A TECHNIQUE FOR ESTIMATING RMS WAVEHEIGHT AND DOMINANT WAVE
PERIOD USING A COHERENT SHIPBOARD RADAR

Dennis B. Trizna

David L. Porter

Radar Division
Naval Research Laboratory
Washington, DC 20375

Engineering Staff
NOAA NOS
Rockville, MD 20852

Abstract

Techniques are described which utilize a marine navigation radar to measure dominant wave period and radar Doppler spectral characteristics of sea scatter, and allow an estimate of rms wave height. Along with a measure of the sea surface radar cross section, one can then estimate wind stress, including both gravity and capillary wave contributions. Such techniques could ultimately be used to provide surface truth for satellite remote sensors, as well as serve a source of synoptic data if a sufficient number of commercial vessels were equipped appropriately. We also present some preliminary experimental measurements from a program utilizing NOAA and Navy resources.

1. Shipboard Radar Measurements

The measurement of winds using radar scatterometers aboard satellite appears to be a promising tool for global mapping of winds. The development of the radar scatterometer technique has been based upon the correlation of multi-aspect angle measurements of backscattered power from the sea surface with wind speed measured at a standard height aboard ships at sea. However, experiments conducted over the Gulf Stream indicate that wind stress correlates with the radar measurement better than wind speed (Weissman, et al, 1980). Donelan (1982) and Xu (1984) have independently suggested how gravity waves may play a role in contributing to wind stress, which could explain the scatter observed to date in relating wind stress to wind speed when gravity waves are not considered.

The first measurement discussed is that of dominant ocean wavelength. SAR radars have verified early airborne high-resolution radar observations that the maximum signal amplitude is associated with the wave crests. Hansen and Cavaleri (1982) showed that this is even more strongly the case for near grazing incidence for near shore conditions, and we have found this to be true for shipboard radar measurements as well. Since a typical marine navigation radar has a pulse length of the order of 50 ns, it can resolve scatter from wave crests of the dominant wave for ocean wavelengths as short as 30 m, assuming a worst case 4 to 1 ratio of ocean wavelength to radar pulse length. Thus waves of 5-s periods and longer can be measured. This measure of dominant wavelength

is necessary for both ascertaining capillary wave densities properly, as well as for Doppler measurements discussed next. A long pulse radar, averaging echo power over many dominant ocean waves, cannot distinguish between the case with a given capillary wave density and dominant wave period, and the case of one half the given capillary density and half the dominant wavelength, for example.

The second measurement is that of Doppler shift of the radar return from the wave crests. One of the authors has recently formulated a semi-empirical model for the Doppler shift of the peak of the sea scatter spectrum at microwave frequencies, and found good agreement with measured values reported in the literature for vertically polarized data (Trizna, 1984a & 1984b). The model for the Doppler shift is based upon the two-scale model of sea scatter, and includes contributions due to the phase velocity of the Bragg-resonant short wave scatterers, the orbital wave velocity of the gravity waves by which the short waves are advected, and minor contributions due to wind drift and Stokes drift currents.

Figure 1 shows some results from that work, using data which was reported by Mel'nichuk and Chernikov (1971). This is a plot of the measured peak Doppler shift versus wind speed. The curves are values of the peak Doppler shift predicted by the model for different fetches. An analogous plot of the radar sea echo peak Doppler shift versus wave height shows similar behavior. Hence, measured values of the Doppler shift of the peak of the sea echo Doppler spectrum, along with locally measured values of wind speed from aboard the ship, could be used to identify the fetch of the gravity wave system responsible for the radar scatter Doppler shifts. Using the measured Doppler shifts in conjunction with the model curves of Doppler shift versus wave height would allow one to infer the rms wave height as well.

The third measurement discussed is that of high-resolution sea echo radar cross section, i.e., low grazing angle scatterometry. The largest contribution to the capillary wave spectral distribution lies on the forward crests of waves, which is illuminated by the radar when pointing in the upwind direction. According to the two scale model (Wright, 1968), the backscatter amplitude is directly proportional to the spectral distribution

of Bragg-resonant wave components, i.e., those with wave length equal to one half the radar wavelength for low grazing angles. Whereas an air or spaceborne scatterometer typically illuminates an area containing many ocean wave dominant wavelengths, the radar pulse length for a navigation radar is much less than the dominant wave length. Hence, it is able to measure the variation of the capillary wave density across the wave for non-shadowing conditions, and near the crest of the wave even for partial shadowing. One might expect the spectral density of capillary waves near the wave crests to more nearly correlate with wind stress than that averaged over the whole wave, since this is where the strongest interaction between the wind field and the water surface occurs. Thus, this high resolution radar measurement would be better able to accurately measure capillary wave density than a traditional scatterometer which averages over the entire wave structure.

