The influence of an oil-film covered sea surface on the reflection and upward transmission of light

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Sea surface
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Light transmission
Model remote sensing

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Abstract

This paper presents the results of investigations focused on the influence of oil spills on the optical properties of the sea surface. The model of light transmission and reflection from the triple air-oil-water layer system is presented. The mathematical equations include the complex refractivity of various oils previously identified in the laboratory. Upward transmission and reflectivity dependences on wavelength and angle of incidence were investigated, as were the temperature and thickness of oil layers. The results show that the short functions of the three above-mentioned parameters oscillate rapidly. Several functions were identified after averaging over thickness. The investigations were carried out with the intention of using their results in a model of the upward light field over an oil-polluted sea surface.

1. Introduction

It is well known that oil spills interfere with gas and energy exchange, and reduce evaporation (Kaniewski and Otremba, 1993). They also cause changes in the thermal conditions of the near-surface layer (Karbowniczek-Gratkowska and Zieliński, 1990) as well as errors in remote sensing measurements.

To estimate the exchange of solar energy between oil-polluted sea areas and the atmosphere, modifications of optical sea-surface characteristics need to be predicted. The same situation applies when optical remote sensing methods are to be used to determine other parameters of the sea in regions exposed to oil pollution. Unfortunately insufficient data are available on light field deformations caused by oil substances. This paper therefore deals with the basic optical mechanisms taking place on a sea surface polluted with an oil film. It will enable the oil factor to be included in light field modelling under various environmental conditions.

The algorithms used in this paper allow the downward transmission to be determined as in Otremba and Targowski (1994). In that work, the light transmission through an oil-polluted water surface was described by the position of nonhomogeneities occurring in the oil film. In this paper the author presents the contrasts and dye penetration that occur between a clean sea surface and an oil polluted sea surface depending on the thickness of the slick and the angle of observation. The phenomena influencing the picture of an oil polluted sea surface were divided into two groups. The first group, described in section 4, involves the transmission parameters of light scattered by the seawater. The second group, described in section 5, relates to the parameters of light reflected from the sea surface.

Despite the fact that the results presented in this paper contain data to be used in light field modelling, when considered individually, they offer a view of modifications to the picture of the sea at sites where oil slicks appear. The conclusions at the end of the paper show the main processes responsible for the variability in the reflectivity function and transmissivity of light leaving the sea. The investigations were carried out for polarised and nonpolarised light, thus enabling the main optical contrasts between clean and polluted sea areas to be pinpointed.

2. The role of an oil film in light field formation

The upward underwater light field is a derivative of a number of events in which photons of solar radiation participate from the moment they reach the atmosphere. The solar energy flux reaching the sea surface determines spatial and spectral distributions (described by the radiance L). Generally, the radiance L can be divided into two components, L^S and L^D. L^S represents the surface radiation caused by the incident radiation and L^D is diffused radiation (Dera, 1992). That part of the radiation reaching the sea surface is reflected in accordance with the Fresnell theory. The remaining part penetrates the water, where it is either absorbed or, after being scattered one or more times, is reflected back to the atmosphere. If the environmental influence on the radiation is neglected, it can be presented as

$$L^{S(refl)} + L^{D(refl)} + L^{E(trans)}, \tag{1}$$

where

$L^{S(refl)}$ – radiance of a beam of directed sunrays under the sea surface,
$L^{D(refl)}$ – radiance of the light scattered from the whole sky,
$L^{E(trans)}$ – radiance of the light emerging from the sea transmitted through the sea surface.

The last component, $L^{E(trans)}$ depends on both L^D and L^S . There is a transfer function depending on the optical properties of the seawater (refraction, absorption and scattering coefficients) and on the state of the sea surface described by the statistical function of a surface slope distribution.

Each of the upward radiation components depends on the optical properties of the sea surface. This is especially true in the presence of a film, when the reflective and transmission coefficients are modified. Therefore, in modelling the upward light field, it is necessary to know the angular and spectral reflectivity characteristics of the interphase air-oil polluted water, as well as the angular and spectral characteristics of the transmission coefficient of the light leaving the sea.

The parameters are substituted for the Fresnell rules applicable to clean water.

With regard to the requirements of the model taking a free sea surface into consideration, the fundamental description of the optical parameters of seawater polluted with a thin layer of oil can be reduced to the following parameters:

- downward transmittance $T_\downarrow$:

$$T_\downarrow = \frac{L^{\mathrm{transmitted}}_{\mathrm{downward}}}{L^{\mathrm{incident}}_{\mathrm{downward}}} = \frac{E^t_\downarrow}{E^i_\downarrow}, \tag{2}$$

- downward reflectance function $R_\downarrow$:

$$R_\downarrow = \frac{L^{\mathrm{reflected}}_{\mathrm{upward}}}{L^{\mathrm{incident}}_{\mathrm{downward}}} = \frac{E^r_\uparrow}{E^i_\downarrow}, \tag{3}$$

- upward transmittance $T_\uparrow$:

$$T_\uparrow = \frac{L^{\mathrm{transmitted}}_{\mathrm{upward}}}{L^{\mathrm{incident}}_{\mathrm{upward}}} = \frac{E^t_\uparrow}{E^i_\uparrow}, \tag{4}$$

- upward reflectance function $R_\uparrow$:

$$R_\uparrow = \frac{L^{\mathrm{reflected}}_{\mathrm{downward}}}{L^{\mathrm{incident}}_{\mathrm{upward}}} = \frac{E^r_\downarrow}{E^i_\uparrow}, \tag{5}$$

where

$L^{\mathrm{transmitted}}_{\mathrm{downward}}$ – radiance of the light transmitted down through the oil-polluted sea surface,

$L^{\mathrm{incident}}_{\mathrm{downward}}$ – radiance of the light incident on the surface,

$L^{\mathrm{reflected}}_{\mathrm{upward}}$ – radiance of the light reflected back into the atmosphere,

$L^{\mathrm{transmitted}}_{\mathrm{upward}}$ – radiance of the light transmitted up through the oil polluted sea surface,

$L^{incident}_{upward}$ – radiance of the light incident upward (from the bulk of the water) to the surface,

$L^{reflected}_{downward}$ – radiance of the light reflected downwards (to the bulk of the water) from the surface,

$E^{t}_{\downarrow}$ – irradiance of the light transmitted through an oil-polluted sea surface,

$E^{i}_{\downarrow}$ – irradiance of the light incident on the sea surface,

$E^{r}_{\uparrow}$ – irradiance of the light reflected from a polluted sea surface,

$E^{t}_{\uparrow}$ – irradiance of the light transmitted through a polluted sea surface from the bulk of the water to the atmosphere,

$E^{i}_{\uparrow}$ – irradiance of the light incident from the bulk of water on the seawater,

$E^{r}_{\downarrow}$ – irradiance of the light reflected from the polluted sea surface to the bulk of water,

and also all the above coefficients, but for polarised light.

