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Influence of oil dispersed in seawater on the bi-directional reflectance distribution function (BRDF)

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The bidirectional reflectance distribution function (BRDF) of the sea areas polluted by oil-in-water emulsion has been studied at the ends and in the centre of the visible light spectrum. The Monte Carlo code was applied to model water leaving radiance for the entire upper hemisphere. Solar irradiance was represented by 1 billion virtual photons which reach the sea surface at an angle of 40 deg. The results are displayed as the BRDF *vs*. two variables: zenith and azimuth angles. The strong impact of wavelength on the BRDF has been revealed while, the size distribution of oil droplets has an insignificant impact. The presence of oil emulsion modifies the shape of the BRDF significantly, and the latter depends on the oil type. Irradiance reflectances and radiance reflectances derived from BRDFs obtained are also presented.

Keywords: oil, seawater, phase function, inherent optical properties (IOP), radiance, bidirectional reflectance distribution function (BRDF), modelling.

1. Introduction

The sea, lake or river areas polluted by oil substances can modify the above above water radiance distribution. It has been found that oil film affects the angular distribution of water leaving radiance [1]. Also oil present in the sea environment, in the form of emulsion, can modify the light flux leaving sea surface. Introductory results of the modelling of visibility of oil emulsion in seawater have already been described [2]. However, only roughly derived phase function (PF) of spherical oil droplets suspended in seawater has been applied. Results of PF modelling using a well-verified code for Mie solution were reported lately [3]. Phase function and both scattering and absorption coefficients of oil-in-water for various oil droplets size distribution together with optical properties of natural components of the seawater have opened up the possibility of constructing an optical model of sea environment polluted by oil emulsion and subsequently, the possibility of studying radiative transfer of oil polluted sea area.

The bidirectional reflectance distribution function (BRDF) was first applied to remote investigation of land areas [4]. It is a strictly defined physical parameter, which describes the ability of the surface of land, or aquatic areas to reflect light. Simply, if incident angular (for the whole upper hemisphere) radiance L_i is known, the reflected radiance L_r can be determined using the following integral:

$$L_r(\theta_r, \varphi_r) = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} r(\theta_i, \varphi_i, \theta_r, \varphi_r) L_i(\theta_i, \varphi_i) \sin\theta_i \cos\theta_i \mathrm{d}\theta_i \mathrm{d}\varphi_i \tag{1}$$

where: $L_r(\theta_r, \varphi_r)$ – reflected radiance, $r(\theta_i, \varphi_i, \theta_r, \varphi_r)$ – BRDF, $L_i(\theta_i, \varphi_i)$ – incident radiance, θ_i – nadir angle for incident photons ($0 < \theta < \pi/2$), φ_i – azimuth angle for incident photons, θ_r – nadir angle for reflected photons ($\pi/2 < \theta < \pi$), φ_r – azimuth angle for reflected photons.

The integral (1) has a closed reference with the definition of the BRDF firstly proposed by NICODEMUS [5]:

$$r(\theta_i, \varphi_i, \theta_r, \varphi_r) = \frac{\mathrm{d}L_r(\theta_r, \varphi_r)}{L_i(\theta_i, \varphi_i) \sin\theta_i \cos\theta_i \mathrm{d}\theta_i \mathrm{d}\varphi_i}. \tag{2}$$

The numerator in Eq. (2) expresses the infinitesimal reflected radiance observed from the direction created by angles θ_r and φ_r caused by the infinitesimal incident irradiance (denominator) from direction determined by angles θ_i and φ_i. As regards actual measurement of BRDF the denominator expresses irradiance from only one direction (θ_i, φ_i) while the rest of hemisphere must be dark, the numerator being the radiance measured from defined direction (θ_r, φ_r). Measurements of the BRDF of terrestrial areas are performed using special radiometers [6]. Unfortunately, in the ocean areas measurement of the BRDF is impossible as yet. However, there are popular operational reflectances (possible to measure in environment but dependent on solar light condition) in ocean optics, namely: irradiance reflectance R_E and radiance reflectance R_L called also remote sensing reflectance R_{rs}. Those operational reflectances can be derived using the BRDF:

