Ocean Surface Roughness Inferred from Dual-frequency Altimeter Backscattering Cross Sections

Paul A. Hwang, William J. Teague, David W. Wang, and Gregg A. Jacobs
Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS 39529

ABSTRACT

TOPEX altimeter provides dual-frequency measurements of the radar backscattering cross section from the sea surface (Ku and C bands, radar wavelengths 2.2 and 5.4 cm, respectively). These data are analyzed to infer the properties of the ocean surface roughness. One of the prominent features of the dual-frequency data is that the cross section differences are mostly (more than 90 percent) between 3 to 4 dB over a wide range of wind speeds. This suggests that the ratio of the filtered mean square slopes of C and Ku bands is between 0.4 and 0.5. In other words, the mean square slope of a narrow band of surface waves contributing to the backscattering difference (the ratio of the upper and lower ranges of the wavelengths in the band is less than 2.5) is more than the C-band scattering mean square slope, which is contributed by wave components with length scales many orders larger than 2.5! This is a very surprising result. The implication of this result on the wavenumber spectral function requires further investigation.

1. Introduction

Short waves on the ocean surface serve as the major contributor to the ocean surface roughness, understanding of their properties is important to ocean remote sensing and air-sea interaction research. While acquiring in situ measurements of short scale waves is difficult and the progress in field studies of short ocean waves is slow, a considerable amount of high-quality radar backscattering cross sections data has been generated from airborne or spaceborne platforms through the years. In this paper, we investigate the information imbedded in the dual-frequency (Ku- and C-band) output from the TOPEX altimeter. Many papers have been written about the TOPEX data set (e.g., special issues in JGR, Dec 1994, 1995). In section 2, several interesting features on the correlation between Ku- and C-band cross sections are described. The most striking point is that in more than 90 percent of the cases, the ratio of Ku- and C-band cross sections is within a narrow range between 0.4 to 0.5. To the first order of approximation, this ratio indicates that the filtered roughness contribution to C-band scattering is less than one half of the filtered roughness contributing to Ku-band scattering. In other words, the surface roughness contributed by the narrow gap (a factor of 2.5 between the longest and the shortest waves in the gap) in the centimeter to decimeter wavelength band is more than the roughness composed of all the waves (wavelengths from ~decimeters to a few decameters or longer) contributing to C-band backscattering. The implication of this result on the characteristics of wavenumber spectrum deserved more attention.

2. Altimeter cross section and sea surface roughness

a. Dual frequency cross sections

Since its deployment in October 1992, TOPEX altimeter has provided more than 7 years continuous output of the Ku (13.6 GHz, radar wavelength 2.2 cm) and C (5.6 GHz, radar wavelength 5.4 cm) band backscattering cross sections from the world's ocean surface. To the first order of approximation, the altimeter backscattering cross section is inversely proportional to the low-pass filtered ocean surface roughness (e.g., Barrick 1968; Brown 1978). These measurements represent a tremendous dataset for the study of the ocean surface roughness. Fig. 1a plots the simultaneously measured Ku- and C-band backscattering cross sections, σ_{0C} and σ_{0Ku}, in dB units. These data are from Track 69 in the region of Yellow and East China Seas (Hwang et al. 1999). In general, there is a clear monotonic increase of σ_{0C} with σ_{0Ku}. The dB difference between C- and Ku- band cross sections remains in a narrow range, the majority of data (32110 out of 35163 data points, or 91.3%) fall between 3 and 4 dB (fig. 1b).

b. Filtered mean square slopes

As mentioned earlier, the altimeter backscattering cross section is inversely proportional to the low-pass filtered ocean surface roughness (e.g., Barrick 1968; Brown 1978). The roughness derived from the first order solution is found to be considerably higher than in situ measurements obtained by optical sensors (Hwang 1997). Hwang et al. (1998) consider that surface waves much longer than the radar wavelength serve to tilt the roughness that scatters the radar waves, thus even for an nadir-pointing altimeter, the calculation of backscattering cross-section needs to consider slant-angle scattering. This consideration results in an attenuation of the backscattering intensity. The computation taking into account the tilting effect is in much better agreement with field data, with a typical improvement of 2 to 4 dB for Ku-band measurements (fig. 8 of Hwang et al. 1998). Assuming that the distribution of the tilting components of ocean waves is gaussian, the radar cross section is related to surface roughness by (Hwang et al. 1998)

