposed by Wright (1968) assumes that physical optics is valid for near-normal incidence with only large scale waves contributing to the scattered field. For angles of incidence greater than \( 25^\circ \), the perturbation solution is modified to include the tilting of small scale Bragg wave patches by the larger scale waves. In a recent paper, Brown (1978) devised a more general analytical technique to incorporate both the near-specular physical optics scattering pertinent to nadir-looking instruments such as the altimeter and the wide-angle tilted plane Bragg solutions. This model indicates that the sea return from a scatterometer will result from the components of the wave wave wavenumber spectrum in the neighborhood of the Bragg wavenumber \( k_b \); the extent of this neighborhood is proportional to the mean-square slopes of the large-scale wave structure present.

Assuming that the large-scale wave structure is negligible, it is apparent from (3) that knowledge of the capillary wave spectrum is essential. If \( \sigma^0(\theta, \phi) \) as measured by a scatterometer varies at a constant \( \theta \) and \( \phi \), then the changes must be due to differences in the spectrum assuming that the perturbation theory model is correct. Studies by Pierson (1975) and Mitsuyasu and Honda (1974) indicated that the spectrum does change with wind speed. However, as noted by Moore and Fung (1979), there was a serious lack of understanding of the capillary spectrum in the early days of scatterometry. This necessitated the adoption of an empirical technique rather than the use of a physically-based scattering model. As reported by Jones et al. (1975), early measurements of the ocean's microwave backscattering coefficient suggested that it was related to the windspeed \( U \) by a power-law expression, such as

\[
\sigma^0(a) = \sigma_0^B \tag{4}
\]

where \( \sigma_0 \) and \( g \) are empirical coefficients and \( \sigma_0^B \) is in the form of a power ratio. This type expression is still in use. For the Seasat-A satellite scatterometer (SASS), a relationship was adopted in the form

\[
\sigma^0(\theta, \phi) = g(U, \phi) + h(U, \phi) \log U \tag{5}
\]

where \( \theta \) is the incidence angle, \( \phi \) is the satellite azimuth minus the true wind direction, \( g \) and \( h \) are empirical functions, and \( \sigma^0 \) is in \( dB \). Figure 1 shows the linear relationships between \( \sigma^0 \) in \( dB \) and the base 10 logarithm of the wind speed adopted for three different sensors used in scatterometry. RADSCAT is the aircraft instrument used by Jones et al. (1977). The data points displayed are aircraft data used to compute the RADSCAT linear regression shown in the figure. The lines from Skylab 2 and 3 (Cardone et al., 1976) and Seasat (Schroeder et al., 1982) represent the empirical algorithms used for those two satellite scatterometer missions to relate \( \sigma^0 \) to windspeed. Whether these empirical formulas are appropriate for the remote sensing of wind speed is the subject of our discussion here.

As noted by Moore and Fung (1979) the empirical formulas proposed by Pierson and Stacy (1973) and Pierson (1975) have been extensively used in scatterometry to represent the capillary spectrum. But in the past ten years, our knowledge of the capillary wave spectrum has increased dramatically. With it has come an increase as well in our understanding of the physical processes which limit the effectiveness of equation (5).

Figure 1. Empirically-derived algorithms used to model backscattering cross-section as a function of wind speed for RADSCAT (---), Skylab 2 and 3 (----), and Seasat (----). The incidence angle is \( 30^\circ \), the azimuth is the upwind direction, and the transmitted and received signal polarizations are vertical.

The overshoot of the spectral density at a fixed frequency (or wave number) is undoubtedly one of the most important of these. Based on both laboratory and field observations, Barnett (1966), Barnett and Wilkerson (1967) and Barnett and Sutherland (1968) first reported the phenomenon in a wind wave development process as a function of fetch. Later, using radar measurements in the laboratory, Larson and Wright (1975) and Plant and Wright (1977) found that the overshoot phenomenon can occur as a function of duration too. Still a third kind of overshoot that occurs under steady state conditions as a function of wind stress (but independent of fetch) was reported briefly by Long and Huang (1976) in a study of the development of gravity-capillary waves. Figure 2 contains the variation of slope spectral density for wave components in the wind's direction as a function of friction velocity \( u_* \) as measured by Long and Huang (1976). Results for four different fetches are shown and the frequency of the components used in the figure is 13.5 Hz. For the 13.9 GHz radar systems used in all of the satellite scatterometers to date, water waves of this frequency (having wavelengths of about 1.7 cm) satisfy the Bragg resonance condition if observed by the instrument at an incidence angle of about \( 47^\circ \). The overshoot in this data is obvious.

