Modelling of the optical contrast of an oil film on a sea surface

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Abstract: The water-leaving radiance field above a sea surface polluted by an oil film has been modelled using a Monte Carlo radiative transfer technique with large numbers of photons incident at a selected zenith angle. The calculated radiance was recorded for each of the 240 sectors of equal solid angle the upper hemisphere had been divided into. The results are presented in the form of a bi-directional reflectance distribution function (BRDF) and as a contrast function parameterised by observation angle for various angles of incident sunlight and for various states of the sea surface roughness. The conditions for observing maximal and minimal contrast are described.

OCIS codes: (330.1800) Contrast sensitivity; (010.4450) Ocean optics; (310.0310) Thin film, optical properties; (999.9999) Modelling of radiance; (999.9999) Marine pollution monitoring

References and links

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1. Introduction

Occurrence of an oil film on the sea surface impacts the conditions of the radiance field forming in the water as well as the water leaving radiance. The mechanism of this phenomenon depends to a large degree on the optical properties of the sea surface. The properties are expressed by functions that describe angular changes of a reflection coefficient and a transmission coefficient at an air-water boundary. Moreover, the functions depend on optical properties of the oil, its thickness and incident light zenith angle (either for downwelling or upwelling radiance) [1]. From the point of view of remote sensing techniques of water bodies, the oil presence can lead to erroneous interpretations of the sea image. Moreover the determination of the optical contrast of oil film on the sea with various surface roughness conditions may be helpful for oil slick monitoring techniques.

The upwelling radiance can be modelled with a simulation using a large number of downwelling photons tracing their histories as they are backscattered to the sea surface (the Monte Carlo technique). This method is used in marine optics when analytical modelling of light fluxes is either not possible, or does not ensure sufficient precision. Examples of its application are analysis of a light field in sea water containing a high quantity of gaseous bubbles [2] or examination of the self shading effect of optical equipment [3, 4].

The optical response of the sea in relation to above-water methods of remote sensing can be described by either the bi-directional reflectance distribution function (BRDF) or by the contrast distribution function (CDF). This work is an analysis of the impact of a thin oil film floating on the sea surface on the CDF value. The study has also taken into account other important parameters influencing the CDF, which were included in the optical model of a sea area described below.

2. Model

2. 1 Water body

The studies uses a model of a sea area of 30 m depth with a free surface in a state of a fully developed wind induced waves. The sea surface roughness corresponds to wind velocity in the range from 0 to 10 m/s in the Cox and Munk [5] model. The sea bottom optical properties are represented by the reflection coefficient $r_b = 0.02$ and the diffuse scattering coefficient $s_d = 0.08$. These parameters correspond to a sandy seafloor [6].

The modelled seawater is a medium, which at a wavelength λ = 550 nm, has the following optical properties: index of refraction n = 1.34 (oceanic water), absorption coefficient a = 0.025 m^{-1} and scattering coefficient b = 0.1 m^{-1}. Values of absorption and scattering coefficients correspond to seawater in a coastal zone of optical type *case II water* [7]. The scattering phase function used is the one measured by Petzold [8] in turbid water.

2. 2 Oil film

A homogeneous layer of a crude oil of 5 µm thickness is the model used for the oil film. The optical properties of the oil layer are described by four angular functions, *i. e.* reflection and transmission coefficients in two cases: light downwelling from the atmosphere and upwelling from the water. Otremba [1] discusses the shapes of the functions in relation to a wavelength and to a type of oil. Data on the optical properties of the crude oil *Romashkino* are taken from that paper. This crude oil belongs to oils that are relatively strongly light absorbing and refracting (at a wavelength 550 nm, the oil absorption coefficient is a = 114000 m^{-1} and the index of refraction is $n_o = 1.488$.

3. Calculations

BRDF is defined as the ratio of the above-water upward radiance L (θ_r, φ_r) (in a direction defined by a zenith angle θ_r and an azimuth angle φ_r) to the sun irradiance E (θ_i, φ_i) from a direction θ_i, φ_i (1):

$$r(\theta_r, \varphi_r, \theta_i, \varphi_i) = \frac{L(\theta_r, \varphi_r)}{E(\theta_i, \varphi_i)} \tag{1}$$

This is a value which, if the above-water downward radiance is known, allows determination of the above-water upward radiance field according to the relation (2):

$$L(\theta_r, \varphi_r) = \int_0^{\pi/2} \int_0^{2\pi} r(\theta_i, \varphi_i, \theta_r, \varphi_r)\, L(\theta_i, \varphi_i) \sin\theta_i \;\, d\varphi_i \;\, d\theta_i \tag{2}$$

Sea surface polluted by the oil film which when observed at wavelength λ is characterised by the contrast in relation to a clean surface expressed by the following relation (3):

$$c(\theta_r, \varphi_r, \lambda) = \frac{L_p(\theta_r, \varphi_r, \lambda) - L_c(\theta_r, \varphi_r, \lambda)}{L_c(\theta_r, \varphi_r, \lambda)} \qquad (3)$$

where: L_p (θ_r, φ_r) is the upward radiance above the polluted sea surface and L_c (θ_r, φ_r) is the upward radiance above the clean sea surface.