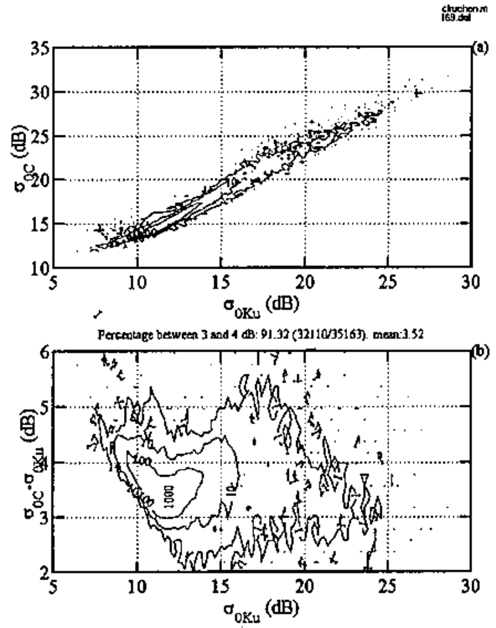

Fig. 1. Contour plot showing the data distribution of (a) Ku- and C-band altimeter cross sections, and (b) the cross section difference. The data are from Topex track 69 in the Yellow and East China Seas region.

$$\sigma_0 = \frac{|R(0)|^2}{s_f^{\,2}} \sqrt{\frac{s_f^{\,2}}{s_f^{\,2} + 2\sigma_t^{\,2}}}, \qquad (1)$$

where s_f^2 is the filtered mean square slope, σ_t^2 is the variance of the tilting surface roughness and $|R(0)|^2$ is the Fresnel reflection coefficient.

In this approach, the total wind-induced ocean surface roughness is divided into three components: tilting, scattering, and diffraction,

$$s^2 = s_t^{\,2} + s_f^{\,2} + s_d^{\,2}. \qquad (2)$$

It is also assumed that the contribution due to diffraction is negligible. The magnitude of each roughness component can be calculated from the wavenumber spectrum of short waves (e.g., Hwang 1997). To define the length scales dividing the three components, the following procedure is applied. Based on the argument that scattering from a surface is a localized process (Hwang et al. 1998, fig. 7) and assuming that the characteristic length scale of scattering roughness is proportional to the wavelength of the surface wave, the dimensionless length scale (in a similar definition to scattering from particles) is

$$x = \kappa a, \qquad (3)$$

where κ is the wavenumber of incident radar waves. Assuming that the division of diffraction, scattering, and tilting are determined by x=1 and x=30, respectively, the dimensional wavenumbers dividing tilting and scattering (k_{ts}), and scattering and diffraction (k_{sd}), for Ku- and C-band are [900, 35] and [368, 12] rad/m, respectively (Hwang et al. 1998).

The mean square slope of the filtered surface roughness contributing to the radar scattering can be calculated from the slope spectrum of surface waves, $\chi_1(k)$,

$$s_{fKu}^{\,2} = \int_{k_{tsKu}}^{k_{sdKu}} \chi_1(k)dk \qquad (4)$$

$$s_{fC}^{\,2} = \int_{k_{tsC}}^{k_{sdC}} \chi_1(k)dk \qquad (5)$$

similarly, the tilting roughness components for Ku and C bands are

$$s_{tKu}^{\,2} = \int_{0}^{k_{tsKu}} \chi_1(k)dk \qquad (6)$$

$$s_{fC}^2 = \int_0^{k_{uC}} \chi_1(k)dk \qquad (7)$$

Our understanding on the wavenumber spectrum in the short wave region is still very limited and only a handful of field measurements have been reported. Given this state of insufficient knowledge of the spectral properties of short ocean waves, Fig. 2c presents two calculations of s_{fC}^2/s_{fKu}^2, with and without tilting effect, shown with circles and crosses, respectively. When tilting effect is not considered, over a broad range of wind speed, the filtered mean square slope contributing to C-band scattering, s_{fC}^2, is approximately 45% of s_{fKu}^2, the filtered mean square slope contributing to Ku-band scattering. With tilting consideration, the ratio of the surface slope components contributing to scattering for the two radar bands drops to 27%. In either case, this result indicate that the mean square slope in the narrow band of wavelengths responsible for the difference between Ku- and C-band scattering (range of length scales 2.5) is much higher than the mean square slopes provided by the broad band of wavelengths contributing to C-band scattering (range of length scales ~1000). Because the spectral model requires wind speed as an input parameter, altimeter measurements collocated with a buoy in the Gulf of Mexico is used (Hwang et al. 1998). The size of this dataset is considerably smaller but the basic properties between Ku- and C-band cross sections (fig. 2a, b) are similar to those shown in Fig. 1. Of the 1317 total data points, 1238 (94.0%) of them have cross-section differences between 3 to 4 dB. The spectral model used to compute the tilting and scattering components is Hwang (1977). Other spectral models and altimeter datasets can be used, and the major conclusion from this calculation is similar.

