International Geoscience and Remote Sensing Symposium, 1996

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Abstract Ocean backscatter data over a wide variety of oceanic and atmospheric conditions were obtained by the Jet Propulsion Laboratory NUSCAT K_u-band scatterometer during the Surface Wave Dynamics Experiment (SWADE). A sea surface temperature front at the Gulf-Stream boundary existed in the SWADE measurement area. Swells up to 6 m in significant wave height and a large range of wind speed was encountered. Relations of backscatter with friction velocity are derived from the NUSCAT-SWADE data set. The increasing trend observed in the backscatter with younger wave age agrees with a rougher surface condition for a younger wave field. The results, obtained from the same data base, show that backscatter are more sensitive to friction velocity with smaller deviation factors compared to the backscatter functions of wave age. NUSCAT data indicate that the azimuth direction, at which the backscatter is maximum, is in between the wind direction and the dominant wave direction at light wind conditions. Excluding cases of large swells, there is no systematic trend between backscatter and significant wave height.

INTRODUCTION

The NASA Scatterometer (NSCAT) will be launched to measure backscatter at K_u band for remote sensing of surface winds over oceans [1]. Thus it is important to study effects of environmental conditions on the backscatter. In this paper, backscatter signatures at K_u band as functions of oceanic and atmospheric parameters are investigated with the NUSCAT-SWADE data base. NUSCAT is an airborne K_u-band scatterometer developed at the Jet Propulsion Laboratory. The scatterometer was mounted on the NASA Ames C130 aircraft on a gimbal with a full azimuth scanning capability. The range of incidence angles was from 0° to 60° for both vertical and horizontal polarizations. The scatterometer has a high signal to noise ratio and a large dynamic range to measure ocean backscatter for a wide range of air and sea conditions.

SWADE was carried out in an instrumented oceanic area off the coast of Virginia and Maryland. During an intensive observation period (IOP) of SWADE in the winter of 1991, thirty hours of backscatter data were collected in ten flights by NUSCAT. The Gulf Stream boundary was included in the area of the experiment. Sea surface temperatures across the boundary were different by as much as 10°C. Swells reached to 6 m in significant wave height. A wide range of wind speeds were encountered during the experiment. Various atmospheric and and oceanic parameters were measured by an array of buoys deployed in the SWADE area. These measurements together with the backscatter data form the basis of the analysis in this paper. Backscatter signatures are investigated for the dependence on friction velocity, wave age, and significant wave height.

ACROSS THE GULF STREAM BOUNDARY

In a number of flight lines across the north wall of the Gulf Stream, NUSCAT was flown over the sea surface temperature front at the Gulf-Stream boundary. These flights provide backscatter data to study the temperature effects.

In a NUSCAT flight on 28 February 1991, the boundary of the Gulf Stream was between Discus C buoy located on the warm side and Discus A on the cold side. NUSCAT data corresponding to this case were at vertical polarization and 30° incidence angle. The observed increase from the cold side to the warm side was about 5.5 dB at downwind, 5.2 dB at upwind, and 4.5 at crosswind. Accounting for the wind speed difference between the two sides of the sea surface temperature front, SASS-II geophysical model function [2], which relates backscatter to neutral wind at 19.5 m, gives only a 3 dB difference. Large differences in backscatter at K_u band were also observed for the horizontal polarization at various incidence angles in several other flights. These case studies indicates that ocean backscatter also depends on other atmospheric and oceanic parameters beside the neutral wind speed.

BACKSCATTER AND FRICTION VELOCITY

Radar returns from the ocean surfaces are related to friction velocity, u_*, in both the Bragg and the sea-spike scattering components [3]. Liu and Large [4] used u_* derived from direct observations to show the correlation of backscatter with u_*. Li et al. [5] demonstrated the dependence of backscatter on u_* based on experimental measurements from the Frontal Air-Sea Interaction Experiment.

In this paper, we utilize the NUSCAT-SWADE data base to study the dependence of σ^0 on u_*. Friction velocity u_* used in this analysis is determined from buoy data with the formulation by Large and Pond [6] for ocean momentum flux measurements. Fig. 1 presents backscatter as a function of friction velocity for the horizontal polarization and incidence angles from 10° to 60° in the upwind direction. NUSCAT data are represented by the symbols and the continuous curves are for linear fitting functions in the logarithmic domain. At the incidence angle of 10°, the backscatter is insensitive to the friction velocity. For larger incidence angles, the horizontal backscatter is sensitive to the friction velocity with stronger backscatter for larger u_*. The slope of the linear curves in the logarithmic domain correspond to the positive exponents of u_*. Similar results are obtained for both horizontal and vertical directions in terms of upwind, downwind, and crosswind normalized radar cross sections.

