Simulation of the contrast of the sea areas polluted by oil spilled on the surface and dispersed in the water column

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1 INTRODUCTION

Films and suspensions appear to be the most popular forms of oil pollution in the sea. The question is how the oil pollution influences the processes responsible for light transport in the sea body and above the sea surface. If 'remote sensing' problems are considered, then the bi-directional reflectance distribution function (BRDF) is the magnitude, which would be applied to describe the optical properties of sea observed from above surface (Otremba & Piskozub, 2001). In oceanographic applications the only selected elements of the BRDF - named 'reflectance' or 'reflectance function' - are determined. Oceanographers usually use this term to describe the BRDF for only one angle of observance equal to zero and for the definite angle of sunlight incidence and they try to determine the relationships between the components of sea-water and spectra of reflectance. Impact of oil film on above water radiance field was considered in earlier papers by Otremba (1997, 1999). This paper describes the investigations focused on laying down the rules of forming the contrast of sea areas polluted by dispersed oil.

Impact of oil suspension on reflectance function has not been considered yet due to the difficulties with describing the inherent optical parameters of sea-water polluted by oil droplets. Recently this difficulty was overcome by using the so called 'Mie solution' (Otremba & Krol, 2001, 2002). In that paper optical parameters of crude oil 'Petrobaltic' type (extracted in the Baltic Sea seabed) were applied. Results presented in the above papers were used in this paper.

To assess the role of oil suspension in shaping the reflectance function various concentration of oil suspension were applied. Values of concentration are connected with thickness of polluted layer. All concentrations were such that they resulted in the same amount of oil in the water column per unit of square of sea surface.

2 METHOD

Simulations of light forecasting in water column were carried out using the 'Monte Carlo' code, which relies on analyzing the destination of a big number of photons. In this method every photon is a subject to events that occur with defined probability. These events can be: reflection on water surface, scattering on the suspended particle, scattering on seabed, absorption in the water, and absorption in the seabed. Probabilities of these events must be strictly defined. There is a relationships between the probabilities and optical parameters of sea-water and dimensions of layers characterized by definite optical parameters as absorption coefficient and scattering coefficient - when water column is considered, and the 'Fresnell rules' - when water surface is considered. Both absorption and scattering coefficients depend on the type and concentration of substances residing in the bulk of water.

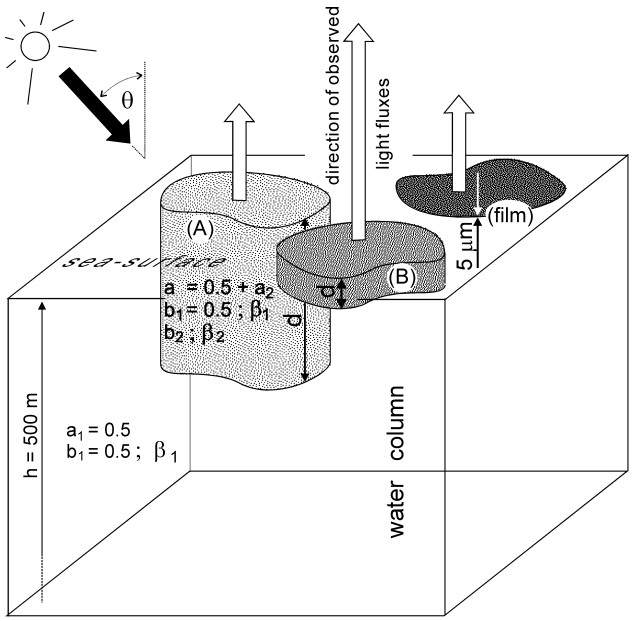

Figure 1. Model of the sea area polluted by oil.

Optical model of the sea area polluted by oil is schematically presented in Figure 1. In that model one can notice that the optical properties of clean water are represented by absorption coefficient $a_1 = 0.5$ and scattering coefficient $b_1 = 0.5$. These values are valid for coastal waters of the Baltic Sea (Otremba & Krol, 2002). The scattering phase function β_1 is applied after Petzold (1977). Polluted areas are represented by the sum of absorption coefficient of clean water a_1 and absorption coefficient of oil suspension a_2, and two scattering coefficients. The first of them is the above-mentioned b_1, and second one is b_2 that refers to oil suspension in water. Coefficient b_1 is associated with scattering phase function β_1, whereas b_2 – with scattering coefficient β_2 applied after Otremba & Krol (2002). Both b_2 and β_2 are adequate for suspension obtained by dispersion of crude oil of 'Petrobaltic' type in seawater.

