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The Modification of *X* and *L* Band Radar Signals by Monomolecular Sea Slicks

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One methyl oleate and two oleyl alcohol surface films were produced on the surface of the North Sea under comparable oceanographic and meteorological conditions in order to investigate their influence on *X* and *L* band radar backscatter. Signals are backscattered in these bands primarily by surface waves with lengths of about 2 and 12 cm, respectively, and backscattered power levels in both bands were reduced by the slicks. The reduction was larger at *X* band than at *L* band, however, indicating that shorter waves are more intensely damped by the surface films. The oleyl alcohol film caused greater attenuation of short gravity waves than the film of methyl oleate, thus demonstrating the importance of the physicochemical properties of films on the damping of wind-generated gravity capillary waves. Finally, these experiments indicate a distinct dependence of the degree of damping on the angle between wind and waves. Wind-generated waves traveling in the wind direction are more intensely damped by surface films than are waves traveling at larger angles to the wind.

1. INTRODUCTION

Natural and man-made organic surface films, which often occur on the sea surface [*Barger et al.*, 1974; *Hühnerfuss et al.*, 1977], strongly affect the surface wave field [*Barger et al.*, 1970; *Mallinger and Mickelson*, 1973; *Hühnerfuss et al.*, 1981*a*, this issue (*a*)]. As a consequence, most air-sea interaction processes and electromagnetic emission in the visible and microwave bands, as well as scattering of these electromagnetic waves, are influenced by such films [*Hühnerfuss and Garrett*, 1981]. During the JONSWAP 75 (Joint North Sea Wave Project 1975) experiment the influence of oleyl alcohol surface films on the radar cross section was determined both by an airborne scatterometer (K_u band 13.9 GHz; *Hühnerfuss et al.* [1978]), and by a tower-based scatterometer (*X* band 9.5 GHz; *Hühnerfuss et al.* [1981*a*]). In both cases a significant decrease of the radar backscattering cross section in the presence of an oleyl alcohol slick was observed (K_u band decrease 7.3 ± 3.5 dB; *X* band decrease 6.35 ± 1.87 dB). Furthermore, the radar cross-section data obtained from an airplane during upwind and cross-wind flight tracks and the comparison of wave attenuation ratios obtained from an omnidirectional wave staff and by the unidirectional tower based scatterometer measurements suggested that wave attenuation by surface films shows a directional dependence. However, due to the low statistical significance of the data this hypothesis could not be verified in this earlier experiment. It was further predicted from the JONSWAP 75 wave staff data that the *L* band radar cross section is reduced almost as strongly by slicks as the *X* band radar cross section [*Hühnerfuss et al.* 1981*a*].

Natural surface films consist of a wide variety of surface active compounds, which may potentially interfere with the wind wave field in various ways, thus exhibiting different influences on backscattered radar signals. Therefore, two experimental surface film forming substances, which from a physicochemical point of view are characteristic of natural slicks, were disseminated on the sea surface during the MARSEN 79 (Marine Remote Sensing Experiment 1979) slick experiment. The aim of the slick experiment was fourfold. An examination of the relative *X* and *L* band backscatter power reductions was undertaken by comparing backscattered power in the two bands, the effect of the different chemical structure of the films on power reduction was investigated, the hypothesized dependence of wave damping by slicks on wind/wave angle was examined, and finally, a comparison of radar data and wave staff data in the presence of slicks was envisaged.

According to the composite surface theory of radar backscatter from the sea surface [*Wright*, 1968; *Valenzuela*, 1978], backscattered power is proportional to the energy density of the surface wave which satisfies a 'Bragg resonance' criterion. Thus the effect of the surface films on short waves (Bragg waves) with wavelengths of about 2 and 12 cm (at *X* and *L* bands, respectively), which were traveling toward the radar, could be measured in these experiments.

2. EXPERIMENTAL

On September 22, 1979 an oleyl alcohol surface film (slick 1) was produced on the sea surface upwind of the North Sea research platform 'Nordsee' (54° 42′ 9.3″ N; 7° 10′ 7.4″ E). Six days later, on September 28, 1979, a methyl oleate film (slick 2) followed by an oleyl alcohol film (slick 3) were laid down in the same area. The method used to produce these slicks, which is extensively described by *Hühnerfuss and Garrett* [1981], involved a systematic dissemination of frozen chunks (80 g) of 96.5% oleyl alcohol (9-octadecen-1-ol, *Z* isomer), and 74.8% methyl oleate (9-octadecenoic acid methyl ester, *Z* isomer) from a helicopter. The chemical substances were supplied by Henkel KGaA, Düsseldorf, Federal Republic of Germany (FRG) and were used to produce MARSEN slicks without further purification. Although the latter substance was not of high purity, its surface chemical properties and wave-damping characteristics

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were closely similar with those of high purity methyl oleate (99+%).

