Model of optical path for multispectral sensing of the marine environment

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Received March 15, 2000

We present a model of the optical path at sensing the seawater medium. The model is based on the two-flux approximation of the radiative transfer theory and a piecewise linear representation of the vertical distribution of admixtures. We also propose a method for solving the inverse problem of optical sensing. This method provides for reconstruction of the characteristics of the spatial distribution of admixtures in the near-surface layer of ocean waters.

For the full and efficient use of optical methods when studying the marine environment, adequate models of optical sensing paths are needed. In this paper we consider a model based on the two-flux approximation of the theory of radiative transfer and the piecewise linear approximation of the vertical distribution of admixtures. A method is proposed for solving the inverse problem of optical sensing. This method allows one to reconstruct spatial distribution of the admixture concentration in the near-surface layer of seawater with the resolution that is determined by the instrumentation used.[1–5]

The model and the method make use of the fact that variability of optical properties of the sea medium is caused by the presence of a finite number of admixtures in the form of suspensions and solutions in the “pure” seawater. Both the model and the method have been developed within the framework of the following assumptions:

– the two-flux approximation of the radiative transfer theory can be used[6,7];

– optical characteristics of the sea water (scattering coefficient, extinction coefficient, and others) are linear functions of the concentration of admixtures[8];

– the vertical distribution of optical properties of the seawater is approximated by a piecewise linear function of the depth (in particular, linear or piecewise constant one) (Ref. 2);

– factors that can distort the results of multispectral photometric measurements (state of the atmosphere and sea surface in the region under study,[2] instrumental functions, and others) do not change during the measurements;

– the spectral regions used are narrow enough ($\Delta\lambda/2 \sim 10$ nm);

– each of the optical parameters of the seawater can be presented in the following form:

$$P_n(\lambda, z) = P_{n0}(\lambda) + \sum_{k=1}^{K} P_{nk}(\lambda)\, C_k(z), \qquad (1)$$

where $P_n(\lambda, z)$ is the nth optical parameter at the wavelength λ and the depth z; $P_{n0}(\lambda, z)$ is the corresponding parameter of the “pure” seawater; $C_k(z)$ is the concentration of the kth admixture at the depth z; $P_{nk}(\lambda)$ is the contribution of the kth admixture to the value of the nth parameter at its unit concentration; K is the total number of admixtures taken into account in the model;

– the vertical distributions of the concentrations of optically active admixtures are approximated by the following model:

$$C_k(z) = T_{ki}(z - Z_{i-1}) + Y_{ki}, \quad z \in [Z_{i-1}, Z_i], \qquad (2)$$

where $i = 1, M + 1$, $Z_0 = 0$, $Z_{M+1} < \infty$; $M + 1$ is the number of layers in the considered model; Z_i is the depth of the lower boundary of the ith layer; Y_{ki} is the concentration of the kth admixture at the Z_{i-1} level; T_{ki} is the gradient of concentration of the kth admixture in the ith layer.

The model of vertical distribution of the admixture concentrations (2) and the model arrangement of the experiment on multispectral optical sensing are shown in Fig. 1.

Within the framework of the above assumptions, the equation for the coefficient of diffuse reflection of the near-surface sea layer was derived (at $T_{ki} \equiv 0$):

$$R(\lambda) = E_\uparrow(\lambda)/E_\downarrow(\lambda) = \frac{1}{2}\left[\frac{B_1(\lambda)}{A_1(\lambda)} + \sum_{i=1}^{M}\left\{\left(\frac{B_{i+1}(\lambda)}{A_{i+1}(\lambda)} - \frac{B_i(\lambda)}{A_i(\lambda)}\right)\times \right.\right.$$
$$\left.\left.\times \exp\left(-2\sum_{m=0}^{i-1}\{A_{m+1}(\lambda)(Z_{m+1} - Z_m)\}\right)\right\}\right], \qquad (3)$$