Function β_2 is independent of oil concentration, but both a_2 and b_2 - are. Their values can be calculated using formulae 1 and 2:

$$a_2 = \tfrac{5}{d}\, 0.005 \qquad (1)$$

$$b_2 = \tfrac{5}{d}\, 0.5 \qquad (2)$$

where d - thickness of layer of a part of water column polluted by oil suspension (thickness of 'oil clouds').

Values of a_2 and b_2 depend on oil concentration. There were got into consideration information that if oil concentration equals 1 ppm (1 cm^3 of oil per 1 m^3 of water) then a_2 oscillates near 0.005 and b_2 - near 0.5 (Otremba and Krol, 2002). For example, concentration 1 ppm is achieved when thickness of 'oil cloud' equals 5 m. In such situation, amount of oil contained in water column equals 5 cm^2 per 1 m^2 of sea area. Such amount is equivalent to oil film floating on sea surface, of 5 µm thickness.

In each simulation 10 mln of virtual sun-photons were used. Photons were thrown under definite angles of incidence θ. Results of simulations were registered as reflectance defined by expression 3:

$$r = \tfrac{L}{E} \qquad (3)$$

where: L = above sea surface upward radiance, E = sunlight irradiance at a definite angle θ. The model of radiance L relates to the amount of virtual photons leaving virtual sea surface and falling into solid angle

$0.01 \times 2\pi$ sr under perpendicular direction. The model of irradiance E relates to the amount (10 mln) of virtual photons falling on virtual sea surface at an angle θ.
Also the summary reflectance defined similarly to that in formula 3 was modeled, but in that case the irradiance E is a scalar irradiance calculated for the whole hemisphere, which emits light scattered by atmosphere. Diffuse illumination (named also as cosine or Lambertian illumination) is the model of illumination producing by the clear sky. Diffuse illumination is precisely defined by angular distribution of radiance by the following expression (4).

$$r = L_o \cos\theta \tag{4}$$

where: L_o = downward radiance in perpendicular direction, θ = nadir angle.

3 RESULTS

The simulation of reflectances for film of 5 μm thickness made by crude oil 'Petrobaltic' was carried out. The results obtained for various angles of incidence are presented in Figure 2. As this chart shows – reflectances related to both clean and polluted waters are similar, but for clean water - greater and for polluted water - lower. Only for angle of incidence similar to the angle of observation - reflectance for polluted water is greater than for the clean one.

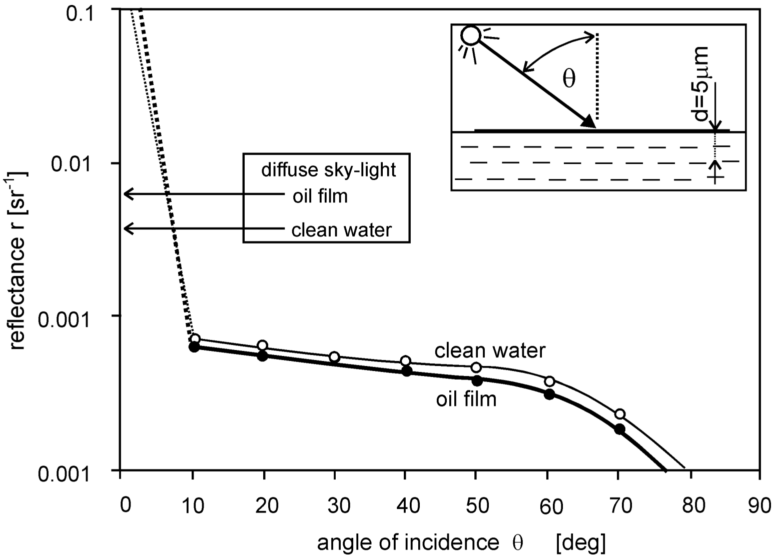

Figure 2. Results of modeling of reflectance *r* vs. angle of light incidence θ for clean seawater area (thin line) and for polluted by oil film seawater area (thick line).

