

Attenuation of Capillary and Gravity Waves at Sea by Monomolecular Organic Surface Films

HEINRICH HÜHNERFUSS,¹ WERNER ALPERS,² WILLIAM D. GARRETT,³
PHILIPP A. LANGE,⁴ AND SIEGFRIED STOLTE⁵

During the MARSEN 79 experiment, attenuation of capillary and gravity water waves by two oleyl alcohol and one methyl oleate surface films ('slicks') was investigated. A slight influence of an oleyl alcohol slick occurs at frequencies between 0.5 Hz and 0.7 Hz and above 0.7 Hz (wavelength $L = 3.2$ m) wave attenuation becomes significant. A methyl oleate slick causes only a slight wave damping in the frequency range $f < 5$ Hz ($L > 6.7$ cm). In the capillary wave range $f \geq 14$ Hz the wave-damping characteristics for the two surface film substances are comparable. In the high-frequency capillary wave range $f > 20$ Hz, however, methyl oleate surface films act more strongly on the wave field, as was demonstrated by additional wind-wave tunnel experiments. The different wave attenuation characteristics of these two surface active compounds are attributed to different interaction between their hydrophilic part and the adjacent water layer.

1. INTRODUCTION

Experimental sea slicks have been used as a tool for modifying air-sea interaction processes thus gaining further insight into distinct mechanisms of energy transfer by wind-wave coupling and wave-wave interactions (for reviews, see *Hühnerfuss and Garrett* [1981]). As a consequence of the modified sea surface roughness in the presence of a slick, the 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].

The above pioneering results summarized by *Hühnerfuss and Garrett* [1981] stressed the necessity for a careful large-scale experiment with well-defined artificial monomolecular sea slicks, during which both the modified sea surface roughness and the modification of the signals of different active and passive remote sensors was to be investigated simultaneously. The knowledge of these modifications is of particular interest, since several planktonic species, fish, etc., may also secrete organic substances of chemical and physicochemical characteristics similar to the film-forming compounds used in our work. The natural surface films thus formed may accumulate at the ocean surface under certain oceanographic and meteorological conditions [*Hühnerfuss et al.*, 1977] within some hours, cover large sea areas, and thus interfere with the signals of various remote sensors.

Therefore one part of the MARSEN (Marine Remote Sensing) experiment 1979 was devoted to the investigation of the influence of monomolecular surface films on water wave spectra and on the signals of X and L band radars, L and S band microwave radiometers, and AOL LIDAR, by applying well-

defined artificial surface films which are representative of natural surface films. The results of the MARSEN slick experiment, which partly supplied rather unexpected data, are reported in four papers: the L and S band microwave radiometer results appeared in the first special MARSEN issue [*Alpers et al.*, 1982], whereas the X and L band radar data [*Hühnerfuss et al.*, this issue (a)] and the AOL LIDAR data [*Hühnerfuss et al.*, this issue (b)] are discussed in two subsequent papers of the present special MARSEN issue.

In this paper the attenuation of gravity and capillary waves by monomolecular sea slicks measured by a tower-based wave staff is reported. The results, which have been obtained by the other sensors discussed in the two companion papers, will be discussed based on the wave staff results.

The influence of monomolecular surface films on the mechanisms of various air-sea interaction processes is not well understood, especially with regard to gravity wave damping. *Gottifredi and Jameson* [1968] claimed that the wave-damping effect of slicks ought to be confined to water waves in the frequency range $f \geq 1.25$ Hz (wavelength $L \leq 1$ m), while other authors [*Barger et al.*, 1970; *Hühnerfuss et al.*, 1981a] concluded from experimental data that even longer gravity waves might be subject to some damping. However, the slicks used by the latter authors were not large, allowing data collection of up to a maximum of 500 seconds. Statistically relevant effects in the gravity wave range require data recording times of at least 25-30 minutes. Therefore one scientific goal of the MARSEN slick experiment was the production of a large-sized monomolecular surface film which would meet these statistical requirements.

A second objective was concerned with the influence of monomolecular surface films of different chemical structure on capillary and gravity waves. As a result of their different wave-damping characteristics determined in preliminary wind-wave-tunnel experiments and their similarity to natural surface films, two chemical substances of different chemical structure were used during the MARSEN experiment: oleyl alcohol (9-octadecen-1-ol, Z isomer) and methyl oleate (9-octadecenoic acid methyl ester, Z isomer). These two surface films with different chemical structures were produced within 2 hours of one another, so that the meteorological and oceanographic conditions were as similar as possible to allow good comparison between data obtained in the presence of both surface films. Wind-wave tunnel data will be included in this paper to

¹ Institut für Organische Chemie und Biochemie, Universität Hamburg, 2000 Hamburg 13, Federal Republic of Germany.

