A thin oil film covering the sea surface as a modifier of the downward transmission of light

OCEANOLOGIA, 39 (4), 1997.
pp. 397–411.

KEYWORDS
Sea surface
Crude oil pollution
Light reflection
Light transmission
Model remote sensing

Zbigniew Otremba
Department of Physics,
Maritime Academy,
Gdynia

Manuscript received December 5, 1997, in final form December 30, 1997.

Abstract

Selected results of investigations into the optical properties of thin oil films on a sea surface are presented. The plots of angular functions are given for the coefficient of the reflection of the light arriving at the sea surface from the depths and for the coefficient of transmission of the light entering the water across an oil film. The calculations on a triple-layer model (air-oil-water) takes into account the results of temperature measurements and the spectral relationships of the complex refractive index for two optically diverse types of crude oil – 'Petrobaltic' and 'Romashkino'.

1. Introduction

When the air-sea interface becomes covered by a thin layer of oil, a set of conditions for the transmission and reflection of light comes into being that differs from those obtaining at an unpolluted water surface. The theory of optical phenomena occurring at two adjacent partition surfaces (water-oil and oil-water) was initially worked out in the 1950s (Heavens, 1955; Born and Wolf, 1959), and subsequently improved upon (Vasicek, 1960; Anders, 1967; Abeles, 1971; Knittl, 1976). It was later applied in studies of the effect of oil films on the visible light spectrum below the sea surface and on seawater temperature (Zolotarev *et al.*, 1977; Gurevitsh and Shifrin, 1978; Arst and Kard, 1983; Karbowniczek-Gratkowska, 1993). The reflection and transmission of light were analysed with the aim of applying them in the modelling of the above-water upward light field (Otremba, 1994a,b).

That paper gave the results of an investigation into the upward light transmission coefficient and the coefficient of reflection of downward irradiance. One of those results was that, depending on the angle of incidence, light polarised perpendicularly to the incident plane was reflected up to ten times more strongly from a polluted surface than from an unpolluted one.

The nature of the downward irradiance derived from natural insolation is crucial to numerous processes occurring in the sea. It too is modified by an oil film polluting the water surface. The present paper gives the results of an investigation carried out to find information useful in modelling the downward light field below an oil-polluted sea surface. They include the angular relationships of the coefficient of reflection at an air-oiled water interface and those of the transmission coefficient of an oil film on a water surface; they replaced the well-known Fresnel formula describing the surface optics of unpolluted water. As far as the reflection coefficient is concerned, it is the light incident on the water surface from below that is of interest, whereas in the case of the transmission coefficient, it is the incoming light from above.

2. Method

The optical parameters of water covered with a film of oil were determined using an algorithm modelled after Knittl (1976) for investigating the optical properties of multilayer systems (Otremba and Targowski, 1994); the version applied here, however, was reduced to three layers (air-oil film-water) and allowed for the optical properties of the type of oil used. The optical parameters of seawater and various types of oil (*i.e.* the refractive index n and the light absorption coefficient a expressed in m^{-1}) had been

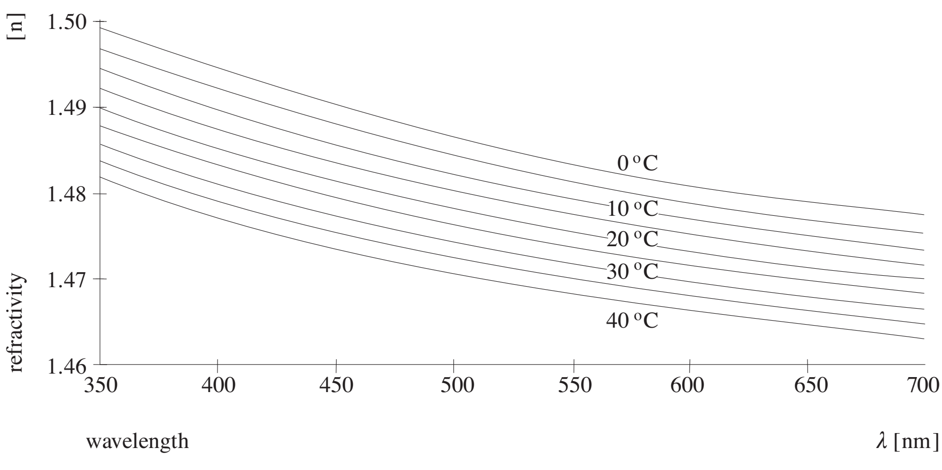

Fig. 1. Refractivity of artificially aged 'Petrobaltic' crude oil *vs.* wavelength

determined previously and incorporated in formulas expressing temperature and spectral relationships. Fig. 1 shows plots of the refractive index *vs.* wavelength for 'Petrobaltic', the kind of oil likely to occur in the Baltic environment owing to crude oil exploration in the Polish economic zone. Parameters n and a refer to oils artificially aged for 100 h.

The algorithm acts as a PC program, the dialogue windows of which allow the type of oil to be selected from the following: 'Romashkino' crude oil, 'Petrobaltic' crude oil (fresh and artificially aged), lubricating oil, kerosene and fuel oil. The refractive index n and absorption coefficient a are highest in 'Romashkino' crude oil and lowest in 'Petrobaltic' crude oil.