Several dozen simulations were also carried out for various thicknesses of oil clouds *d* and various angles of light incidence *θ*. Results are presented as reflectance *r* vs. thickness *d* at the Figure 3. In this figure curves for various angles of incidence (from 10^o to 80^o with distance of 10^o) are placed.

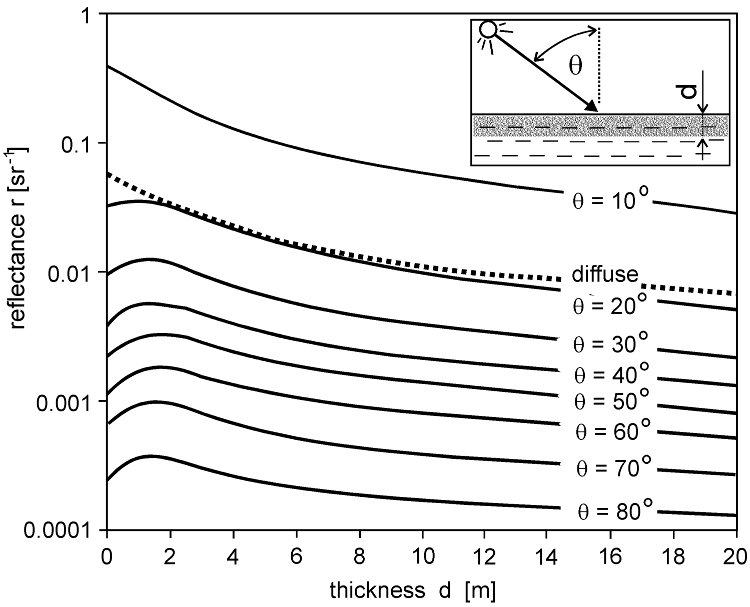

Figure 3. Results of modeling of reflectance *r* vs. thickness of oil cloud *d* in the sea column for various for various angles of light incidence θ. Doted line refers to a case, when Lambertian distribution of radiance is applied.

In Figure 3 the summary reflectance modeled for diffuse illumination is marked (by dotted line), except for reflectances modeled for directional illuminations.

As Figure 3 shows, the maximum of reflectance appears if thickness of oil cloud oscillates near 1 m. That maximum is not registered for small angle of incidence and for diffuse illumination.
Also the tested influence of an angle of incidence on reflectance for exemplary thickness of oil cloud, namely for 5 m was tested. The results are shown in Figure 4, where the results for clear water are also presented. Shapes of plots for clear water area and for polluted by oil suspension water area are quite different. Especially for low value of reflectance detected for polluted water excides several times reflectance for clear water.

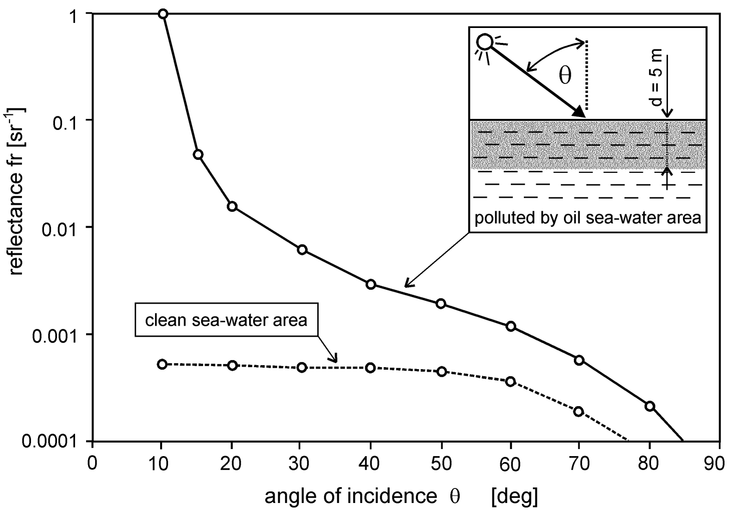

Figure 4. Results of modeling of reflectance r vs. angle light incidence θ for clean seawater area (dotted line) and for polluted by oil suspension seawater area (solid line).