The environmental parameters, slick sizes, and the sensors utilized during the MARSEN 79 slick experiments are summarized in Table 1. In this paper we report data obtained by one *X* band and three *L* band radars as the surface films drifted by the platform. The results obtained by wave staff [*Hühnerfuss et al.*, this issue (*a*)] passive microwave [*Alpers et al.*, 1982], and by LIDAR measurements [*Hühnerfuss et al.*, this issue (*b*)] will be presented separately.

The data presented in this paper originate from the dual-frequency *L* band pulsed scatterometer of the Naval Research Laboratory (NRL), the dual-frequency *X* band CW (continous wave) scatterometer of NRL, the single-frequency *L* band CW scatterometer of NASA Langley Research Center, and the dual-frequency *L* band scatterometer of the Deutsche Versuchsanstalt für Luft- und Raumfahrt (DFVLR) and the Max-Planck-Institut für Meteorologie. During the slick experiments the dual-frequency systems were operated in a single-frequency mode. The antennas of the NRL *L* band, the NASA *L* band, and DFVLR *L* band scatterometers were pointed at the sea surface at different azimuthal angles in order to gain further insight into directional dependence of wave damping by slicks. The radar parameters employed during passage of the three MARSEN 79 slicks are summarized in Table 2.

The radar data will be compared with results obtained by the FWG, Kiel (FRG), wave staff [*Stolte*, 1982]. For a description of the wave staff characteristics and a detailed interpretation of the wave staff slick data, see *Hühnerfuss et al.*, [this issue (*a*)].

3. RESULTS

Figures 1–4 show time records of backscattered power from the four radars as the three slicks passed the tower. These records have all been low-pass filtered at 0.01 Hz except for the data from the DFVLR *L* band system, which was not filtered, and except for the data for slick 2 from the NRL *L* band system, which was filtered at 0.05 Hz. The gaps in this latter data record are due to system malfunction; the portions shown are free of this problem. Recording of the data was begun for the NRL *X* band radar and the NASA *L* band system only shortly before slick 2 on September 28, accounting for the lack of data in Figures 1 and 2 for slick 2 before noon.

Several features of these records are of interest. There are relatively large variations in the backscattered power over time scales on the order of a few minutes both when slicks are present and when they are absent. These variations, however, seem to be somewhat larger in the presence of the slicks in some cases. In such cases, one suspects that the surface film is not uniformly spread across the surface. Even these variations, however, cannot mask the obvious reduction in the return signal in most cases. The general impression is that the return at *X* band is somewhat more strongly reduced by the slick than at *L* band. Since the Bragg wavelength at *X* band is shorter than at *L* band, this rsult is not unexpected. Note, however, that a significant reduction in received power at *L* band occurred for the oleyl alcohol slicks (1 and 3) when the angle between the radar look direction and the wind was small. This is in line with the predictions of *Hühnerfuss et al.* [1981*a*], based on wave staff data that significant damping should occur for waves in the short gravity wave range.

A more quantitative idea of the amount of damping caused by the slicks may be obtained by averaging these data over approximately 20-minute intervals before, during, and after the

TABLE 1. Date, Time Environmental Parameters of the MARSEN 79 Slick Experiment, and the Available Data Sources From Wave Staff and Different Remote Sensors

	Date, 1979	Local Time,* GMT + 1 h	Wind Direction	Wind Speed ms^{-1}, U_{10}/U_{46}	Significant Wave Height, m	Slick Size, km^2	Slick Drift Velocity, ms^{-1}	Air Temperature, K	Water Temperature, K	Data Sources
Slick 1 (oleyl alcohol)	Sept. 22	09:45–10:00	310°	4.05/6.3	1.47	1.5	0.59	284.3	287.3	wave staff† *X* band scatterometer† two *L* band scatterometers† *L* band microwave radiometer‡ *S* band microwave radiometer‡ LIDAR‡
Slick 2 (methyl oleate)	Sept. 28	12:05–12:22	290°	5.54/6.5	1.50	1.0	0.7	286.1	287.1	wave staff† *X* band scatterometer† three *L* band scatterometers†
Slick 3 (oleyl alcohol)	Sept. 28	13:25–14:00	290°	5.27/6.2	1.49	2.3	0.7	286.1	287.1	wave staff† *X* band scatterometer† three *L* band scatterometers†

* Time during which slick remained directly at platform site; within the footprints of the different sensors at slightly varying times (see Figures 1–4).