where

$$A_i(\lambda) = \mu^{-1} \times$$
$$\times\left(a_w(\lambda) + \phi_w(\lambda) b_w(\lambda) + \sum_{k=1}^{K}\{a_{0k}(\lambda) + \phi_{0k}(\lambda) b_{0k}(\lambda)\} Y_{ki}\right);$$

$$B_i(\lambda) = \mu^{-1}\left(\phi_w(\lambda) b_w(\lambda) + \sum_{k=1}^{K}\{\phi_{0k}(\lambda) b_{0k}(\lambda)\} Y_{ki}\right); \qquad (4)$$

$a_w(\lambda)$ is the absorption coefficient of an elementary volume of the “pure” seawater; $b_w(\lambda)$ is the scattering coefficient of an elementary volume of the “pure” seawater; $a_{0k}(\lambda)$ is the specific absorption coefficient of the kth admixture; $b_{0k}(\lambda)$ is the specific scattering coefficient of the kth admixture; $\phi_w(\lambda)$, $\phi_{0k}(\lambda)$, and μ are tabulated parameters used in the two-flux approximation.[9]

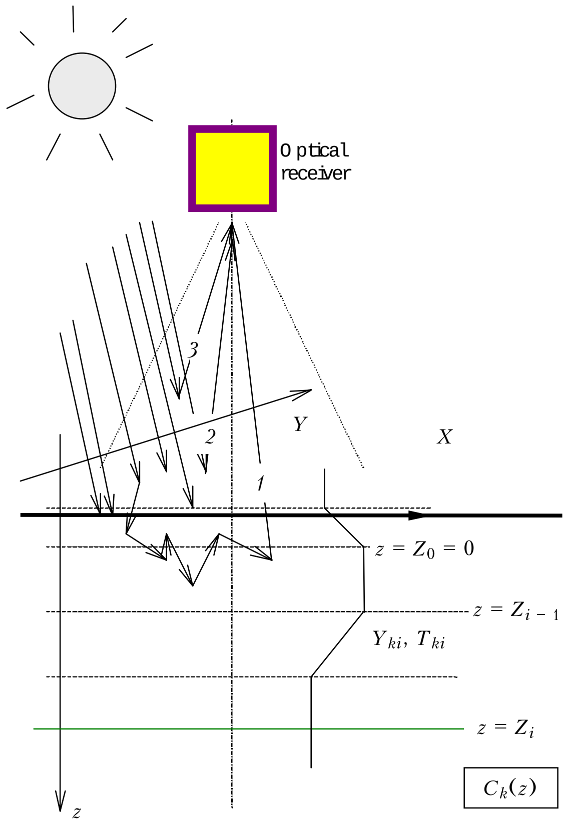

Fig. 1.

Equation (3), with due regard for the relation $\Delta z_n = z_n - z_{n-1}$, is similar to Eq. (2) derived in Ref. 10. The difference is that Eq. (3) uses the coefficients $A_i(\lambda)$ and $B_i(\lambda)$ related through Eqs. (4) to the parameters of the model, whereas Eq. (2) includes only the characteristics $k_{di}(\lambda)$ and $b_{bi}(\lambda)$. Therefore, for the model calculations to agree with the experimental data, the model parameters were taken so that $A_i(\lambda) = k_{di}(\lambda)$ and $B_i(\lambda) = b_{bi}(\lambda)$.

Equation (3) makes the basis both for simulating the variability of the diffuse reflection coefficient $R(\lambda, \mathbf{r})$ at the given perturbations of the parameters T_{ki}, Y_{ki}, and Z_i and for the method of determination of these parameters at all points $\mathbf{r}$ of the region under study, at which the upwelling irradiance at the sea level $E_{\uparrow}(\lambda, \mathbf{r})$ was measured.

