Suppression of Oceanic Ripples by Surfactant–Spectral Effects Deduced from Sun-Glitter, Wave-Staff and Microwave Measurements

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ABSTRACT

Experimental results on suppression of fine sea-surface structures by surfactant in terms of the roughness length obtained from wind profiles and of the wave-energy density from sun-glitter photographs, wave-staff measurements, and microwave returns are analyzed. The suppression was shown to be most effective at low winds, say below 7 m s^{-1}, and for wave components with their lengths between 2 and 40 cm. Both wave-staff and microwave measurements further indicate that the maximum suppression can be up to about 95%, occurring at surface-wave lengths of 4–5 cm. Other features of reported experiments were also discussed.

1. Introduction

Phenomena at the interface between the atmosphere and ocean greatly influencing transfer processes across the sea surface have been at the center of air–sea interaction research for decades. Recent attempts in the remote sensing of oceans have pressed for further understanding of the interface, as sea-surface sensors have been used in all trials. Much of these intensive efforts has been directed at conditions under high winds, where strong signal returns from the sea surface are received. Prevailing winds over the world's oceans, however, are generally light; photographs of their surfaces show probable substantial coverages of natural films under light-wind conditions (Scully-Power 1986).

Cox and Munk (1954) reported first systematic observations on damping of ocean ripples by the surface film. Barger et al. (1970) followed with a series of studies of its effects on the sea-surface roughness through measurements of wind profiles. Many more investigations over artificial slicks have been conducted recently with wave staffs (Hühnerfuss et al. 1981, 1983a; Yermakov et al. 1985; Ermakov et al. 1986), and with microwave sensors (Hühnerfuss et al. 1978, 1981, 1983b; Johnson and Croswell 1982). Data from all these field studies were reanalyzed along with those of laboratory observations (Gottifredi and Jameson 1968; Hühnerfuss et al. 1982); the results were found to be generally consistent. Evidence indicates that wave-damping effects of surface films observed over the sea surface are generally at low winds with velocities below 7 m s^{-1}, as suggested earlier by Wu (1971), and are for short gravity waves with their length in the range between 2 and 40 cm, instead of capillary waves as discussed in the original reports. These reports are believed to be useful in not only understanding suppression of oceanic ripples by surfactants, but also in choosing microwave sensors for detecting oil spills (Krishen 1973).

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2. Measurements through wind profiles

a. Roughness length of the sea surface

The roughness of sea surface is commonly described by the roughness length defined in the following (Wu 1968),

$$U/u_* = \frac{1}{\kappa}\ln(z/z_0) \qquad (1)$$

where U is the wind velocity at elevation z above the mean sea surface; u_* is the wind-friction velocity, $u_* = (\tau/\rho)^{1/2}$ in which τ is the wind stress and ρ the air density; $\kappa = 0.4$ is the von Kármán constant; and z_0 is the sea-surface roughness length. It has been shown that the roughness length is associated with ocean ripples (Wu 1970, 1986).

Effects of slick upon the atmospheric surface layer have been studied by Barger et al. (1970), with a spontaneous spreading of oleyl alcohol (Z-9-octadecen-1-ol) over the sea surface. Vertical wind profiles over both clean and slick surfaces were found to follow the logarithmic distribution shown in Eq. (1). Values of the roughness length z_0 obtained by them over both surfaces are reproduced in Fig. 1, where U_{10} is the wind velocity measured at 10 m above the mean sea surface.

b. Roughness suppression by the surface film

As the wind velocity increases from 1 to 4 m s^{-1}, the roughness length of the clean surface is seen in Fig.

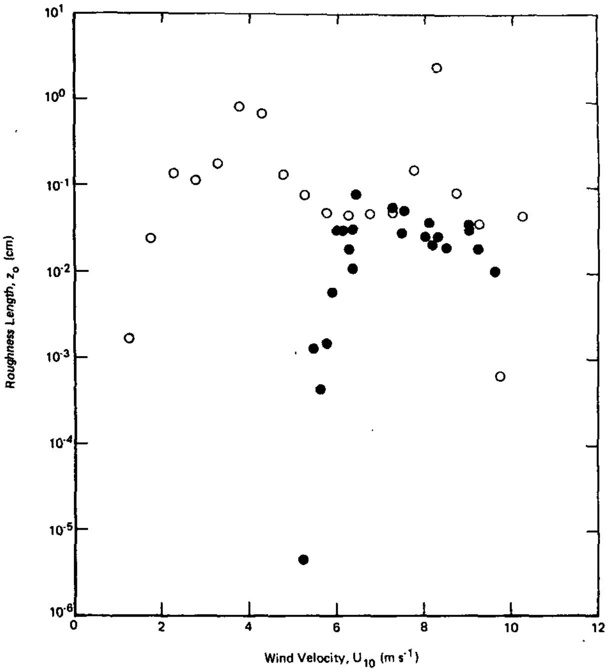

FIG. 1. Comparison of roughness lengths measured over clean (○) and slick (●) surfaces. The results are reproduced from Barger et al. (1970).