Coefficients n and a are grouped together in a single parameter m (1) known as the complex refractive index (Feynman *et al.*, 1963):

$$m = n - i\,k. \tag{1}$$

The factor κ (2) is the dimensionless coefficient of absorption and is related to a through the wavelength λ as follows:

$$k = a\,\lambda/4\pi. \tag{2}$$

On passing through an oil film a light wave is not only attenuated, it is also modulated by phase-delayed waves derived from multiple reflections at the air-oil and oil-air interfaces. The same applies to the reflected wave – this is the effect of interference due to reflections at the interfaces. Fig. 2 shows diagrammatically the formation of light beams penetrating the oil

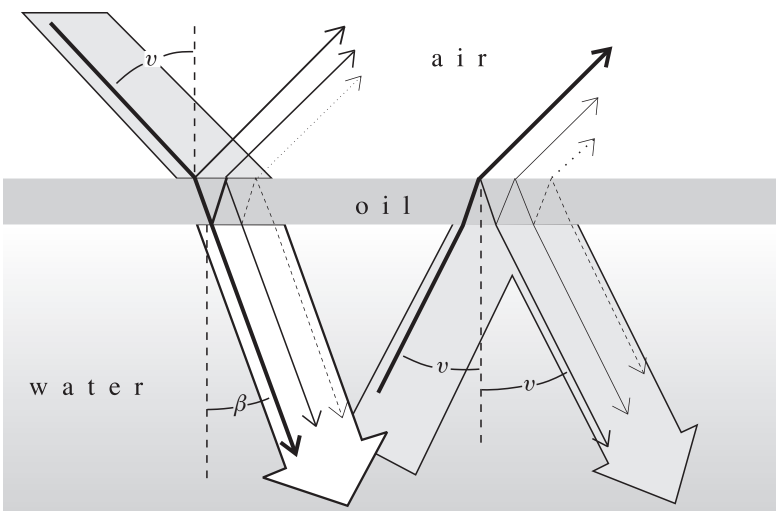

Fig. 2. Simplified scheme of downward radiance of a beam forming below a sea surface covered by oil. The waves of broken-down or reflected light are modulated by waves coming from reflections originating at water-oil and oil-air interfaces

film and the beams reflected from it. The downward transmittance $T_{\downarrow}$ (3) and upward reflectance function $R_{\uparrow}$ (4) analysed here are defined by the ratio of the relevant directed light beams:

$$T_{\downarrow} = \frac{L_{\text{downward}}^{\text{transmitted}}}{L_{\text{downward}}^{\text{incident}}}, \tag{3}$$

where

$L_{\text{downward}}^{\text{incident}}$ – radiance of light incident on a water surface at an angle υ,

$L_{\text{downward}}^{\text{transmitted}}$ – radiance of light transmitted through the water surface at an angle β,

where

$\beta = \arcsin \frac{\sin \upsilon}{n_{\text{water}}}$ (for both clean and oiled water surfaces),

$$R_{\downarrow} = \frac{L_{\text{downward}}^{\text{reflected}}}{L_{\text{upward}}^{\text{incident}}}, \tag{4}$$

where

$L_{\text{upward}}^{\text{incident}}$ – radiance of light incident on a water surface at an angle υ,

$L_{\text{downward}}^{\text{reflected}}$ – radiance of light reflected from the sea surface at an angle υ.

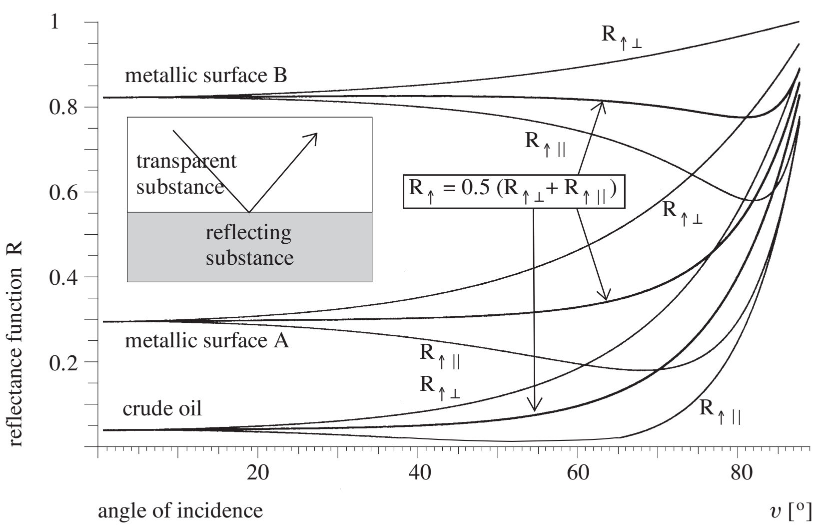

Fig. 3. Angular dependence of reflectance function for a typical crude oil (refractive index $n = 1.5$, non-dimensional coefficient of light absorption $k = 0.001$) and for a metallic surface A ($n = 1.5$, $k = 1$) and B ($n = 1.5$, $k = 3$). The lines consist of perpendicularly polarised ($R_{\uparrow\perp}$), pararelly polarised ($R_{\uparrow\|}$) and unpolarised ($R_{\uparrow}$) light

To illustrate the scale of possible variations in the optical properties of different media (not only oils), the relationships between the reflection coefficient and the angle of incidence for a typical oil and a metal have been plotted on the same graph (Fig. 3). These results are similar to those given by Kisiel (1973) for silver and aluminium. Smooth metallic surfaces reflect light far more strongly than do water or oils, a phenomenon that can be explained by classical electrodynamics (Feynman *et al.*, 1963; Born and Wolf, 1959). Where metals are concerned, light reflection depends not only on the refractive index n (defined as the ratio of the velocity of light in a vacuum to that in the medium) but also on the light absorption coefficient a. For oils a is too small for it to have any effect on the coefficient of reflection from a thick layer of oil. On the other hand, the reflection of light from a thin film of oil is closely dependent on a.

