Use of polarization characteristics of upwelling radiation to isolate diffuse component of sea water reflectance

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The technique is described to isolate the diffuse component of the sea water reflectance by measuring the *S* and *P* polarization components of the upwelling radiation. This technique far extends capabilities of remote shipborne measurement of the chlorophyll A concentration from the ocean color and enhances their accuracy. In particular, it allows measurements at rough sea, overcast conditions, and at different sighting angles. Examples of applying this technique to field measurements of the chlorophyll A concentration are presented.

The nowadays state-of-the-art of aerospace instrumentation allows one to solve one of the most important problem of remote sensing, namely, determination of the global distribution of chlorophyll in the ocean and study of its dynamics. Starting from the mid-seventies, such studies are conducted with the use of optical scanners of the sea surface carried by satellites. Now the SeaWiFS spaceborne optical scanner is in operation. It measures the spectral composition of the upwelling radiation from the sea in six spectral channels of the visible region. Two more spectral channels in the far red are intended for measuring optical characteristics of the atmosphere. The SeaWiFS database is available on the INTERNET.

Despite a great number of algorithms for processing information from optical scanners developed by now, the algorithm of blue-green ratio is most widely used in the practice of satellite sensing. It is based on the empirical relation between the chlorophyll A concentration and the ratio of spectral bands of sea brightness in the blue-green spectral region. Since the ocean color depends on the content of not only chlorophyll, but also of dissolved organic matter and suspended particles (sediments), the algorithm of blue-green ratio can be used correctly only in the case of close correlation among these three components.

Ocean waters are classified based on how strongly the optical properties of the water depend on the chlorophyll content in it. The first type incorporates waters in which stable correlation is observed of the concentration of chlorophyll, with dissolved organic matter, and sediments. The open ocean is a typical case of water of the first type; the correlation is caused by the fact that all substances originate from biomass.[1]

The high degree of correlation between the elements determining optical properties of the sea water allows one to use rather simple empirical dependences with universal regression coefficients to calculate the chlorophyll content. These dependences are valid for great expanses of the Global Ocean. The coastal water is often classified as water of the second type. Actually, even in the coastal water phytoplankton, sediments, and yellow substance mostly correlate quite well,[2] but this correlation is subject to significant variability in space and time due to such phenomena as river water sewage, bottom deposits, and industrial wastes. By definition, the water of the second type is characterized by three independent concentration variables, but it is nothing more than an abstraction.

On the other hand, the algorithm of blue-green ratio cannot be directly applied to waters of the second type without correction of numerical parameters representing the variability of the coastal water composition. It is unlikely that universal algorithm can be developed for interpretation of data of a varying medium without restrictions on its variability range or without calibration measurements.

The algorithm is adapted to local conditions by joint remote and contact measurements of the chlorophyll A concentration. According to the traditional technique of remote measurement of chlorophyll in the sea water, the brightness of upwelling radiation is measured along nadir direction to the sea surface under clear sky conditions and calm sea. The condition of sensing along nadir direction practically does not allow optical measurements from on board a vessel, since the vessel body distorts the light field near the measurement area. For purposes of calibration from a ship, optical sensing is performed at some angle to the normal of the sea surface. To decrease the influence of light spots on the sensing results, the spectrometer sighting axis should lie in the plane of the solar vertical and be oriented outward the Sun. If the condition of nadir measurement is violated, then the recorded upwelling radiation includes a significant part of sky radiation specularly reflected from the sea surface. This part depends on both the sounding angle and the state of the sea surface and the sky. The error in separating out of the diffuse component coming from under the sea surface from the total upwelling light flux can give a significant error in determination of the chlorophyll A concentration. When using the algorithm of blue-green ratio, the 5% measurement error in the brightness of radiation upwelling from under the sea surface results in the error in the chlorophyll concentration more than 30% as high (Ref. 3). The problem of separating the light fluxes of the radiation reflected by sea into the diffuse (upwelling from under the sea surface) and specularly reflected components can be successfully solved by independent measurement of the *S* and *P* polarization components of the upwelling radiation.