† Measurement performed from research platform Nordsee (FPN).

‡ Airborne sensor.

TABLE 2. Radar Parameters During the MARSEN 79 Slick Experiment

	NRL *X* Band				NASA *L* Band				NRL *L* Band				DFVLR *L* Band			
	Antenna Direction	Grazing Angle	Polarization	L_B, cm	Antenna Direction	Grazing Angle	Polarization	L_B, cm	Antenna Direction	Grazing Angle	Polarization	L_B, cm	Antenna Direction	Grazing Angle	Polarization	L_B, cm
Slick 1	225°	35°	V	1.95	210°	35°	V	12.2	280°	7.9°	V	12.3				
Slick 2	270°	32°	H	1.89	225°	35°	H	12.2	275°	6.3°	V	12.3	290°	4.6°	V	11.4
Slick 3	270°	32°	H	1.89	225°	35°	H	12.2	275°	6.3°	V	12.3	290°	4.6°	V	11.4

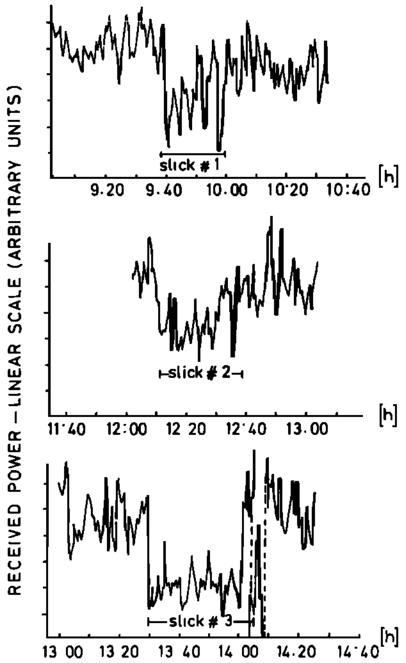

Fig. 1. Time records of power backscattered to the NRL *X* band radar during passage of the three MARSEN 79 slicks. All records are low-pass filtered at 0.01 Hz.

slicks. We have calculated the ratio of scattered power levels in the presence of slicks to the average levels before and after the slicks and from these have calculated a percent reduction caused by the slicks. These are plotted in Figure 5 versus the angle between radar look direction (opposite the Bragg wave propagation direction) and the wind direction. In this figure, open symbols refer to the methyl oleate slick (slick 2) while closed symbols refer to the two oleyl alcohol slicks (slicks 1 and 3). The effect of the chemical structure of the film forming compound is apparent. Methyl oleate, which has a film pres-

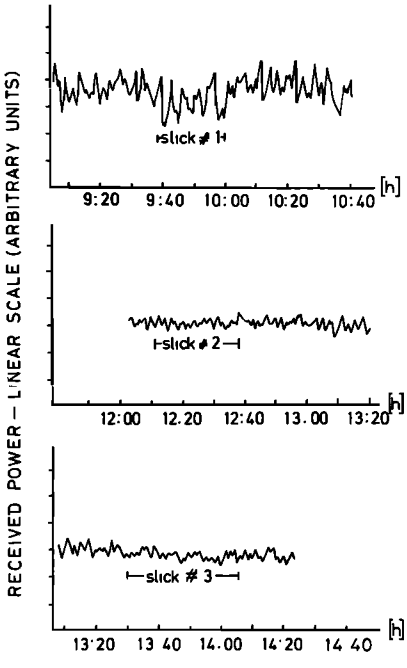

Fig. 2. Time records of power backscattered to the NASA *L* band radar during passage of the three MARSEN 79 slicks. All records are low-pass filtered at 0.01 Hz.