$$R_E = \frac{E_r(0^+)}{E_i(0^+)}$$

$$= \frac{\int_0^{2\pi} \int_{\frac{\pi}{2}}^{\pi} \left[\int_0^{2\pi} \int_0^{\frac{\pi}{2}} r(\theta_i, \varphi_i, \theta_r, \varphi_r) L_i(\theta_i, \varphi_i) \sin\theta_i \cos\theta_i \mathrm{d}\theta_i \mathrm{d}\varphi_i \right] \cos\theta_r \sin\theta_r \mathrm{d}\theta_r \mathrm{d}\varphi_r}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} L_i(\theta_i, \varphi_i) \cos\theta_i \sin\theta_i \,\mathrm{d}\theta_i \,\mathrm{d}\varphi_i}, \tag{3}$$

$$R_L = \frac{L_r(\theta_r = 0, 0^+)}{E_i(0^+)}$$

$$= \frac{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} r(\theta_i, \varphi_i, \theta_r = 0)\, L_i(\theta_i, \varphi_i) \cos\theta_i \sin\theta_i \, d\theta_i \, d\varphi_i}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} L_i(\theta_i, \varphi_i, \lambda) \cos\theta_i \sin\theta_i \, d\theta_i \, d\varphi_i}. \tag{4}$$

In the above equations $E_r(0^+)$ denotes the water-leaving irradiance just above the water surface, $E_i(0^+)$ – the solar irradiance just above the water, $L_r(\theta_r = 0, 0^+)$ – water leaving radiance measured perpendicularly to the surface [7]. Notation 0^+ indicates that the defined parameter is measured just above the surface (analogously 0^- relates to just below the surface). Indexes *i* (incident) or *r* (reflected) [8, 9] are sometimes replaced respectively by *d* (downwelling) and *u* (upwelling) [7, 10], especially when the defined parameters are related to nadir angle θ equal 0 or π only.

The BRDF of the sea area can be modelled using the Monte Carlo method, in which optical model of aquatic environment is applied to simulate the radiative transfer by analyzing the virtual migration and definitive destination of photons which are directed to sea surface on the trot. The Monte Carlo code has been just successfully used in the BRDF modelling when sea surface is covered by a thin oil film [1]. In this paper the attention is mainly focused on the scale of the influence of oil-in-water emulsions phase function on the shape of BRDF of sea area polluted by oil immersed in the bulk of water.

2. Model of the environment under study

Optical features of seawater are described by absorption coefficient *a*, scattering coefficient *b* and by phase function of light scattering $p(\theta)$. Values of absorption and scattering coefficients have been chosen just as in the paper on the BRDF of sea areas covered by oil film [2], namely for typical turbid coastal case II sea water appropriate for the Gulf of Gdańsk (Poland) in the southern Baltic Sea (see the Table), and the phase function $p_n(\theta)$ characteristic of turbid water after PETZOLD [11] was applied. Optical parameters *a* and *b* of water from oil polluted area, as well as water from

T a b l e. Optical parameters of reference seawater.

Optical parameter	420 nm	550 nm	700 nm
Light absorption coefficient *a* [m^{-1}]	0.7	0.27	0.8
Light scattering coefficient *b* [m^{-1}]	0.7	0.5	0.55

reference sea area were represented by the same values. However, it was assumed that for polluted sea area contribution of those parameters of oil-in-water emulsion and of natural sea components is the same. The phase function $p_o(\theta)$ of oil component was derived and already presented [3]. In this paper, a series of various phase functions for oil emulsion have been applied. They relate to:

– two types of oil: *Petrobaltic* extracted from southern Baltic in the Polish Economic Zone, *Romashkino* from reservoir in the Tatarstan (country in a former Soviet Union);

– three wavelengths (420 nm, 550 nm, 700 nm);

– two oil droplets size distributions (one adequate for 1 week old and one – for 2 weeks).