The algorithm of blue-green ratio is based on the analysis of the spectral behavior of the sea water reflectance, which is determined by the brightness ratio of the radiation diffusely reflected by the sea $B_{-}(\lambda)$ (radiation upwelling from under the sea surface) to the intensity of the incident radiation $E_{\text{inc}}(\lambda)$:

$$R(\lambda) = B_{-}(\lambda)/E_{\text{inc}}(\lambda), \tag{1}$$

where the "–" subscript means that the sea brightness $B(\lambda)$ is only caused by the radiation coming from under the sea surface. The empirical equation, which is most widely used for calculating the chlorophyll A concentration, has the form[4]:

$$C_{\text{chl}} = 10^{a_1 + a_2 \log(R(490)/R(550))}, \tag{2}$$

where a_1 and a_2 are the regression coefficients; $R(490)$ and $R(550)$ are the sea water reflectance at the wavelengths of 490 and 550 nm.

The measured brightness, $B_{\text{m}}(\lambda)$, of the sea includes, besides $B_{-}(\lambda)$, the B_{s} and B_{ls} components as well. The component B_{s} is caused by the sky radiation specularly reflected from the sea surface. The component B_{ls} is caused by solar light spots and diffusely scattered radiation from foam on the sea surface. The spectral composition of the B_{ls} and E_{inc} components is the same, and their ratio is a spectral constant Δ (Ref. 5):

$$B_{\text{m}}(\lambda) = B_{-}(\lambda) + B_{\text{s}}(\lambda) + B_{\text{ls}}(\lambda), \tag{3}$$

$$B_{\text{ls}} = \Delta E_{\text{inc}}. \tag{4}$$

Thus, from Eqs. (1), (3), and (4) it follows that to determine $R(\lambda)$, one has to measure $B_{\text{s}}(\lambda)$, $E_{\text{inc}}(\lambda)$, and Δ in addition to the sea brightness.

The incident radiation intensity E_{inc} can be readily determined from the measured brightness of the diffuse Lambert surface set within the device's field of view. The spectral constant Δ can be determined from the condition that no radiation is upwelling from under the sea surface at the wavelengths longer than 700 nm:

$$R(\lambda > 700) = \Delta. \tag{5}$$

The B_{s} component is proportional to the sky brightness B_{sky}, which falls in the device's field of view after reflection from the sea surface:

$$B_{\text{s}} = rB_{\text{sky}}. \tag{6}$$

In the case of an even specular sea surface, the coefficient of proportionality r is equal to the Fresnel reflectance and can be calculated from the sighting angle (the angle between the normal of the sea surface and the sighting axis). In this case the sky area, whose brightness should be measured, can be determined quite readily. The sea water reflectance, according to Eqs. (1), (3), and (4), can be written as

$$R(\lambda) = [B_{\text{m}}(\lambda) - rB_{\text{sky}}]/E_{\text{inc}} - \Delta. \tag{7}$$

Let us determine R_{m} and R_{sky} as remotely measured reflectance of the sea water and the sky:

$$R_{\text{m}} = B_{\text{m}}/E_{\text{inc}}, \quad R_{\text{sky}} = B_{\text{sky}}/E_{\text{inc}}.$$

Then Eq. (7) takes the form

$$R(\lambda) = R_{\text{m}}(\lambda) - rR_{\text{sky}}(\lambda) - \Delta. \tag{8}$$

Reflecting properties of the rough sea depends not only on the sighting angle, but also on the wave slopes. One of the manifestations of the small-scale wind ripples in the device's field of view is the increasing contribution to the reflectance coming from elementary areas of the sea surface with smaller slopes. As a result, the contribution of higher sky area to the formation of radiation reflected by the sea surface increases too.[6] Having unknown characteristics of the sea roughness, it is difficult to determine the sky area for B_{sky} measurement and to calculate the sea surface reflectance. The use of the Fresnel reflectance calculated using the sighting angle can give significant errors in $B_{-}(\lambda)$ and, consequently, in the sea surface reflectance $R(\lambda)$. Equation (6) can be used successfully even with the sky area determined incorrectly if the coefficient r is determined from measurements, rather than calculated with the help of Fresnel reflectance, because the spectral composition of radiation scattered by the sky only slightly depends on the zenith angle. As an example, Fig. 1 shows the measured normalized spectra of the sky brightness at different sighting angles.

