OCEAN OPTICS IN APPLICATION TO REMOTE DETECTION OF AN OIL-IN-WATER EMULSION ORIGINATING FROM THE ENGINE ROOM

Zbigniew Otremba

Gdynia Maritime University, Department of Physics
Morska Street 81-87, 81-225 Gdynia, Poland
tel.: +48 58 6901385, fax: +48 58 6206701
e-mail: zotremba@am.gdynia.pl

Kamila Rudź

Gdynia Maritime University, Department of Marine Engineering
Morska Street 81-87, 81-225 Gdynia, Poland
tel.: +48 58 6901385, fax: +48 58 6206701
e-mail: kamilar@am.gdynia.pl

Abstract

Relatively great number of detected and confirmed oil spillages in the Polish marine areas reveals that discharge of oil substances from any one of a large number of ships to the marine environment is real in any time. Surface oil contamination can be easily detected by satellite or airborne radar techniques, but unfortunately oil dispersed in the bulk of water cannot be detected at the present.

Discharge waters usually contain small amounts of oil substances in the form of dispersed droplets (emulsion). It is revealed that oil emulsion cause measurable changes in the optical properties of seawater. In practice, detection of changes of these properties should be possible by the standard radiance or irradiance reflectance meter. This paper presents a computed photon trace simulation applied to the marine environment polluted by oil-in-water emulsion. Model of marine area consists of whether conditions, sun elevation, sea depth, optical properties of seawater related to various transparency/turbidity: from clean oceanic waters to turbid coastal seawater (as water from Gulf of Gdańsk is). Model of oil pollution is represented by oil droplets size distribution and by spectra of both attenuation-coefficient and refraction-coefficient related to two optically absolutely different kinds of oil. It is revealed that the values of irradiance reflectance are significantly differ for the clean sea area in relation to the polluted one, even for small amounts of engine-room origin oil pollution.

Keywords: *environmental protection, oil pollution, engine room, ocean optics, Monte Carlo modelling*

1. Introduction

Marine environment is continuously exposed to the vessel exploitive materials which are various forms of oil, especially crude-oil and their residents in water, vessel engine lubricate-oils and fuel-oils. In the Baltic Sea area official indicators of oil pollution have been introduced as a result of the HELCOM recommendations. The indicating system consists of a number of spillages combined with a size of spillages detected thanks to the international air surveillance with remote sensing equipment [2]. It is revealed that hundreds of spills are registered every year in areas that are covered by routine aerial inspections in the Baltic Sea [3]. Similar number of spillages is detected in the sea area gardened by the west European countries in North Sea areas [1]. The whole area of European seas is covered by the system of satellite radar observation that helps in quick detection of sea areas possibly covered by oil-related substances. It is obvious that aerial inspections can detect only surface forms of oil (films), whereas oil substances can take various physical forms in the sea environment. Oil-in-water emulsions are the most popular forms of oil sunken in the sea. Emulsion can appear in the sea as a result of sea surface motion (waves) and after dispersants use when spillage is removed from the seasurface. Illegal dumping of oil dispersed in the waste water has also been reported.

There are various reasons to analyze optical phenomena in the oil-polluted sea environment. The principal questions are: oil pollution detection, type and form of oil qualifying, concentration or overall mass of oil as well as extension of polluted area estimation. A valid question also addresses the scale of oil disturbance on optical investigations of natural processes in marine environments.

Oil sunken in the sea water masses can be remotely detected only by optical method, because only visible light is able relatively easy penetrate the water column – if the bulk of water contains oil emulsion, diffuse part of above water radiance field is significantly modified. This phenomenon can be observed by plane or satellite detectors.

Both factors, oil film and oil emulsion can be investigated as above water light field modifier using so called Monte Carlo method. It is possible since optical features of oil films and emulsions are quantified. Oil films floating on the water surface are optically represented by four functions, i.e. transmittance and reflectance angular distributions, separately for upward and downward direction (every function for defined wavelength and thickness of oil film) [8], whereas oil emulsions are represented by light absorption coefficient and volume scattering function (both for defined wavelength) [12].