1 to increase sharply. This is due to a rapid growth of small waves in this region, accompanying the transition of atmospheric surface layer from aerodynamically smooth to rough. It suffices for our purposes to say that a rapid onset of growth of roughness elements over the clean surface is clearly demonstrated. During the slick passage, small waves were observed to be damped; the roughness length as seen in Fig. 1 to change drastically. The rapid onset of roughness growth is also demonstrated but shifted to wind velocities between 5 and 7 m s^{-1}. Below this velocity region the sea surface is smooth; above this velocity region the roughness length of the slick surface is comparable to that of the clean surface. This was suggested to be associated with the disruption of surface film by the wind (Wu 1971). Note that the critical wind velocity may vary with the chemical structure of surfactants (Hühnerfuss et al. 1982).

The atmospheric surface layer for the wind-velocity range of 2–7 m s^{-1} is in the transition region from aerodynamically smooth to rough (Wu 1981). The slick damps out waves serving as roughness elements, and thus delays the transition. In summary, the results presented in Fig. 1 illustrate quite distinctly the rupture of film and its overall effects on fine structures of the sea surface; the wave spectrum, however, must be resorted in order to learn the range of wavelengths affected. [Note that the oleyl alcohol was spread from a fast running boat in Barger et al.'s experiment; in order to avoid unknown effects of disturbances produced by the boat on the air–sea interface and the surface film, later deployment involving a dissemination of frozen alcohol chunks dropped from the air (Hühnerfuss and Garrett 1981) is advisable.]

3. Measurements with sun-glitter photography

a. Mean-square slope obtained from sun glitter

The energy of ocean ripples can be best described by the mean-square slope $\overline{s^2}$ of the sea surface. The latter can be related to the directional wavenumber spectrum $\psi(\mathbf{k})$ as (Phillips 1977),

$$\overline{s^2} = \int_0^\infty k^2\psi(\mathbf{k})d\mathbf{k}$$

$$\psi(\mathbf{k}) = (B/\pi)k^{-4}, \quad k_\gamma > k > k_0$$

$$\psi(\mathbf{k}) = (B'/\pi)k^{-4}, \quad k_\nu > k > k_\gamma \tag{2}$$

where $\mathbf{k}$ and k are the wavenumber vector and scalor, k_0 is at the spectral maximum, at k_γ gravity and surface tension have equal effects on the wave propagation, and k_ν is the neutrally stable wavenumber; B and B' are spectral coefficients for the gravity and capillary ranges, respectively. The spectrum of gravity waves near the spectral peak was modified recently (Phillips, 1985); our interest here, however, is near the high-frequency end where Eq. (2) still holds.

b. Spectral region affected by oil slicks

Cox and Munk (1954) deduced mean-square slopes of the sea surface from the sun glitter; their data are replotted in Fig. 2. A portion of their measurements were conducted in the interior of a dense slick, where waves shorter than roughly a foot were observed visually to be absent. Consequently, for this portion of the data produced solely by gravity waves, Eq. (2) can be written as

$$\overline{s^2} = B\ln[(U_{10}^2/g)k_s] \tag{3}$$

in which the approximation $k_0 = g/U_{10}^2$ was substituted where g is the gravitational acceleration. Fitting Eq. (3) to the data, Wu (1972) obtained: $B = 0.0046$ and $\lambda_s = 2\pi/k_s = 38$ cm; λ_s is then the length of longest waves damped by the film, and is in rather close agreement with the observed value.

