NASA/CR-97- 205780

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OCT/97

## NASA Innovative Research Program

# Research in Observations of Oceanic Air/Sea Interaction

Grant NAGW 2875

Final Report: Aug. 1995

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## Summary

The primary purpose of this research has been (1) to develop an innovative research radar scatterometer system capable of directly measuring both the radar backscatter and the small-scale and large-scale ocean wave field simultaneously and (2) deploy this instrument to collect data to support studies of air/sea interaction. The instrument has been successfully completed and deployed. The system deployment lasted for six months during 1995. Results to date suggest that the data is remarkably useful in air/sea interaction studies. While the data analysis is continuing, two journal and fifteen conference papers have been published. Six papers are currently in review with two additional journal papers scheduled for publication. Three Master's theses on this research have been completed. A Ph.D. student is currently finalizing his dissertation which should be completed by the end of the calendar year. We have received additional ("mainstream") funding from the NASA oceans branch to continue data analysis and instrument operations. We are actively pursuing results from the data expect additional publications to follow. This final report briefly describes the instrument system we developed and results to-date from the deployment. Additional detail is contained in the attached papers selected from the bibliography.

## RESULTS

The instrument system design has proven robust and practical during the six month long field deployment on Lake Ontario conducted during mid CY95. Over 20 GB of data were collected with the instrument in continuous operation. Data gaps were primarily due to power failures on the platform. Photographs of the system are shown in Figs. 1 and 2. Data from the experiment continues to be analyzed. Analyses of the data to date have resulted in a number of papers and several Master's thesis. The data is already providing valuable insights into various aspects of air/sea interaction.

Collaborations with Dr. Mike Freilich at Oregon State University (OSU) and Dr. Mark Donelan at the Canada Centre for Inland Waters (CCIW) have been developed. Dr. Donelan facilitated the use of the CCIW platform during the 1994 deployment. He is also providing data on the directional surface wave spectra to support advanced data analysis. In conjunction with Dr. Freilich, we have received funding from the NASA Oceans Branch to redeploy the instrument in 1995 to collect additional data from an ocean platform. This deployment will occur on a Shell Oil platform in mid September and will continue through at least the end of the year. This additional data will span additional ranges of wave, water, and wind conditions to extend our analysis range.

## Wind Speed Sensitivity

YSCAT data has been analyzed in several studies to understand the sensitivity of the radar backscatter to the wind speed as a function of the Bragg (wave in resonance with the radar signal) wavelength. While other studies are ongoing, a preliminary analysis (Long et al, 1995) is attached. This paper considers the wind sensitivity of the radar backscatter over the wind speed range of 4.5 m/s to 12 m/s and radar frequencies of 2.0, 3.05, 5.30, 10.02, and 14.0 GHz. Assuming a simple power law model to describe the relationship between backscatter and wind speed, both wind speed exponents and upwind/downwind (u/d) ratios of the backscatter were found using least squares linear regression. The analysis of the wind speed exponents and u/d ratios show that shorter Bragg wavelengths (< 4 cm) are the most sensitive to wind speed and direction. These results confirm previous conjectures based on limited-frequency results.

Analysis of the wind speed exponent versus incidence angle and frequency showed that the wind speed exponent typically increased with increasing incidence angle from 20° to 50°: Most cases displayed a peak at 50°, however, the results at 2 GHz did not show any apparent dependence on incidence angle. As a function of Bragg wavelength, all results showed that the wind exponent increased with decreasing Bragg wavelength. In comparison to previous studies, the YSCAT wind exponent is higher for small Bragg wavelengths especially at V-pol. This difference may be attributed to differences in the drag coefficient of Lake Ontario and that of the open ocean. Further studies will be conducted in the Gulf of Mexico to verify this hypothesis.

Using the regression fits, the upwind/downwind (u/d) ratio of the backscatter was determined as a function of wind speed and Bragg wavelength. The data displayed two important trends. First, the u/d ratio increased with decreasing Bragg wavelength and second, the u/d ratio decreased with increasing wind speed. These trends are consistent with results published by other researchers.