Taking into account relations (1) and (3) for light coming from the direction θ_i, φ_I the contrast (CDF) is expressed by a relation (4):

$$c(\theta_r, \varphi_r, \theta_i, \varphi_i, \lambda) = \frac{r_p(\theta_r, \varphi_r, \theta_i, \varphi_i, \lambda) - r_c(\theta_r, \varphi_r, \theta_i, \varphi_i, \lambda)}{r_c(\theta_r, \varphi_r, \theta_i, \varphi_i, \lambda)} \qquad (4)$$

where: r_p (θ_r, φ_r, θ_i, φ_i, λ) expresses BRDF at a wavelength λ for a polluted sea surface and r_c(θ_r, φ_r, θ_i, φ_i, λ) for a clean sea surface.

To model the BRDF, Monte Carlo techniques were applied. This method involves tracing the history of a large number of photons and determining their fate using the inherent optical properties of the sea water in a statistical way. Upwelling above water radiance L (θ_r, φ_r) is represented by the number of photons N (θ_r, φ_r) heading into a solid angle π/120 sr around the direction θ_r, φ_r calculated per a solid angle unit. Downwelling irradiance E(θ_i, φ_i) is represented by the number of photons (always set to 10^7 in this study) sent towards the water surface.

The study analyses BRDF for a single wavelength (550 nm) along the wind direction ($\varphi_i = \varphi_r = 0$). Therefore, CDF is expressed as a function of two variables (5):

$$c(\theta_r, \theta_i) = \frac{N_p(\theta_r, \theta_i) - N_c(\theta_r, \theta_i)}{N_c(\theta_r, \theta_i)} \qquad (5)$$

where: N_c (θ_r, θ_i) represents the upwelling radiance for clean sea surface and N_p(θ_r, θ_i) for oil polluted water.

4. Results

Selected examples of BRDF calculation results are presented in Figures 1 and 2. Figure 1 shows results referring to the rough sea. A shift of the BRDF maximum beyond the maximum for a flat sea surface is caused by an asymmetry of the distribution of wave inclinations against the wind direction. The effect increases with increasing zenith angles of incident light and the sea surface roughness (parameterised by the wind velocity parameter). The limited vertical axis scale applied in Figure 2 allows incorporation of results applicable to a sea with a flat surface. The BRDF distribution for the flat surface depends on incident light zenith angle. The graph asymmetry increases with increasing zenith angle due to the dominant forward light scattering in the water.

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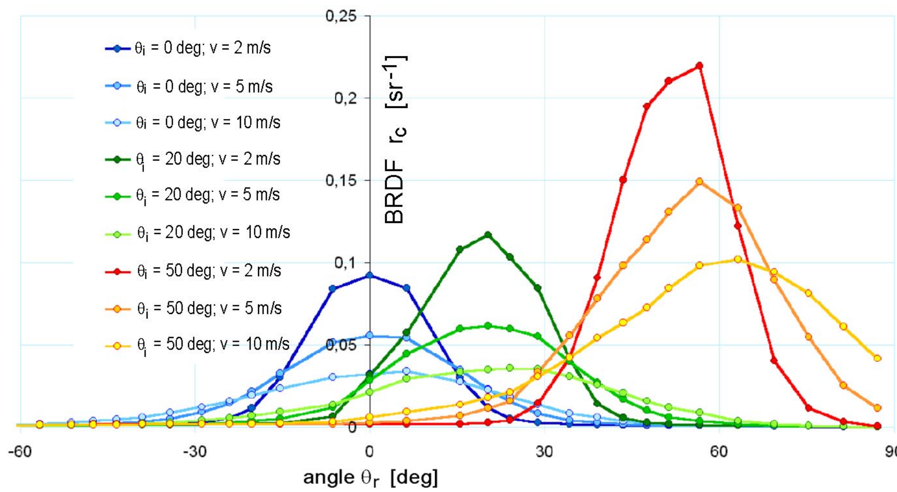

Fig. 1. BRDF for various angles of incidence (0°, 20°, 50°) and various sea surface states (related to the wind speeds (0 m/s, 2 m/s, 5 m/s, 10 m/s)