The main idea of the proposed model and method can be illustrated using a simple example. Let only one admixture be present in the sea, and it is distributed over the depth so that there are three layers with different but constant (independent of horizontal coordinates and time) concentrations of the admixture. The only parameter that depends on the coordinates and time is the depth of the interface between the first (upper) and the second layers Z_1. It is assumed that its fluctuations are connected with the presence of the inner waves in the sea depth. Using Eq. (3), it is easy to obtain the form of $R(\lambda, \mathbf{r})$ with contributions from scattering in the atmosphere and reflection from the sea surface. The 2D pattern of $R(\mathbf{r})$ at a given λ can be found in Ref. 5. It was proposed, in this reference, to model the “actual” pattern of the upwelling irradiance $E_{\uparrow}(\lambda, \mathbf{r})$ taking into account the contributions coming from the following factors:

– radiation multiply scattered in the sea depth (*1* in Fig. 1);

– radiation reflected from the air-water interface (*2* in Fig. 1);

– radiation scattered in the atmosphere (*3* in Fig. 1).

Thus, $E_{\uparrow}(\lambda, \mathbf{r})$ in one spectral channel (with the central wavelength λ) was modeled as

$$E_{\uparrow}(\lambda, \mathbf{r}) = \xi(\lambda, \mathbf{r})\,[R(\lambda, \mathbf{r}) + \zeta(\lambda, \mathbf{r})]; \qquad (5)$$
$$\xi(\lambda, \mathbf{r}) = \xi(\lambda) + \delta\xi(\lambda, \mathbf{r}); \quad \zeta(\lambda, \mathbf{r}) = \zeta(\lambda) + \delta\zeta(\lambda, \mathbf{r}),$$

where $\delta\xi(\lambda, \mathbf{r})$ and $\delta\zeta(\lambda, \mathbf{r})$ are small as compared with $\xi(\lambda)$ and $\zeta(\lambda)$.

Let us now consider some aspects and examples of solution of the inverse problem of optical sensing. In the general case, solution of the inverse problem of optical sensing is based on the fact that the function $R(\lambda; x, y, z_0) = E_{\uparrow}(\lambda; x, y, z_0)/E_{\downarrow}(\lambda; x, y, z_0)$ – the coefficient of diffuse reflection of the seawater ($z_0 = 0$), can be found from the data of optical measurements in N spectral regions. At $N \geq 2K(M + 1) + M$ the set of equations (3) can be solved for the λ-independent parameters T_{ki}, Y_{ki}, and Z_i characterizing the vertical distribution of admixtures using ordinary methods of solving systems of equations.

If the accepted model of the vertical distribution of admixtures (in this case, pigments of phytoplankton – chlorophyll) is adequate to the actual situation, and the variability of R (λ = 443 nm) is caused only by the displacement of the upper boundary of the layer z_1, then it is easy to determine the variability z_1 from the results of optical sensing (measurements of $R(\lambda)$) (curve $Z1a$ in Fig. 2).

However, under condition (5) the attempt to determine the variability z_1 only from the results of passive remote optical sensing is a typical example of the ill-posed inverse problem[8] (curve $Z1b$ in Fig. 2).

The idea of the proposed method[1] for reconstructing the spatial distribution of admixture concentrations from the data of multispectral optical sensing of the sea depth is to complement these data with data of experimental measurements of the vertical distribution of optical parameters of the seawater at some reference points in the region under study.

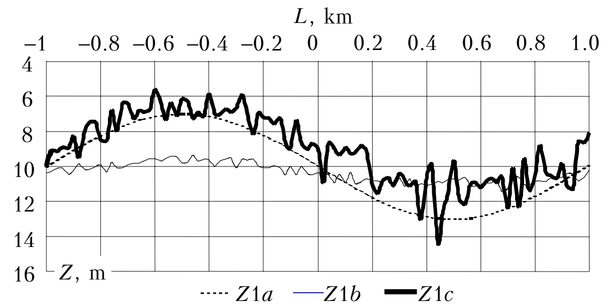

Fig. 2. Variability $z_1(x) = Z1$ reconstructed from data on $R = R(\lambda = 443$ nm$)$ value. The horizontal axis is the distance L, in km, measured from the conditionally chosen origin of coordinates in the direction of the wave vector of the background inner wave. The vertical axis is the depth Z, in m.