Using a least squares exponential or polynomial fit, the behavior of the wind speed exponent and u/d were compared. Analysis of these comparisons gives the following conclusions:

1. V-pol backscatter is slightly more sensitive than H-pol to wind speed.
2. H-pol backscatter is more sensitive than V-pol to wind direction.
3. Bragg wavelengths less than 4 cm are the most sensitive to wind speed and direction.
4. The H-pol u/d ratio is larger than the u/d ratio at V-pol.
5. For small Bragg wavelengths the H-pol u/d ratio has a greater change as a function of wind speed than the V-pol u/d ratio.

The results of this study show that wind speed sensitivity is maximized at Ku-band suggesting that spaceborne scatterometers should be operated at this frequency. It should be noted, however, that the variability in the backscatter with other environmental variables is also maximized at Ku-band.

## Azimuth Modulation at Low-Incidence Angles

One of the most interesting results of the YSCAT data is the observation of wind direction (azimuth) modulation of the radar backscatter at near-nadir incidence angles. Previously it had been thought that near-normal incidence angle backscatter was not affected by the wind direction. However, the attached paper by Greenwood et al. (1995) presents a theoretical model for near-nadir radar scattering which clearly shows that azimuth modulation does occur for wind speeds less than 10-12 m/s. As described in the paper, this modulation was clearly observed in YSCAT data. These results have important implications for spaceborne scatterometer systems which use near-nadir incidence angles for calibration. Further, these results suggest that it may be possible to accurately infer wind direction at very low wind speeds at low incidence angles. Further investigation is on-going.

## Surface Scattering Statistics

We have been carefully examining the scattering statistics of YSCAT data to better understand the underlying scattering mechanism. This study has been motivated by the fact that current theoretical models for radar scattering off the ocean's surface, while predicting some of the broad details of the observed radar return, do not accurately describe the complete radar return.

Two possible reasons can be postulated about why this is the case. First, it may be that additional scattering mechanisms may be involved which are not included in the current model. Candidate scattering mechanisms which have been proposed include wave breaking and wedge scattering. A second possibility may be that Bragg scatterers (the scatterers included in the current model) are in fact the dominant scatterers, but that they are improperly included in the model.

A Ph.D. student is nearing completion of his dissertation in this area. The purpose of his research is to measure and study the statistics of the sea scattered radar return and determine if evidence exists of other scattering mechanisms involved in the scattering process. Two main categories of statistics are studied: velocity statistics derived from the Doppler shift of the radar return and power statistics derived from the distribution of the scattered return.

Because the scales of the waves involved in Bragg scattering and wave breaking are so different the dispersion relation which predicts the phase velocity of a given ocean wave predicts that Bragg scatterers will have a much lower apparent velocity than breaking waves or wedges. Therefore, if either of these two additional scattering mechanisms contribute significantly to the total radar cross section the average velocity of observed scatterers should be higher than that predicted for Bragg only scattering.

The average scatterer velocity is computed by computing histograms of the return power and binning according to line of sight (LOS) velocity (Doppler shift) and computing the first moment. This centroid is considered to be the effective velocity of the scatterers. A simple model of ocean scattering which includes the presence of long wavelength swell in addition to small Bragg waves indicates that the centroid velocity may be increased by the effect of the long waves tilting the Bragg waves towards or away from the radar.

Taking this into account, the centroid velocity observed by the YSCAT radar system is not significantly higher than that predicted by the Bragg over the range of conditions observed during the 1994 experiment. The range of conditions observed are: incidence angle ranges from 20° - 60°, frequencies from 2-14 GHz, and wind speeds from 1-10 m/s from both upwind and downwind.

In order to look at the velocities another way, one can compute the average scatterer velocity (that is the average observed velocity weighting low and high power measurements equally) rather then the centroid velocity. The velocities observed in this manner were also found to be in line with that predicted by the Bragg composite model.