The optical phenomena taking place in an oil film do so in oil layers thicker than 2 μm. There is evidence from current research to suggest that the optical phenomena of extremely thin films of crude oil differ from those in the flat, homogeneous layer model.

3. The effect of an oil film on the transmission of light entering seawater

Light passing through an oiled water surface has to overcome two interfaces – air-oil and oil-water – not to mention the light-absorbent space

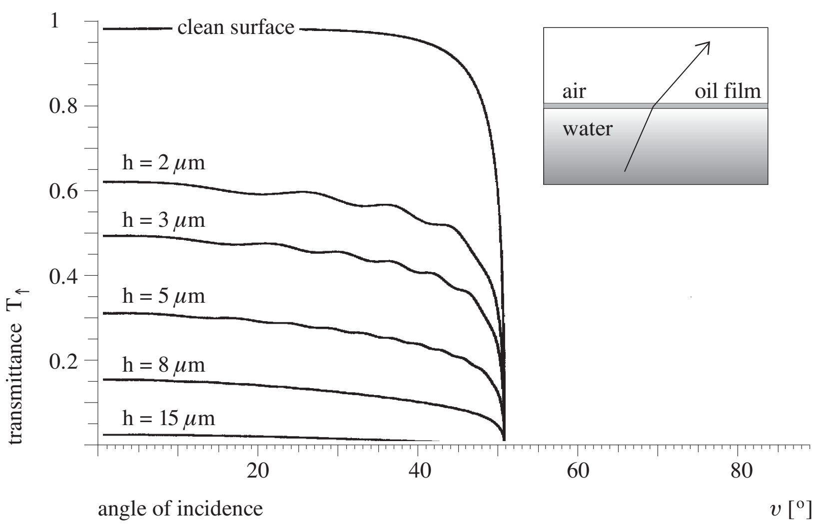

Fig. 4. Angular transmittance functions of light leaving the water surface covered by oil for various oil layer thicknesses ('Romashkino' crude oil at temperature $T = 10°C$, wavelength $\lambda = 500$ nm ($n = 1.49$, $k = 0.006$))

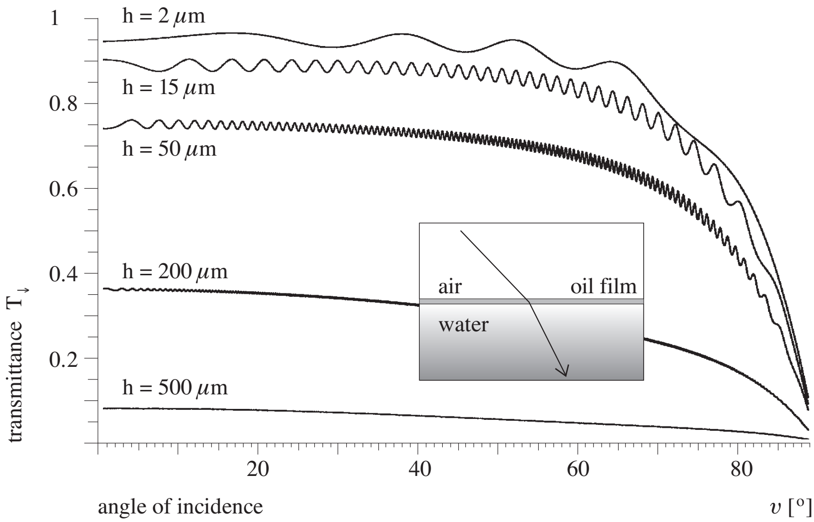

Fig. 5. Angular transmittance functions of light entering water oiled by 'Petrobaltic' crude at temperature $T = 10°C$, wavelength $\lambda = 500$ nm ($n = 1.478$, $k = 0.000132$)

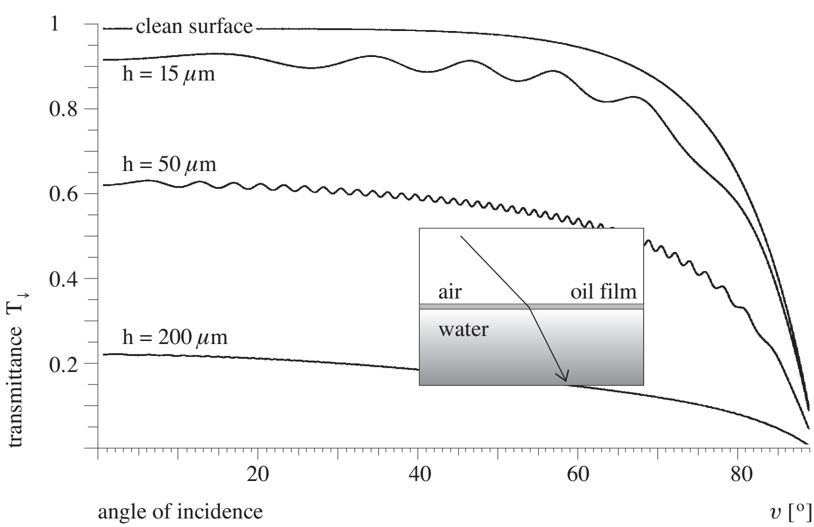

Fig. 6. As Fig. 5, but for wavelength $\lambda = 400$ nm ($n = 1.49$, $k = 0.0004$)