² Institut für Geophysik der Universität Hamburg und Max-Planck-Institut für Meteorologie, 2000 Hamburg 13, Federal Republic of Germany.

³ Naval Research Laboratory, Washington, D. C. 20375.

⁴ Bundesanstalt für Wasserbau, 2000 Hamburg 56, Federal Republic of Germany.

⁵ Forschungsanstalt der Bundeswehr für Wasserschall- und Geophysik, 2300 Kiel, Federal Republic of Germany.

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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 Direc- tion	Wind Speed, ms ⁻¹ , U ₁₀ /U ₄₆	Signif- icant 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	0.70	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	0.70	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.

†Measurement performed from research platform *Nordsee* (Forschungsplattform Nordsee: FPN).

‡Airborne sensor.

assist in the interpretation of the results of the experimental slick investigations performed at sea.

2. EXPERIMENTAL

During the Marine Remote Sensing Experiment 1979 (MARSEN 79), three surface films were produced on the sea surface in the area next to the North Sea platform *Nordsee* (54°42'9.3" N, 7°10'7.4" E). The method, which is extensively described by *Hühnerfuss and Garrett* [1981], involved a systematic dissemination of frozen chunks (80 g) of 96.5% oyleyl alcohol (9-octadecen-1-ol, Z isomer) and 74.8% methyl oleate (9-octadecenoic acid methyl ester, Z isomer). The chemical substances were supplied by Henkel KGaA, Düsseldorf (Federal Republic of Germany) and were used to produce MARSEN slicks without further purification. Although the latter substance was not of high purity, its surface chemical properties 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 experiment are summarized in Table 1. In this paper we report the wave staff data; the radar [*Hühnerfuss et al.*, this issue (a)], passive microwave [*Alpers et al.*, 1982], and LIDAR [*Hühnerfuss et al.*, this issue (b)] are presented separately.

Wave staff measurements were performed inside and outside the slick area. The technical description of the wave staff is given by *Stolte* [1982]. The statistical parameters used for the spectral analysis of the three slick events are summarized

in Table 2. It has to be stressed that the wave staff data were calculated from water wave spectra which were neither corrected for orbital velocity or wave-induced Stokes drift nor tidal currents, i.e., the results presented in this paper are based on so-called 'spectra of encounter,' as usually reported in literature. The wave staff outputs have been calibrated. Thus variances of approximated wave slopes could be calculated from the obtained wave spectra by well-known methods [*Kinsman*, 1965].

The performance of the wave staff in the presence of slick material has been checked by laboratory experiments: *Lo-bemeier* [1978] performed calibration measurements between 0 and 52 Hz and salt concentrations (salinity) between 0‰ and 46‰ with carefully cleaned water and water surfaces covered with the above slick material. It was clearly shown that the slick material does not affect the calibration. Therefore it can be safely assumed that no deterioration of wave staff performance due to the presence of the slick occurs in the frequency range reported in this paper.

The sea state was fully developed upwind of the three slicks. This is exemplarily demonstrated in Figure 1, which shows the wave spectrum measured upwind of slick 3, i.e., the nonslick sea area 'after slick 3' schematically depicted in Figure 2. The expressions 'before slick' and 'after slick' denominate nonslick sea areas downwind and upwind of an existing slick, respectively. However, care has been taken that the distances of these nonslick areas from the edge of the slick were long enough that the wind and water waves were not affected by

TABLE 2. Statistical Parameters Used for Spectral Analysis of the Three MARSEN 79 Slick Experiments

	Record Time	Frequency Resolution, Hz	Degrees of Freedom
Slick 1	11 min 44 s	0.44	418
Slick 2	9 min 36 s	0.44	342
Slick 3*	28 min 48 s	0.44	1026
Slick 3†	28 min 48 s	0.09	162
Slick 3A, 3B, 3C‡	9 min 36 s	0.44	342

*Frequency range 0.2–21 Hz evaluated.

†Frequency range 0.06–1 Hz evaluated.

‡See Figure 2.

the slick within these areas. This was controlled by comparing the upwind and downwind wave spectra determined in these two nonslick areas.

The same caution has been applied with regard to the distances between the methyl oleate slick (slick 2) and the oleyl alcohol slick (slick 3), which were produced on the sea surface within two hours on September 28, 1979 in order to study the influence of surface films of different chemical and physicochemical characteristics under comparable meteorological and oceanographic conditions. The distance between the upwind edge of slick 2 and downwind edge of slick 3 was about 2.6 km. The wind-wave-tunnel used to produce some of the data reported here is described elsewhere [Hühnerfuss et al., 1976].