Curiously though, the ratio of the centroid velocity to the scatterer velocity was found to increase with wind speed in the downwind direction and decrease with wind speed in the upwind direction. This effect was found to be consistent with the composite model through the use of the hydrodynamic modulation transfer function postulated by several researchers.

The results of computing the average velocities did not show evidence of significant contributions from other scattering mechanisms. The next step in looking for additional mechanisms requires one to look at the average cross section associated with the different velocity measurements. When this was done it was found that faster velocity measurements were consistently associated with large average cross sections. On its face this result agrees with both breaking waves and the composite model. However, the magnitude and incidence angle dependence of the cross section increase with velocity was consistent with the composite model. Inspection of the velocity distribution functions also did not reveal the presence of abnormally fast scatterers being observed in a significant way.

Separate from the velocity statistics are the power distribution statistics. This is in a sense more important than the velocity statistics since it is the mean of the power distribution that is measured by operational scatterometers. It is generally agreed that current scattering models cannot be tweaked to predict both V-pol mean powers and H-pol mean powers simultaneously.

The magnitude of the mean predicted by the composite models is difficult to determine since many of the parameters involved are unknown. Researchers routinely use "reasonable" values to compare their models to results. However this makes precise comparison with data difficult. Several qualities about the mean can be compared with data.

First, the dependence of the mean on incidence angle can be determined and compared with that predicted by current models. The model dependence of the mean on incidence angle requires one to determine a form of the wave spectrum. By fitting the observed incidence angle dependence to the model, one can determine what shape of wave spectrum could have produced the data. When this was done to the YSCAT data, it was found that the shape of the spectrum was slightly steeper than generally predicted for ocean waves. This could be the result of either additional scattering mechanisms or possibly a different shape of wave spectrum on Lake Ontario than the ocean.

The general shape of the power distribution predicted for small rms wave slopes can be shown to be log-normal. In general, the observed distribution is very close to a log-normal. When compared to another proposed distribution, the Rayleigh and the more general Weibull, the fitting error was usually about 10 dB smaller for the log-normal. There was a consistent upper tail in the distributions that can be shown to be caused by large wave slopes and are predicted by the composite model.

In general, this study shows that under the conditions and parameters of this experiment, there is no strong evidence of large contributions to the radar cross section of the sea surface by wave breaking or wedge scattering. If the generally accepted figure that the current model under predicts the radar return by 3 dB is used, clearly wave-breaking and wedge scattering cannot account for this.

This leads one to conclude that the second of the two possibilities proposed in the opening of this paper exists, that there is not a large missing scattering mechanism that needs to be added to the composite scattering model. In fact the composite scattering model, even in a relatively simple form, predicts the shape of the observed power distributions as well as the velocity of the observed scatterers. Therefore, one must conclude that we need to refine our understanding of the development of Bragg waves, and the wave height spectrum in general, rather than trying to include these additional scattering mechanisms which do not contribute significantly to the radar return under the conditions presented here.

A Ph.D. student is preparing several papers on these results and additional papers are in the planning stages. Papers with collaborating colleagues are also being developed.

## FUTURE PLANS

While funds for this NASA IRP were depleted in CY95, we anticipate continuing to use the valuable data set collected as part of this research in a wide variety of additional studies. As previously indicated, we have received additional funding from the NASA Oceans office to redeploy the system to collect additional data beginning in September and perform additional data analyses. We hope to collect data to support the calibration of the NASA Scatterometer, planned for launch in Aug. 1996. Further analysis of exiting data will continue, leading to additional papers.

## BIBLIOGRAPHY

Two journal papers and fifteen conference papers resulting from this research has been published thus far. Two journal papers are scheduled to appear while six are currently in review with two in the final stages of preparation. These papers are listed below. Additional journal and conference papers are planned. Our research project has been the subject of a number of newspaper articles in local and state papers and a report on the state wide evening TV news. We have prepared several displays for Utah state fairs and participated in several NASA-sponsored symposia.