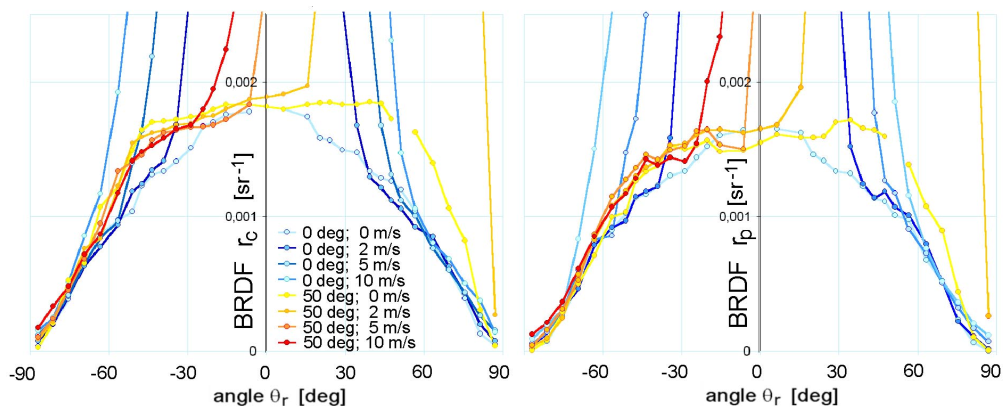

Fig. 2. BRDF for the exemplary incidence angles (0° and 50°) and various sea surface states (as in Fig. 1), however at a limited scale of BRDF. Left – a clean surface, right – a polluted surface

The results of the BRDF calculations are shown in graphs of the contrast as a function of observation direction (Fig. 3). The graphs are grouped according to the light incidence zenith angle (0°, 20°, 50°) for four states of sea roughness parameterised by the wind velocities of 0 m/s, 2 m/s, 5 m/s, 10 m/s.

If the surface is flat then the contrast is negative. Its value has a plateau within a range from -60° to 60°. Beyond this range, the value decreases rapidly towards highly negative values. The zenith angle of the downwelling light does not impact the angular function of water leaving radiance with the oil film polluted flat sea surface.

The presence of simulated sea waves causes a contrast change from negative to positive values. It this case, the contrast has a plateau around the value of 0.8. Its position and width depend on the sea roughness and on the downwelling light zenith angle. For large zenith angles (Fig. 3, the bottom graph), the contrast maximum is positioned close to the value of the incident light zenith angle on the opposite side of the zenith. This means that an observer with the sun behind his back sees the polluted area as a dark patch (negative contrast) while an observer facing the sun sees a light patch (positive contrast).