3. DISCUSSION OF RESULTS

3.1. Attenuation of Capillary and Gravity Waves

A first indication for an influence of the three surface films on different parts of the wave spectrum can be obtained from calculations of the variances of slope from the wave staff data (Table 3). Especially, the results of slick 3, based on a data acquisition time of 28 min 48 s, clearly show that wave attenuation is caused by oleyl alcohol surface films not only in the high-frequency range but also in the range 0.02–5 Hz.

In order to investigate the wave frequencies at which wave damping by oleyl alcohol surface films becomes significant from a statistical point of view, the spectral energy densities were calculated with a frequency resolution of $\Delta f = 0.09$ Hz in the frequency range 0.04–1 Hz for both a slick-covered and a nonslick area. The wave attenuation ratios of slick 3, i.e., ratio of the energy of waves in slick 3 area and the wave energy of the nonslick area, are depicted in Figure 3. For frequencies above 0.5 Hz ($L \leq 6$ m) the waves are slightly damped by the oleyl alcohol surface film, and at $f = 0.7$ Hz ($L = 3.2$ m), wave damping becomes significant.

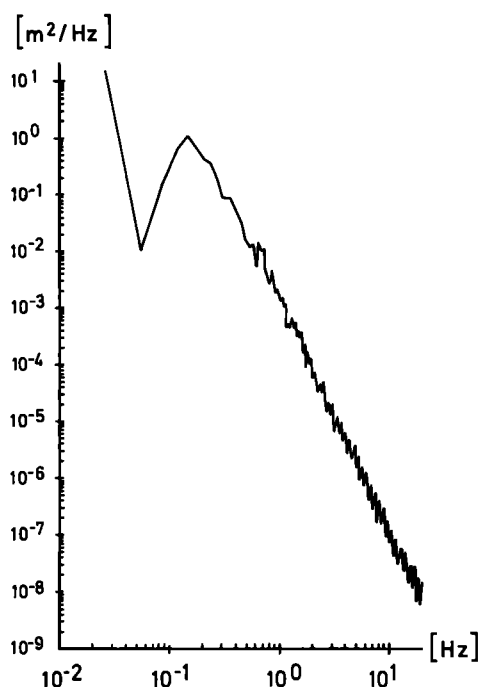


Fig. 1. Water wave spectrum obtained by wave staff measurements upwind of an oleyl alcohol slick (slick 3).

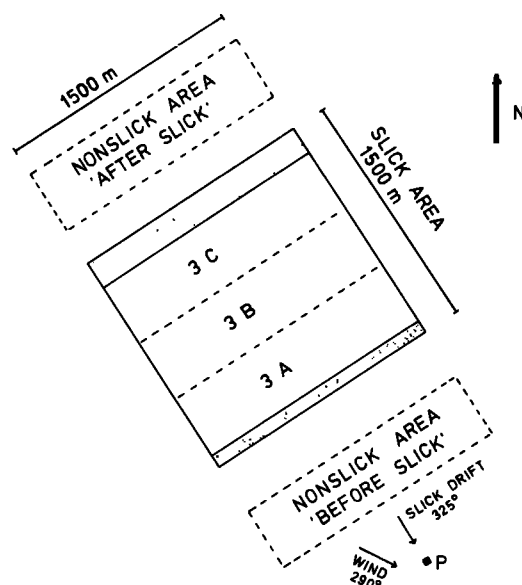


Fig. 2. Spatial distribution of the nonslick areas ('before slick 3' and 'after slick 3'), and the three sections of oleyl alcohol slick 3, 3A, 3B, and 3C, which are evaluated for determining wind fetch dependence of wave attenuation within a slick covered sea area. Data of the dotted slick area have not been used.

The wave damping as a function of wind fetch within the slick covered areas has been investigated by dividing the slick 3 data into three subsequent segments 3A, 3B, and 3C (Figure 2) of 9 min 36 s duration each. Because of the relatively short record times, the results in the long gravity wave range are not very conclusive. Also there is more scatter in the wave amplitude data in this frequency range. However, when attenuation ratios for segments C (short fetch) and B (long fetch) are compared (Figure 4), a trend can be observed. No influence on longer waves occurs when the waves are in segment C, whereas wave damping seems to become significant for waves with frequencies ≥ 3 –4 Hz. Data obtained from segment B indicate that in this long-fetch region a stronger wave damping occurs both in the capillary and gravity wave range.

