Radar Backscatter from a Wind Roughened Water Surface in the Bragg Regime

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Abstract - **Measurements of the normalized radar cross section (σ°) made by the YSCAT ultra-wideband scatterometer during an extended deployment at Lake Ontario are analyzed and compared with anemometer wind measurements to study the sensitivity of σ^o to the wind speed as a function of the Bragg wavelength. Wind speeds from 4.5 m/s to 12 m/s are studied at frequencies of 2 to 14 GHz and incidence angles within the Bragg regime, 30° to 50°. Adopting a power law model to describe the relationship between σ^o and wind speed, the wind speed exponents and upwind/downwind (u/d) ratios of σ^o are presented as a function of the ocean Bragg wavelength. Analysis of the wind speed dependence of the normalized measurement variance suggests that Bragg scattering does not explain the observed scattering characteristics.**

I. INTRODUCTION

An ultra-wideband scatterometer, known as YSCAT, has been built to study the dependence of the normalized radar backscatter (σ°) on wind and environmental parameters. The system was deployed for six months in 1994 on the Canada Center for Inland Waters (CCIW) Research Tower at Lake Ontario [1]. This paper presents wind speed sensitivity results based on approximately 3 months of YSCAT data.

II. BACKGROUND

For moderate incidence angles (20°-60°) at microwave frequencies, the sea surface scattering is primarily dependent on small scale (1-15 cm) gravity/capillary waves due to Bragg scattering. The backscatter return is assumed to be caused from the water wave component which is in resonance with the incident radiation. The resonant water wavelength Λ is related to electromagnetic wavelength λ by $\Lambda = \lambda/2\sin(\theta)$ where θ is the incidence angle. For microwave frequencies of 2-18 GHz, and moderate incidence angles, the Bragg wavelength varies from approximately 1 cm to 20 cm, a range which includes capillary and short gravity waves.

While a strict power-law formulation may not hold at all wind speeds, power law models are in good agreement with experimental data for mid-range wind speeds (5 - 16 m/s) and moderate incidence angles. We have adopted a very simple power-law model function to analyze the wind speed sensitivity of σ^o

$$\sigma^\circ = AU^\gamma$$

where γ is the wind speed exponent and A is a constant. Both γ and A vary with electromagnetic frequency, incidence angle, relative azimuth angle, and polarization. In this paper only upwind and downwind directions are considered.

III. EXPERIMENT DESCRIPTION

YSCAT is a bistatic CW radar scatterometer which can be operated at any frequency from 2-18 GHz. It transmits either a V or H polarization signal and has a dual polarization receiver. The transmit antenna is a 3 ft ellipsoidal figure antenna which provides a nearly constant beamwidth of 5° from 4-18 GHz. At 2 GHz the beamwidth < 8°. The incidence and azimuth angles of the antennas are controlled using stepping motors. The incidence angle can be adjusted from nadir (0°) to greater than 90°. The azimuth angle can range over ±80°.

In situ sensors include two anemometers at 10 m, an aspirated temperature sensor, a humidity gauge, a water temperature gauge, and a rain gauge. A bivane anemometer and multiwire wavegauge array are sampled at 10 Hz to enable computation of the wind stress and directional wave spectrum.

YSCAT was deployed from May 1994 through November 1994 on the CCIW Research Tower located on Lake Ontario. Approximately 3 months of data, collected from May 6 to August 1, are analyzed in this paper.

IV. DATA ANALYSIS RESULTS AND DISCUSSION

To investigate the sensitivity of σ^o at different frequencies, linear regression is used to estimate γ with outliers discarded. Outliers are defined as points that are more than $\pm 2\sigma$ from an initial regression fit using all the points [2]. Plots of σ^o (in dB) versus the log of wind speed display the usual linear trend (see Fig. 1). Confidence intervals were computed assuming a conservative 20 ms correlation time [2,4]. The resulting 95% confidence interval is typically less than ±0.1 dB for the σ^o regression.