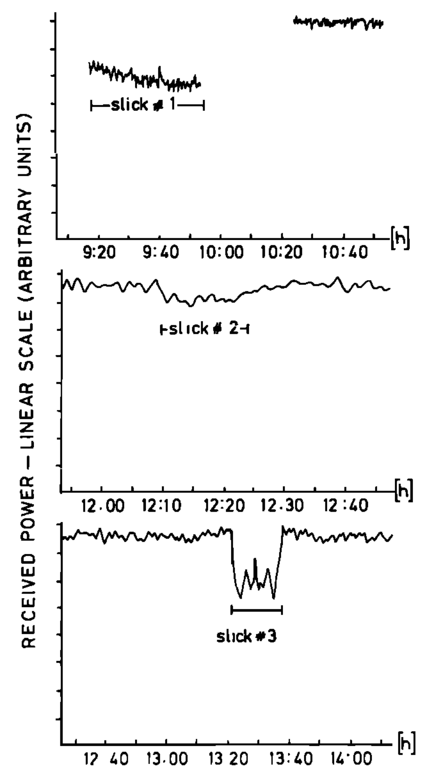

Fig. 3. Time records of power backscattered to the NRL L band radar during passage of the three MARSEN 79 slicks. The top record is low-pass filtered at 0.05 Hz; the others are low-pass filtered at 0.01 Hz.

sure only half that of oleyl alcohol [*Garrett and Barger* 1980], reduced the scattered power much less than oleyl alcohol.

The other feature of the damping of short waves by slicks which is apparent from Figure 5 is that there is a distinct dependence on the angle between wave propagation direction and wind direction. Wind-generated waves traveling in the direction of the wind are more intensely damped by the presence of slicks than are waves traveling at large angles to the wind. The effect appears to be more pronounced in the case of oleyl alcohol slicks than methyl oleate slicks but is present for both. Thus the directional spectrum of wind-generated gravity capillary waves is more nearly isotropic in the presence of surface films than it is for clean water surfaces.

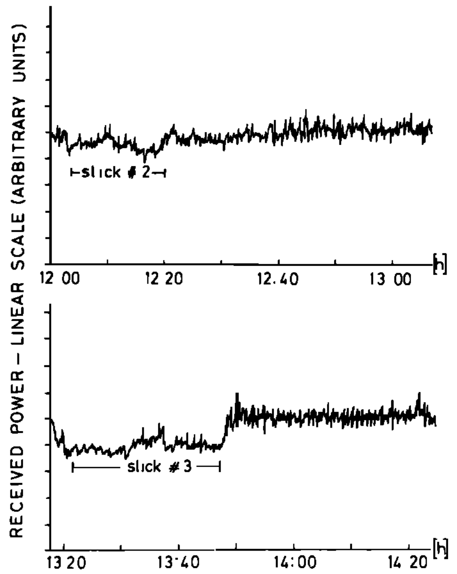

Fig. 4. Time records of power backscattered to the DFVLR L band radar during passage of the MARSEN 79 slick 2 and slick 3. No records are low-pass filtered.

The effect on a wave staff record is shown for slicks 2 and 3 in Figure 6 and 7, respectively. The data show a marked decrease for encountered frequencies above 1 Hz. A direct comparison of area extensive (microwave) and point probe (wave staffs) measurement is not possible, since at X band, for example, the Doppler band width is on the order of tens of hertz. For a discussion of the ω-k relationship for frequencies an order of magnitudes or more above the dominant wave frequency see *Phillips* [1981] and *Keller et al.* [1974]. It is reasonable, however, to associate higher average frequencies with higher wave numbers. Therefore we have plotted the microwave data against c/L_B also in Figures 6 and 7, where c the phase speed of an infinitesimal wave of wavelength L_B in the absence of slicks.

In accordance with the above discussed directional dependence of wave damping by surface films, the wave attenuation ratios measured by wave staffs in the presence of a strongly wave damping oleyl alcohol surface film lie between the values obtained by radars looking into different directions (Figure 6). This observation is consistent with the assumption that wave staffs measure amplitudes omnidirectionally, i.e., integrating over 360°, whereas scatterometers sense unidirectionally due to look direction. In the case of a less intensely wave-damping methyl oleate surface film (Figure 7) the wave attenuation ratios calculated from both wave staff data and from X and L band radar data are comparable.