Comparison between data of segments B and A (Figure 5) shows that no further increase of wave damping in the short gravity and capillary wave range is observed, i.e., the maximum wave attenuation is already achieved in segment B. It can be assumed that longer gravity waves are still subject to further damping in segment A, but as mentioned above, this cannot be verified with only 9 min of data.

In the capillary wave range, $f = 16$ –17 Hz, a sudden decrease of wave damping seems to occur (Figures 4 and 5). A similar effect has been observed during one JONSWAP 75 slick experiment [Hühnerfuss et al., 1981a, slick 3] in the frequency range 9.3–13.9 Hz. When evaluating this JONSWAP 75 slick experiment 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. [1981b] 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. that in the presence of a surface film a lower 'effective wind speed' instead of the actually measured

TABLE 3. Variances of Wave Slope (vws) in the Frequency Ranges $f = 0.02\text{--}5$ Hz, $0.02\text{--}10$ Hz, and $5\text{--}10$ Hz

	0.02–5 Hz		0.02–10 Hz		5–10 Hz	
	vws	was	vws	was	vws	was
Before slick 1	0.9178×10^{-2}		0.1807×10^{-1}		0.8892×10^{-2}	
Slick 1	0.8565×10^{-2}	8%	0.1389×10^{-1}	21%	0.5325×10^{-2}	36%
After slick 1	0.9434×10^{-2}		0.1721×10^{-1}		0.7776×10^{-2}	
Before slick 2	0.1004×10^{-1}		0.2086×10^{-1}		0.1082×10^{-1}	
Slick 2	0.9686×10^{-2}	4%	0.1674×10^{-1}	17%	0.7054×10^{-2}	30%
After slick 2	0.1011×10^{-1}		0.1936×10^{-1}		0.9250×10^{-2}	
Before slick 3	0.1049×10^{-1}		0.1983×10^{-1}		0.9340×10^{-2}	
Slick 3	0.9279×10^{-2}	12%	0.1621×10^{-1}	20%	0.6931×10^{-2}	29%
After slick 3	0.1061×10^{-1}		0.2078×10^{-1}		0.1017×10^{-1}	

Variances were obtained from wave spectra in the presence of two oleyl alcohol slicks (Slick 1, Slick 3), a methyl oleate slick (Slick 2), and of the nonslick surfaces before and after these slicks. The corresponding wave attenuation by the three slicks (was) calculated from these vws data is also given (in percent).

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 Figures 4 and 5 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.

The intensity of this peak shift does not only depend on the chemical structure of the surface films but also on the meteorological and oceanographic conditions, e.g., wind speed and wind direction. In Figure 6 the wave attenuation ratios of slick 3 are compared with those of slick 1. Apart from a noisier appearance of the curve, which may be due to the shorter record time in the presence of Slick 1, the wave damping characteristics look very similar. A decrease of wave attenuation in the capillary wave range can be observed again, but under the meteorological conditions of September 22, 1979 this peak in the wave attenuation curve appears at a frequency $f \approx 14$ Hz.

3.2. Wave Attenuation by Different Surface Films

Since natural surface films consist of a mixture of various chemical compounds, it is of considerable interest to compare wave attenuation effects of surface films of different chemical and physico-chemical characteristics. For this reason, on September 28, 1979 one methyl oleate (slick 2) and one oleyl alcohol (slick 3) surface film were produced on the sea surface so that they drifted beneath the North Sea platform *Nordsee* within 2 hours of one another. As can be seen in Table 1, the environmental parameters were very constant that day, thus allowing reliable comparison between both experiments.

A first insight into the different influence of both slicks on water waves is afforded by comparing the variances of the wave slopes in the frequency regions $f = 0.02\text{--}5$ Hz, $f = 0.02\text{--}10$ Hz, and $f = 5\text{--}10$ Hz (Table 3). In the gravity wave range between 0.02 Hz and 5 Hz, the methyl oleate film (slick 2) attenuates the waves only slightly, whereas the oleyl alcohol film (slick 3) has a significantly stronger influence. In the range $f = 5\text{--}10$ Hz, however, both slicks affect the wave spectrum in a similar manner.