between them. The quantity of light crossing an air-oiled water interface depends on the angle of incidence and always falls to zero at the critical angle for an air-clean water interface (48.8°), which is confirmed by the plots in Fig. 4. It appears, therefore, that the presence of an oil film does not alter the magnitude of the critical angle. Figs. 5, 6 and 7 show the angular transmittance plots of light incident on a polluted surface from above. Figs. 5 and 6 apply to 'Petrobaltic' crude oil; in Fig. 5 the light wavelength $\lambda = 500$ nm, in Fig. 6 it is $\lambda = 400$ nm. The plots in Fig. 6 are moved down with respect to the same layers in Fig. 5 because the light absorption coefficient is greater for short-wave than for long-wave light. The density of the oscillations on these plots depends on the thickness of the oil layer, and also, though only to a limited extent, on the wavelength. But a thin layer has no effect on the amplitude of the light waves. With 'Petrobaltic' crude ($\lambda = 500$ nm), for example, oscillations are detectable for layers even as thin as 200 μm, so this oil is a good light transmitter. 'Romashkino' crude, however, is a poor transmitter; this is evident from the plots in Fig. 7, where the same relationships are depicted as in Figs. 5 and 6. Indeed, it allows so little light to pass through that no oscillations are visible on the angular transmittance plots.

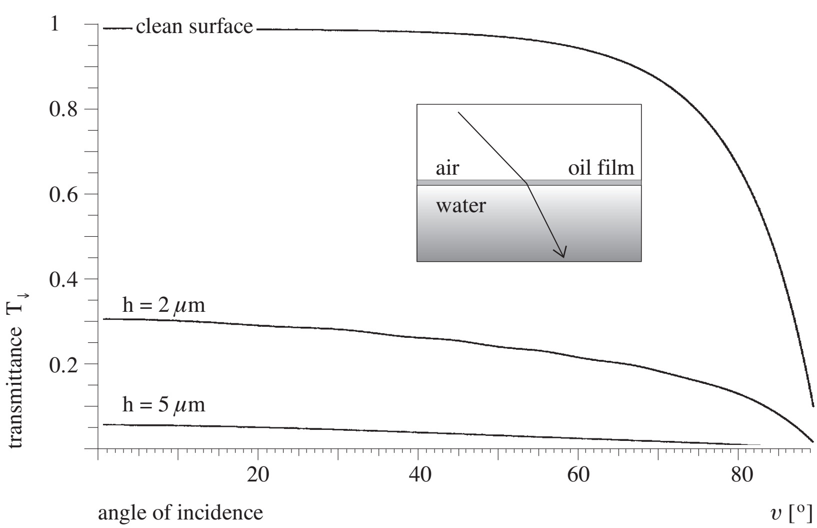

Fig. 7. As Fig. 6, but for 'Romashkino' crude oil ($n = 1.5$, $k = 0.01$)

The effect of temperature on film transmittance was also examined. However, the results shown in Fig. 8 suggest that it can be neglected, since the relative transmittance *vs.* angle of incidence plots for various temperatures almost overlap.

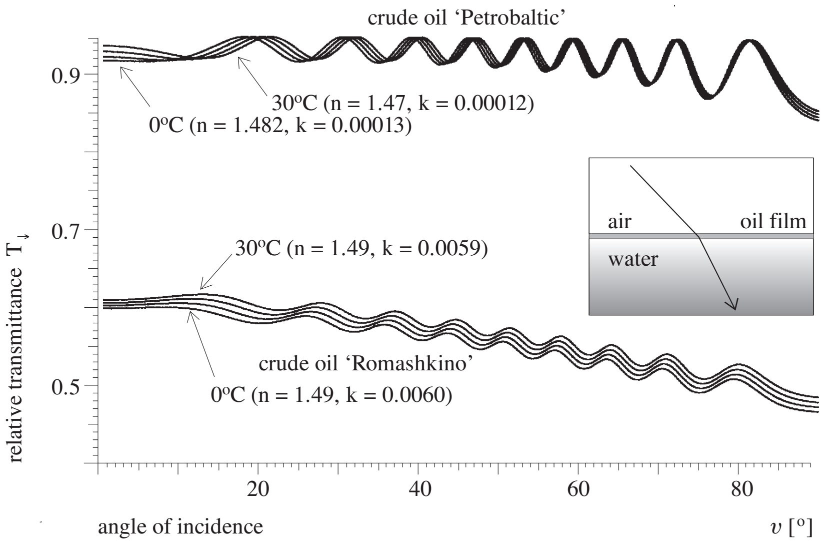

Fig. 8. Angular dependence of relative transmittance $T_{r\downarrow}$ for two types of crude oil ('Romashkino' and 'Petrobaltic') at various temperatures. Wavelength $\lambda = 600$ nm, temperature $T = 10°$C, thickness of oil layer $h = 5\,\mu$m