Relative to those obtained inside the slick, the data from the clean surface at low winds are seen in Fig. 2 to have an almost parallel upward shift. The mean-square slope corresponding to this shift, about 0.0115, must be associated with wave components having wavenumbers greater than k_s. Consequently, the cutoff wavenumber k_c at low winds was obtained by Wu (1972) from Eqs. (2) and (3), provided of course that k_c is smaller than k_γ,

$$0.0046\ln(k_c/k_s) = 0.0115, \quad k_c = 2.5\ \text{cm}^{-1}. \tag{4}$$

The value of k_c is seen indeed smaller than k_γ, which

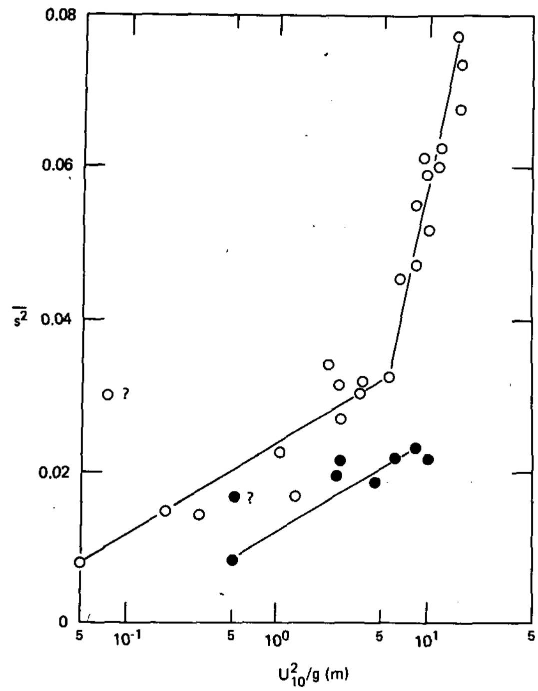

FIG. 2. Contributions of mean-square sea-surface slopes by waves. The data obtained from the clean surface are shown as open circles, and from the slick surface as solid circles. The two data points deviating clearly from the main group and marked with question marks were ignored for the curve fitting. All the data were obtained by Cox and Munk (1954).

is about 3.6 cm^{-1}. (The capillary range is generally classified for waves having lengths shorter than 1.73 cm or frequencies greater than 13.7 Hz). The closeness of these two values, k_c and k_γ, was interpreted to indicate that the portion of mean-square slopes at high winds above the extension of the line fitted to the clean-surface data at low winds comes from wave components in the capillary range (Wu 1972). The spectral coefficient in the capillary range was found to be $B' = 0.0315$, it is much greater than the coefficient in the gravity range. Consequently, when the capillary range started to make an effective contribution at wind velocities greater than 7 m s^{-1}, the mean-square slope increased rapidly.

In summary, the results on the longest wave damped by the film discussed here are not inconsistent with those reported previously on the damping of mechanically generated waves by surfactants (Gottifredi and Jameson 1968; Hühnerfuss et al. 1982). Damping was observed in the former study to be confined to waves shorter than 1 m in length, and in the latter to become significant at frequencies above 1.7–2 Hz, corresponding the wavelengths of 54–39 cm. It should be noted, however, that longer waves of a wind-generated sea may be affected indirectly through the nonlinear wave-wave interaction due to the direct damping of short waves. As for shortest wind-waves damped by the film, its effects apparently extend to components as short as those available over the sea surface at low winds ($U_{10} < 7$ m s^{-1}), being about 2.5 cm. A few data points over the slick surface even with U_{10} extending to 10 m s^{-1} are seen in Fig. 2 as still following the trend persisting over low winds. Accepting the above discussions that the data in capillary and gravity ranges follow distinctly different trends and that k_c in Eq. (5) is smaller than k_γ, it appears that damping effects of the surface film on ocean ripples extended to, but just fell short of, the capillary range.

4. Measurements with wave staff

a. *Direct spectral measurements with wave staff*

Wave attenuation by oleyl alcohol and methyl oleate surface films were investigated by Hühnerfuss et al. (1983a). Measurements were performed with a wave staff in the North Sea, as the slick drifted past it; conditions of their experiments are summarized in Table 1.

The data collected from inside and outside the slick area were processed to determine the wave spectra, which were not corrected for frequency shifts introduced by drift currents. Variances of wave slopes (rms slope) were calculated for different parts of the wave spectrum. Fractional contributions to the rms slope of the clean surface from frequency ranges of 0.02–5 Hz and 5–10 Hz, not shown in Table 1, are about the same for all three tests before the slick arrival. Reductions in the rms slope shown in the table are consistent with those presented in Fig. 2; following conversion to the rms slope, the damping shown in Fig. 2 is about 35% at the lowest wind and 20% at the highest wind.

