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Measurements at 13.9 GHz of the radar backscattering cross section of the North Sea covered with an artificial surface film

Heinrich Hühnerfuss

Institut für Organische Chemie und Biochemie, Universität Hamburg, Martin-Luther-King-Platz 6, 2000 Hamburg 13, Federal Republic of Germany

Werner Alpers

Institut für Geophysik der Universität Hamburg und Max-Planck-Institut für Meteorologie, Bundesstr. 55, 2000 Hamburg 13, Federal Republic of Germany

W. Linwood Jones

National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia 23665

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The reduction of the K_u-band (13.9 GHz) normalized radar cross section (NRCS) by an artificial monomolecular surface film (oleyl alcohol) on the sea surface was measured in the North Sea during the 1975 Joint North Sea Wave Project, JONSWAP 75 experiment. The aim of the surface film experiment was to simulate natural surface films which often occur on the ocean surface and are produced by plankton or fish. NRCS measurements were obtained from an aircraft at incidence angles of 41° and 47° at vertical and horizontal polarizations. For winds between 3.5 and 4.4 m/sec the maximum measured reduction was 7.3 ± 3.5 dB relative to the mean. In-situ measurements showed that the oleyl alcohol film reduced the surface tension from 74 to 43 dyne/cm. Similar reductions in surface tension have also been measured on the ocean due to natural surface films of biological origin. It is noted that variations of the NRCS due to natural surface film effects may significantly limit the techniques used currently to infer surface wind vector over biologically active ocean regions.

INTRODUCTION

Natural monomolecular films ("slicks") often occur on the sea surface in coastal regions of high biological productivity [*Barger et al.*, 1974; *Brockmann et al.*, 1976], but under certain conditions they also occur on the open ocean [*Hühnerfuss et al.*, 1977]. It is well known that surface films damp surface waves. Experiments in the open sea with artificial monomolecular surface films have shown an energy decrease of about 50% in the wave spectrum between 0.4–1.0 Hz (L = 9.75–1.56 m) [*Barger et al.*, 1970] and 0.3.–0.6 Hz (L = 17.3–4.3 m) [*Mallinger and Mickelson*, 1973]. The slick-forming material used by both groups was oleyl alcohol (9-Octadecen-1-ol, cis-isomer). The measurement of wave spectra by Barger *et al.* was obtained by means of in-situ capacitance wave gauges, whereas Mallinger and Mickelson used a remote sensing laser profilometer technique.

Another method for measuring short gravity and capillary ocean waves uses the Bragg scattering of microwaves [*Wright*, 1966, 1968; *Valenzuela et al.*, 1971]. At oblique incidence angles (approximately 30° to 70°) to first order in wave slope the backscattered power is proportional to the energy density of the surface waves at the Bragg wavelength. For first-order scattering, this length is given by

$$L = \lambda_0/2 \sin \Theta$$

where λ_0 is the free space radar wavelength and Θ the incidence angle measured with respect to the normal to the mean surface. Therefore, the relative change in backscattered power due to surface films is equal to the relative change in wave spectral energy at this particular wavelength. However, this equality is only valid if the dielectric

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constant relevant for microwave scattering is not affected by the slick, as one would expect for monomolecular films. Since natural films of biological origin are also mainly monomolecular surface films, and since they can decrease the surface tension by almost the same order of magnitude as the oleyl alcohol film, one may expect variations in radar cross sections between biologically active and passive regions of the ocean of the same order.

The reduction of the ocean radar cross sections by crude and refined oil spills has been observed by several investigators [*Guinard and Purves*, 1970; *van Kuilenberg,* 1975; *Fontanel,* 1977; *Nelepo*, 1977], and similar results have been reported for a wave tank experiment [*van Kuilenberg*, 1975]. However, prior to this paper no controlled experiments with *monomolecular surface films*, where the slick characteristics and the resulting reduction in radar cross section were measured, have been reported. In this experiment, the decrease of the ocean radar cross section due to a uniformly distributed monomolecular oleyl alcohol film were measured for horizontal and vertical polarizations at K_u band (13.9 GHz).

It is stressed that the radar detection of crude oil spills on the ocean poses quite a different problem from the physical and chemical point of view. Crude oil forms relatively thick layers (thickness some millimeters or centimeters) on the sea surface in contrast to monomolecular films (thickness about 2 nm) and have a different dielectric constant. Therefore, the results obtained on this experiment do not apply in general to the crude oil case.