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wind-wave interactions. By theoretical analyses wind wave fields eventually become swell-dominated. As the wind and waves interact wind energy is transferred to a wide range of wave numbers. Resonant theory (Phillips, 1977), however, requires that selected components receive more energy than others. Weakly nonlinear interactions, then, cause the energy to be shifted continuously towards lower wave numbers where it tends to accumulate at a peak leaving both sides of the spectrum near the peak very steep. Consequently, if we monitor the development of particular spectral components in the lower frequency region they will have maximum values when the peak of the spectrum is located at those specific frequencies. As the wind speed, fetch or duration increases, the peak passes that frequency, the energy intensity drops, and an overshoot results.

For short gravity waves (λ < 10 cm), or gravity-capillary waves (λ = 2 cm), the development of the waves is quite different. As soon as the wind starts, these short waves will be generated instantaneously over all fetches as reported by Long and Huang (1976). Furthermore, increase of the wind duration will not necessarily increase the wave intensity either, except at the beginning fraction of a second. This explosive type of short wave generation known as the cat's-paws (Mollo-Christensen and Dorman, 1973) is due to the local shear instability. The special characteristics of these waves is that they are only functions of local wind stress. For the short waves, at a constant frequency, it can be seen in Figure 2 that the spectral density varies with wind speed in a nonlinear fashion. As the wind increases, frequencies below the peak value there is a tremendous rate of growth until the locally wind generated spectral peak is located at that frequency. Then, under the influence of nonlinear wave-wave interaction and the resonant wind-wave interaction mechanism the amplitude decreases before it again begins to grow but at a slower rate.

The dynamic process discussed in this section has been reported in the literature and is known to have impact on the wave height spectrum in the capillary region. The question now is whether or not these spectral variations have influenced scatterometer performance in the past. Results from the Skylab and Seasat scatterometer missions have been published and are useful for this purpose.

EXAMINATION OF PUBLISHED SCATTEROMETER RESULTS

For Skylab, Jones et al. (1975) reported that a power-law response to wind speed seemed to be appropriate. In Figure 3, their empirical algorithm is shown along with measured values and corresponding surface truth wind speed values for an incidence angle of 50°. Although the algorithms in general represent the scatter of the data, in local wind speed regions there appears to be considerable structure that is not, of course, modeled by the power-law curve. For example, at about 8 m/s wind speed, there was a large measured increase in σ°. Using a conversion formula suggested by Garratt (1977), Figure 3 shows that at that wind speed the friction velocity is about 23 cm/s, which is the speed at which the overshoot occurs for 13.5 Hz waves as shown in Figure 2.

![Figure 2](image-url)  
Figure 2. The growth of the upwind-downwind 13.5 Hz components of the slope spectrum with friction velocity. Four different fetches are shown (Long and Huang).

![Figure 3](image-url)  
Figure 3. Variation of the surface scattering coefficient with friction velocity and wind speed. The radar data were measured during the Skylab 2 and 3 missions and are plotted versus surface truth wind measurements. The power law fit shown is the model chosen to represent these data.

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Additionally, data from the Seasat-A satellite scatterometer (SASS) recently published by Jones et al. (1982) shows a similar feature. Figure 4 in this paper is taken from Jones et al. (1982) and shows the difference between SASS measured wind speed and surface truth wind speed as a function of the latter. Below 15 m/s, SASS consistently overestimates the wind speed in comparison to the surface truth while above 15 m/s it underestimates the speed. The differences are largest both in the mean and standard deviation for all experiments in the range of 5-10 m/s. This can be explained by noting that the power law fit through the data in Figure 3 lies below the data in the 8-15 m/s region. If a measurement yielded a value of $\sigma^2 = -20$ dB (scattering coefficient = 0.01), the algorithm produces a wind speed estimate of 10 m/sec, while the data actually indicates that 8 m/sec is a better estimate. Consequently, the SASS-surface truth differences in Figure 4 can be explained by the same argument used for the Skylab results. A power law algorithm can not account for the structure which exists in published correlations of backscattered cross-section with wind speed.

Finally, it should be noted from Figure 1 that the original aircraft data used to derive the early RADSCAT power law expressions were only taken at a few discrete wind speeds. The values used were at 3, 6.5, 13.47, 15, and 23.6 m/s. The pronounced structure in the $\sigma^2 - u_w$ relationship at 8-10 m/s was not sampled at all in the aircraft data collection experiments.

![Combined Polarization](image)

![Number of Comparisons](image)

**Figure 4.** The mean difference and standard deviation of differences between SASS measured wind speeds and ground truth wind speeds (Jones et al., 1982).