Totally – 12 cases were analyzed.

Optical features of two kinds of oil mentioned above are described in the earlier paper [12] (the *Petrobaltic* oil represents oil types of relatively low values of the real and imaginary parts of the complex refractive index, whereas the *Romashkino* oil has opposite parameters). Tests were carried out for oil concentration of 0.5 ppm (whereas admissible oil concentration in vessel waste water is 15 ppm).

3. Monte Carlo model settings

The Monte Carlo sampling method has been used for sea environment simulation. All Monte Carlo simulations were carried out using 1 billion incident photons, which play the role of a virtual model of incident solar irradiance. Photons were directed on the plane sea surface at an angle of θ_i = 40 deg. The Monte Carlo input data, *i.e.*, the probability of photon absorption p_a and photon scattering p_s on defined length of photon run, are determined from values of an absorption coefficient a (Eq. (5)), and a scattering coefficient b (Eq. (6)), respectively, whereas the cumulative function of probability of photon scattering under defined angle $d(\theta)$ is derived from the phase function $p(\theta)$ (Eq. (7)).

$$p_a = 1 - \exp(-a), \tag{5}$$

$$p_s = 1 - \exp(-b), \tag{6}$$

$$d(\theta) = \frac{\int_0^{\theta} p(\theta)\mathrm{d}\theta}{\int_0^{\pi} p(\theta)\mathrm{d}\theta}. \tag{7}$$

Analogously, other environment properties like the Fresnel equations (which describe air-water boundary optical properties) or bottom light reflection have been converted to adequate probability densities. One thousand eight hundred and thirty three virtual receivers of photons – counting photons entering solid angles of various values – cover the upper hemisphere. One thousand two hundred and ninety six receivers capture photons in sectors of size of 0.004363323130 sr; 252 – were 2.5 times less; 144 – 5 times less; 144 – the narrowest and closest to the zenith sectors of a size 10 times less. Thus, it was possible to obtain the values of the BRDF for all 1836 directions covering the whole upper hemisphere as the output data. The accuracy of the Monte Carlo simulation depends on the number of incident photons, on an angle θ_r and on a value of solid angle photon receivers. The settings listed above give a relatively small error of the output data, which is not greater than 1% for angles less than 60°. Further statistical spread of output data increases and above 80° the error can reach even 50%. The negative aspects of simulations based on such settings are that they are time-consuming. It appears that in order to obtain the BRDF values for each of 1836 hemisphere sectors with satisfactory accuracy, 8–12 hours of the PC-computer work is necessary. The time-period of one simulation grows with an increase of scattering coefficients or a decrease of absorption coefficient (because average lifetime of photons in the bulk of water grows) and inversely gets less when scattering coefficient decreases or absorption coefficient increases.

4. Results

Simulations of radiative transfer were carried out for 15 cases: 12 cases for sea areas containing oil-in-water emulsion and 3 – for natural seawater. The output data of simulations were given in the form of matrices (size 55×36) representing the BRDFs for 1836 upper hemisphere directions. The BRDFs obtained were smoothed to statistical noise reduction [13], and presented in cylindrical coordinates in which radial coordinate r expresses zenith angle θ_r, angle coordinate φ – azimuth angle φ_r,