THE EXPERIMENT

During the Joint North Sea Wave Project, JONSWAP 75 experiment, on September 4, 1975, an artificial monomolecular surface film of oleyl alcohol of about 1.5 km^2 in area was produced in the North Sea area 27 km off the island of Sylt. The method [*Hühnerfuss and Lange*, 1975] involved a systematic dissemination of frozen chunks (80 gram) of 96.5% pure oleyl alcohol (9-Octadecen-1-ol, cis-isomer) from a helicopter. The frozen chunks were prepared by freezing the material to −24°C in small drinking cups, and were then transported to the helicopter in large Dewar containers.

Under the influence of the surface active material, the surface tension decreased from the normal value of about 74 dyn/cm to about 43 dyn/cm. These data were obtained by in-situ measurement using the spreading oil method developed by *Adam* [1937].

Normalized radar cross section (NRCS) measurements were made with an airborne 13.9 GHz pencil beam scatterometer (AAFE RADSCAT) carried by the National Aeronautics and Space Administration (NASA) C-130 aircraft. The antenna was pointed aft at incidence angles of 41° and 47° and produced an eliptical footprint of approximately 40 × 60 m on the sea surface. Further, the radar returns were integrated for 500 ms, which resulted in an effective resolution cell of 40 m cross track × 100 m along the track. Aircraft lines were flown in various directions over the slick and the surrounding areas so that good comparable data of the slick covered and clean surface were available. As a criterion for finding the optimal flight lines we used primarily the visually recognizable modification of the reflection of the sea surface in comparison with the surrounding area.

The wind speed measured at the station PISA, 27 km offshore, changed from 7.7–6.2 m/sec at the time when the slick was produced (at 07:45 GMT) to 3.5–5.7 m/sec when the radar measurements were performed (between 08:51 and 09:46 GMT). The wave spectrum was measured at station PISA at 08:00 GMT by a wavestaff. It showed a wind wave peak at $f = 0.20$ Hz and a swell peak at $f = 0.10$ Hz. The significant wave height was $H_{1/3} = 1.3$ m. Six flight lines are shown in Figure 1 where the changes in the NRCS due to the presence

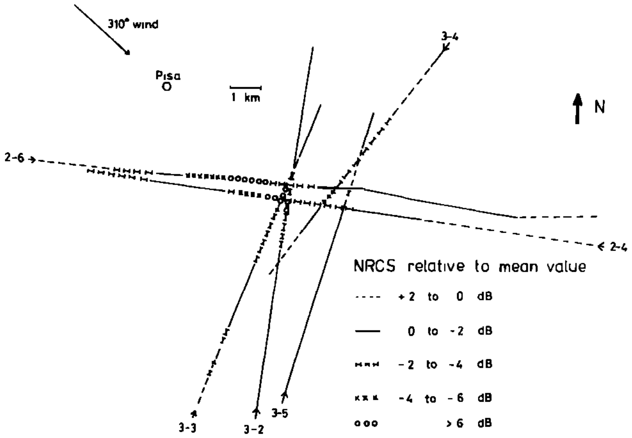

Fig. 1. Measured K_u-band NRCS over an oleyl alcohol slick during JONSWAP 75, September 4, 1975. The reduction relative to the non-slick area is indicated by different symbols (see legend).

TABLE 1. Normalized radar cross section for different flight lines before reaching the slick (A), within the slick (B), and after having left the slick (C). Flight lines 2-4 and 2-6 are in the east/west direction and are more parallel to the wind direction, while flight lines 3-2 and 3-3 are north/south flights and approximately in the cross-wind direction.

Flight line No.	Number of measurements	Meas. time (sec)	Polarization	Incid. angle (degrees)	Mean wind speed (m/sec)	NRCS (dB) (mean value)
2-4 A	82	46.8	VV	47	3.5-4.4	−36.4 ± 1.4
2-4 B	12	6.2		47	3.5-4.4	−43.7 ± 3.2
2-4 C	89	47.3		47	3.5-4.4	−37.7 ± 1.7
2-6 A	64	52.4	VV	41	3.2-3.3	−34.5 ± 3.1
2-6 B	18	8.8		41	3.2-3.3	−41.3 ± 4.1
2-6 C	78	41.5		41	3.2-3.3	−34.6 ± 1.5
3-2 A	86	46.0	VV	47	3.5-4.4	−38.4 ± 1.3
3-2 B	17	8.4		47	3.5-4.4	−43.1 ± 2.6
3-2 C	63	50.4		47	3.5-4.4	−39.4 ± 1.1
3-3 A	88	48.2	HH	47	3.2-3.5	−46.4 ± 2.1
3-3 B	4	6.6		47	3.2-3.5	−51.0 ± 0.7
3-3 C	37	19.4		47	3.2-3.5	−45.7 ± 2.2

of the slick are marked by different symbols on the lines (2 dB differences). Four of the flight lines (2-4, 2-6, 3-2, and 3-3) encountered the slick, whereas the flight lines 3-4 and 3-5 missed it.