3 DISCUSSION

To assess visibility of sea area polluted by oil, the results obtained were recalculated into a factor, called contrast of polluted area in relation to the clean one. Definition of the contrast is presented in formula (5):

$$c = \frac{r_p - r_c}{r_c} \tag{5}$$

where: r_p = reflectance for polluted area, r_c = reflectance for clean area. In order to make the determination of contrast possible, the simulation for the clean area analogous to the simulation for the polluted area was also carried out.

The contrast of the sea area polluted by oil film as a function of angle of incidence is presented in Figure 5. Negative values of contrast result from light attenuation in oil film. Positive contrast for angle of incidence equal to the angle of observation is caused by reflectivity of polluted water surface two times greater than for the clean one.

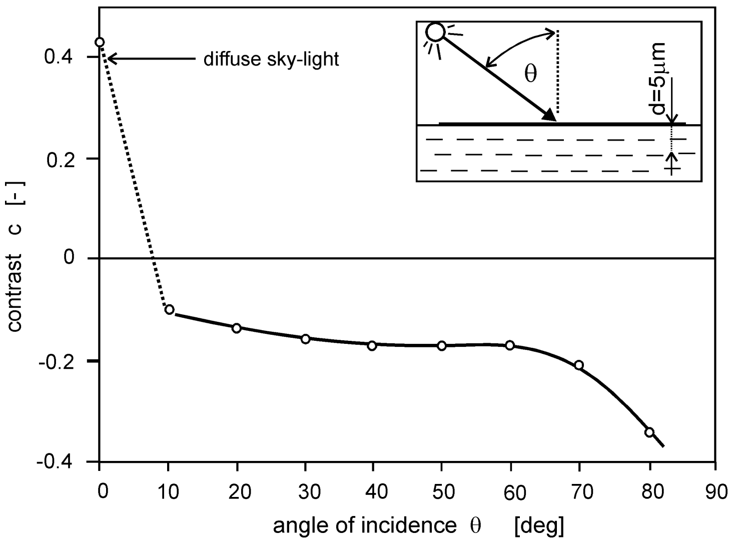

Figure 5. Contrast c of sea area polluted by oil film vs. angle of incidence θ.

Contrast as a function of oil cloud thickness is presented in Figure 6.

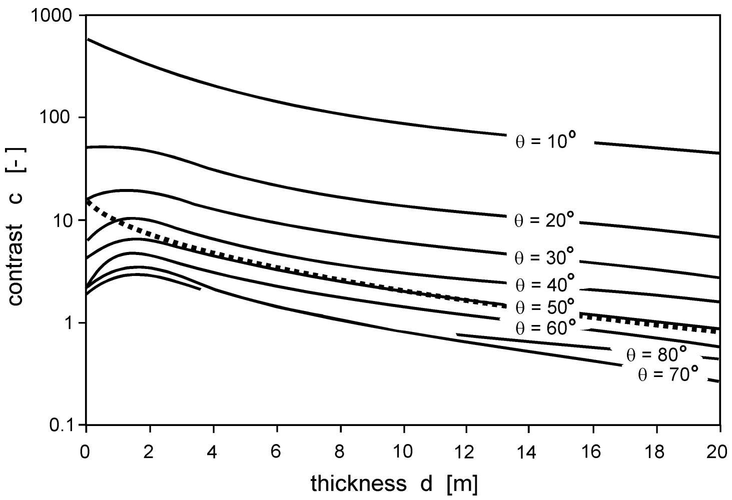

Figure 6. Contrast c of sea area polluted by oil suspension vs. thickness of polluted sea layer. Dotted line refers to diffuse illumination.

Very high level of contrast, which appears for small angles of sunlight incidence, is caused by very high back-scattering of light on oil droplets suspended in water. Suspension made by oil droplets produces back-scattering many times greater than natural marine components does. This effect is caused by the greater relative refractive index of oil in relation to substances filling the plankton cells.

It is worth to notice, that between contrast and thickness of oil cloud no-monotonic dependence occurs– especially for a great angle of light incidence. The maximum appears if thickness reaches the value nearest to 1 m.