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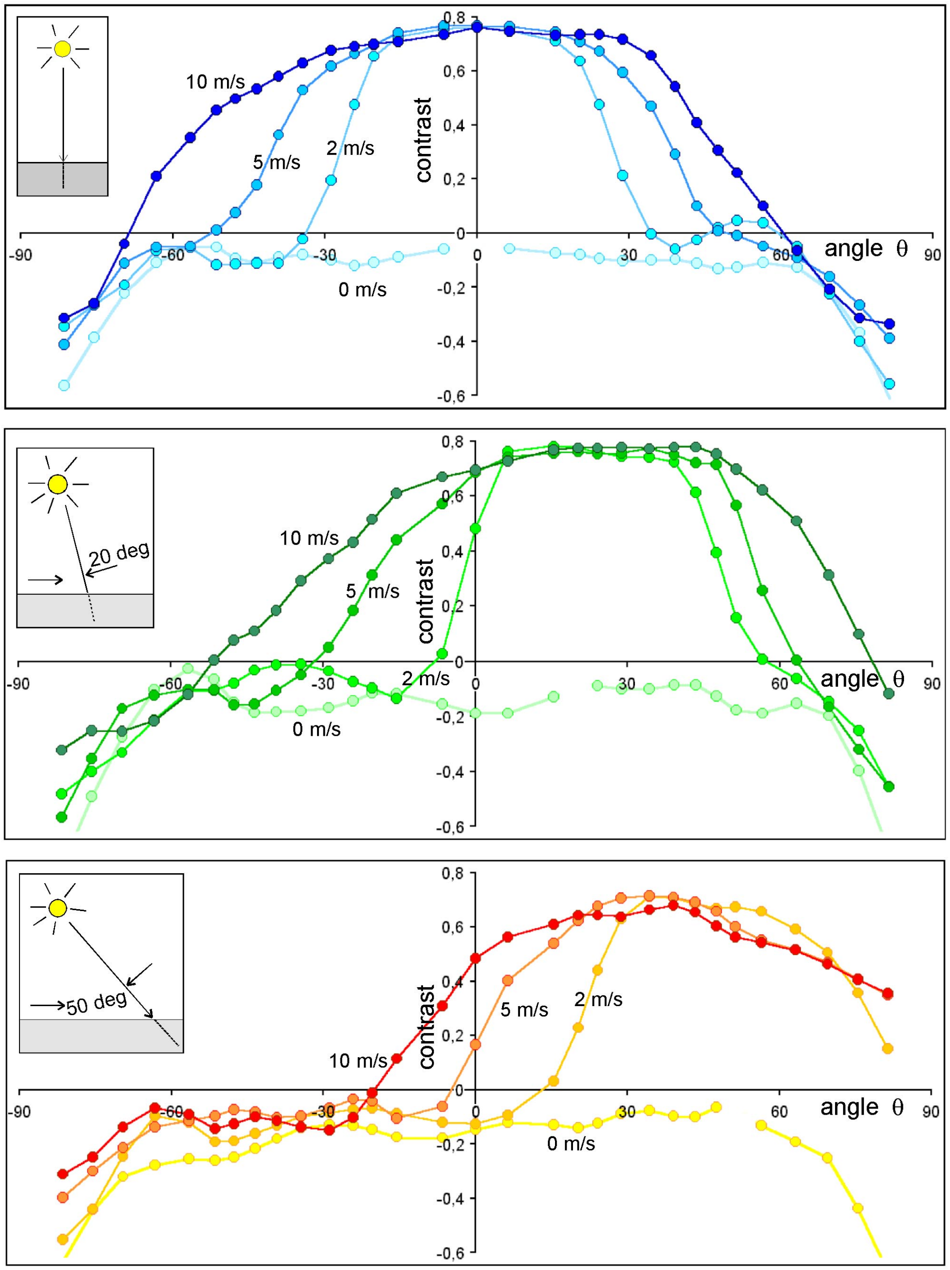

Fig. 3 Contrast of an oil film at various light incidence angles (0^o – upper, 20^o – middle, 50^o – lower) and at various wind speeds (0 m/s, 2 m/s, 5 m/s, 10 m/s)

Although the model of the polluted sea used in this study considers a high number of factors (probably the most important ones) influencing the studied phenomenon, it does not exhaust all possible parameters which can impact the contrast. Some possible additional factors are changes of the water optical properties (absorption and scattering coefficients and scattering phase function of the sea water) as well as the angular, spatial and spectral distribution of the downwelling light, a light wavelength (at which the contrast is

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determined), sea depth, sea bottom type, plankton and oil film fluorescence as well as a thickness of the oil layer. It must be mentioned that thick oil layers influence the distribution of wave inclinations.

Table 1. Conversion points (angle of observations when contrast appears zero) for various angle of incidence and various wind speed

Sea state*	$\theta_i = 0^o$	$\theta_i = 20^o$	$\theta_i = 50^o$
v = 0 m/s	-	-	-
v = 2 m/s	-35^o and $35^o – 50^o$	-10^o and 55^o	15^o
v = 5 m/s	-50^o and 45^o	-30^o and 65^o	-5^o
v = 10 m/s	-70^o and 60^o	-50^o and 80^o	-20^o

*Sea stated described by wind speed due to Cox and Munk distribution [5]

Within the applied model, several situations can be selected where there is no contrast. Table 1 shows values of the observation angles in which the contrast equals zero for given incident light directions and the sea states.

5. Summary

The obtained quantitative data of the contrast of sea surface covered by a thin oil layer against clean sea surface allows specification of situations in which contrast is negative, positive or not sensed.

In general, when sea surface is flat, the contrast is always negative since the light intensity of water leaving radiance decreases. On the other hand, roughness of the sea surface results in the occurrence of positive contrast. The contrast value is influenced by the incident light factors, the sea state and the observation direction.

As a rule, when observing the surface from the vertical direction, even a small surface roughness results always in a positive contrast value.

The contrast is most pronounced when the observer sees the oil slick close to the sun reflection (positive contrast) and when the slick is observed at a low angle, almost horizontally (negative contrast). Of course, in the former case the contrast may be observed only off the actual sun glitter region.

Several situations can be distinguished at which the contrast between the polluted surface and the clean one drops to zero. The null contrast situation happens usually when observing the slick at moderate inclinations. The more rough the sea surface, the larger is the zenith angle at which null contrast is observed. When the sun is low over the horizon, the null contrast conditions are possible only when the sun is behind the observer’s back.

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