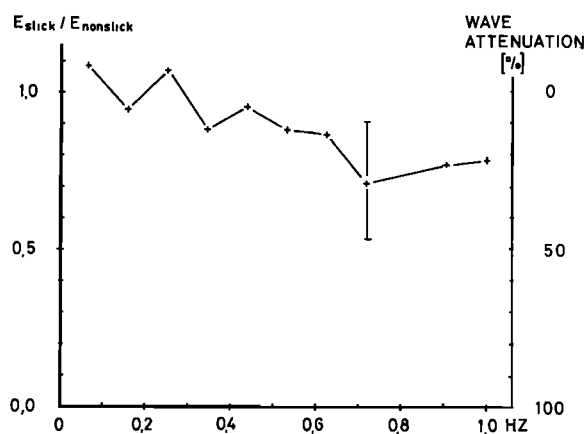


Fig. 3. The ratio of spectral energy density (oleyl alcohol slick 3/nonslick area ('before slick')) versus frequency as measured by the wave staff. The scale on the right hand side shows the corresponding values for the wave attenuation in per cent. The error bars (90% confidence limits) indicate wave attenuation to become significant at about 0.7 Hz.

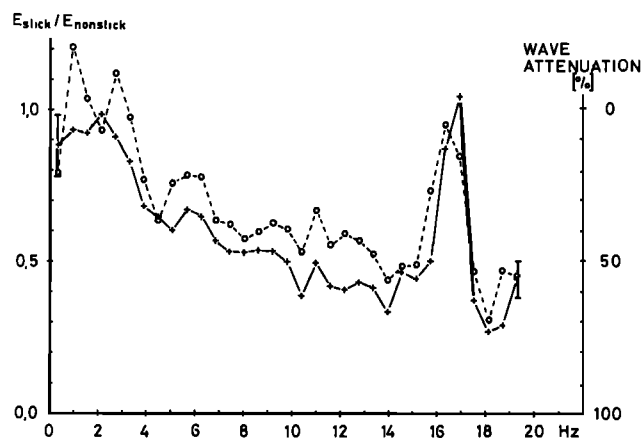


Fig. 4. The ratio of spectral energy density (section 3C of oleyl alcohol slick 3/nonslick area ('before slick 3'); dashed line; section 3B of oleyl alcohol slick 3/nonslick area ('before slick 3'); solid line) versus frequency as measured by the wave staff. The scale on the right-hand side shows the corresponding values for the wave attenuation in per cent.

These results are confirmed by comparing the wave attenuation curves of slicks 2 and 3, which are shown in Figure 7. The slick 2 data are based on a record time of only 9 min 36 s, which may explain the noisy attenuation ratio curve. Wave attenuation in the presence of a methyl oleate surface film (slick 2) was clearly less than that caused by oleyl alcohol (slick 3) in the short gravity wave range. In the long gravity wave range, $f < 5$ Hz, no significant wave damping is observed, and in the capillary wave range $f \geq 14$ Hz, the wave damping characteristics for the two surface films are comparable.

Again, intensive decrease of wave attenuation is observed in the capillary wave region in the presence of a methyl oleate surface film (slick 2), but compared to slick 3, the peak maximum in the wave attenuation curve (Figure 7) is shifted to lower frequencies (peak maximum for slick 2 is 15.6 Hz; peak maximum for slick 3 is 16.8 Hz). This is qualitatively consistent with wind-wave tunnel experiments, which have proved similar relative peak shifts in the presence of oleyl alcohol and methyl oleate surface films [Hühnerfuss et al., 1981b].

3.3. Comparison With Wind-Wave Tunnel Experiments

A direct comparison of wind-wave tunnel results with data obtained on the open sea is always difficult. The peak maxima of wind-wave tunnel spectra are shifted about one order of magnitude to higher frequencies if the same free stream velocities are used, and several authors [e.g., Komen, 1980] have stressed that nonlinear interactions are more pronounced in certain frequency ranges of wind-wave tunnel spectra. But since the shape of the spectra obtained from both sea and wind tunnel data is very similar, it has been tentatively assumed that at least the relative influence of different substances on wave spectra is similar on the open sea and in a wind wave tunnel.

Wave attenuation ratios were calculated from wind-wave spectra (free stream velocity of wind 5.5 m s^{-1}) measured in the Hamburg wind-wave tunnel in the presence of oleyl alcohol and methyl oleate surface films (Figures 8a and 8b). In the short gravity wave range, $f = 2\text{--}9$ Hz, an oleyl alcohol surface film exhibits a stronger wave damping effect than a methyl oleate slick. At $f = 9\text{--}16$ Hz, wave attenuation becomes com-