**LABORATORY RESULTS**

In an early section evidence was presented which indicated that the capillary spectrum does not grow smoothly with wind speed but experiences overshoot. In the preceding section, published results from the satellite instruments on Skylab and Seasat were discussed. These indicate that the radar-measured backscattered cross-section, $\sigma^2$, also does not vary smoothly with wind speed as represented by the empirical formula given by (3). To shed more light on this problem and to produce further evidence with which to support or discount these observations, a simple radar instrument has been constructed for use in the WFF Wind-Wave Tank Facility. The instrument's design and its performance in a laboratory experiment to study the validity of (3) and (5) are described in the following discussion.

The radar itself is of simple design. A modulated 10 GHz RF signal is routed through a waveguide sliding screw tuner to a horn antenna. The latter component is characterized by a gain of 12.2 dB and a beamwidth of about 40°. The reflected signal is received by the same horn and is this time routed by the circulator to a crystal detector which converts the received modulated RF signal to a modulated voltage. Next, an HP415E SWR meter is used to demodulate the signal and to supply up to 60 dB of amplification. Finally, the output from the SWR meter is smoothed by passing it through an integrating voltmeter. The time period of integration is adjustable and the output can be recorded on magnetic tape or hard disk if required.

To study the effect of wind speed on the measured backscattered RF power, all that is required with this apparatus is to record the average voltage signal level and the friction velocity in the tank. Because a crystal detector, which is a square-law device, is used, the instrument does make a power measurement. The measurement of wind speed and/or friction velocity is routinely made in the Wind-Wave Tank Facility with a Datametrics type 1014 electronic manometer in conjunction with a type 372 ultra-high accuracy transducer and pitot tube.

An experiment has been performed in the following manner. The radar was positioned along and above the tank so that for a 30° incidence angle, it was illuminating a spot upwind on the surface having roughly the same fetch as the nearby pitot tube. The radar signal one-way propagation distance was about 80 cm and the illuminated spot was about 21 cm by 60 cm in area. The radar is subject to backscatter from the walls and top of the tank as well as from the surface. Therefore, for a calm surface, the sliding screw tuner was used to minimize the magnitude of the received background signal. Then any signal with a roughened surface could be referenced to this background level. In effect this procedure corrects for the unwanted wall and top reflections.

Wind profiles and 10.0 GHz $\sigma^2$ measurements were made in this fashion on two different days and the results are shown in Figure 5. The open symbols represent the measurements from the two days. The lines are again the power law fits used for RADSCAT, Skylab, and SASS. It should be noted that these models were developed for instruments operating at 13.9 GHz where the laboratory radar is at 10 GHz but the difference due to the frequency is expected to be small. In contrast to the models, the data levels off at a distinct plateau at and above $u_w = 40$ m/s. Comparisons to Figure 3 show that the shape assumed by these data is similar to that reported for the Skylab ground truth study except that the plateau for
skewness, which is used in this paper to relate wind speed at higher friction velocities are decreased nearly instantaneously by the wind and can be produced. These waves lacked the capillary waves present in the ocean. For the two measurements, the cross-section measurements were also made when random, plunger-produced background waves were introduced. Because these waves are so pervasive in the ocean, much additional work is underway to further characterize their effects on scatterometry. Just these two data points are sufficient to show that the background waves can not be neglected in scatterometry.

CONCLUSIONS

In this paper, evidence has been presented which indicates that the scatterometer algorithms in use that relate received backscattered power measurements to wind speed are in need of refinement. Using published measurements of the amplitude of the capillary wave spectrum and its variation with wind speed, it has been shown that the variation is not smoothly-varying due to the impact of important wave dynamics processes such as overshoot. Furthermore, Skylab and Seasat scatterometer results published in the open literature indicate that the backscattered power returns do not vary smoothly with wind speed either.

To verify these observations, a laboratory experiment involving a simple radar set operated as a scatterometer and wind profile measurements was conducted. The results of these tests corroborate the hypothesis that the scatterometer wind speed algorithm is in need of improvement. Indeed, with the new knowledge of the capillary wave spectrum, it may be possible to replace the empirical power law relationship used in the past with algorithms based on backscattering cross-section theory. Much additional work is needed, both theoretical and in the laboratory, to explain the structure in the backscattered power versus friction velocity data presented in this paper. Some parallels between the overshoot phenomenon and this structure have been noted. If they are physically linked the mechanism has not yet been identified. However, it appears that with additional work it will be possible to replace existing algorithms with deterministic revisions. Existing scatterometer hardware and algorithms can produce invaluable measurements of the oceanic wind field already. But by incorporating modifications based on a more detailed treatment of oceanic microscale dynamics, it is possible to improve the accuracy of the data products substantially.

REFERENCES