In relation to remote sensing full optical characteristics of both land and sea areas give the Bi-directional Reflectance Distribution Function (BRDF). The BRDF definition (expression 1) was proposed firstly by Nicodemus [4] to describe optical features of the land area. Equation 2 shows operational role of BRDF during transformation downward radiance angular distribution to upward one. The BRDF can be regarded as an operator which incident radiance distribution translates to reflected radiance distribution (Fig. 1).

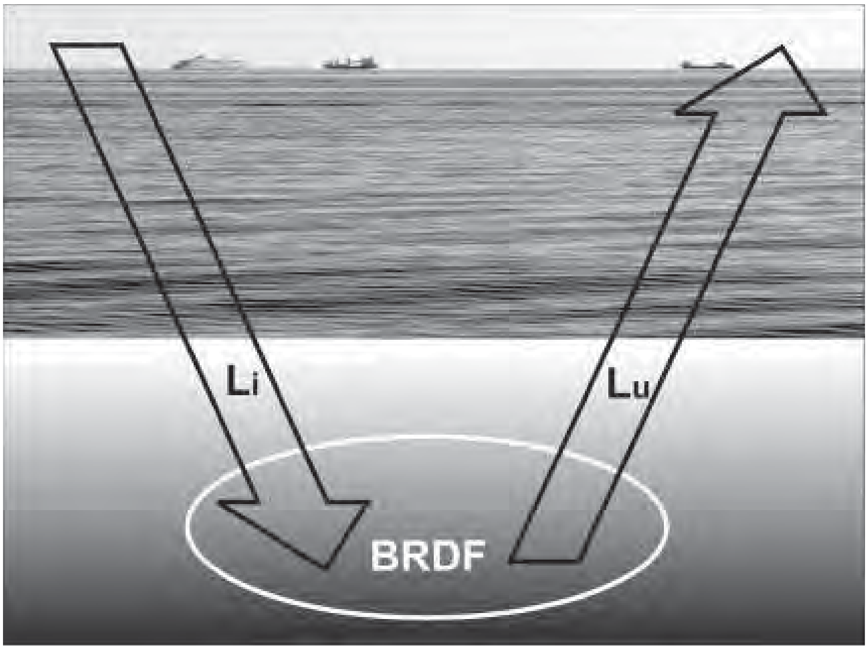

Fig. 1. General scheme illustrating the role of the BRDF in the ocean optics

The BRDF is a 5-dimentional function which holds information about optical features of defined areas of the world. Recently the BRDF was also applied for the sea area characterization [6-8].

The *Bi-directional Reflectance Distribution Function* (BRDF) belongs to the so-called inherent optical properties (independent of solar light condition) and can be treated as a fundament of all particular *'reflectance'* used in marine and terrestrial remote sensing like *'remote sensing reflectance'*, *'radiance reflectance'*, *'irradiance reflectance'* etc.

The BRDF definition (1) was firstly introduced by Nicodemus *et al*. [5].

$$f_r(\theta_r,\varphi_r,\lambda) = \frac{dL_r(\theta_r,\varphi_r,\lambda)}{dE_i(\lambda)}. \tag{1}$$

The above definition $dL(\theta_r,\varphi_r,\lambda)$ contains an infinitesimal change of upwelling *spectral radiance* caused by the infinitesimal change of *spectral vector irradiance* $dE_i(\lambda)$. At the same time $dE_i(\lambda)$ originates from directional light from strictly one direction θ_i,φ_i. Because the *downwelling irradiance* relates to defined direction θ_i,φ_i - this information can be included in the expression 1 [14, 15]:

$$f_r(\theta_i,\varphi_i,\theta_r,\varphi_r,\lambda) = \frac{dL_r(\theta_r,\varphi_r,\lambda)}{dE_i(\theta_i,\varphi_i,\lambda)}. \tag{2}$$