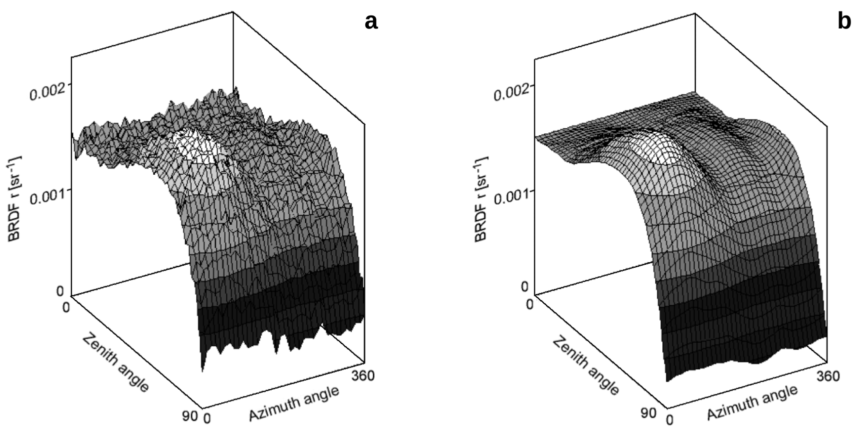

Fig. 1. Matrix of the BRDF obtained from Monte Carlo simulation (**a**) and the same after smoothing (**b**). The same results are displayed in cylindrical coordinates in Fig. 6**b**.

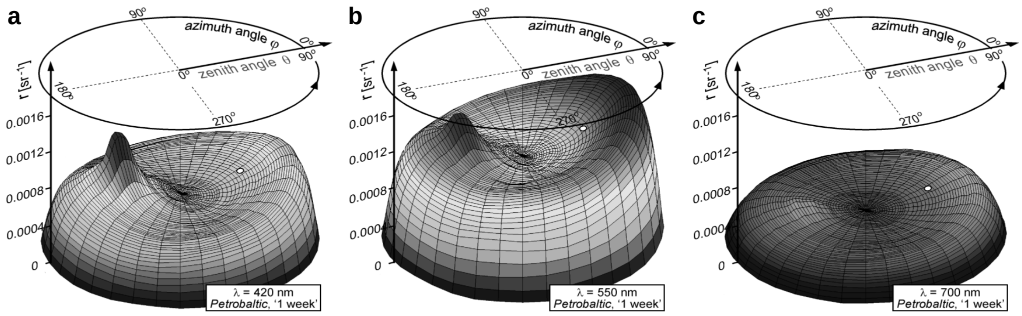

Fig. 2. BRDFs of sea areas polluted by oil-in-water emulsion made from *Petrobaltic* type crude oil for three wavelengths: 420 nm (**a**), 550 nm (**b**), 700 nm (**c**). Emulsion was aged for one week. White points indicate position of specular reflection ($\theta_r = \theta_i = 40°$).

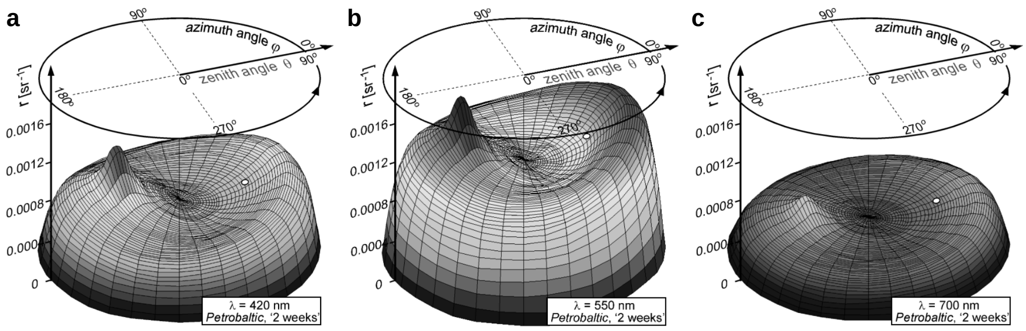

Fig. 3. BRDFs of sea areas polluted by oil-in-water emulsion made from *Petrobaltic* type crude oil for three wavelengths: 420 nm (**a**), 550 nm (**b**), 700 nm (**c**). Emulsion was aged for two weeks.