In order to describe the optical properties of a clean sea surface, it is enough to have a reflectance coefficient determining the other coefficients, in particular

$$T_{\uparrow} = 1 - R_{\uparrow} \qquad \text{and} \qquad T_{\downarrow} = 1 - R_{\downarrow}. \tag{6}$$

Where $T_{\downarrow}$ is determined as a function of the angle of incidence and $T_{\uparrow}$ as a function of observation (angle of refraction), coefficients $T_{\uparrow}$ and $T_{\downarrow}$ can be described by the same function. For mathematical models, it is important that the above parameters are precisely distinguished even though very trivial relationships exist between them in a clean sea. This allows for the easy application of parameters, as presented in Otremba and Piskozub (1993), where Fresnell coefficients were replaced by their previously identified angular functions.

When the oil slick is large, it is necessary to have a transmission coefficient for modelling. This is because the light emitted from below the slick is already modified on reaching the sea surface, before it is scattered in the water. In this paper, transmission coefficient variations for light incident on the sea surface were not analysed since this had already been done in Otremba and Targowski (1994).

3. Method of acquiring fundamental optical parameters

Investigations of the optical parameters of a sea surface polluted with oil have been in progress for several years. Significant progress has been made in analysing the temperature and optical dependences of the reflectance coefficient of an oil-polluted sea surface. The introductory lab tests revealed strong variations of the light reflected from such a sea surface.

The data thereby obtained was greatly time-variable and widely scattered (Mrozek-Lejman, 1984; Otremba, 1986). The repeatability of the reflectance coefficients for oil-polluted water was achieved by automation and more rapid measurements (Otremba, 1986). These results depended on the superficial oil concentration, temperature and salinity (Kaniewski and Otremba, 1990, 1991). Some of the results obtained from those measurements are still being analysed. Great opportunities for interpretation of the results are provided by the previously mentioned computer program, which can be used for nonhomogenous layers (Otremba and Targowski, 1994). This paper presents selected results obtained using a modified version of the program. The general rule is that series of waves reflected at media interfaces (air-oil, oil-water) are summed. Moreover, light attenuation in both the oil layer and the water is taken into consideration. In the algorithm it is represented by the imaginary part of the complex refractive index

$$\mathrm{m} = \mathrm{n} - \mathrm{i}\,\mathrm{k}, \tag{7}$$

where n is the real part of refraction and k is linked to the absorption coefficient (α) and wavelength (λ) as follows:

$$\mathrm{k} = \alpha\,\lambda/4\,\pi \tag{8}$$

(Born and Wolf, 1973; Feynman *et al.*, 1963). The algorithm employed to measure transmission and reflectance coefficients also allows these parameters to be determined as a function of temperature, because the spectral and temperature functions of refractivity and absorptivity for various kinds of oil were included in it. The results of earlier investigations into those coefficients for various kinds of crude oil, fuels and lubrication oils as a function of the temperature, wavelength and ageing of an oil were considered (Kaniewski *et al.*, 1994). A number of graphs with reflection and transmission coefficients were plotted. Only the most important optical phenomena occurring on an oil-polluted water surface and influencing the upward light field were chosen for illustration. This paper presents selected results of the analyses of the downward reflectance coefficient ($\mathrm{R}_{\downarrow}$), relative reflectance coefficient ($\mathrm{R}_{\downarrow\,\mathrm{r}}$), upward transmission ($\mathrm{T}_{\downarrow}$) and relative upward transmission ($\mathrm{T}_{\downarrow\,\mathrm{r}}$) for a water surface polluted with an oil film. Relative values characterise the contrast between the oil slick and a clean sea surface. The following relation exists between the relative and absolute coefficients:

$$\mathrm{R}_{\downarrow\,\mathrm{r}} = \mathrm{R}_{\downarrow}^{(\mathrm{oil})}/\mathrm{R}_{\downarrow}^{(\mathrm{water})}, \quad \mathrm{T}_{\downarrow\,\mathrm{r}} = \mathrm{T}_{\downarrow}^{(\mathrm{oil})}/\mathrm{T}_{\downarrow}^{(\mathrm{water})}. \tag{9}$$

As was mentioned before, the reflectance and transmission coefficients can easily be derived from the Fresnell theory. The results presented in this paper refer to a temperature of 10°C.

4. The influence of an oil film on the transmission of light leaving the sea

Light leaving the sea through an oil slick has different spectral and angular characteristics when compared to light leaving a clean sea. Figs. 1 and 2 show the dependences of transmission coefficients of light leaving the sea on the angle of incidence. The shapes of the curves and light absorption depend on the wavelength, the kind of oil and the thickness of the oil layer. Half the radiation is absorbed in the several-micron thick oil layer ('Ramashkino' or 'Flotta' oil) when a wavelength of 500 nm is employed (see Fig. 1). For light of 400 nm the same effect is obtained with a layer of 1 μm thickness. Baltic 'Petrobaltic' crude oil is more transparent, which results in significant oscillations (see Fig. 2) due to light interference in the oil film. The frequency of these oscillations increases with layer thickness. For a thick layer, their amplitude decreases, and disappears altogether for thicknesses greater than 100 μm at wavelengths smaller than 400 nm (see Fig. 2a), and for thicknesses greater than 200 μm at wavelengths longer than 500 nm (see Fig. 2b). For 'Ramashkino' oil, the oscillations occur only for several-micron thick layers; their amplitude is not great owing to significant light absorption (see Fig. 1).