Hühnerfuss et al. (1983a) also reported some spectrally resolved results at low frequencies for two different slick materials to indicate that the wave attenuation over slicks 1 and 3 (oleyl alcohol) became observable at frequencies greater than 0.7 Hz, and over slick 2 (methyl oleate) at frequencies greater than 5 Hz. In addition to the slope data, a sudden decrease of wave damping was found to occur at frequencies of about 14 Hz for slick 1 and about 16–17 Hz for slick 3. A similar decrease was also observed earlier (Hühnerfuss et al. 1981) but in the frequency range of 9.3–13.9 Hz. Again, all these frequencies were overestimated due to a Doppler shift mentioned earlier.

Experiments were also conducted by Ermakov et al. (1986) with both artificial and natural surface films from an oceanographic platform in the Black Sea; the artificial slick was produced with oleinic acid and vegetable oil. Surface waves were measured with a conductivity type wave gauge under two ranges of wind velocities, 1 and 5–7.5 m s^{-1}. Wave damping was observed to occur between 2 and 20 Hz for the artificial film, and between 2 and 14 Hz for the natural film; in addition, Ermakov et al. observed that there was a maximum damping of wave energy at 5 Hz for low

TABLE 1. Experimental conditions and results of Hühnerfuss et al. (1983a).

Slick	Slick size (km^2)	Wind velocity U_{10} (m s^{-1})	Slick drift velocity (cm s^{-1})	Reduction of rms slope 0.02–5 Hz	0.02–10 Hz	5–10 Hz
1. Oleyl alcohol	1.5	4.05	59	6.7%	23.1%	40.1%
2. Methyl oleate	1.0	5.54	70	3.5	19.8	34.8
3. Oleyl alcohol	2.3	5.27	70	11.5	18.3	25.8

winds and 10 Hz for high winds. Again none of these frequencies were corrected for the Doppler effects.

b. Corrected spectral results of wave damping

First of all, in order to understand further these results measured with the wave staff, we must determine their true frequencies. For the three slicks listed in Table 1 and those of Ermakov et al.'s (1986) experiments, surface drift currents were all measured. A correction formula suggested earlier by Wu (1975) was then used to determine the true frequency from the measured value and the surface drift current. The corrected frequency and its corresponding wavelength are presented in Table 2.

Two things are already apparent from Table 2. The measurements of Hühnerfuss et al. (1983a) actually did not reach the capillary range; such is also true for the measurements of Ermakov et al. (1986). The abnormality observed by Hühnerfuss et al. at two different frequencies, 14 Hz for slick 1 and 16–17 Hz for slicks 2 and 3, are seen in Table 2 to occur at the same frequency of about 6.1–6.3 Hz. Such behavior was not observed by Ermakov et al.; in fact, following correction the maximum damping was observed by them at 4.8 Hz for light winds and 7.8 Hz for high winds. In view of the above, the anomaly observed by Hühnerfuss et al. may still need to be reexamined to determine whether it was due to the wire vibration, as first suspected by them.

Spectrally resolved results were obtained by Yermakov et al. (1985) at low wind velocities of 0.75, 2

TABLE 2. Measured and true frequencies and wavelength.

Slick	Measured frequency (Hz) 2	5	10	14	16.5
	True frequency (Hz)/ (wavelength) (cm)				
Mechanical waves	2				
Huhnerfuss et al. (1982)	(39)				
Slick 1		2.97	4.75	6.08	
Huhnerfuss et al. (1983a)		(18)	(7.3)	(4.8)	
Slicks 2 and 3		2.80	4.46		6.31
Huhnerfuss et al. (1983a)		(20)	(8.2)		(4.5)
1 m s^{-1} wind	1.97	4.80			
Ermakov et al. (1986)	(40)	(7.1)			
6.8 m s^{-1} wind	1.84		7.80		
Ermakov et al. (1986)	(46)		(3.3)		

and 2.75 m s^{-1}. Their experiments were also performed from an oceanographic platform in the Black Sea; oleinic acid was used as the surfactant. Waves were measured with a resistance wire; but surface drift currents were not reported. Following the same procedure discussed in the previous section, we have corrected their results for Doppler effects by adopting the surface drift current as 3% of the wind velocity (Wu 1983). Wave damping was then found to start at about 2 Hz, to increase as the frequency increases, and to become less effective as the frequency further increases beyond 8 Hz; the maximum damping was seen at about 6.5 Hz. All of these differ little from those shown in Table 2. The maximum damping near these frequencies was discussed earlier by Cini and Lombardini (1978, 1981) on the basis of viscoelastic properties of a monolayer.