In the capillary wave range, $f = 16$–17 Hz, a sudden decrease of wave damping seems to occur (Figure 6, Figure 7). A similar effect has been observed during one JONSWAP 75 slick experiment [*Hühnerfuss et al.*, 1981*a*, slick 3] in the frequency range 9.3–13.9 Hz. When evaluating this JONSWAP 75 slick experi-

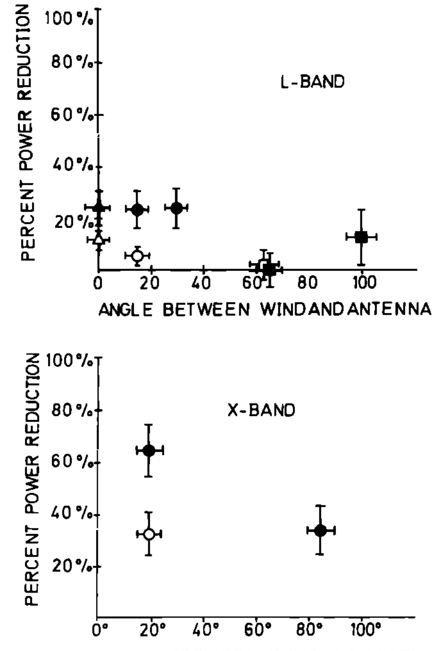

Fig. 5. Percent reduction of backscattered power caused by slicks versus angle between wind and antenna look directions. Values represent approximately 20-minute averages across each slick. Solid symbols are for oleyl alcohol slicks; open symbols refer to the methyl oleate slick 2. Circles are NRL data, squares are NASA data, and triangles are DFVLR data.

ment, it was assumed that resonance effects on that particular day, e.g., vibrations of the suspension of the wave gauge wire might have caused this peak. In the meantime, systematic wind-wave tunnel experiments have supplied a more plausible explanation for this effect: it has been shown by *Hühnerfuss et al.* [1981*b*] that peaks in the wind wave spectrum may shift to higher frequencies if surface films are present. Variations in this frequency shift depend on the chemical character of these surface films. It has been postulated by *Hühnerfuss et al.* [1981*b*] that in the presence of a surface film a lower 'effective wind speed' instead of the actually measured wind velocity is interacting with the water surface because of the modified sea surface roughness, which causes a shift of spectral peaks in the short gravity and capillary wave range. An investigation of the slick and nonslick wave spectra, from which the attenuation ratios depicted in Figure 6 and Figure 7 have been calculated, confirmed this hypothesis. Specifically, a peak in the nonslick wave spectrum at about 16.68 Hz has slightly shifted to 16.84 Hz in the presence of an oleyl alcohol surface film. A further discussion on this phenomenon is given by *Hühnerfuss et al.* [1981*b*, this issue (*a*)].

It has to be stressed that the wave staff data were calculated from water wave spectra, which were neither corrected for orbital velocity, wave induced Stokes drift, nor tidal currents, i.e., the comparison between radar and wave staff data is based on so-called 'spectra of encounter' as usually reported in literature.

4. DISCUSSION AND CONCLUSIONS

This study has shown that waves up to at least 12 cm in length are damped by surface films on water with shorter waves being more strongly damped. This result is consistent with those of *Hühnerfuss et al.* [1981*a*]. The differing wave damping effects of different films indicate that the inextensible film theory of *Phillips* [1977] is inadequate to model the effect of real slicks on wind-generated waves. Furthermore, the present work has verified the earlier suggestions that damping of waves up to at least 12 cm wavelength by surface films depends on the angle between wave propagation and wind.

There are several possible explanations of this latter effect. Since gravity capillary waves traveling at large angles to the wind are smaller in amplitude than those traveling along the wind direction [*Jones et al.*, 1978], damping which is nonlinear in wave amplitude could explain the observations. Thus large amplitude waves would be more strongly damped by surface films than small amplitude ones. Alternatively, slick characteristics could be influenced by the wind in such a manner that they are anisotropic and could therefore anisotropically damp wind waves. A third possibility is that the slick interfers with the generation of the waves by the wind in a manner that depends on angle. The determination of which of these explanations is correct, if any, requires further studies of the effects of surface films on wind-generated waves, preferably under controlled conditions such as those found in wind wave tunnels.