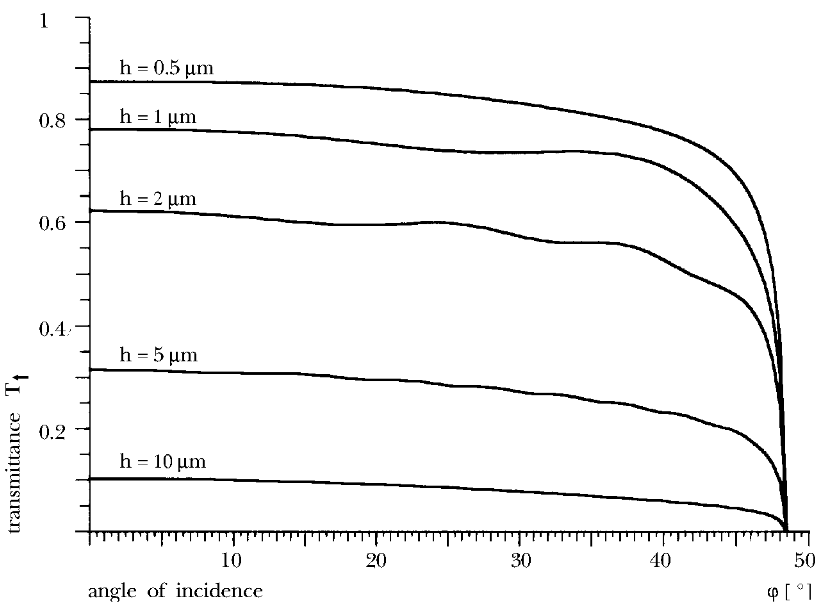
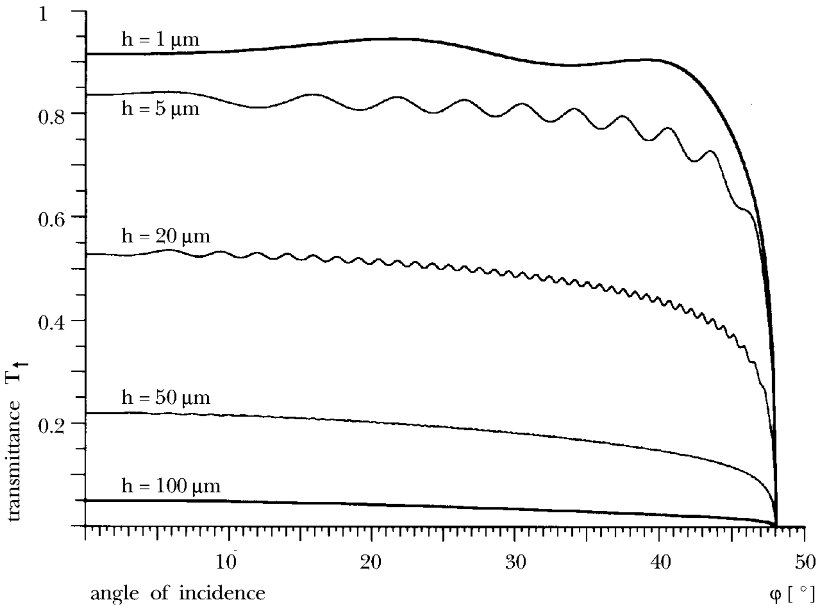


Fig. 1. Dependence of light transmission of an oil-polluted sea surface on various angles of incidence and for various oil layer thicknesses. 'Ramashkino' crude oil at T = 10°C, λ = 500 nm (n = 1.4896, k = 0.00595)

a



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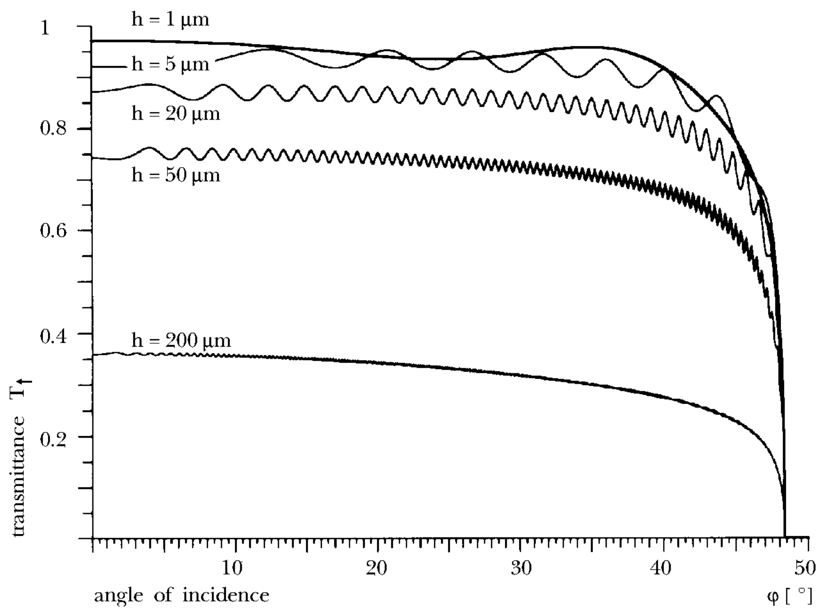


Fig. 2. Light transmission for a beam passing from the sea to the atmosphere through an oil film as an angular dependence for different thickness of oil. 'Petrobaltic' crude oil at T = 10°C, λ = 400 nm (n = 1.4863, k = 0.000631) (a), λ = 500 nm (n = 1.478, k = 0.000132) (b)