The results reported by Yermakov et al. (1985) and corrected for Doppler effects are transferred herewith in terms of the wavelength through the dispersion relation (Lamb 1932),

$$f\lambda = (g\lambda/2\pi + 2\pi T/\rho\lambda)^{1/2} \qquad (5)$$

where f and λ are frequency and length of surface waves, g the gravitational acceleration, ρ the water density, and T the surface tension. The computed results of Yermakov et al. are shown in Fig. 3, where $E_c(f)$ and $E_s(f)$ are spectral densities of waves over respectively clean and slick surfaces. For all three sets of data presented in the figure, the wave damping is seen to increase as the wavelength decreases, and to become ineffective as the wavelength further decreases beyond 2 cm, agreeing with the results deduced earlier from the sun glitter. The maximum damping is seen in Fig. 3 at wavelengths of about 4–5 cm.

5. Measurements with microwave sensors

a. Oceanic measurements at various bands

K_u-Band. Experiments on the influence of oleyl-alcohol surface films on returns of a K_u-band radar were conducted in the North Sea by Hühnerfuss et al. (1978). Normalized radar cross sections (NCRS) were obtained from an aircraft; flights were over the clean sea surface and the artificial monomolecular film 1.5 km^2 in area. The radar was operated at both vertical and horizontal polarizations from incidence angles of 41 to 47 deg; its footprint on the sea surface was elliptical in shape having dimensions of approximately 40 × 60 m. According

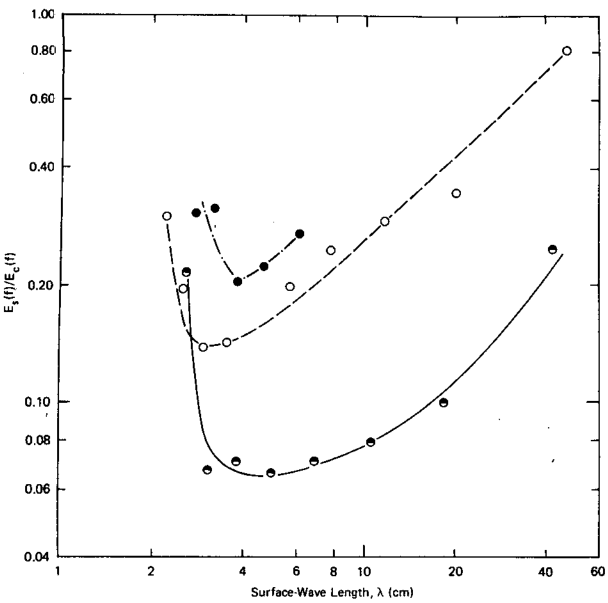

FIG. 3. Damping of waves by surfactants. The results are deduced from Yermakov et al. (1985) obtained at three wind velocities of 0.75 (●), 2 (○) and 2.75 (◓) m s^{-1}.

to the Bragg scattering mechanism (Moore 1985), the radar under these settings responded most sensitively to surface waves of about 1.48 cm in length. The experiments were performed under wind velocities between 3.2 and 4.4 m s^{-1}; the spectrum of surface waves was peaked at 0.2 Hz and that of swells at 0.1 Hz, with the significant wave height of about 1.3 m. The maximum measured reduction between slick and clean surfaces was 7.3 dB. The average reduction in vertically polarized returns from the center of the slick was 6.7 dB, and that from the edge of the slick was 4.2 dB; the average reduction in horizontally polarized returns from the edge of the slick was 5.0 dB.

The same radar was operated by Johnson and Croswell (1982) from an aircraft over the Atlantic Ocean approximately 40 km off the coast of New Jersey. Four controlled spills were produced by dumping approximately 3.4 m^3 oil for each. Two types of oils, light and heavy crude, were used; for each type the oil was treated in one case with a dispersant material sprayed from a helicopter, and untreated in the other case. Wind velocities during the flight were between 5 and 7 m s^{-1}, and the significant wave height was less than 1 m. Radar-scattering changes between the clean and slick surfaces were observed over a range of incidence angles from nadir to approximately 90 deg. Greatest reductions in returns ranging from 8–14 dB were observed at approximately 30 deg, corresponding to the surface-wave length of 2.16 cm. It was also found that the maximum reduction was associated with the thickest film.