The NRCS for the four flight lines which encountered the slick are summarized in Table 1. Figure 2 shows the vertical NRCS as a function of flight distance for flight line 2-4 and 3-2. The mean cross sections are given before the slick was encountered (A), within the slick (B), and behind the slick (C).

DISCUSSION OF EXPERIMENTAL DATA

The maximum measured difference between a slick-covered and a nonslick-covered area was 7.3 ± 3.5 dB (for flight number 2-4), which implies that about 81% of the energy of the surface wave component with a wavelength of about $L = 1.48$ cm (corresponding to the Bragg condition) is lost by damping effects.

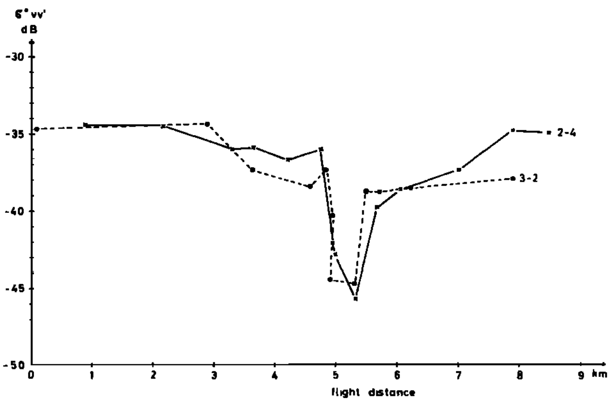

Fig. 2. Vertical normalized radar cross section as a function of flight distance for flight line 2-4 and 3-2. The dip in the curves corresponds to the slick area.

Obviously, the two flight lines in an east/west direction (flight number 2-4 and 2-6) have encountered the center of the slick. The four flight lines in the north/south direction (flight numbers 3-2, 3-3, 3-4, and 3-5), however, have most likely only encountered the border of the slick, which could be inferred from the 2.2–2.7 dB lower difference in the backscattering cross sections between slick-covered and slick-free areas. This could be explained by the fact that the modified reflection of the sea surface caused by the slick can only optimally be observed by the pilot under two distinct angles: one angle some degrees against the sun and another one some degrees with the sun. Consequently, the flight lines 2-4 and 2-6 have been more advantageous for encountering the center of the slick in the morning at 9:00 AM. During flight line 3-3 only four measurements in the slick area were recorded, which makes this data set less reliable in the slick area.

Another possible explanation for the 2.2–2.7 dB lower difference between slick-covered and slick-free sea surfaces in the north/south flight lines in comparison with the east/west flight lines could be the fact that the first lines are approximately in the crosswind direction, whereas the latter ones are more parallel to the wind direction. A wind direction sensivity of the radar cross section in the case of slick-free ocean surfaces has been reported [*Jones et al.*, 1977*a*]. Whether or not a different modification of the backscattering cross section by sea slicks dependent on the antenna direction relative to the wind direction exists must be clarified by further investigations. The data presented in Table 1 cannot confirm this hypothesis because of the large standard deviations encountered.

Using laser profilometer measurements *Mallinger and Mickelson* [1973] found that in the 0.3–0.6 Hz region (wavelengths between 17.3 and 4.3 m) the surface wave energy content within the slick area was approximately 54% of that outside of the slick area. The laser technique, however, is not really suitable over slick surfaces and could have produced erroneous results in that study (D. B. Ross, personal communication, 1978). Since surface tension is the restoring force for capillary waves [*Miles*, 1966], one would expect that shorter waves close to the capillary wave region are damped more strongly by surface films than the longer waves which were measured by Mallinger and Mickelson. This is confirmed by our data, but further systematic measurements are needed to establish the wavelength dependence of wavedamping by surface films.

CONCLUSIONS

The maximum decrease of the K_u-band normalized radar cross section at 47° incidence angles (vertical polarization) by an artificial monomolecular oleyl alcohol film on the sea surface was measured to be 7.3 ± 3.5 dB. This NRCS reduction is approximately equal to that reported in previous oil slick measurements where the surface films were of millimeter to centimeter thickness. The surface tension of the water surface was lowered by 31 dyn/cm by this artificial film. A decrease of the surface tension by natural monomolecular surface films of biological origin can also be of the same order of magnitude. For example the maximum surface tension decrease in the JONSWAP area was measured to be 33 dyn/cm (H. Hühnerfuss *et al.*, unpublished manuscript, 1978). Therefore, the variations of K_u-band NRCS over an ocean of different biological activities, which produce monomolecular films, are expected to have amplitudes of the same order of magnitude as measured in this experiment.

The results presented here imply the necessity of including the physicochemical state-of-the-sea surface when using backscatter measurements from airborne or spaceborne radars to infer surface wind speeds [*Jones et al.*, 1977*b*].

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