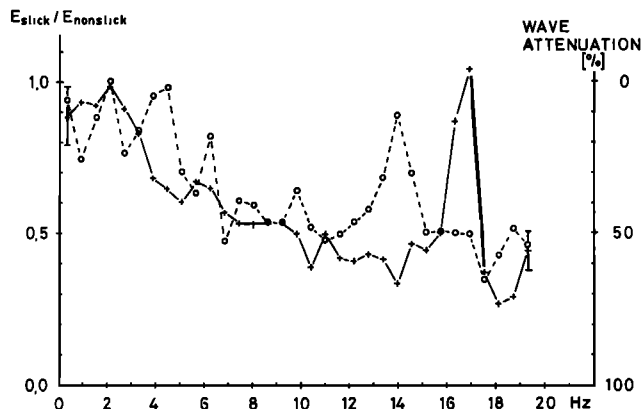


Fig. 6. The ratio of spectral energy density (oleyl alcohol slick 3/nonslick area ('before slick 3'): solid line; oleyl alcohol slick 1/nonslick area ('before slick 1'): dashed line) versus frequency as measured by the wave staff. The scale on the right-hand side shows the corresponding values for the wave attenuation in per cent.

parable, which is in good agreement with the MARSEN sea slick results, while in the high-frequency capillary range, methyl oleate films more strongly dampen the waves.

The different wave attenuation characteristics of these two surface active substances is not fully understood at the present time. It has already been postulated in a previous publication [Hühnerfuss et al., 1981a] that at least three mechanisms may contribute to wave energy dissipation in the presence of a surface film: a direct influence of the slick (viscous damping), modification of wind-wave coupling, and modification of wave-wave interactions.

The direct influence of surface films can be separately investigated in a wind-wave tunnel by allowing mechanically generated waves to propagate over a slick covered surface in the absence of wind (for details, see Hühnerfuss et al. [1982]). The results of an oleyl alcohol and a methyl oleate slick in the frequency range 1–2.5 Hz are shown in Figure 9, where the damping coefficient Δ is plotted versus frequency. A logarithmic damping for linear waves is assumed,

$$a_x = a_0 e^{-\Delta x}$$

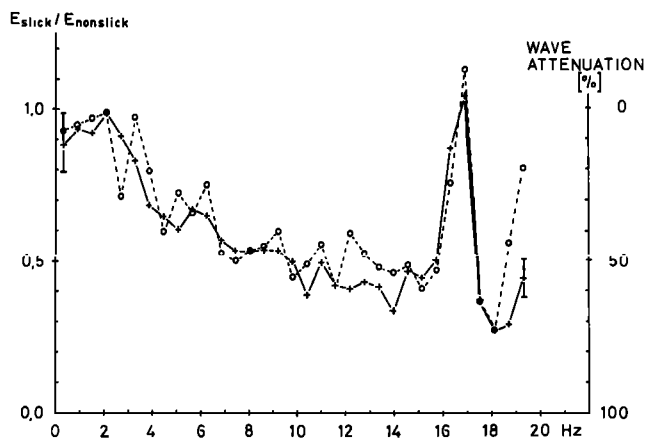


Fig. 5. The ratio of spectral energy density (section 3B of oleyl alcohol slick 3/ nonslick area ('before slick 3') solid line; section 3A of oleyl alcohol slick 3/nonslick area ('before slick 3'): dashed line) versus frequency as measured by the wave staff. The scale on the right-hand side shows the corresponding values for the wave attenuation in per cent.

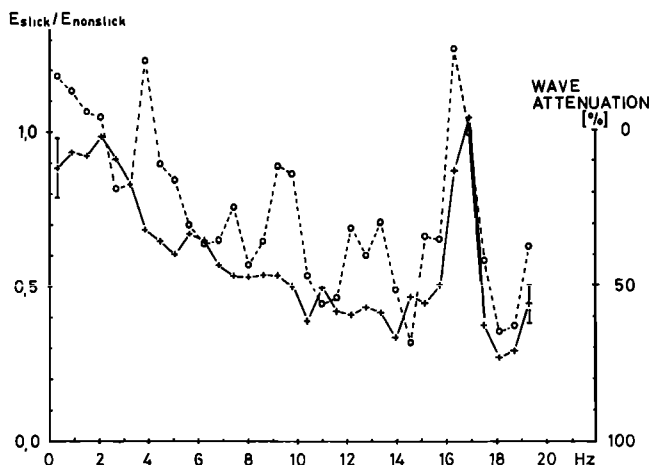


Fig. 7. A comparison of wave attenuation by an oleyl alcohol (slick 3) and a methyl oleate (slick 2) surface film: the ratio of spectral energy density (slick 3/nonslick area ('before slick 3'): solid line; slick 2/nonslick area ('before slick 2'): dashed line) versus frequency as measured by the wave staff. The scale on the right-hand side shows the corresponding values for the wave attenuation in per cent.