X-Band. During the same experment of Hühnerfuss et al. (1978), a tower based 9.5 GHz coherent *X*-band microwave scatterometer was operated; the results were reported by Hühnerfuss et al. (1981). The radar had a wavelength of 3.16 cm, and was operated at incidence angles between 30 and 70 deg. The most significant results were obtained at the incidence angle of 57 deg, providing the surface-wave length of 1.88 cm. In this case, the reduction was 6.35 ± 1.87 dB.

A dual-frequency *X*-band CW (continuous wave) scatterometer was also deployed from a tower during the experiments of Hühnerfuss et al. (1983b). Variations of the wind velocity were reported between 4 and 6.5 m s^{-1}, and the significant wave height was about 1.5 m. Operating at grazing angles of 32–35 deg, the lengths of short waves satisfying the Bragg scattering are respectively 1.95–1.89 cm. Power reductions of returns from the methyl-oleate slick were found to be 32%; they were 33% and 64% from the oleyl-alcohol slick, depending on the angle between directions of the wind and radar antenna.

L-Band. During the same experiment described above in the North Sea (Hühnerfuss et al. 1983b), a single-frequency *L*-band CW scatterometer, a dual-frequency *L*-band pulsed scatterometer, and a dual-frequency *L*-band scatterometer were also tested on the tower. The first radar was set at the grazing angle of 35 deg, the second at 6.3–7.9 deg, and the third at 4.6 deg. As discussed later, the Bragg mechanism was responsible for the backscattering only for that operating at the grazing angle of 35 deg; the Bragg surface waves were 12.2 cm long. Reductions up to 13% were found in most cases with zero reductions for a couple of cases; the reduction was again found to depend on the angle between directions of the wind and radar antenna.

b. Further analyses of microwave returns

Clean sea surface. The results observed with microwave sensors reported above are interesting. Unlike those from the glitter photography and wave-staff measurement, the microwave measurement was indirect, relying on proper interpretations of radar signals. First of all, in all these studies the dielectric constant of sea surface was considered not affected by slicks consisting of monomolecular films. Much also still needs to be learned on the dependency of microwave returns on wave structures, including not only the scattering mechanism directly related to ripples but also the tilting and straining of the scattering surface by long waves. It suffices for now to accept that the Bragg mechanism is operable within the incidence angles 20–70 deg (Moore 1985),

$$\lambda = L/2\sin\theta \tag{6}$$

where L is the length of radar waves, and θ the incidence angle.

Among all the results reported, the most comprehensive set of data were offered by Johnson and Cros-

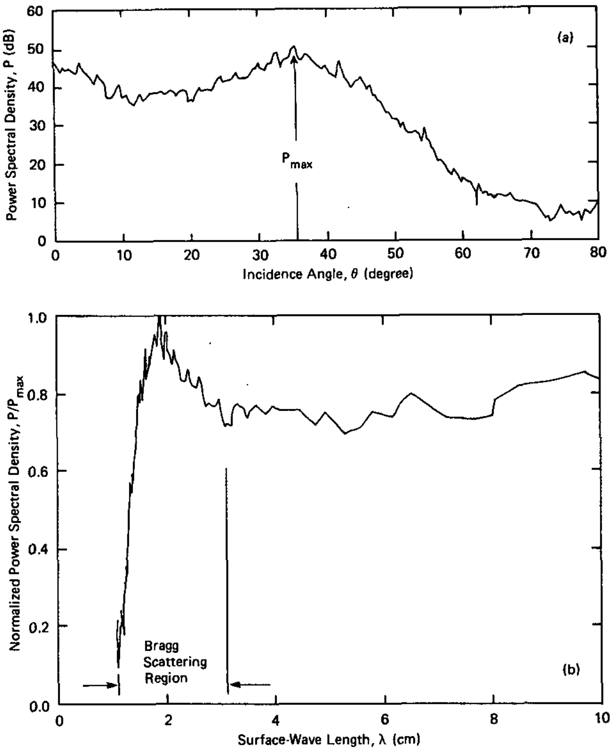

FIG. 4. Microwave returns from clean sea surface. The data in (a) are reproduced from Johnson and Croswell (1982), and the results in (b) were calculated from Bragg scattering relationship.