These data can be obtained from contact sensing (with the use of wel sensors) or active (laser) sensing. As an example, Fig. 3 shows the calculated dependence of the backscatter intensity on the depth of the near-surface chlorophyll layer. This dependence models (by the Monte Carlo method) the laser sensing data for the stratification given in Fig. 2 of Ref. 11 and for the following values of hydrooptical characteristics:

for $\lambda = 443$ nm

− total scattering coefficient is assumed to be the same for both layers, $c_1 = c_2 = 0.3$ m^{-1};

− absorption coefficient is $a_1 = 0.05$ m^{-1} for upper layer and $a_2 = 0.1$ m^{-1} for lower layer;

for $\lambda = 550$ nm

− total scattering coefficient is $c_1 = c_2 = 0.3$ m^{-1} for both layers;

− absorption coefficient is $a_1 = a_2 = 0.05$ m^{-1} for both layers.

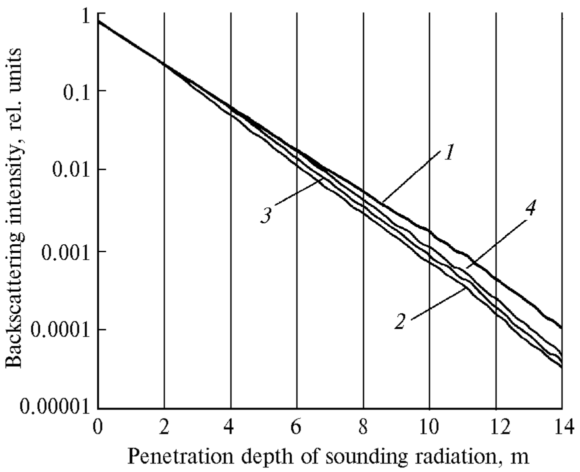

Fig. 3. Backscattering intensity as the chlorophyll layer is at the depth of 2, 4, and 6 m with respect to the layer of the reference signal.

Curve *1* corresponds to the reference channel (i.e., sensing radiation wavelength of 550 nm), in which the contribution of chlorophyll absorption is negligibly small. Therefore, its character does not change as the near-surface chlorophyll layer submerges. Curves *2–4* correspond to the similar dependences for the working channel (with the wavelength of 443 nm in the most intense chlorophyll absorption band) at different depth of the upper boundary of this layer: 2, 4, and 6 m. Each of these curves starts to deviate from the reference curve *1* at the depth corresponding to the position of this boundary. The *a priori* (additional) information obtained in such a way provides for a possibility of significantly improving the stability and reliability of the solution of inverse problem of remote optical sensing.

In particular, it can be used for the development of the methods for correction of measured data that significantly decrease the influence of noise. These methods and algorithms are beyond the scope of this paper. Nevertheless, as an illustration, Fig. 2 shows the pattern of the horizontal variability $z_1 = Z1c$ obtained by applying the processing methods and algorithms. Of course, the "ideal" pattern ($Z1a$) is not reproduced. However, the attention should be paid to the fact that without a correction one may obtain results looking like actual ones, while being doubtful in fact (cp. $Z1a$ with $Z1b$ and $Z1c$).

The considered approach is also used within the framework of more complicated models of the spatial distribution of optical properties of the seawater. The anomalies in the distribution may be caused by perturbations of hydrophysical parameters of the seawater of both natural and anthropogenic origin.

Thus, the presented results of modeling the optical sensing paths allow the capabilities of multispectral optical methods to be extended as applied to the study of the marine environment.

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