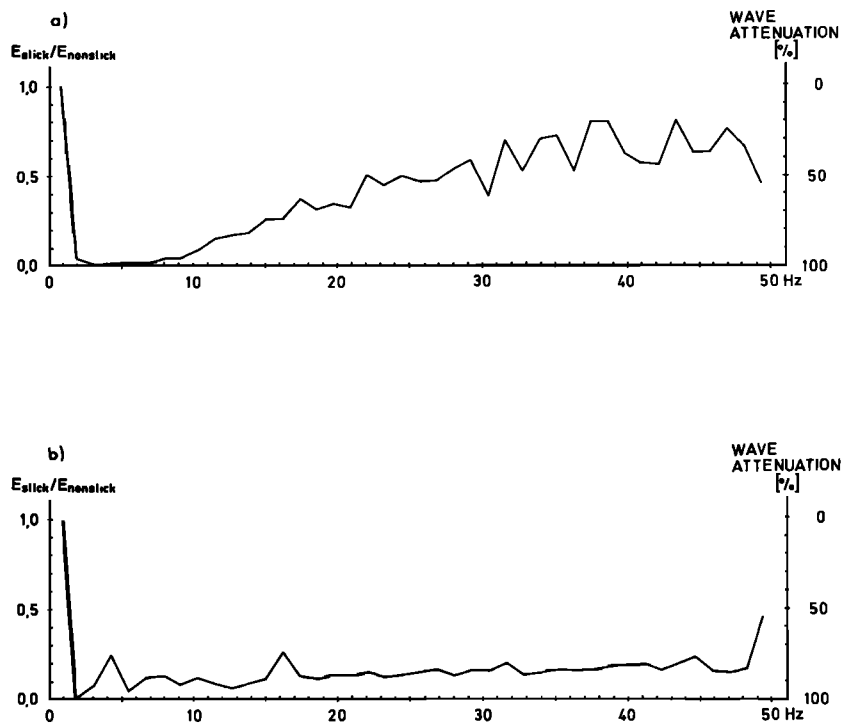


Fig. 8. A comparison of wave attenuation by an oleyl alcohol (Figure 8a) and a methyl oleate (Figure 8b) surface film measured in the Hamburg wind-wave tunnel. The ratio of spectral energy density (slick area/nonslick area) versus frequency. The scale on the right-hand side shows the corresponding values for wave attenuation in per cent.

where a_x denotes the amplitude of a wave of an amplitude a_0 at the origin, after having passed a distance x . Oleyl alcohol has a significantly stronger direct wave damping effect in this frequency range than methyl oleate. This result makes plausible the fact that oleyl alcohol surface films have a stronger influence on wind-wave spectra in the short gravity wave range, but in the high capillary wave region, other dissipation terms apparently overcompensate this stronger direct influence, and a methyl oleate slick acts more strongly upon the waves.

From a chemical point of view the hydrophobic part of both compounds is identical, so the different wave damping characteristics must be due to different rheological properties

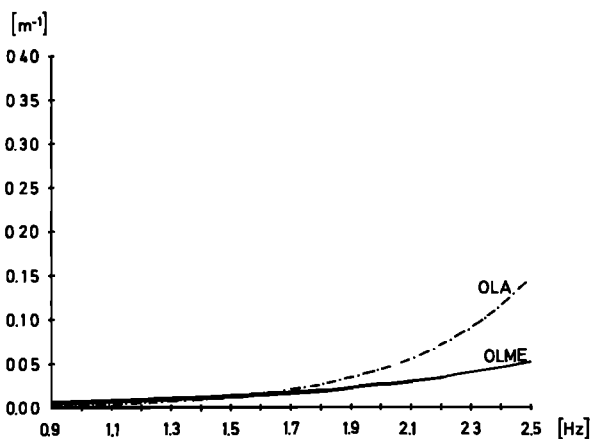


Fig. 9. Damping coefficient Δ per meter versus frequency in hertz measured in a wind-wave tunnel in the presence of mechanically generated water waves in the absence of wind. Comparison between an oleyl alcohol (dot-dashed line) and a methyl oleate (solid line) surface film.

imparted by their different hydrophilic groups. It has been postulated by Hühnerfuss *et al.* [1982] that wave energy dissipation is assumed to occur partly by means of strong interactions between the hydrophilic group of the film-forming substance and water molecules of the adjacent surface layer. During passage of a wave, periodic reorientation of water molecules will occur due to alternating compression and dilation of the surface film. This interaction between the hydrophilic part of the surface active substances and the adjacent water molecules can be treated by two different theoretical approaches.