well (1982); they measured the returns from both clean and slick sea surfaces from a wide range of incidence angles. The clean-surface data in terms of the power-spectral density, P, are reproduced in Fig. 4a, which are important for a proper interpretation of reductions caused by slicks. The returns normalized with their maximum value, marked as P_{max} in Fig. 4a, are presented in Fig. 4b; the scales in the latter are transferred from the power density in dB versus the incidence angle to the power density in % versus the surface-wave length. The range of incidence angles, 20–70 deg, within which the Bragg scattering is operative is marked in Fig. 4b. The return peaked at the incidence angle of 35.8 deg is seen now at the surface-wave length of 1.85 cm. The power density of surface waves on the long-wave side of the peak should increase continuously with the wavelength (Phillips 1985); the returns shown in Fig. 4b, however, do not follow this trend. Causes of this discrepancy are not clear; this portion of the results should, therefore, be viewed with caution. The sharp reduction of power density on the short-wave side of the peak shown in Fig. 4b is very interesting, and will be discussed in a later section.

Slick sea surface. The spectrally resolved results of Johnson and Croswell observed over oil slicks were presented in terms of the wave damping (dB) versus the incidence angle; they were reprocessed and are shown in Fig. 5 again with the ratio between radar-observed spectral energies over slick and clean surfaces (%) versus the surface-wave length. The returns were averaged by them over 5 deg angular bins. According to the Bragg mechanism, the lowest bin included in Fig. 5 is that centered at 22.5 deg with returns from the range of 20–25 deg, and the highest bin is at 67.5 deg with returns from the range of 65–70 deg. Taken together, we see clearly that a significant damping was observed near the wavelength of 2.16 cm, and the maximum damping occurred for waves slightly longer than this length. We see of course that being quite consistent with sun-glitter and wave-staff results, surface films lost their effectiveness in wave damping very rapidly when the wavelength became shorter.

All available individual results on the reduction of microwave returns from the slick sea surface discussed herein are compiled in Table 3 and Fig. 6; some of the results previously expressed as the reduction in dB are now transferred in terms of the ratio between spectral densities over slick and clean surfaces. The wave damping is seen to be most effectively detected with K_u and X bands. Any radar providing Bragg surface waves shorter than the length offered at these bands is

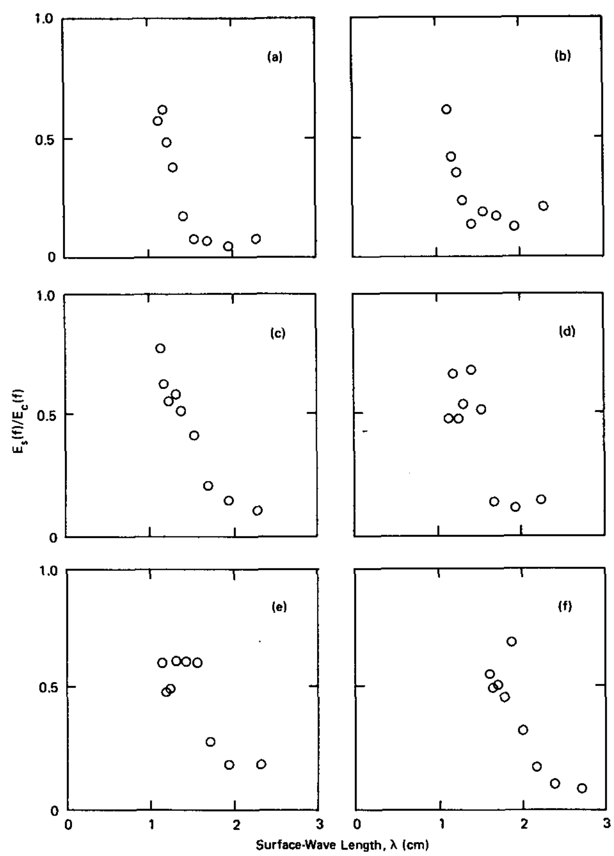

FIG. 5. Damping of surface waves by films. The results were deduced from Johnson and Croswell (1982) with films produced by (a) Murban oil, (b) treated Murban, (c) LaRosa oil, and the others from treated LaRosa.