It is worth to state that E_i would not be integrated by angles θ_i and φ_i, because in that definition E_i is a spectrum of irradiance from only one defined direction θ_i, φ_i (the rest of hemisphere is black). In the measure practice one should assume that L_r is proportional to directional E_i – therefore following simplified form of definition of the BRDF (3) is admissible – so called nondifferential form of the average BRDF (3):

$$f_r(\theta_i,\varphi_i,\theta_r,\varphi_r,\lambda) = \frac{L_r(\theta_r,\varphi_r,\lambda)}{E_i(\theta_i,\varphi_i,\lambda)}. \tag{3}$$

The *reflectance – BRDF* has fundamentally ideal (mathematical) meaning and cannot be correctly measured when the sky is not black. However, the reflectance has a great meaning because “shackles” dozen or so reflective quantities [11].

$$f_r(\theta_i,\varphi_i,\theta_r,\varphi_r,\lambda) = \frac{dL_r(\theta_r,\varphi_r,\lambda)}{L_i(\theta_i,\varphi_i,\lambda)\sin\theta_i\ \cos\theta_i\ d\theta_i\ d\varphi_i\ d\lambda}. \tag{4}$$

Above differential expression can be transformed to the integral one (for define wavelength):

$$L_r(\theta_r,\varphi_r) = \int_0^{2\pi}\int_0^{\frac{\pi}{2}} f_r(\theta_i,\varphi_i,\theta_r,\varphi_r)\ L_i(\theta_i,\varphi_i)\ \ \sin\theta_i\ \ \cos\theta_i\ \ d\theta_i\ d\varphi_i\ , \tag{5}$$

where:
$L_r(\theta_r,\varphi_r)$ - reflected radiance,
$f_r(\theta_i,\varphi_i,\theta_r,\varphi_r)$ - 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

Unfortunately the BRDF is a quantity very hard to measure directly in aquatic environment, but fortunately there is a possibility to model the BRDF using the Monte Carlo method if fundamental inherent optical properties of waters (IOPs) and angular distribution of wave slops are known. The BRDF is currently not applied in operational oceanography. This sphere of knowledge is rather connected with next generation of satellites [10], as well as with other new remote sensing methods taking into consideration not only spectral dependencies but also directional distributions.

2. Methods

Determination of Both the Bi-directional Reflectance Distribution Function and optical contrast of sea areas polluted with oil-in-water emulsion demands several stages of investigations connected with various particular optical problems. The scheme of adequate works is showed in the Fig. 2.

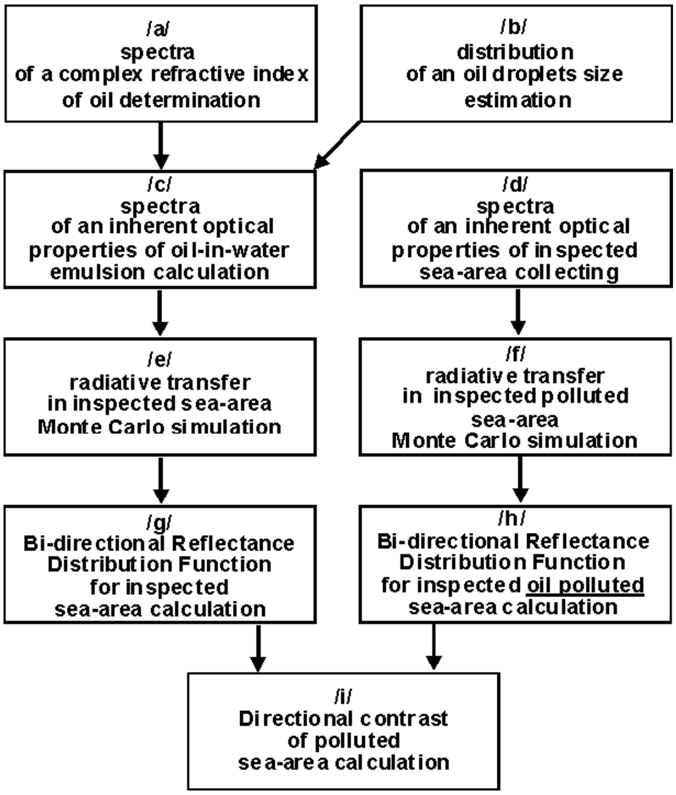

Fig. 2. General scheme of optical properties estimation of the sea-area polluted by oil-in-water emulsion