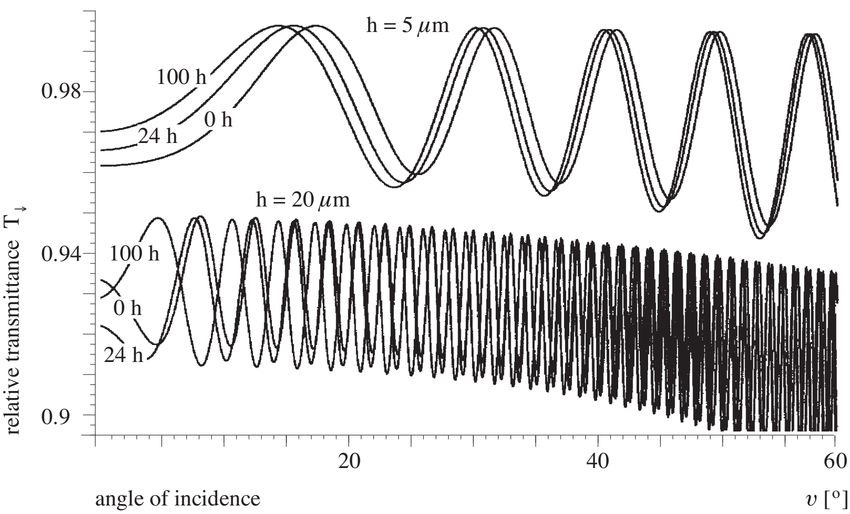

Fig. 9. Angular dependences of relative transmittance for fresh and artificially aged (by 24 h and 100 h) 'Petrobaltic' crude oil for two oil layer thicknesses. Wavelength $\lambda = 600$ nm, temperature $T = 10°$C

The same was done after testing the effect of ageing time on the transparency of a thin film of crude oil. Fig. 9 shows the relative transmittance *vs.* angle of incidence plots for 5 and 20 μm thick films. These indicate that artificially ageing the oil for 100 hours hardly affects the amount of light transmitted through a film of such oil.

The results of a test to check the relationship between transmittance and light polarisation are shown in Fig. 10. The differences in the plots are clearly in evidence when angles of incidence are large. The component perpendicular to the incident plane $T_{\downarrow\perp}$ shows a far greater amplitude of oscillations than does the parallel component $T_{\downarrow\|}$.

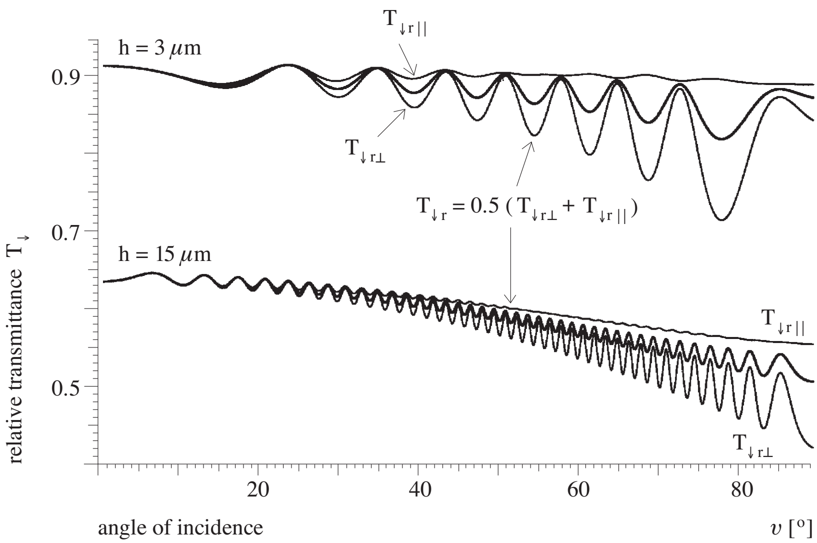

Fig. 10. Relative transmittance of a sea surface oiled by 'Petrobaltic' crude oil as a function of the angle of incidence for two thicknesses for perpendicularly polarised ($R_{\uparrow\perp}$), pararelly polarised ($R_{\|\perp}$) and unpolarised ($R_{\uparrow}$) light. Wavelength $\lambda = 400$ nm, temperature $T = 10°$C ($n = 1.49$, $k = 0.0004$)

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

Light leaving the sea comes up against two interfaces – water-oil and oil-air. At the water-oil interface the refractive index alters abruptly from 1.33 to *ca* 1.5. This change in value is about the same as that which occurs when light passes from air into clean water. Between the oil and the air the refractive index falls by $\Delta n = 0.5$. Hence, at this interface there is strong