A. *Wind Speed Exponent versus Bragg wavelength*

For moderate incidence angles (30° to 50°) within the Bragg regime, the dependence of γ on frequency and incidence angle can be combined into a dependence on just Bragg wavelength Λ. Limiting the incidence angles to between 30° and 50°, the upwind values of γ are plotted against Bragg wavelength in Fig. 2. A least squares exponential fit to the data is also shown. The error bars display the 90% confidence levels of the γ estimates. Downwind measurements were also taken and have smaller error bars due to more available measurements. This figure suggests that σ^o is much more sensitive (i.e., γ is larger) to wind speed at smaller Bragg wavelengths ($\Lambda < 4$ cm) than at longer wavelengths. The differences of γ between the V-pol and H-pol cases are discussed later.

The V-pol 10 GHz and 14 GHz measurements exhibit considerable scatter. This phenomena has also been observed by Keller and Plant [3] who note that the data spread at X-band is always considerable when wind speed is used as the independent variable. Since there is much less scatter in the data at lower frequencies, it is suggested that σ^o at X and Ku bands is more sensitive to other unmodeled geophysical parameters than it is at lower frequencies.

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For H-pol, YSCAT results are comparable to previous results; however, for V-pol, YSCAT values are larger for $\Lambda < 4$ cm. The fact that YSCAT measurements were taken in a fresh water lake rather than in the open ocean may explain why the exponents are higher. In a previous experiment Colton [1] found that σ^o measured at Lake Ontario had a higher wind speed dependence than those over the open ocean. Colton hypothesized that the higher wind speed exponents could be attributed to the difference between the drag coefficient of the open sea and that of Lake Ontario. The drag coefficient on the lake has a higher wind speed dependence because lake waves are often in an active growth stage and are steeper than waves in the ocean. Correcting for the assumed difference in drag coefficient, Colton showed that the wind exponents at 40° and 60° incidence angles decreased by almost a factor of 2. Even with this correction, the curves imply that H-pol is more sensitive to wind speed than V-pol with smaller Bragg wavelengths ($\Lambda < 4$ cm) much more sensitive to wind speed than longer wavelengths.

B. γ *for Upwind, Downwind, and Polarization*

The ratios of γ_U to γ_D for both V-pol and H-pol as a function of Bragg wavelength are given in Fig. 3 where the lines are least squares fits to the data. Note that in both cases the γ_U/γ_D ratio is less than one, but increasing with decreasing Bragg wavelength. This implies that shorter Bragg wavelengths will produce higher upwind/downwind ratios. Figure 3 also illustrates the γ_{HH}/γ_{VV} ratio as a function of Bragg wavelength. Note that V-pol is more sensitive to wind speed, particularly for upwind.

The upwind/downwind (u/d) σ^o ratio, which is a function of wind speed, is

$$\begin{aligned}(\mathrm{u/d})_{dB} &= (\sigma^o_U)_{dB} - (\sigma^o_D)_{dB}\\ &= (A_U - A_D) + (\gamma_U - \gamma_D)10\log_{10}(U)\end{aligned}$$

where A_U and A_D are the A values for the upwind and downwind cases respectively. Figure 4 illustrates the u/d ratio for several wind speeds. The lines in each plot are least squares fits to the data. A first order polynomial is used for the V-pol cases, while a third order polynomial is used for the H-pol cases. The H-pol results show a definite trend of increasing u/d ratio for decreasing Bragg wavelengths. Though the ratio is less than that for H-pol, the V-pol u/d ratios generally increase as Bragg wavelengths decrease. In all instances, the H-pol u/d ratios are higher than V-pol. For both the V-pol and H-pol cases, the u/d ratios decrease as the wind speed increases.

Although σ^o at X-band and Ku-band appears to be more sensitive to wind speed and direction than at C-band, the values of σ^o at the higher frequencies also exhibit much higher variability. This variability may be due to other unmodeled parameters such as air-sea temperature difference and long wave fields. In this respect, C-band is a better operational frequency since the measurements appear to be less sensitive to other environmental parameters.

V-pol appears to be slightly more sensitive to wind speed, but H-pol is much more sensitive to wind direction. In addition, the measurement variability at 10 GHz and 14 GHz is lower for the H-pol cases. These results suggest that H-pol is better than V-pol in determining both wind speed and direction, while V-pol appears superior in measuring wind speed only. It should be noted that these conclusions are based on only the first three months of YSCAT 1994 data.