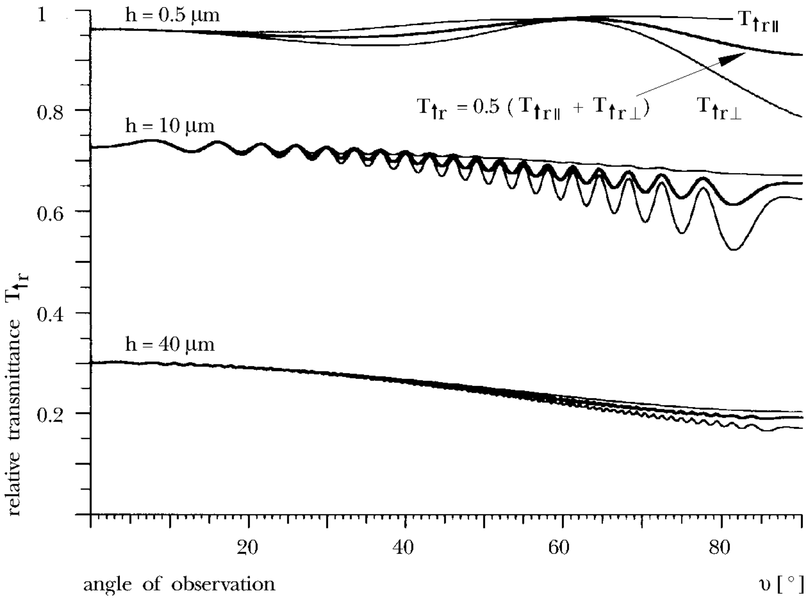


Fig. 3. Transmission of upward incident light beam related to clean water for various oil film thicknesses as a function of the altitude of observation for polarised and unpolarised light and for various thicknesses. 'Petrobaltic' crude oil at T = 10°C, $\lambda = 400$ nm (n = 1.4863, k = 0.00631)

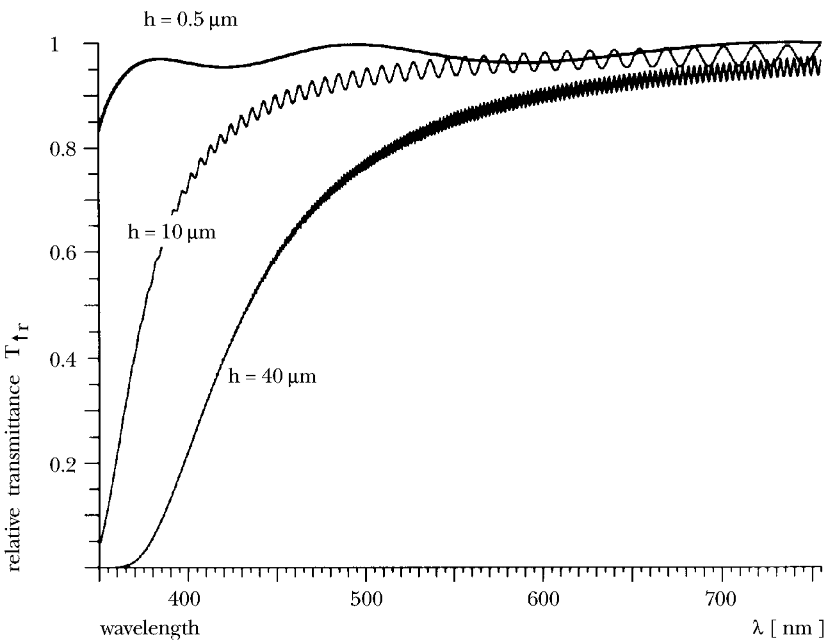


Fig. 4. Transmission spectrum of light passing through a sea surface covered with an oil film related to clean surface as a wavelength dependence for various thicknesses. 'Petrobaltic' crude oil at T = 10°C

Fig. 2 reveals that light absorption is more significant at short wavelengths. It is common knowledge that short waves are absorbed much better than long waves. Fig. 4 reveals that in the investigated range (350 nm to 750 nm) light absorption at wavelengths greater than 500 nm does not change much.

Figs. 3, 4 and 5 illustrate the variations in the transmission coefficient with respect to that of clean water. Fig. 3 shows the dependence of the relative light transmission coefficient as a function of the angle of observation. Furthermore, the variation of parallel $T_{\uparrow r \parallel}$ and perpendicular $T_{\uparrow r \perp}$ components are shown in this figure. The transmission coefficient $T_{\uparrow r}$ does not vary much with the angle of observation if light interference in layers several to several dozen microns thick are ignored. Only $T_{\uparrow r \parallel}$ shows a tendency to decrease close to the critical angle (53°) between the air and sea for polarised light in the direction of the source. The oil film does not cause any changes in the critical angle for light leaving the sea.

Fig. 4 shows the dependence of $T_{\uparrow r}$ on wavelength. For layers several microns in thickness, the dependence on the wavelength is strong. At wavelengths shorter than 500 nm, the transmission coefficient decreases quickly. For ultraviolet radiation, the light is totally absorbed in layers of thickness greater than 30 μm.

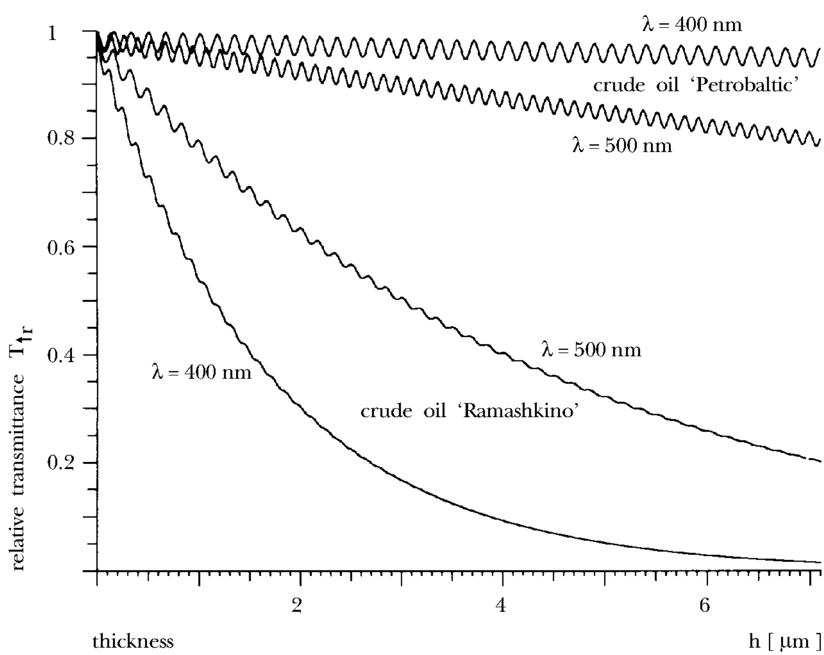


Fig. 5. Decrease in light transmission through a sea surface polluted with oil *vs.* layer thickness

Fig. 5 shows the variations in transmission caused by differences in the layer thickness. As expected, the transmission decreases exponentially with the layer thickness. It does oscillate, however, for small thicknesses.