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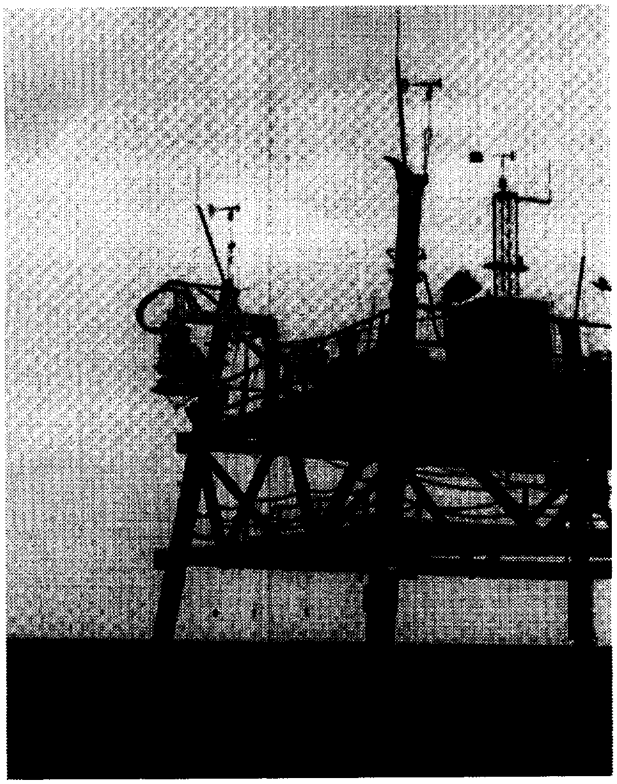

Figure 1. The instrument sensor system mounted on the CCIW research platform in Lake Ontario. The computer and other electronics are contained in the shed in the center of the platform. Note the three anemometers visible on the tower tops and the wave sensors hanging below the platform. Temperature, humidity and rain sensors are mounted on the left-most leg of the platform. Six months of data, from May thru November 1995, were collected.

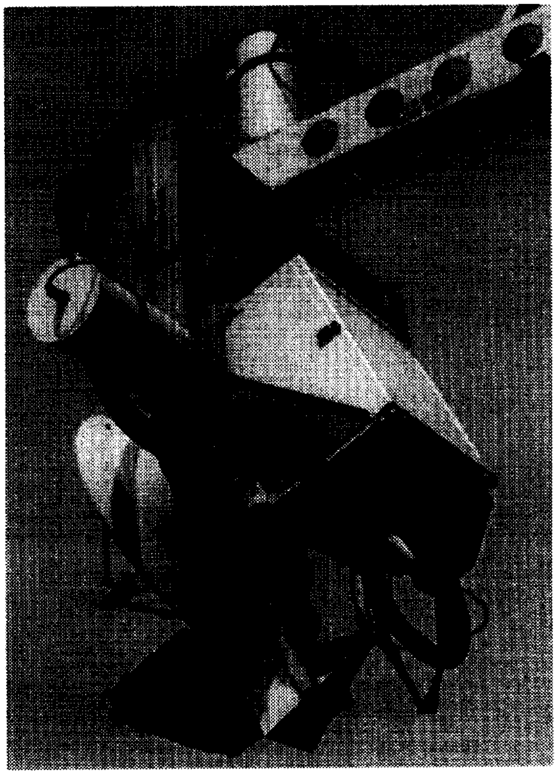

Figure 2. Closeup view of radar sensor. The dish is the fixed-beamwidth transmit antenna. Below it is the wide-band receive horn. The RF electronics are contained in the box behind the antennas. The white cylinders contain the azimuth and elevation positioning motors. The black hose carries chilled air to maintain the electronics in the operating temperature range. The antenna positioning mechanism enables measurements over an incidence angle range of nadir (0°) to grazing (90°) and azimuth angles of ±180°. The radar center frequency may be set anywhere between 2 and 18 GHz.