The first approach involves the alteration of the dielectric properties of the surface layer in the presence of a monolayer. The derivation of this theory, which well explains the modification of passive microwave data in presence of monomolecular surface films, has been presented separately [Alpers *et al.*, 1982].

The second theoretical approach has been formulated by Broecker [1980] and by a working group of the Symposium on Capillary Waves and Gas Exchange in Trier, Federal Republic of Germany, in 1979 [Broecker and Hasse, 1980], who claimed that the complete expression for the Gibbs enthalpy, including the energy and entropy effects resulting from reorientation of the film molecules and from changes in film concentration, should be evaluated and its time dependence be treated with the methods of irreversible thermodynamics. Obviously, additional experiments with other chemical substances are necessary to provide information for the development of a full theoretical description of wave energy dissipation in the presence of different surface films.

4. CONCLUSIONS AND COMPARISON WITH OTHER SENSORS

Wave staff measurements performed in the presence of two oleyl alcohol (slick 1, slick 3) and one methyl oleate (slick 2)

surface film and in adjacent nonslick sea areas under comparable oceanographic and meteorological conditions supplied the following results.

1. Gravity water waves are slightly attenuated by oleyl alcohol surface films between 0.5 Hz and 0.7 Hz, and above 0.7 Hz (wavelength $L = 3.2$ m) the wave damping effect becomes significant (Figure 3).

2. The 'direct' wave damping effect of oleyl alcohol surface films (i.e., the attenuation of mechanically generated water waves) becomes significant at frequencies above 1.7–2 Hz (Figure 9). Therefore the observed influence on longer gravity wind waves can only be due to indirect effects, e.g., the modification of the energy transfer mechanism between long and short water waves and modification of the wind/wave interaction mechanisms.

3. Wave attenuation of short gravity waves by slicks is a function of wind fetch within the slick covered area and approaches a constant value after a fetch of about 1 km (Figures 4 and 5).

4. It can be concluded from the wave attenuation characteristics shown in Figures 4, 5, and 6 that a significant increase of wave damping with increasing frequencies occurs in the frequency range between 2 and about 15 Hz. As a consequence, X band radars responding to water waves of about 2 cm wavelength and L band radars responding to about 20 cm water waves are differently influenced. This effect is extensively discussed in the subsequent radar paper [Hühnerfuss *et al.*, this issue (a)].

5. Monomolecular surface films of different chemical structure exhibited different wave damping characteristics (Figures 7 and 8). This was substantiated by our X and L band radar data [Hühnerfuss *et al.*, this issue (a)], which are also very differently modified by oleyl alcohol and methyl oleate surface films. Therefore natural surface films secreted by various organisms and thus consisting of different substances may modify the signals of X and L band radars very differently.

6. The unexpected brightness temperature decrease within the slick area observed by L band microwave radiometer [Alpers *et al.*, 1982] and the suppression of the laser-induced Raman backscatter measured by an AOL LIDAR [Hühnerfuss *et al.*, this issue (b)] cannot be explained by means of the wave attenuation effects reported in this paper. These modifications are caused by strong interactions between the film-forming substance and the upper water layer: in the case of an oleyl alcohol slick, icelike clathrate structures are induced within a water layer of about 190 μm thickness. As a consequence of this icelike structure, less 'free' water molecules are available, the mobility of the water molecules is reduced, and the 'surface viscosity' and the relaxation time of the water molecules are increased. Based on these molecular theories, the modifications of the signals of both the L band microwave radiometer and the AOL LIDAR can be explained. For further details the reader should refer to the subsequent LIDAR paper [Hühnerfuss *et al.*, this issue (b)], and to the microwave radiometer paper by Alpers *et al.* [1982].

The above summarized results obtained during the MARSEN slick experiment allowed further insight into the influence of surface films of different chemical structure on gravity and capillary water waves and the implications for the modification of signals of various remote sensors. However, since natural surface films consist of a variety of chemical compounds, additional experiments have to be performed in

order to be able to correct the data of these remote sensors obtained over slick-covered sea surfaces, e.g., for calculating wind fields from remote sensing data. In particular, the discrimination between crude oil and monomolecular surface films, which is vital to operational surveillance systems (avoidance of false alarms!), appears to be feasible based on the results of the MARSEN slick experiment. However, this has to be verified by a large-scale experiment, producing a crude oil and different well-defined artificial monomolecular surface films and performing simultaneous measurements with the remote sensors applied during the MARSEN slick experiment.

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