5. Changes in reflectivity

The sea surface changes when it is polluted with oil. There are two reasons for this. The waves are damped (Alpers and Huefnerfuss, 1989), and therefore the reflectivity is changed (Otremba and Piskozub, 1993). The second reason relates to the optical properties of the oil film. The reflectance coefficient and the angle of incidence oscillate significantly, the former reaching a value of 1 when the latter approaches 90°. Moreover, both components of the polarised light oscillate (see Fig. 6). The oscillations decrease with increasing layer thickness and vanish for thick layers. The angular functions are then similar to those derived from the Fresnell theorem (see also Fig. 7). Significant effects are revealed during investigations of the relative reflectance coefficient $R_{\downarrow r}$ with polarised light. Analyses of the relative reflectance coefficient $R_{\downarrow r}$ yield precise information about the contrast between the oil slick and the clean

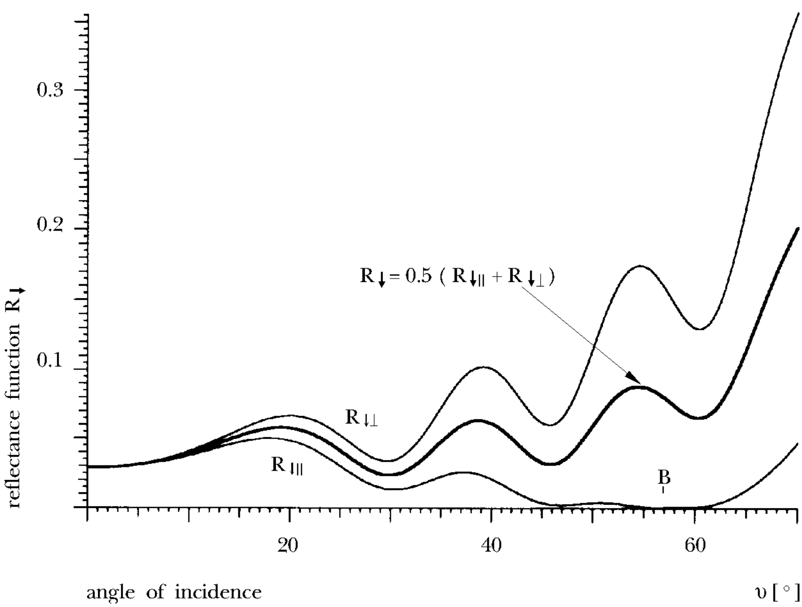
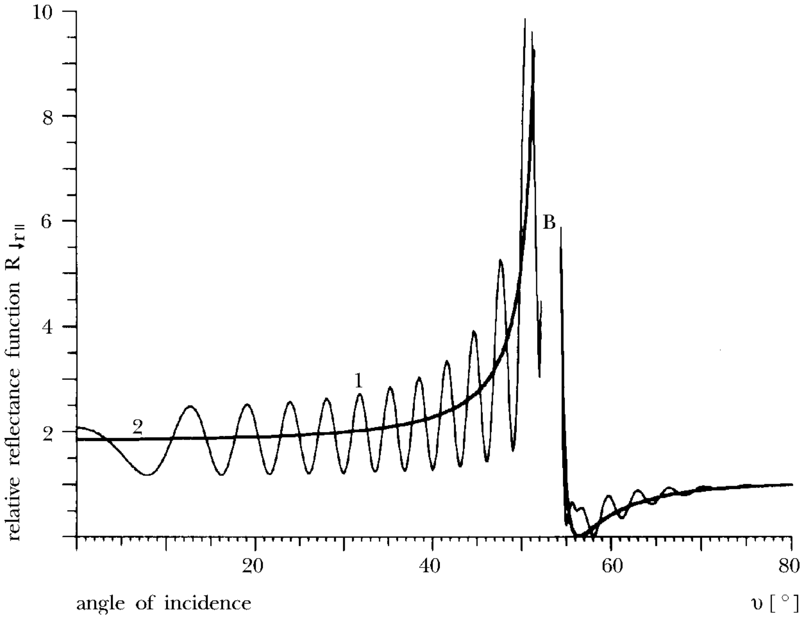


Fig. 6. Reflection of light from a thin oil film as an angular dependence for polarised and unpolarised rays. 'Petrobaltic' crude oil at T = 10°C, λ = 400 nm (n = 1.48631, k = 0.000631). B – the Brewster angle for oil

a



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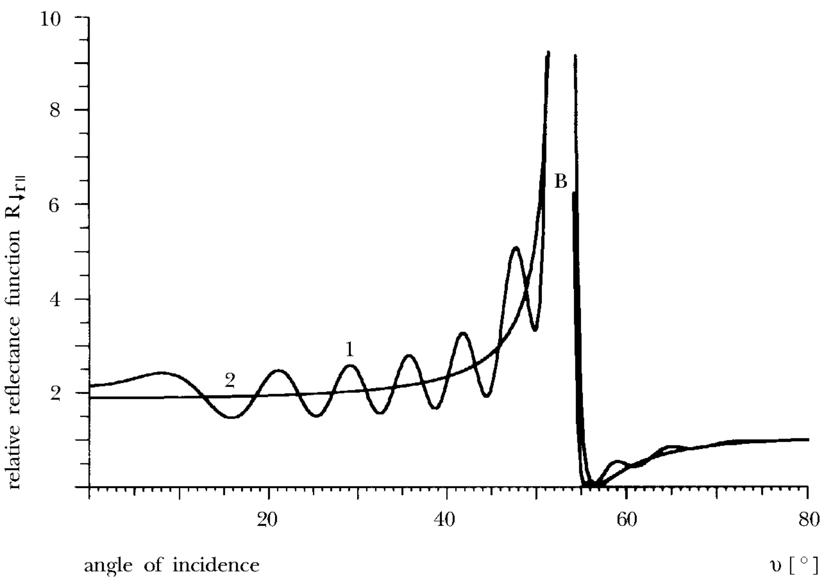