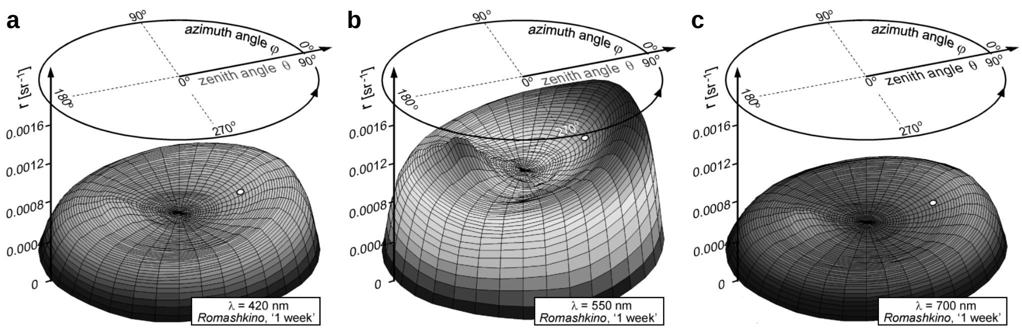

Fig. 4. BRDFs of sea areas polluted by oil-in-water emulsion made from *Romashkino* type crude oil for three wavelengths: 420 nm (**a**), 550 nm (**b**), 700 nm (**c**). Emulsion was aged for one week.

coordinate z – value of BRDF. Figure 1 shows an example of rough and smoothed results obtained from one of the Monte Carlo simulations. This visualizations of a BRDF matrix relates to the reference sea area at wavelength $\lambda = 550$ nm. One can

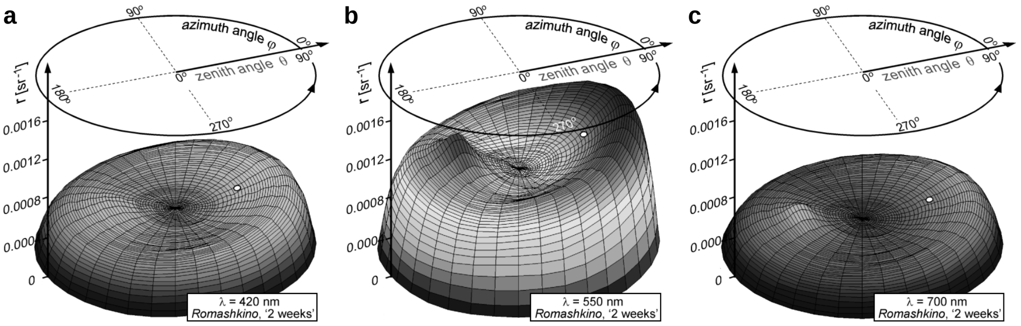

Fig. 5. BRDFs of sea areas polluted by oil-in-water emulsion made from *Romashkino* type crude oil for three wavelengths: 420 nm (**a**), 550 nm (**b**), 700 nm (**c**). Emulsion was aged for two weeks.

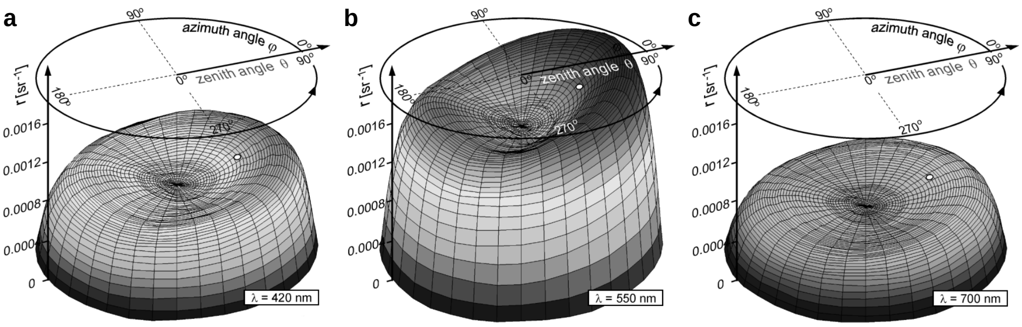

Fig. 6. BRDFs of reference sea areas (without oil pollution) for three wavelengths: 420 nm (**a**), 550 nm (**b**), 700 nm (**c**).

compare both visualizations of the BRDF: in cartesian coordinates (Fig. 1) and in cylindrical ones (Fig. 6**b**).