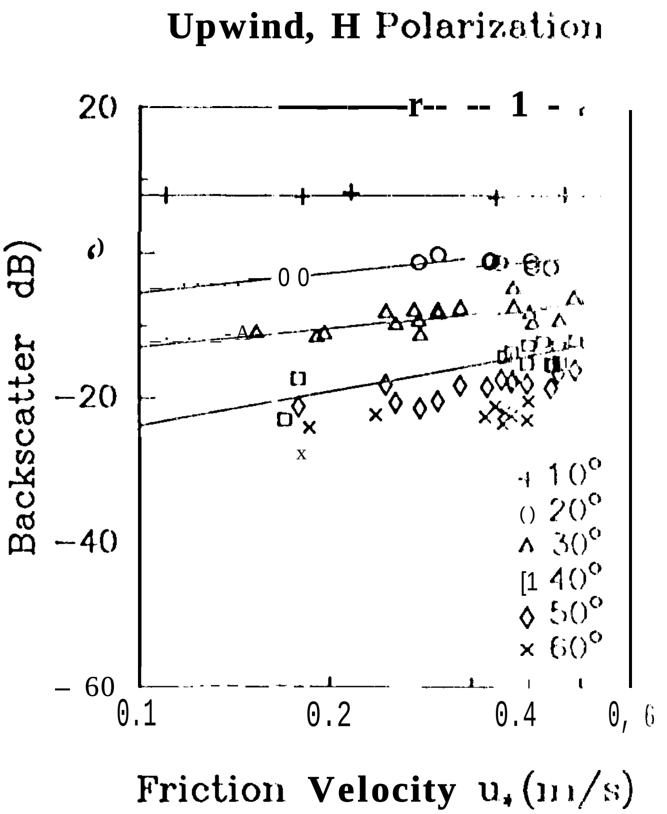

Figure 1. Horizontal backscatter versus friction velocity. The symbols denote NUSCAT data at different incidence angles and the continuous curves are for linear fitting function.

BACKSCATTER AND WAVE AGE

Wave age is determined by the ratio of the the phase speed of the dominant gravity wave over the friction velocity. Geernaert [7] showed that smaller values of wave age correspond to larger drag coefficients and steeper wave slopes. There are plenty of experimental evidences such as [8] and more recently [9] to support the correlation of rougher sea surfaces for younger wave ages. Rougher surfaces give rise to larger backscatter for smaller wave ages. On the contrary, a smoother roughness has been suggested for younger wave ages [10].

Considering these differences, we use NUSCAT data obtained during SWADE to investigate the trend between backscatter and wave age. Fig. 2 plots horizontal backscatter as a function of wave age for incidence angles from 10° to 60°. These results are for the case of upwind backscatter. As observed from Fig. 2, the data have a decreasing trend with wave age, characterized by the negative slopes of the linear fitting curves in the logarithmic domain. An exception is at 10° incidence angle where the backscatter is insensitive to the wave age. For downwind and crosswind directions and also for the vertical backscatter, the results show the decreasing trend with wave age. These observations of backscatter are consistent with a rougher sea surface condition for a smaller wave age.