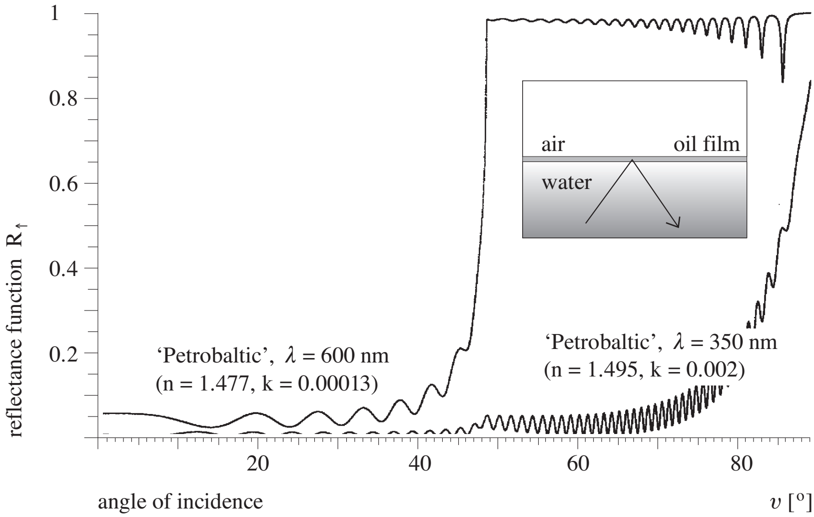

Fig. 11. Reflectance function of an oil film for two types of oiled sea surface. Temperature $T = 10°C$, thickness $h = 4\,\mu m$

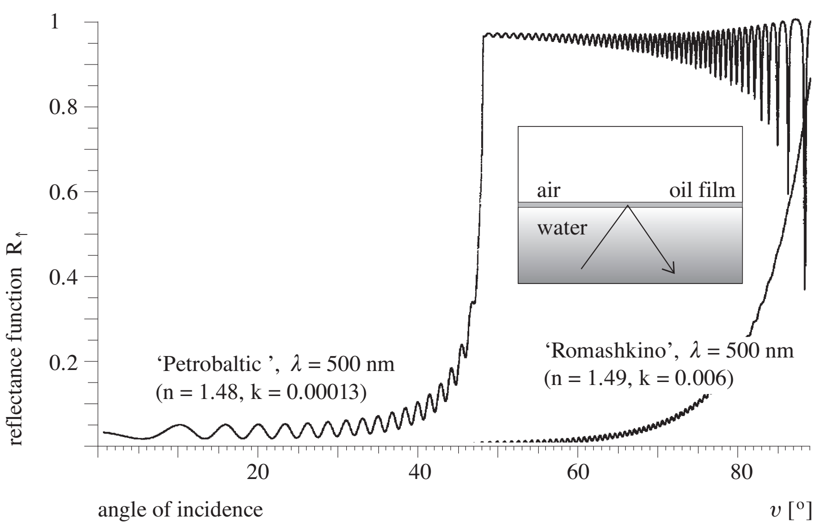

Fig. 12. Reflectivity of an oil film for 'Petrobaltic' and 'Romashkino' crude oils. Temperature $T = 10°C$, thickness $h = 4\,\mu m$

reflection of light, which in the water interferes with the light reflected at the water-oil boundary. The plots on Fig. 11 refer to a 5 μm thick film of 'Petrobaltic' crude, which totally internally reflects the light incident at an angle greater than the critical angle for the oil-air interface. This means that the modulated wave consists of light reflected from the oil-air interface, while the modulating wave is light reflected off the water-oil boundary. Fig. 12 compares the angular dependence of the reflection coefficient on films of 'Romashkino' and 'Petrobaltic' crude oils. It shows that a critical angle exists in the case of 'Petrobaltic' crude, whereas 'Romashkino' crude is characterised by a completely different plot oscillating about the curve corresponding to the reflection from the water-oil boundary.

The refractive index *vs.* oil film thickness curve depends on the direction of the light. If the light is incident on an oiled sea surface from above, the curve oscillates around a horizontal line corresponding to reflection from a thick layer of oil (Otremba, 1994a,b). However, the situation is different when light passes from the water into air. At first, reflection from the oil-air interface is dominant, but as the oil film thickens, reflection from the water-oil interface takes over, since the beam of light reflected from the air-oil boundary is attenuated in the oil layer. This is illustrated in Fig. 13, where the rapid drop in refractive index with increasing oil layer thickness is apparent; this drop is steeper in the case of the practically opaque 'Romashkino' crude than the 'Petrobaltic' crude. Because of the

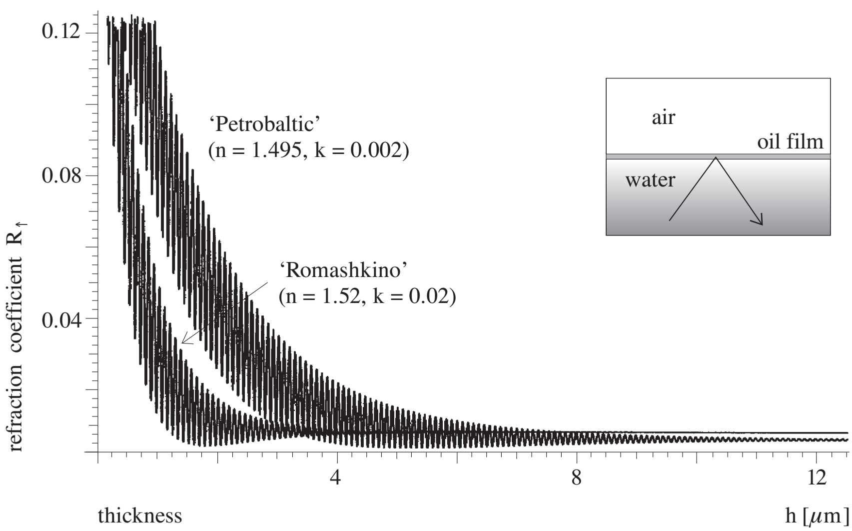

Fig. 13. Reflectivity of an oil film as a function of thickness for 'Petrobaltic' and 'Romashkino' crude oils. Wavelength $\lambda = 350$ nm, temperature $T = 10°$C, angle of incidence $\upsilon = 45°$

slightly higher refractive index in the case of the former, its reflection coefficient is somewhat higher than that of the latter. Reflection of light from layers thicker than 5 μm is *ca* 5 times weaker than reflections from similar layers when light passes through in the opposite direction.