V. SCATTERING MECHANISM

The different behavior of the two polarizations is not fully explained by the composite model of ocean scattering. A possible explanation is that non-Bragg scattering, such as breaking waves and wedge scattering, plays a more important role in ocean scattering than has been previously believed.

The wind speed dependence of the normalized variance can be used to test the hypothesis that Bragg scattering totally dominates the radar return. The normalized variance of the radar return is defined as the sample variance divided by the square of the sample mean. Plant has shown that the normalized variance is proportional to the variance of the power scattered from the individual "facets" of the composite model [4]. Assuming that the facet size does not change with wind speed, and using the fundamental results of small-perturbation scattering, the radar is an "estimator" of the power spectrum of the surface wave height. Estimation theory suggests that the normalized variance depends on sampling parameters but not on spectral amplitude. Of the composite model's parameters only spectral amplitude is dependent on wind speed; hence, the composite model predicts that the normalized variance must be independent of wind speed.

To test this hypothesis using YSCAT data, we assume a very simple power law model for the normalized variance:

$$n_o = BU^\delta$$

where n_o is the normalized variance, B is a constant, U is the wind speed, and δ is the wind speed dependence. Linear regression of the log-normalized variance versus log wind speed provides δ. The results shown in Fig. 5 suggest the composite model holds very well for L and S band for both polarizations ($\delta \sim 0$). V-pol at downwind also shows no wind speed dependence for all frequencies. This result is expected since other scattering mechanisms will be least obvious for this case. However, at frequencies above L band, V-pol upwind and H-pol at either direction exhibit significant wind speed dependence. This suggests that Bragg scattering is not the only sigificant scattering mechansim for these cases.

VI. CONCLUSION

A preliminary analysis of three months of YSCAT data over moderate incidence angles (20° to 50°) and mid-range wind speeds as a function of incidence angle suggest that the wind speed coefficient γ typically increases with increasing incidence angle. Most cases display a peak in γ at $\theta = 50°$, although at 2 GHz there is no apparent dependence on θ. γ also increases with decreasing Bragg wavelength (Λ). Compared to previous studies, γ is higher for small Λ especially at V-pol. This difference may be attributed to differences in the drag coefficient of Lake Ontario and that of the open ocean. The behavior of γ and the upwind/downwind ratio suggest the following:

- V-pol σ^o is slightly more sensitive than H-pol σ^o to wind speed.
- H-pol σ^o is more sensitive than V-pol σ^o to wind direction.
- Bragg wavelengths less than 4 cm are the most sensitive to wind speed and direction.

An analysis of the wind speed dependence of the normalized variance suggests that while the composite model can explain the observed dependence for V-pol at downwind, additional scattering mechanisms are required to explain V-pol at upwind and H-pol scattering.

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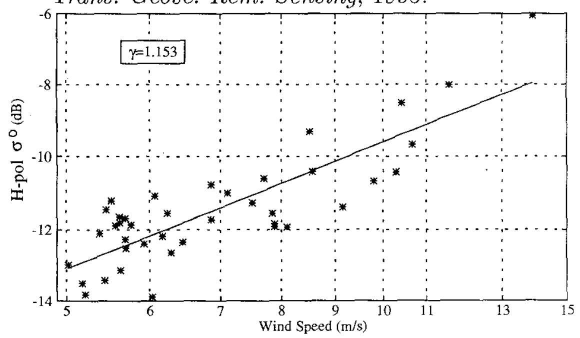

Figure 1. 3 GHz σ^o versus θ at 30° incidence angle.