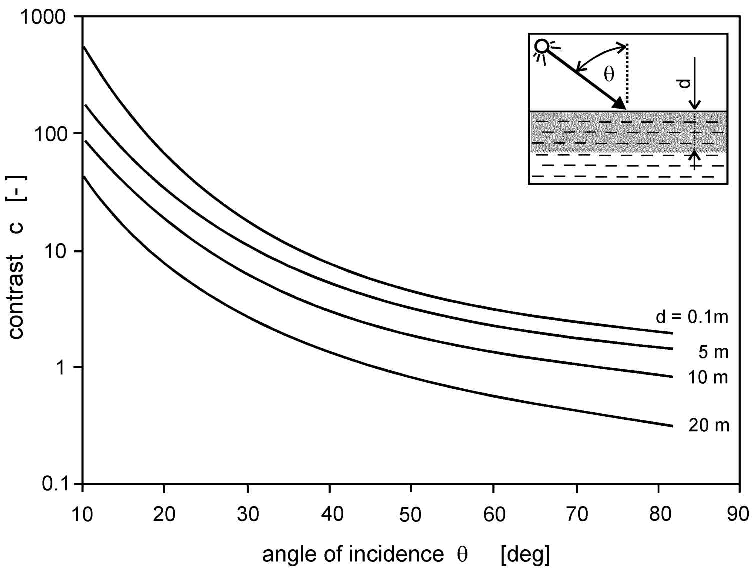

Figure 7. Contrast *c* of sea area polluted by oil suspension vs. angle of light incidence θ.

As a rule the contrast decreases if the angle of incidence increases. That phenomenon is caused by the back-scattering effect. Intensity of back-scattering appears to be more valid when the angle of incidence has a low value – at the time phenomenon of scattering on oil-droplets is stronger than the scattering on plankton-cells. The difference between back-scattering intensity for oil-droplets and plankton-cells causes a limited influence on contrast when angle of incidence reaches great values.

CONCLUSIONS

The results presented indicate the possibility of modeling of reflectance for polluted sea area through the computer simulations of light spreading, but under conditions that the distribution of light illuminating the sea is recognized and also inherent optical parameters of seawater are known. These parameters are the subject of several current investigations (Stramski et al., 2001, Loisel et al., 2001).

I am convinced that results reported in this paper will be of interest or modelers involved in creating of above sea surface upward radiance complex model.

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Otremba Z. Kontrastu modelēšana ar naftu piesārņotai jūras virsmai un ūdens kolonai.
Raksts atspoguļo rezultātus, kuri iegūti modelējot atstarošanas funkciju ar naftu piesārņotai jūras virsmai. Tā pārklāta ar pilienu suspensijas plēvi. Plēves biezums ir 5 μm, kas atbilst 5 cm^3 naftas uz vienu kvadrātmetru jūras virsmas. Atbilstoši apstākļi tika radīti uz ūdens kolonas virsmas dažādiem dispersētās naftas plēves biezumiem jūrā. Veikti aprēķini liela fotonu skaita dzīves modelēšanai, ja tie bombardē jūras virsmu (Monte-Carlo metode). Tika noskaidrots, ka eksistē nemonotona atstarošanas atkarība no naftas "mākoņa" biezuma jūras virsmā.

Otremba Z. Simulation of the contrast of the sea areas polluted by oil spilled on the surface and dispersed in the water column.
This paper presents the results of the modeling of reflectance function of the sea polluted by oil that appears as film and as suspensions of droplets. The film thickness is 5 μm, which relates to 5 cm^3 of oil per 1 m^2 of sea area. The same amounts of oil in the water column in relation to the sea unit area as for film were applied for various thicknesses of sea-layer polluted by dispersed oil. The calculations were made by the simulation of the life of a big number of photons falling on the sea surface (Monte Carlo method). Non-monotonic dependence of the thickness of the oil 'cloud' in the bulk of sea on the reflectance was detected.

Отремба З. Моделирование контраста поверхностей моря и колонны, загрязненных нефтью.
В статье приведены результаты моделирооваиния функции отражения поверхности моря загрязненной нефтью. Поверхность покрыта пленкой, образованной суспензией капель. Толщина пленки составляет 5 μм, что соответствует 5 см^3 нефти на один квадратный метр поверхности. Соответствующие условия были созданы для поверхности колонны воды, где были образованы дисперсионные пленки нефти различной толщины. Выполнено моделирования жизни большого числа фотонов падающих на поверхность моря (метод Монте-Карло). Выявлена немонотонная зависимость отражающей функции от толщины "облака" нефти на поверхность моря.