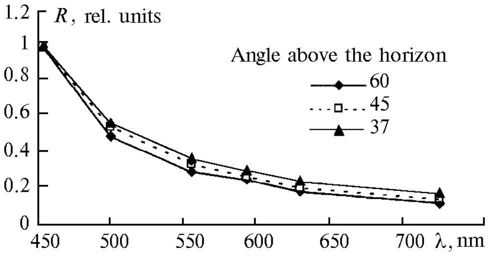


Fig. 1. Spectral behavior of the sky reflectance at different angles of observation.

Under real conditions of shipborne measurements, $R(\lambda)$ can be determined with the use of polarization properties of the upwelling radiation. In so doing, one should measure the S and P polarization components of the measured quantities. This can be done by setting a polarizer in front of the device's objective. It is well known that the radiation upwelling from under the surface is almost unpolarized if the brightness of the upwelling radiation is measured in the plane of the solar vertical on the side opposite to the Sun.[7] This means that the sea water reflectance $R(\lambda)$ is the same for the S and P polarization components. The polarization spectrophotometer we used for brightness measurements is capable of measuring the S and P polarization components of the upwelling radiation in six spectral channels each 20-nm wide and centered at 454, 500, 554, 590, 626, and 720 nm (Ref. 8). Based on the above-said and Eq. (8), we obtain a system of six equations (the number of spectral channels λ_i) relative to four unknown values r^s, r^p, Δ^s, and Δ^p :

$$R^s_{\text{m}}(\lambda_i) - r^s R^s_{\text{sky}}(\lambda_i) - \Delta^s = R^p_{\text{m}}(\lambda_i) - r^p R^p_{\text{sky}}(\lambda_i) - \Delta^p, \tag{9}$$

where the subscripts correspond to the polarization components.

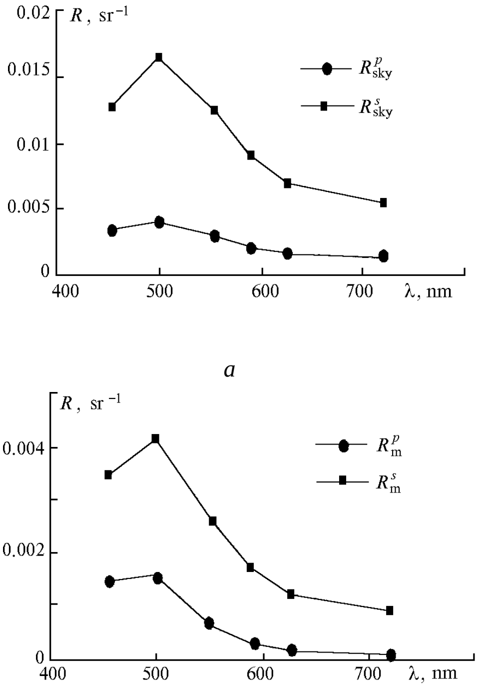
The system (9) can be solved by the method of least squares. It should be noted that upon solving of the system (9) we find the difference of the polarization components of the spectral constant $(\Delta^s - \Delta^p)$, rather than the components Δ^s and Δ^p themselves. Therefore, the values of Δ^s and Δ^p

should be determined from the condition (5). Substitution of thus found parameters in Eq (8) for the corresponding polarization component gives the spectral behavior of the sea water reflectance.

The results of application of the described procedure to obtaining the sea water reflectance from the data of polarization measurements are shown in Fig. 2.

Figure 2 shows the spectral behavior of the sky and sea water reflectance. The measurements were conducted under clear sky conditions in the plane of the solar vertical on the side opposite to the Sun. The angle of sight of the sea surface and the sky area is 70° as counted from the vertical to the sea surface. The angle of the Sun elevation above the horizon was 60°. The degree of polarization of the sky radiation was 0.6 (at the wavelength of 500 nm).