Fig. 7. Variation of relative reflectivity depending on the angle of incidence of a polarised light beam for two kinds of oil film. T = 10°C, λ = 400 nm, 1 – 'Petrobaltic' crude oil (n = 1.4863, k = 0.000631), 2 – 'Ramashkino' crude oil (n = 1.5027, k = 0.01246). Thickness: 10 μm (a), 2 μm (b). B – the section between the Brewster angles for water and oil (*cf.* Fig. 9b)

water surface. As mentioned before, it is easy to convert R_r to R using the Fresnell theorem. Fig. 7 shows the variations in $R_{\downarrow r \parallel}$. Approaching the Brewster angle for water, the $R_{\downarrow r \parallel}$ value increases several times and then drops to almost zero for the Brewster angle for oil. Then it reaches a value of 1 for an angle of incidence of 90°. These conclusions refer to layers at least several microns in thickness. For thin layers (see Fig. 8), the above tendencies are disturbed by large amplitude oscillations. This figure shows only examples of dependences because they vary even for slight changes in thickness. Similarly intense oscillations are shown in Fig. 9a, which depicts the variations in the relative reflectance coefficient for polarised light and unpolarised light for a thin film. Fig. 9b shows the averaged functions of the relative reflectance coefficient *vs.* the angle of incidence for all thicknesses smaller than 100 μm. Their shape is comparable with those of *e.g.* a 'Ramashkino' oil layer 100 μm in thickness, *i.e.* for thick layers which absorb light strongly. The reflectance coefficient depends strongly on the wavelength. Very thin layers can easily be monochromatic (*e.g.* the colours of an oil film in a puddle). For thicker layers, oscillations are more and more frequent and their

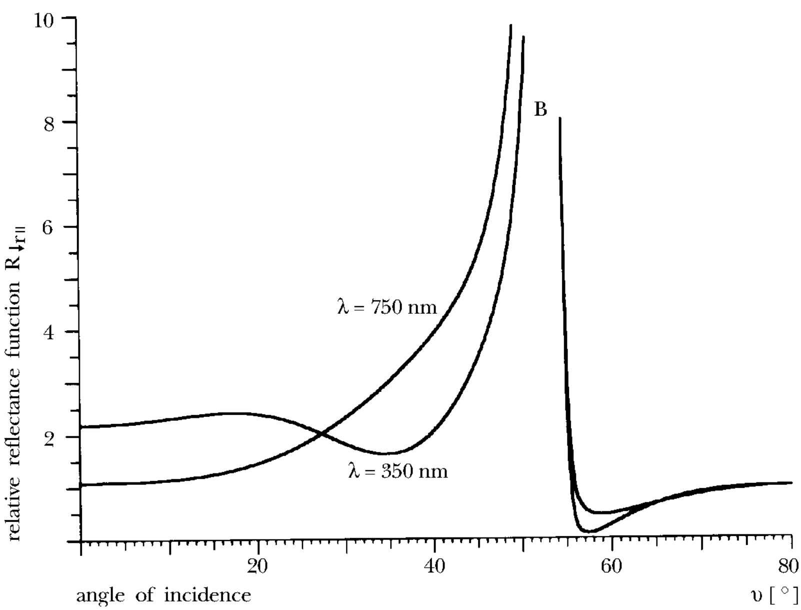
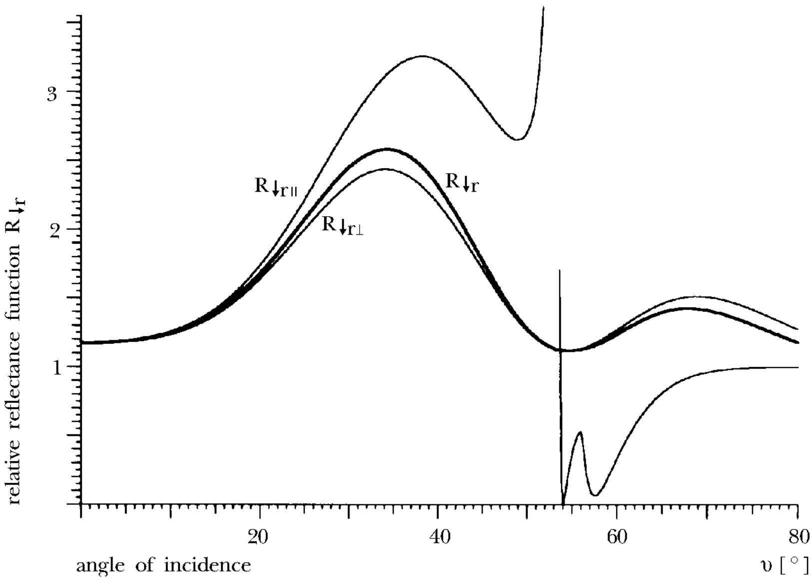