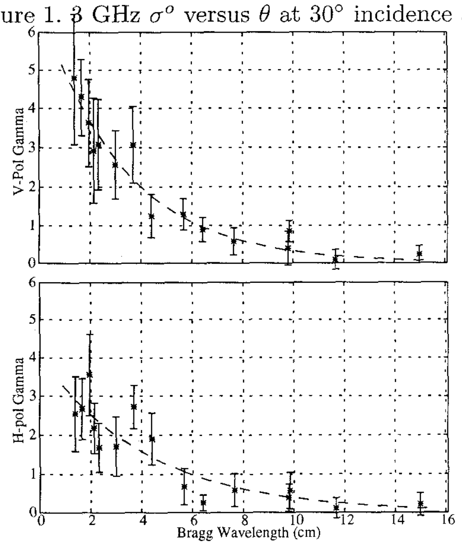

Figure 2. Upwind γ versus Bragg wavelength.

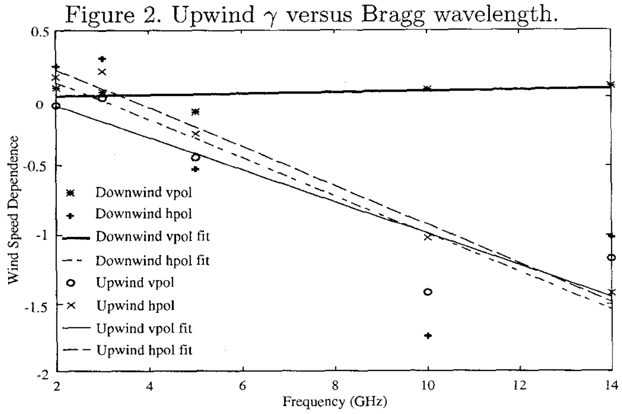

Figure 5. δ versus EM frequency.

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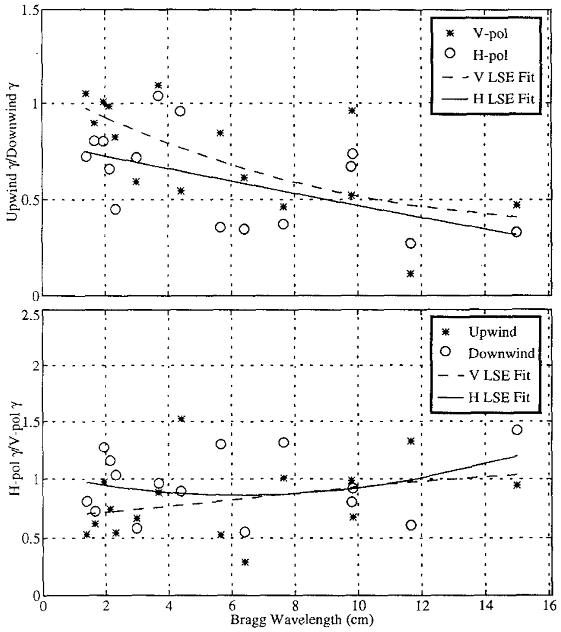

Figure 3. γ_{HH}/γ_{VV} ratio and γ_U/γ_D ratio as function of Bragg wavelength.

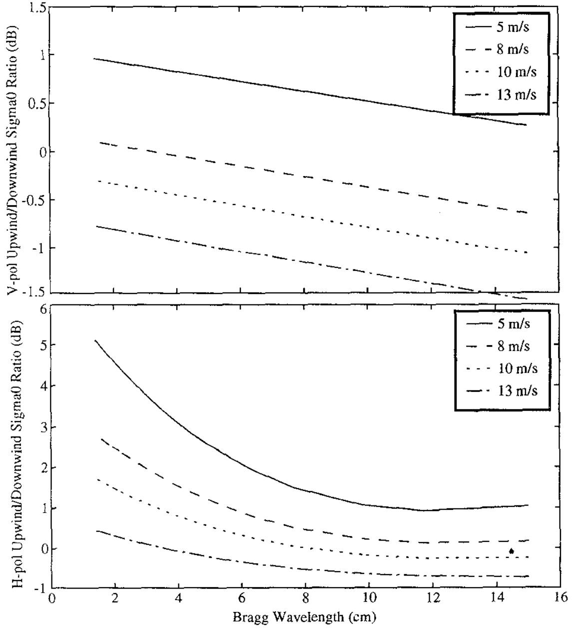

Figure 4. Upwind/Downwind ratio as function of Bragg wavelength for various wind speeds.