Results for oil-polluted sea area are divided into three cases for the following wavelengths: 420 nm, 550 nm and 700 nm. Figure 2 shows the BRDFs for sea area polluted by *Petrobaltic* crude oil as one-week-old in-water emulsion. Figure 3 – the same as in Fig. 2 but for a two-week-old emulsion. Analogical cases are presented in Figs. 4 and 5 but for *Romashkino* crude oil. Figure 6 shows the BRDFs for a reference sea area.

5. Discussion

Both solar light wavelength and the type of oil have an impact on the BRDF shape. If a wavelength is considered, one can notice that the values of the BRDF are relatively small at the ends of light spectrum in comparison with the BRDF obtained in the center of the spectrum. Generally, the presence of oil emulsion in the water causes a decrease of the BRDF as well as the modification of the shape of this function. It is characteristic that if a certain sea area is polluted by an oil emulsion the peak representing light backscattering appears. Such a peak does not exist in the BRDFs of reference seawater. The altitude of a backscattering peak is bigger in the BRDFs related to *Petrobaltic* transparent oil in comparison with the BRDF related to *Romashkino* oil. At the short wave end of the spectrum the BRDFs for *Romashkino* have very small peaks. This phenomenon occurs because the absorption coefficient of *Romashkino* oil emulsion has a relatively high value in relation to the scattering coefficient.

The above mentioned backscattering peaks for the reference sea area are invisible for any wavelength, however a small increase of the BRDF is noticeable around solar light direction (especially for $\lambda = 550$ nm). The phenomenon of the existence of backscattering peak for sea area polluted by oil-in-water emulsion shows the possibility of identifying oil pollution in the sea using the shape of the BRDF being analyzed. Comparing the BRDFs for one-week old (Figs. 2 and 4) and two-week-old (Fig. 3 and 5) emulsions one can notice that the oil droplet size distribution only slightly affects the BRDF.

The next benefit of modelling the BRDF is in the potential for the derivation of practically measurable reflectances like the irradiance reflectance or radiance reflectance. Those reflectances were numerically calculated using Eqs. (3) and (4). The radiance reflectance is higher in the middle than at the ends of the spectrum and also is higher for the reference water than for the polluted one. As mentioned in Sec. 2, the optical parameters a and b of polluted and reference water have the same values. Therefore, one should interpret the differences in R_L as a consequence of dissimilarity of phase functions. Namely, the differences in values of R_L observed in Fig. 7 are caused by the differences between phase functions of oil droplets and phase function of natural seawater components. Comparing values of R_L for two kinds of oil one can notice that when oil has low transparency (*Romashkino*-type) R_L takes lower value in comparison with more transparent oil (*Petrobaltic*). However, this difference disappears at long-wave end of light spectrum. On the other hand, if the irradiance

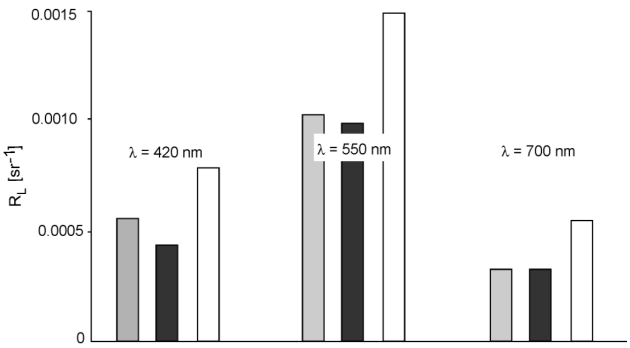

Fig. 7. Radiance reflectance of the sea areas polluted by oil-in-water emulsion (gray bars) and the same for the reference sea area (white bars). Bright gray bars relate to *Petrobaltic*-type oil, dark gray ones – to *Romashkino*-type oil.