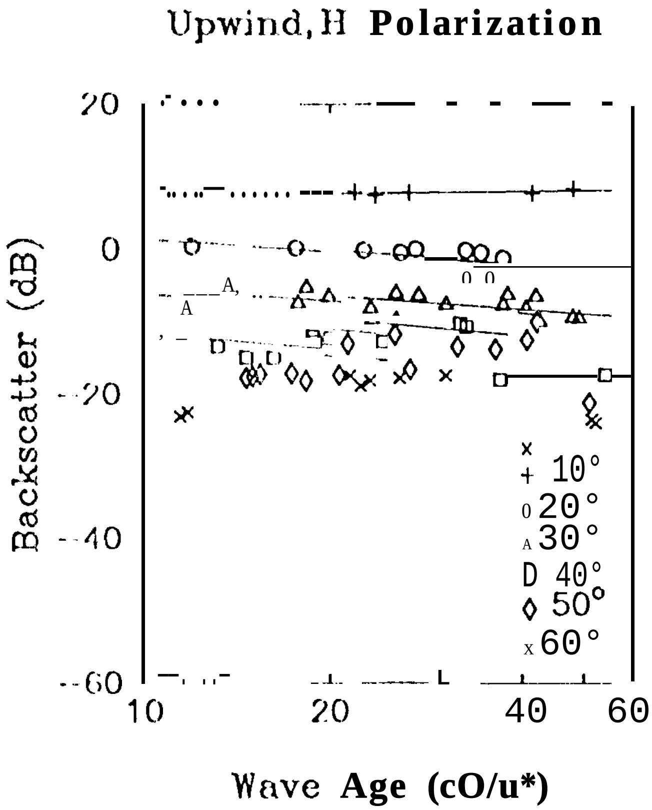

Figure 2. Horizontal backscatter versus wave age. The symbols denote NUSCAT data at different incidence angles and the continuous curves are for linear fitting functions.

BACKSCATTER AND WAVE HEIGHT

Swells with a large significant wave height have been shown to have a strong impact on ocean backscatter at light wind conditions but not at moderate winds [11]. Tower measurements also suggested that backscatter can be affected by long waves at lower wind speeds [12]. Another study concluded that effects of varying wave height on radar measurements is of little importance [13]. Thus in general, backscatter seems to have a weak dependence on significant wave height.

Results from NUSCAT-SWADE indicated that the azimuth direction, at which the backscatter is maximum, is in between the wind direction and the dominant wave direction at light wind conditions. An examination of a direction wave spectrum at an intermediate wind speed shows that NUSCAT maximum direction aligned with high frequency wave components. Figure 3 presents upwind horizontal backscatter as a function of significant wave height excluding cases of swells with a larger wave height. No systematic correlation between the backscatter and the wave height is observed. Similar observations apply to vertical backscatter

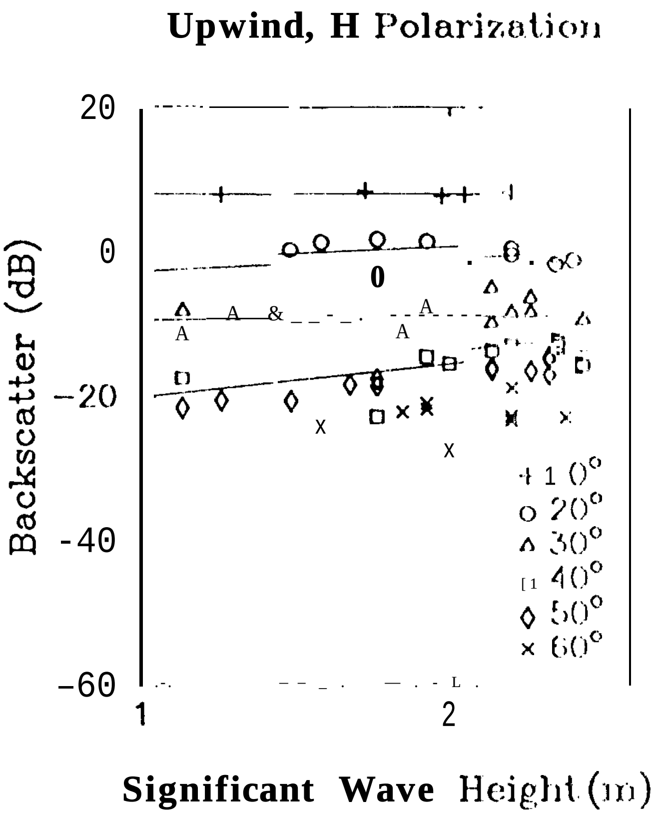

Figure 3. Horizontal backscatter versus significant wave height. The symbols denote NUSCAT data at different incidence angles and the continuous curves are for linear fitting functions.

SUMMARY

Ocean backscatter at K_u band was successfully measured by the Jet Propulsion Laboratory NUSCAT scatterometer during SWADE over a wide variety of atmospheric and oceanic conditions. Relations of backscatter with friction velocity have a positive trend with positive exponents of u_*. Results show the trend of increasing backscatter with younger wave, which corresponds to a rougher surface for a younger wave field. No systematic trend between backscatter and significant wave height is observed.

ACKNOWLEDGMENTS

This work was performed under a contract with the National Aeronautics and Space Administration at the Jet Propulsion Laboratory, California Institute of Technology. The authors thank Dr. J. D. Oberholtzer, Dr. K. Steele, and Dr. D. Wang for the buoy data.

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