2. Some Preliminary Results of Shipboard Measurements

We have instrumented a NOAA research vessel, the Researcher, with a digital recording capability for collection of X-band horizontally polarized radar sea scatter. In its high-resolution mode, the X-band marine navigation radar transmits a pulse length of 65 ns at a 3600 Hz pulse repetition frequency, at an antenna scan rate of 30 rpm. The antenna has a half power beam width of 1 deg in azimuth and of the order of 30 deg in elevation. The broad elevation pattern ensures a minimum variation in sea echo due to pitching and rolling motions, which typically are no more than 15 deg. We have employed a digital recording system which collects a 256 record of 8-bit samples every 7 deg in azimuth, thus allowing for uniform filling in azimuth for many antenna rotations. The pointing direction of the antenna is encoded into the data stream as well. The receiver is log-linear over 60-dB of dynamic range. The entire radar has been calibrated using a radar calibration sphere. Sea scatter experiments have been performed in the North Atlantic, and additional experiments are planned in other areas. Analysis of the North Atlantic data has just begun, and some examples of the characteristics of the radar scatter are shown next.

Figure 2 shows a plot of amplitude versus range for an azimuthal position which lays within one degree of the upwind direction. The periodicity of the return agrees very well with the dominant wave period reported by three NOAA buoys in the region off the coast of New England where the experiments were conducted. This periodicity of the radar return does not occur far off the wind direction, indicating a very coherent wave train in the wind direction at the dominant wave length of the gravity wave system. It is not known whether swell propagating at an angle off the wind direction also produce a periodic return, but attempts will be made to test this hypothesis.

The measurement of the Doppler spectrum of the radar sea echo has not yet been attempted, but

awaits appropriate modification of the radar.

Data like that of Figure 1 were sorted by azimuth and histograms were calculated for a fixed range bin. Some results are shown in Figure 3 for a wedge shaped section, 20 deg either side of the wind direction. It appears that a bi-modal distribution exists, and that the median value for each distribution can be determined from this plot.

Cumulative distributions for these horizontally polarized data are fitted best by two Weibull distributions, similar to the data of Hansen and Cavaleri, who collected both horizontally and vertically polarized data for a given set of wave conditions. The Weibull distribution will fit a straight line when plotted on Rayleigh axes. Hansen and Cavaleri found that the lower amplitude region of the horizontally polarized return is fit by a line which has the same slope as that of their vertically polarized data, but about 10 to 12 dB lower in RCS value. We suggest here that this agrees well with the two scale model prediction for Bragg scatter from capillary waves for the two polarizations. (The two scale model suggests such a difference, which applies to median values of the return, but which will also apply to the differences between the straight line fits for the cumulative if they have the same slope.) The higher level distribution of Figure 3 is hypothesized to be due to scatter from wave crests, although a specific scattering mechanism is not suggested here.

3. Discussion

The experimental median radar cross sections will be correlated with wind stress estimates from NOAA open ocean buoy data, in effect a high-resolution scatterometry experiment. The upwind radar echo periodicity allows the dominant wave length to be determined from the same data set. Information needed for estimates of gravity wave contributions to the wind stress will be derived from Doppler radar sea echo spectra in future experiments. These measurements will be used in conjunction with a model which allows an estimate of the rms wave height, given the spectral peak Doppler shift and the radar-determined dominant wave length of the ocean spectrum. With these measurements, all the information required for correlating high-resolution radar sea echo data with long gravity wave and short capillary wave contributions to the wind stress will be possible for the first time. With such an empirical correlation established, such a shipboard radar system could provide a source of information for synoptic data, as well as surface truth for future satellite systems.

4. References

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Figure 1. Doppler shifts of sea scatter spectral peaks for vertical polarization are plotted versus wind speed. Model curves from Trizna (1984) for 25, 50, 100, 200, and 400 km fetches for the predicted Doppler shifts are overlayed upon the data.

Figure 2. Radar backscattered power (arbitrary scale) is plotted versus radar range (arbitrary origin) for an upwind shipboard radar azimuthal aspect. The periodicity defined by peaks 1, 2, 3, 5, and 6 agrees well with the dominant ocean wavelength reported by NOAA buoys in the area.

Figure 3. A bi-modal distribution function is observed in this plot of sea surface radar cross section versus percentage of occurrence. Data from a single range bin were ordered from several hundred pulses within ± 20 deg about the wind direction.