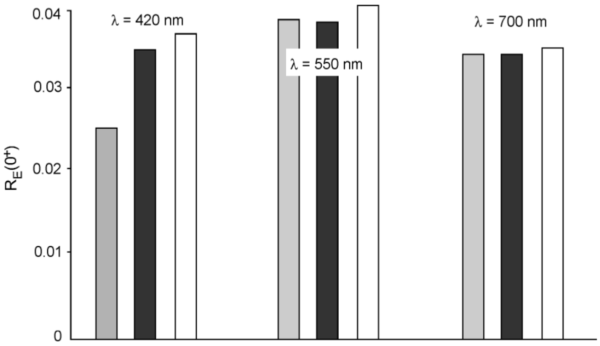

Fig. 8. Irradiance reflectance of the sea areas polluted by oil-in-water emulsion (gray bars) and the same for the reference sea area (white bars). Bright gray bars relate to *Petrobaltic*-type oil, dark gray ones – to *Romashkino*-type oil.

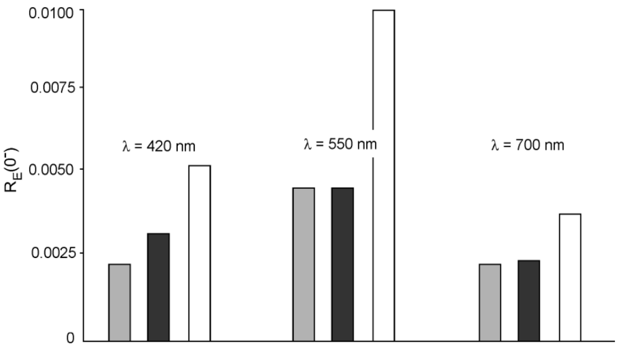

Fig. 9. Just below the sea surface irradiance reflectance of the sea areas polluted by oil-in-water emulsion (gray bars) and the same for the reference sea area (white bars). Bright gray bars relate to *Petrobaltic*-type oil, dark gray ones – to *Romashkino*-type oil.

reflectance R_E is considered (Fig. 8), values of R_E are higher for oil of low transparency – inversely to those for R_L (but only at short-wave end of light spectrum, because in the middle and long-wave end values of R_E are the same). More distinct differences in R_E are observed when photon receiver is positioned just below the sea surface, because the dazzle phenomenon induced by mirror-like reflection of the sun is then avoided. To estimate this effect also for such a case the underwater irradiance reflectance $R(0^-)$ was also determined (Fig. 9).

Values of $R(0^-)$ are almost 2 times higher for reference water than for the polluted water. It is worth noticing that during the investigation in real sea environment such measurement would not be possible by any distant method, because a sensor of $R(0^-)$ has to be immersed in the water. Additionally, in such a situation problems with self-shading of irradiance meter must be solved [14]. High accuracy of virtually measured R_L (Fig. 7) and R_E (Figs. 8 and 9) is achieved owing to the Monte Carlo model settings described in Sec. 3; it was confirmed that the dissipation of the results did not exceed 0.5%.

The only changes of the BRDF caused by oil emulsion were analyzed in investigation described in this paper. Analogous studies can be carried out also for other permanent or incidental components of sea areas, such as some plankton cells, air bubbles, sand-dust and unexpected contaminants. The efficiency of modelling the BRDF and consequently the modelling of the BRDF derivatives, *i.e.*, radiance reflectance and irradiance reflectance will depend on good knowledge of the inherent optical properties of all substances suspended in the bulk of water. These inherent optical properties include: absorption coefficient a, scattering coefficient b and phase function $p(\theta)$. At the same time it should be mentioned that the attenuation coefficient of water or a Secchi disc depth are insufficient for the BRDF modelling.

Methods presented in this paper can also be very useful for interpretation of the images of water areas, and will help with the reverse problem solutions (determination of water components using the shapes of the BRDFs). Investigation described in this paper could be conducted in estuary, lake and river waters, but under condition that the knowledge on inherent optical properties (IOPs) of such waters is more developed.

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