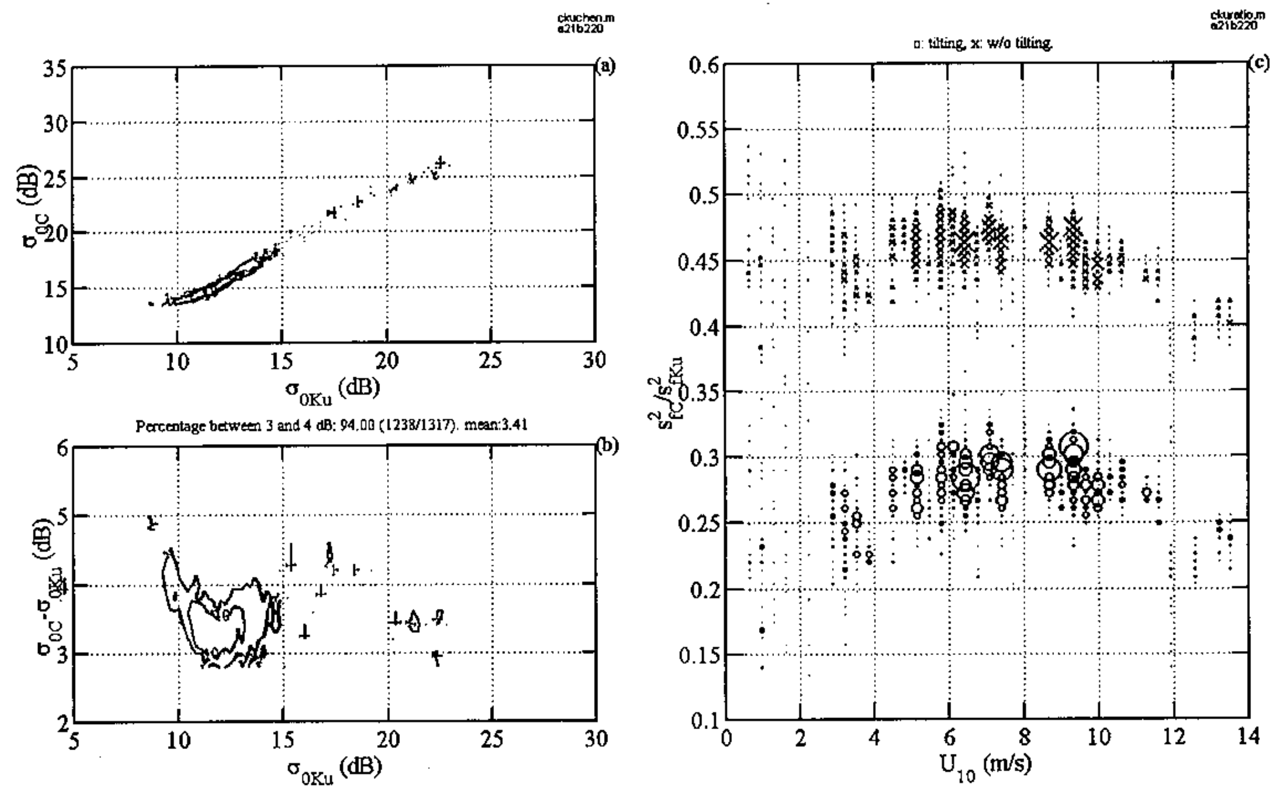

Fig. 2. (a) and (b), same as Fig. 1 for Topex track 21 with collocated buoy data in the Gulf of Mexico region, (c) the ratio of the filtered mean square slopes contributing to C- and Ku-band backscatter. Crosses: without tilting effect, circles: with tilting consideration.

3. Summary

The global database of TOPEX dual-frequency altimeter measurements shows that the difference of Ku- and C-band scattering cross sections from the ocean surface is between 3 to 4 dB over a broad range of wind conditions. Translated into ocean surface roughness, these measurements suggest that the total mean square slope contributing to C-band scattering is less than the mean square slope responsible for the difference between Ku- and C-band scattering. The wavelength bandwidth of the former is on the order of 1000 (from ~0.1 to ~100 m), and the bandwidth for the later is 2.5 (from ~0.02 to ~0.05 m). The implication of this result on the characteristics of wave spectrum is significant and requires further investigation.

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References

Barrick, D. E. , 1968: Rough surface scattering based on the specular point theory, IEEE *Trans. Antennas. Propag.*, Ap-16, 449-454.

Brown, G. S. , 1978: Backscattering from a Gaussian-distributed perfectly conducting rough surface, IEEE *Trans. Antennas. Propag.*, Ap-26, 472-482.

Hwang, P. A., 1997: A study of the short water waves in the ocean. Part 2. Spectral model and mean square slope. *J. Atmos. and Oceanic Tech.,* **14**, 1174-1186, 1997.

——, W. J. Teague, G. A. Jacobs, and D. W. Wang, 1998: A statistical comparison of wind speed, wave height and wave period derived from satellite altimeters and ocean buoys in the Gulf of Mexico Region, *J. Geophys. Res.*, **103**, 10451-10468.

——, Bratos, S. M., Teague, W. J., Wang, D. W., Jacobs, G. A., and Resio, D. T. , 1999: Winds and waves in the Yellow and East China Seas: A comparison of spaceborne altimeter measurements and model results, *J. Oceanogr.*, **55**, 307-325.