Caution has to be exercised when comparing wave attentuation ratios calculated from radar and from wave staff data as depicted in Figures 6 and 7: some investigators [e.g., *Stolte*, 1982] have suggested some corrections of the 'spectra of encounter' (which are usually measured by wave staffs), in order to get 'real spectra.' The proposed corrections take into account deviations from the real spectra due to the orbital velocity of gravity waves, wave-induced Stokes drift, and tidal currents. However, there arose some controversy as to whether all these effects really lead to significant deviations from the 'real spectra.' Hasselmann pointed out (K. Hasselmann, 1982, private communication) that, e.g., biassing effects due to orbital velocity of gravity waves are presumably of importance only at higher wind speeds, which were not encountered during the MARSEN 79 slick experiments.

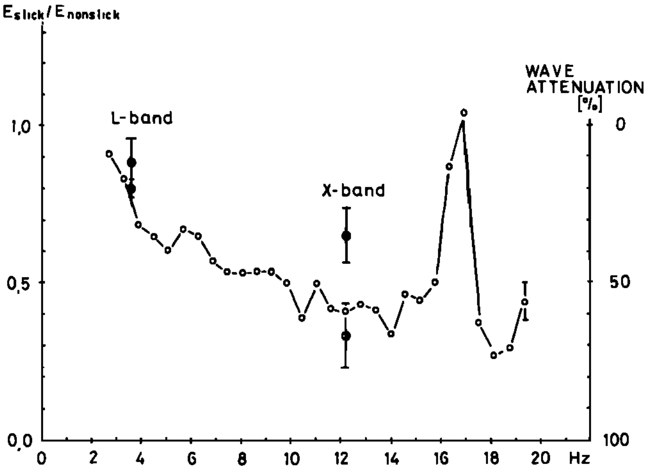

Fig. 6. The ratio of wave energy (slick 3/nonslick area 'before slick') versus frequency measured by wave staff. The scale on the right-hand side shows the corresponding values for the wave attenuation in per cent. For comparison the values of the *X* band radar (crossed circles, upper value obtained in the presence of slick 1: angle between wind and antenna direction $\Psi = 85°$; lower value obtained in the presence of slick 3: $\Psi = 20°$) and *L* band radars (solid circles, upper value obtained in the presence of slick 1: $\Psi = 100°$; lower value obtained in the presence of slick 3: $\Psi = 15°$) are inserted. Microwave data were plotted versus c/L_B.

In spite of these principal uncertainties the comparison between wave staff data and radar data appears to reveal that in the presence of monomolecular surface films, which strongly attenuate short gravity waves, wave attenuation ratios calculated from wave staff data may significantly deviate from those calculated from radar data. If surface films with less intensive wave damping abilities are present, wave attenuation ratios measured by radar and wave staffs are comparable.

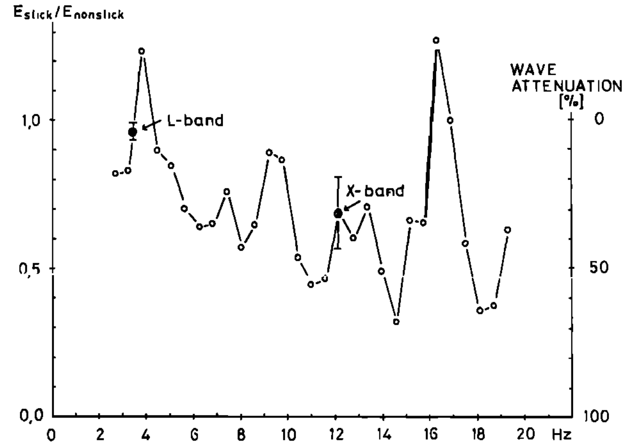

Fig. 7. The ratio of wave energy (slick 2/nonslick area 'before slick') versus frequency measured by wave staff. The scale on the right-hand side shows the corresponding values for the wave attenuation in per cent. For comparison the values of the *X* band (crossed circles) and *L* band (solid circles) radars are inserted (angle between wind and antenna directions 20° and 15°, respectively). Microwave data were plotted against c/L_B.

Since natural surface films may very differently influence the sea surface roughness depending on their chemical structure, the results presented in this paper suggest that caution has to be applied when interpreting radar data measured at lower wind speeds, i.e., under meteorological conditions which are known to be a favorable condition for the formation of natural monomolecular surface films [*Hühnerfuss et al.*, 1977].

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