Fig. 14 depicts the curves of reflection coefficient *vs.* wavelength: as the wavelength increases, so does the reflection coefficient. This is due to the diminishing light absorption coefficient in the oil and the resultant rise in importance of reflection from the oil-air boundary. The opposite effect, brought about by spectral changes in the refractive index, was observed in similar curves for light passing through an oil film in the opposite direction. A film of 'Petrobaltic' crude reflects visible light several factors more strongly than a similar film of 'Romashkino' crude. When light travels in the opposite direction, the reverse obtains: reflection from a film of the latter oil is stronger. The shape of the reflectance function vs. wavelength curve also depends on the thickness of the layer, which is illustrated in Fig. 15. Thick layers do not display spectral changes in the reflectance function, unlike thin layers, in which increasing wavelength causes more and more light to be reflected. It must be emphasised at this juncture that the effect of wavelength is due neither to the classical effect of light interference, as is the case with thin layers, nor to changes in the refractive index n, since it is the coefficient of light absorption a, diminishing as it does with increasing wavelength, that exerts the greatest influence on the growth of the

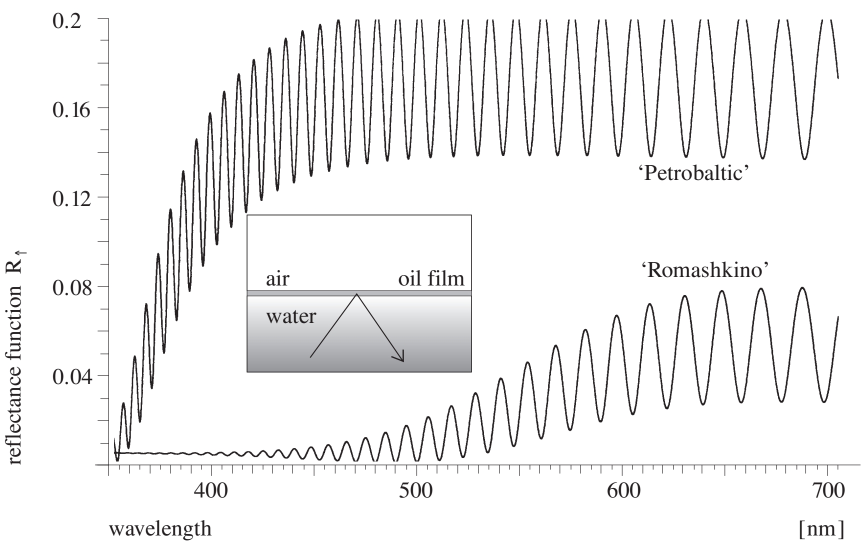

Fig. 14. Reflectivity of an oil film as a function of wavelength for 'Petrobaltic' and 'Romashkino' crude oils. Thickness $h = 5\,\mu$m, angle of incidence $\upsilon = 45°$, temperature $T = 10°$C

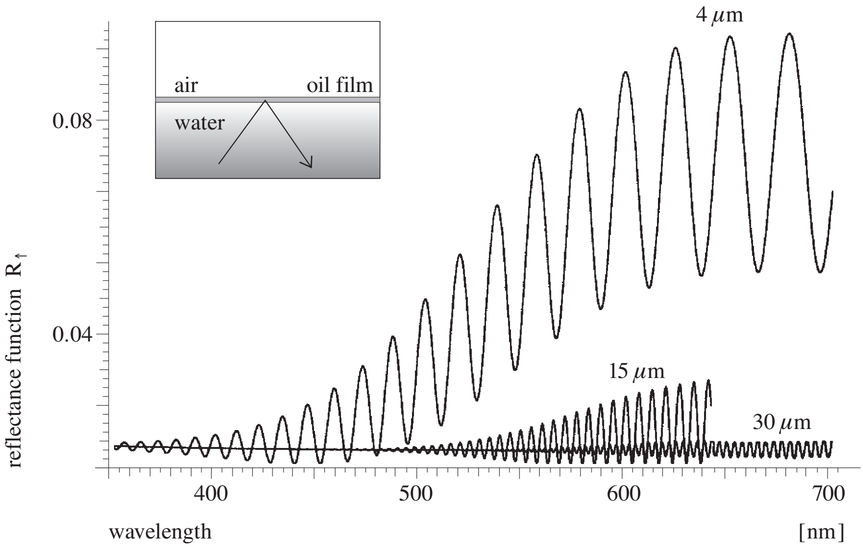

Fig. 15. Reflectivity of a 'Romashkino' crude oil film as a function of wavelength for various thicknesses of oil. Angle of incidence $\upsilon = 45°$, temperature $T = 10°\mathrm{C}$

mean coefficient of reflection. The upshot of this is that light reflected from the oil-air interface predominates at longer wavelengths, where, because of the abrupt alteration in the refractive index, more light is reflected than at the water-oil boundary.