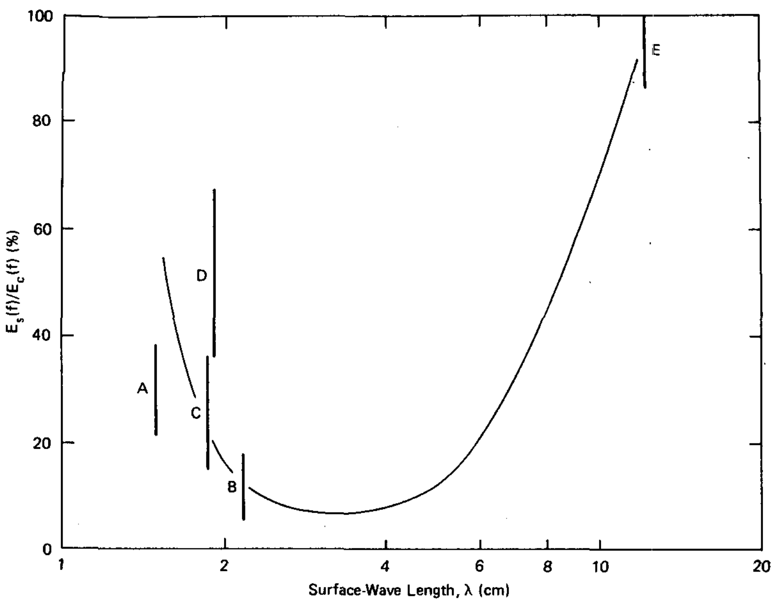

FIG. 6. Summary of available slick measurements with microwave sensors. The experiments are identified with letters shown in Table 3.

perhaps slightly too short for slick studies; on the other hand, the surface waves contributing to the returns of L-band are too long to be effective.

Taking into account the trends shown in Figs. 3 and 5, a curve is drawn in Fig. 6 to represent the damping of microwave returns from sea-surface slicks. A consistent trend, therefore, emerges among all results: the effectiveness of wave damping by surface film is principally at wave components in the centimeter range. Among all the bands available, the K_u- and X-bands as mentioned above provide the best observations of the surface film; the maximum damping, however, occurs at the radar wavelength between those of X- and L-bands, say the C-band. The maximum in radar backscattering depression was associated recently by Alpers and Hühnerfuss (1988) to the Marangoni damping of ocean surface waves by the viscoelastic surface film (Marangoni 1872; Lucassen 1968; Cini and Lombardini 1981). This, therefore, further substantiates the curve drawn in Fig. 6.

6. Conclusion

All available results were reanalyzed and found to indicate quite consistently that the effective wave damping by surface film occurs principally at low winds, say below 7 m s^{-1}. The optical type measurements with sun-glitter photography indicate that the damping occurs primarily for gravity components starting with the wavelength of 38 cm and extending to wave components as short as about 2 cm. Contrary to discussions in original reports (Hühnerfuss et al. 1981, 1983a; Yermakov et al. 1985; Ermakov et al. 1986), all measurements with the wave staff never reached waves short enough to be in the capillary region. Quantitatively, the damping of wind-waves was primarily associated with ripples with their length in the centimeter range, starting from about 2 cm in length and extending to waves as long as 40 cm; the maximum damping was observed to occur with waves of about 4–5 cm long.

TABLE 3. Summary of microwave results. The results of Johnson and Croswell were over oil spills and the others over monomolecular slicks.

	Experiments	Surface-wave length (cm)	Ranges of $E_s(f)/E_c(f)$
A.	K_u-Band (Hühnerfuss et al., 1978)	1.48	0.21–0.38
B.	K_u-Band (Johnson and Croswell, 1982)	2.16	0.06–0.18
C.	X-Band (Hühnerfuss et al., 1981)	1.88	0.15–0.36
D.	X-Band (Hühnerfuss et al., 1983b)	1.92	0.36–0.67
E.	L-Band (Hühnerfuss et al., 1983b)	11.97	~0.76

Undoubtedly, the capillary waves can be effectively damped by the surface film as reported by Davies and Vose (1965) and suggested by Garrett (1967). However, at low wind velocities where the film is not broken up by the wind, the wave spectrum simply does not reach the capillary range. This rather surprising conclusion reached earlier by Wu (1972) appears to be consistent with recent observations discussed here.

Very encouragingly, all reported studies have contributed to advance our understanding in this important area; we must recognize, however, that these results only provide a good start. Much more still needs to be studied on variation of film properties (Hühnerfuss et al. 1982) and environmental factors (Johnson and Croswell 1982; Hühnerfuss et al. 1983b) affecting the wave damping and microwave returns from sea slicks.

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