Avery stage of determination of the optical properties of the polluted sea-area can be briefly described as follow:

ad. a. Complex refractive index contains real part of refractive index called coefficient of refraction, and imaginary part called nondimentional absorption coefficient. Both are determined in the laboratory for various wavelengths and temperatures [7].

ad. b. Oil droplet size distributions are determined in the laboratory for artificially prepared emulsion of oil in seawater stabilized in conditions similar to natural ones [8]

ad. c. Spectra of inherent optical properties (IOPs) of oil-in-water emulsion are calculated using the so-called *Mie* solution. Correct results of IOPs of oil-in-water emulsions were published until 2004 [8]. The earlier published results were only rough ones.

ad. d. There is a serious problem with obtaining of IOPs of natural seawaters (insufficient number of measurements). In this paper the exemplary data for Gulf of Gdansk are used.

ad. e. Radiative transfer is simulated using the Monte Carlo code. Solar irradiance is simulated by one billion of virtual photons [12].

ad. f. Similar like stage e.

ad. g and h. The BRDF is calculated using the results obtained after radiative transfer simulation (stages d and e).

ad. i. The contrast is calculated using results obtained in stages g and h.

3. Selected results

Output data of radiative transfer simulation by the Monte Carlo method creates a matrix containing 1836 values of the BRDF. Every matrix has a dimension 51×36 (51 values of nadir angles and 36 values of azimuth angle). Simulations were carried out for various angles of solar light incidence.

Examples of final results are presented in Fig. 3, in which the BRDF for sea area polluted by oil-in-water emulsion polluted and for sea area free of oil are presented. Those results are related to low oil concentration ca. 1 cm^3 of oil in 1 m^3 of seawater (1 ppm).

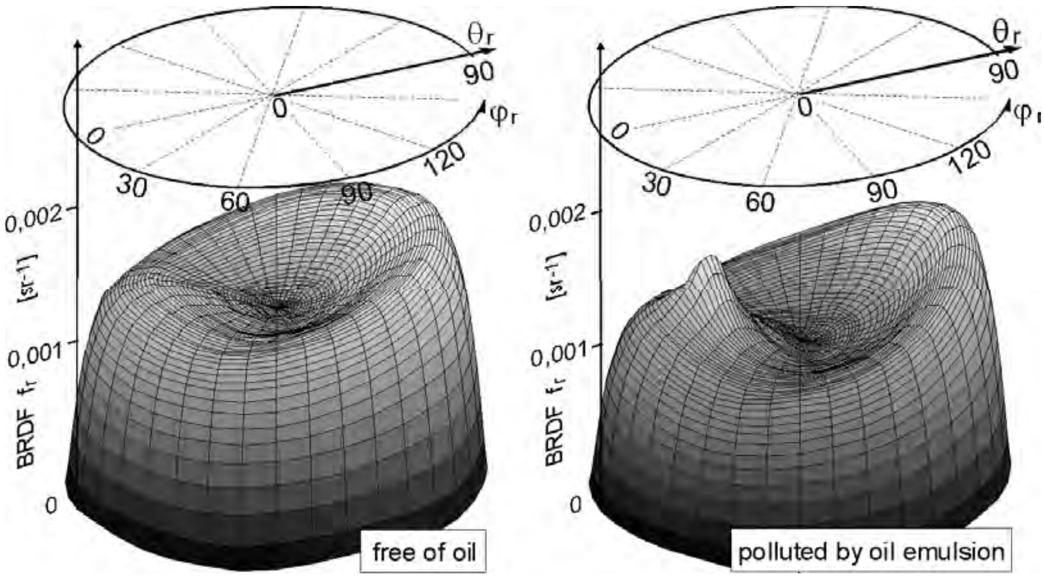

Fig. 3. The bidirectional reflectance distribution function (BRDF) of se a areas free of oil (the left) and of sea areas polluted by oil emulsion (the right). Modesl of investigated environment are related to coastal waters, angle of solar light incidence equal θ_i = 40°, wavelength λ = 550 nm