5. Conclusions

This work has shown that transmittance vs. angle of incidence plots for light travelling from air to water differ from those for light passing in the opposite direction. Light travelling upwards is restricted by the critical angle of 48.8° determined only by the refractive index of water. This limitation does not apply to downward-travelling light, even though the refractive index drops at the oil-water interface. Studies of the downward transmittance of light do not provide any new information in themselves; even so, much of significance can be gleaned from the changes in curve shape for different types of oil, artificially aged to different extents, and for a variety of wavelengths, which can be put to good use in further work on modelling the downward light field under a sea surface covered with oil slicks. For example, the temperature of water covered by oil slicks and their ageing (weathering) time have no significant effect on light transmission. The shape of the averaged line about which the curves oscillate is dependent solely on the thickness of the oil layer and the type of oil involved.

The characteristics of light reflection from oiled water can be presented as a set of relationships divisible into two groups:

- the oscillations of curves on plots of reflectance functions *vs.* angle of incidence, wavelength or oil layer thickness;
- changes in shapes of averaged plots (around which the curves oscillate).

In laboratory investigations (on real systems) the oscillation effect is many times weaker than that predicted by theoretical analyses. Hence averaged plots are of greater significance for practical purposes.

The reflection of light incident from below on an oiled surface is strongly dependent on the thickness of the oil layer and its coefficient of light absorption. Reflection from a film of opaque oil is therefore weaker than from a transparent film. Total internal reflection (48.8°) occurs for thin translucent layers and gradually disappears with increasing thickness and light absorption coefficient. The wavelength strongly affects the coefficient of reflectance from thin layers and disappears when these thicken (a few tens of μm in the case of both 'Romashkino' and 'Petrobaltic' crudes).

The examples given in this paper represent a set of relationships associated with the interaction of light with an oil film. They provide information that can be put to use in modelling the above- and below-water light fields by replacing the Fresnel rules by rules describing the angular dependence of transmittance and the light reflection coefficient (separately for light travelling downwards and upwards). The dependence between the refractive index and transmittance on the one hand, and the angle of incidence for a 5 μm thick film of 'Romashkino' crude on the other for both directions of light travel (a total of 4 functions) was applied in modelling the above-water light field using the 'Monte Carlo' method (Otremba and Piskozub, 1993). However, no homogeneous functions have as yet been identified that could embrace simultaneously not only the angular relationships but also the effects of wavelength, film thickness and type of oil. Nevertheless, the investigations, the results of which have been presented in this paper, are a stage in a project which is aiming towards establishing such relationships.

References

Abeles F., 1971, *Optical properties of metallic films*, [in] *Physics of thin films*, M. H. Francombe and D. W. Hoffman (eds.), Acad. Press, New York–London, 6, 171–221.

Anders H., 1967, *Thin films in optics*, Focal Press, London, 350 pp.

Arst H., Kard P., 1983, *Radiative heating of a sea covered by a thin oil film*, Sbornik Trudov, Inst. of Thermophysics and Electrophysics, AN ESSR, 1120–1130, (in Russian).

Born M., Wolf E., 1959, *Principles of optics*, 1st ed., Pergamon Press, London, 624–629.

Feynman R., Lighton R., Sands M., 1963, *The Feynman lectures on physics*, Addison-Wesley Publ. Comp., Reading Massachusetts, 2, 207–217.

Heavens O., 1955, *Optical properties of solid films*, Butterworth's, London, 182 pp.

Gurevitsh I., Shifrin K., 1978, *Light reflection from an oil-polluted sea surface*, [in] *Optical methods of investigations of oceans and other reservoirs*, Nauka, Novosibirsk, 166–183, (in Russian).

Karbowniczek-Gratkowska, G., 1993, *Optical features of the air-oil layer-seawater system*, Proc. Conf. on Technical and Ecological Aspects of Oil Residence in the Baltic Sea, Maritime Acad., Gdynia, 136–144, (in Polish).

Kisiel, B. A., 1973, *Reflection of light*, Nauka, Moskva, 352 pp., (in Russian).

Knittl Z., 1976, *Optics of thin films*, John Wiley and Sons, London–New York–Toronto, 540 pp.

Otremba Z., 1994a, *The influence of an oil-film covered sea surface on the reflection and upward transmission of light*, Oceanologia, 36 (2), 138–153.

Otremba Z., 1994b, *The reflection of light from seawater polluted with a thin non-homogeneous oil layer: theoretical dependence on wavelength, thickness and angle of incidence*, Stud. i Mater. Oceanol., 66, 137–148.

Otremba Z., Piskozub J., 1993, *Role of oil films in upward light field formation – the first results of calculations by the and 'Monte Carlo' method*, Proc. Conf. on Technical and Ecological Aspects of Oil Residence in the Baltic Sea, Maritime Acad., Gdynia, 265–271, (in Polish).

Otremba Z., Targowski W., 1994, *The impact of the nonhomogeneity of oil films covering a sea surface on light transmission: theoretical calculations*, Stud. i Mater. Oceanol., 66, 3–14.

Vasicek, 1960, *Optics of thin films*, North Holland, Amsterdam, 533 pp.

Zolotarev V. M., Kitushina I. A., Sutovsky S. M., 1977, *Optical features of crude oil in the spectral range 0.4–15 mm*, Okeanologiya, 17, 6–10, (in Russian).