Fig. 8. Angular dependence of relative reflectivity from a thin oil film (thickness: 1 μm) for a polarised light beam at two wavelengths. B – the section between the Brewster angles for water and oil (*cf.* Fig. 9b)

a



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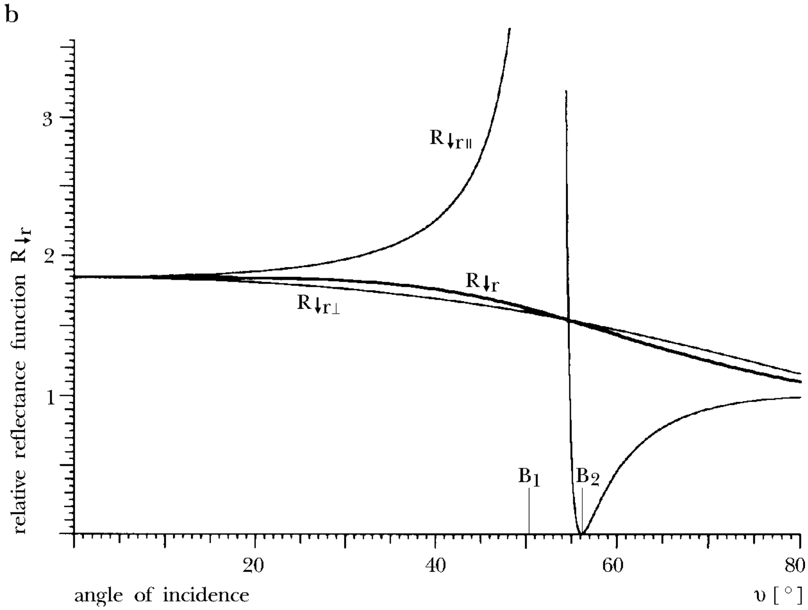
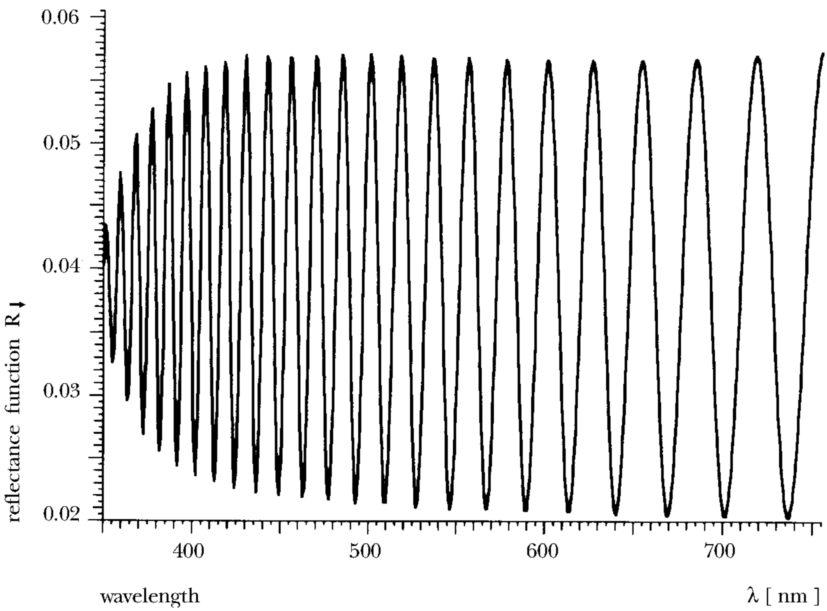


Fig. 9. Light reflection from a seawater surface covered with an oil film at different angles of incidence and unpolarised beams: for a thin oil film (1 μm) (a), functions given by averaging over various thicknesses of oil film (b). B_1 – the Brewster angle for water, B_2 – the Brewster angle for oil

a



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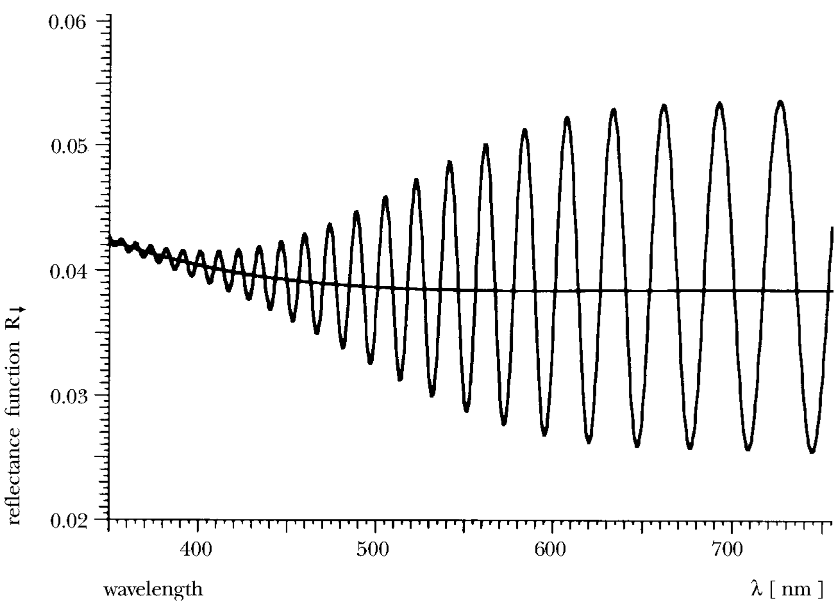

Fig. 10. Dependence of the reflectivity oscillation of an oil film covering the sea surface on the wavelength. Thickness: 5 μm for ‘Petrobaltic’ crude oil (a), for ‘Ramashkino’ crude oil (b). Non-oscillating line relates to a thick layer of oil