4. Discussion

Shapes of the BRDF are different for the sea areas free of oil and polluted by oil. Such fact gives expectance that optical contrast between polluted sea area and clean one should appear. Optical contrast derived using formula 2 is presented in Fig. 4.

$$C = \frac{f_{rp} - f_{rc}}{f_{rc}}, \tag{6}$$

where:

f_{rp} - BRDF for polluted sea area,

f_{rc} - BRDF for free of oil sea area.

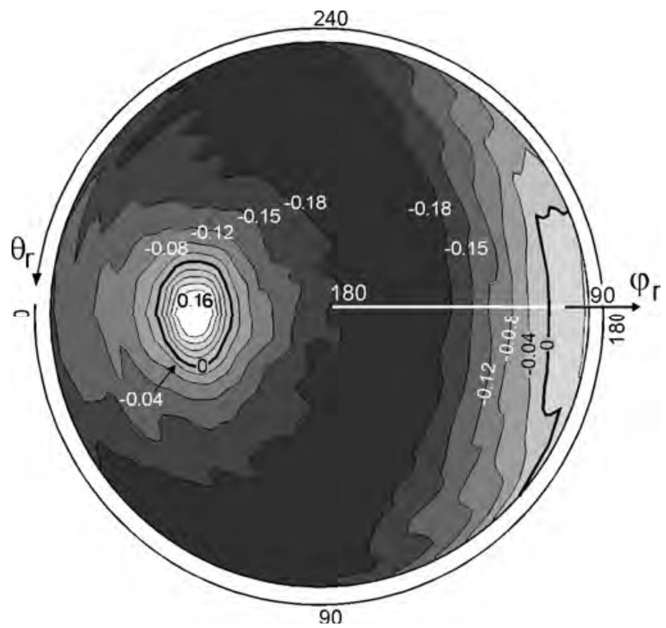

Fig. 4. Optical contrast modelled for the sea poll uted by oil-i n-water emulsion vs. one free of oil. Contrast was derived using results presented in Fig. 3 (diagram was published [13])

An example of the directional distribution of optical contrast displays possibility of prediction of visibility of oil immersed in the bulk of water but under a few conditions like knowledge of optical properties of seawater masses in defined area as well as optical properties of oil-in-water emulsions. On the other hand, if the BRDF measurement is possible in the future, the knowledge about the relationships between the BRDF shape and seawater constituents will help to identify various substances in the bulk of water.

Is there any possibility of oil-in-water emulsion detection in the bulk of sea? The answer can be 'yes' – but under two following conditions:

a) direction of observation is shackled with the solar light conditions,
b) concentration of oil is not so low.

ad. a. Analyses presented in this paper relate to the directional solar illumination under angle of 40°. Full information on the BRDF of the sea areas polluted with oil-related substances would demand more time consuming investigations.

ad. b. In this paper results for concentration of oil of 1 ppm is described.

Optical processes taken into consideration in described results were stressed to the light absorption and the light scattering. The light scattering is called sometimes 'nonelastic scattering' in distinction with the so-called 'elastic scattering' (when the energy of photons change appears - for example Raman scattering or fluorescence). Intensity of nonelastic scattering is relatively low in comparison with the other optical phenomena, therefore such scattering plays minor role in the determination of oil clouds in the bulk of water.

Optical processes considered in this paper relate itself to the so-called passive remote sensing (natural solar illumination). Absolutely different problem would involve the active remote sensing aspect in which artificial light (laser light) is used for optical ranging in the bulk of sea. Such investigations would be possible using lidar techniques, but unfortunately are not getting out successfully yet.

The above described procedure relates not only to oil substances in the bulk of seawater, but also to other natural or manmade suspensions and dilutions. It should be mentioned that the way of study of optical phenomena in the sea presented in this paper is rather new, and has been introduced to the ocean optics recently.

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