Figure 3 shows the results of reconstruction of the sea water reflectance $R(\lambda)$. The curves $R^s(\lambda)$ and $R^p(\lambda)$ were obtained for the *S* and *P* polarization measurements using Eq. (8) with r^s and r^p found from solution of the system of equations (9). The close agreement between $R^s(\lambda)$ and $R^p(\lambda)$ in the entire spectral region is indicative of the low degree of polarization of the radiation upwelling from under the sea surface and supports the efficiency of the proposed method.



a

b

Fig. 2. Polarization components of reflectance

The actual value of the sea water reflectance can be written as

$$R(\lambda_i) = R^p(\lambda_i) + R^s(\lambda_i) \approx 2R^p(\lambda_i),$$

where λ_i is the wavelength of light isolated with the *i*th spectral channel of the measuring device.

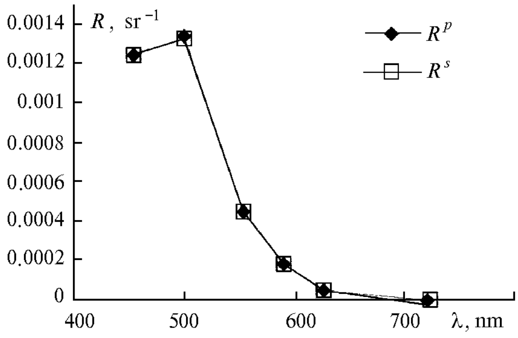


Fig. 3. Spectral curves of the components R^p and R^s of sea water reflectance obtained from measurement of the *P* and *S* polarization components.

Using the procedure of linear interpolation, we can find the values *R*(490) and *R*(550). Substitution of these values in Eq. (2) allows the chlorophyll A concentration to be estimated by the algorithm of blue-green ratio [with the values of the regression coefficients $a_1 = 0.444$ and $a_2 = -2.431$ (Ref. 4)]. For the considered example the chlorophyll concentration is $C_{\mathrm{chl}} = 0.14$ μg/l. The measurements of C_{chl} in samples of the near-surface water by the standard photometric method gave the value 0.1 μg/l.

It is interesting to compare the results of optical measurements of C_{chl} by the polarization technique with those obtained in the measurements using natural light. As an example, Tables 1 (clear sky) and 2 (overcast conditions) give the data on the chlorophyll A concentration obtained using optical measurements by the technique described in this paper in some regions of the Atlantic Ocean.

Table 1

Measurement conditions, measured parameters	Polarization measurement	Measurement in natural light
Local time	14:00	–
Cloudiness	0 ball	–
Degree of sky polarization	60%	–
Sighting angle (from normal to surface)	70°	–
Sun elevation	60°	–
Phytoplankton concentration (standard measurements)	0.1 μg/l	–
Phytoplankton concentration [estimation by Eq. (2)]	0.15 μg/l	0.19 μg/l
Relative deviation from standard measurements	50%	90%

Table 2

Measurement conditions, measured parameters	Polarization measurement	Measurement in natural light
Local time	10:00	–
Cloudiness	10 ball	–
Degree of sky polarization	6%	–
Sighting angle	53°	–
Sun elevation	35°	–

Phytoplankton concentration (standard measurements)	0.1 μg/l	–
Phytoplankton concentration [estimation by Eq. (2)]	0.13 μg/l	0.21 μg/l
Relative deviation from standard measurements	30%	110%

We have tested this technique using a long series of comparable data of optical and standard measurements of the chlorophyll concentration in various regions of the Atlantic, Indian, and Pacific Oceans under different weather conditions. In all these cases, the error of optical measurements was quite acceptable for measurements of such a kind. The proposed technique extends significantly the range of meteorological conditions suitable for optical measurements of the chlorophyll A concentration.

In conclusion, it should be noted that it is not strictly required to measure the brightness of the upwelling radiation in the plane of the solar vertical. In the case of violation of this requirement, one should take into account the degree of polarization of the diffuse component of the sea water reflectance in the system of equations (9). This only increases the number of unknown values to be found by solving this system of equations. Since we are restricted to six equations (six spectral channels of the measuring device), a new unknown variable can deteriorate the convergence of solutions obtained using the method of least squares. It was just the reason why we dealt only with the measurements conducted in the plane of the solar vertical.

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