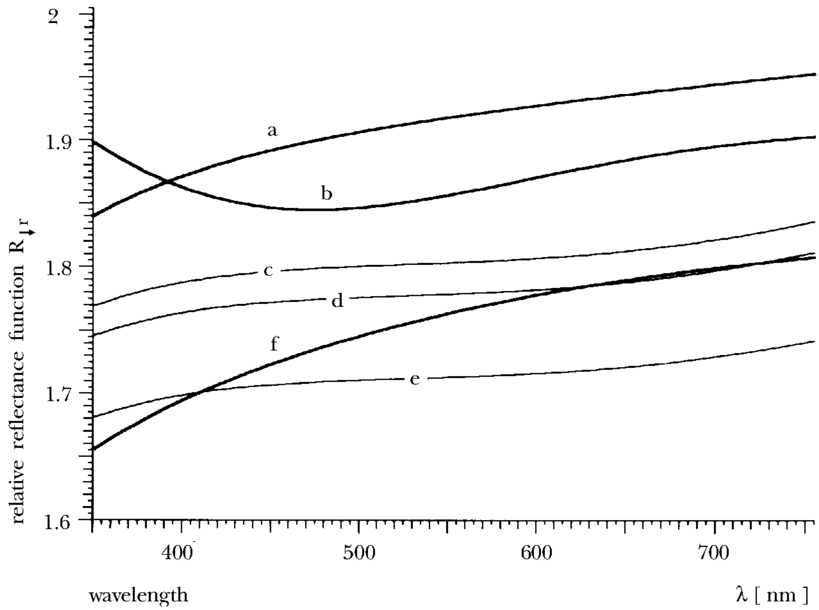

Fig. 11. Averaged relative reflectivity for different kinds of oil films as a wavelength dependence: a – 'Marinol' lubrication oil, b – 'Ramashkino' crude oil, c – 'Petrobaltic' crude oil aged for 100 hours, d – 'Petrobaltic' aged for 24 hours, e – 'Petrobaltic' fresh, f – fuel oil

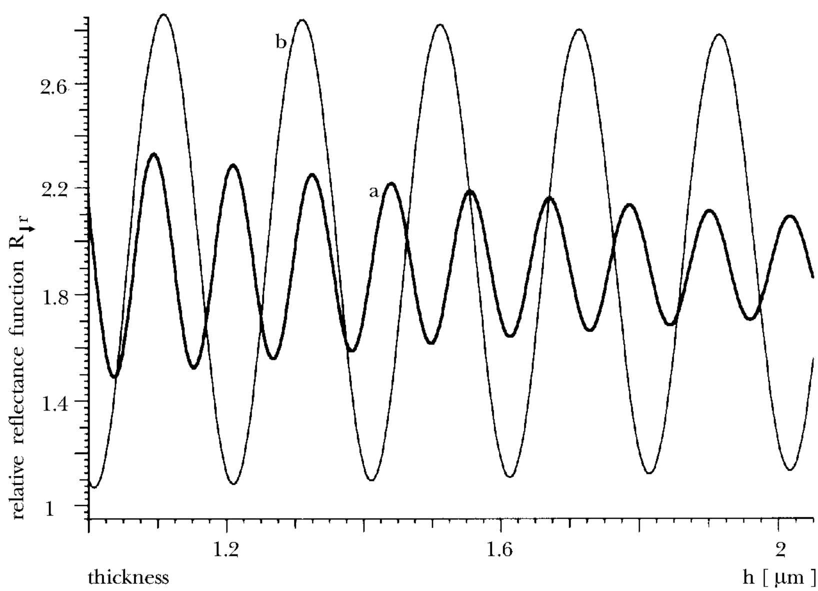

Fig. 12. Reflectivity of the sea surface covered by oil films of different thicknesses ('Ramashkino' crude oil) for two wavelengths: a – 350 nm (n = 1.5178, k = 0.01539), b – 600 nm (n = 1.4877, k = 0.00303)

amplitude is damped. For short waves, oscillations are small (see Fig. 10a) or do not occur (see Fig. 10b). Fig. 10b shows the averaged function (continuous line) obtained for a number of thicknesses, suggesting a slight dependence between the coefficient of reflectance and wavelength. Fig. 11 shows the averaged relative reflection function for various kinds of oil. The shape of the functions is similar for all kinds of oil with the exception of heavy oil at short waves. The greater the wavelength, the greater the relative reflectance coefficient for all kinds of oil, and the absolute coefficient does not change much for wavelengths longer than 500 nm. Fig. 12 illustrates a short oscillation frequency depending on the wavelength due to the dependence of oil refractance coefficient on the wavelength.

6. Conclusions

Oscillations of the reflectance coefficient, which is a function of layer thickness, do not appear only if the observations are carried out at a wide angle when monochromatic light is is used, or at a narrow angle when white light or a wide band of coloured light is used. Oscillations of the reflectance coefficients for monochromatic light as a function of the angle of incidence or wavelength will disappear when the observations apply to a large enough area for which the layer thickness varies. The result will refer to the averaged layer thickness in the area investigated.

The intensity of radiation from an oil spill is modified by two processes – damping of the transmission of light leaving the water and the increase in reflected light right at the surface. The level of water surface darkness where the oil spill occurs does not depend on the observation angle where only light leaving the sea is concerned (Fig. 3). The amount of reflected light, however, decreases with the increase in the angle of incidence (Fig. 7b). These conclusions refer to both non-polarised and vertically polarised light. Close to the Brewster angle, the relative amount of polarised light increases (Fig. 7). Therefore, the oil spill reflects light significantly more strongly than clean water. It must be mentioned that the absolute intensity of such light is negligible both for clean and oil-polluted water. For this reason the device whose construction could be based on this phenomenon should be equipped with a very sensitive light detector and strong light source in the case of active remote sensing. The presence of oil on the sea surface leads to changes in the relative amount of light reflected from oil polluted areas with respect to wavelengths (Fig. 10). This is an important fact in remote sensing. The ratio of the relative reflectance coefficient for long waves (about 750 nm) and the coefficient for short waves (about 450 nm) is in excess of 1.

The changes in transmission and reflection properties presented in this paper allow the influence of the film on the quantity and quality of light leaving the sea surface to be determined. The results can also be implemented in the model of the upward, above-surface light field. This will yield additional information about the influence of oil pollution on the optical properties of the sea surface under particular environmental conditions.

Further investigations of the oil-polluted sea-surface albedo for particular wind speeds and cloud cover, as well as angular distributions of upward radiation are planned. The full description of abovewater and underwater light fields will be accomplished when the optical properties of seawater with oil dispersions and dissolved petroleum hydrocarbons are known and applied to models of light fields. Knowledge of the relation between a particular type of oil pollution and light field distribution will allow the precise identification of polluted areas as well as the determination of the oil spill and will improve the interpretation of remote sensing data.

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