On a possibility of remote evaluation of some optical properties of sea-water*

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Abstract

A simple method of remote quantitative evaluation of the ratio of back-scattering to absorption of light in sea water is presented. Two basic concepts have been developed, the first one about remote determination of surface effects using the measurements in near infrared as a reference point, and the second one about the measurement of azimuthally averaged angular distribution of incident radiance.

1. Introduction

Generally, in remote sensing two basic methodological problems can be distinguished. The first one concerns the separation of the component containing useful information from the background. The second one will be extraction of the information being looked for. As far as the first problem is concerned, the ratio of respective signals depends strongly on actual external conditions and may vary in quite a wide range. Practically, only after determining the background it is possible to go on further with solving the entire task, which is to obtain an information about the medium without touching it.

Here the problem is narrowed to passive sensing just above the sea surface, with the aim to obtain the value of some inherent optical parameters of the homogeneous water. In addition to the upward vertical radiance, the angular distribution of atmospheric sea-level radiance is also assumed to be known, since it can be measured without contact with the water. The background here will be the upward radiance reflected from the water surface.

2. Surface effects

The first of general simplifying assumptions concerns the sea surface state. It is assumed that no foam is formed during waving and the slopes have the Gaussian distribution, being axially symmetrical. The latter assumption is very useful, for it

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allows to substitute the full angular distribution of incident radiance by the distribution averaged over the azimuthal angle, denoted as $\bar{L}_0(\mu)$, where μ is cosine of the zenith angle. The surface state parameter coming into consideration will be dispersion of wave slopes distribution σ^2, and the optical parameter of the water to be determined will be the ratio of backscattering to absorption coefficients, denoted as $\eta = b_b/a$.

Generally, the relationship between the upward vertical radiance $\bar{L}_u$ and the quantities mentioned above may be written as follows:

$$L_u = \int_0^1 \bar{L}_0(\mu) R_F(\mu, \sigma) \mathrm{d}\mu + \int_0^1 \bar{L}_0(\mu) R_D(\mu, \sigma, \eta, p) \mathrm{d}\mu, \tag{1}$$

where

$$\int_0^1 \bar{L}_0(\mu) R_F(\mu, \sigma) \mathrm{d}\mu = L_1 \tag{1a}$$

is the radiance reflected from the water surface and

$$\int_0^1 \bar{L}_0(\mu) R_D(\mu, \sigma, \eta, p) \mathrm{d}\mu = L_2 \tag{1b}$$

is the radiance scattered underwater, where:

R_F, R_D – reflection functions summarizing all the environmental effects leading to creation of the radiances L_1 and L_2, respectively,

p – scattering phase function, which generally must not be omitted as an inherent optical property of water.

The solution of the problem consists in finding from equation (1) the inverse function, giving values of the parameter η as a quasi-function of L_u. The first difficulty consists in the fact that only the sum of radiances L_1 and L_2 can be measured directly from above the water and the radiance L_2 is an implicit function of the ratio η. The radiance L_2 can be determined if the radiance L_1 is known, as:

$$L_2 = L_u - L_1 . \tag{2}$$

The first methodical proposal concerns a direct measurement of the radiance L_1, reflected from the surface. For this purpose, the two features of radiance transfer in water prove to be very useful. One of them is a sharp increase of light absorption when the wavelength shifts toward the red end of spectrum and farther (Jerlov, 1976), which causes a fast decrease of the ratio $\eta = b_b/a$. Another feature, shown further in the paper and confirmed experimentally using the reflection function R as an example (Morel, Prieur, 1977), is almost linear decrease of the upward radiance L_2 scattered under-water, with the decrease of the ratio of back-scattering to absorption coefficients (Gordon, 1977, 1978; Gordon, Brown, Jacobs, 1975). Taking the above into account, one can say that for the wavelengths longer than – let's say – about 700 nm, in the measured total upward radiance L_u, the component L_2 becomes very small (Plass, Kattawar, 1975) and thus may be neglected. After denoting with an asterisk the values of radiances for such wavelengths, it is possible to write:

$$L_1^* = L_u^*, \tag{3}$$

which means that the reflected radiance is approximately equal to the total measured radiance.

Now the expression for the reflection function R_F should be written more explicitly. Due to the assumption of the surface slope distribution being the symmetrical Gaussian one, with dispersion σ^2, it is possible to write the function R_F in the following form (see the transfer function k_{1w} – Olszewski, 1981):

$$R_F = G(\mu) \cdot x \cdot [F(\mu)]^x, \tag{4}$$

where $x = \sigma^{-2}$. Introducing it into equation (1a) we have:

$$L_1^* = \int_0^1 \bar{L}_0^*(\mu) G(\mu) \cdot x [F(\mu)]^x \mathrm{d}\mu. \tag{5}$$

The x value can be found with the help of one of known numerical methods for solving such types of equations. Here the Newton-Raphson method has been chosen, as a fairly rapid and requiring no special conditions (Margenau, Murphy, 1956). In the method, a function of x must be constructed from equation (1) as follows:

$$f(x) = \int_0^1 \bar{L}_0^*(\mu) G(\mu) [F(\mu)]^x \mathrm{d}\mu - \frac{L_1^*}{x} \tag{6}$$

and its first derivative, which happens to be easy for calculation:

$$f'(x) = \int_0^1 \bar{L}_0^*(\mu) G(\mu) \ln F(\mu) [F(\mu)]^x \mathrm{d}\mu + \frac{L_1^*}{x^2}. \tag{7}$$

The n-th approximation of the x value is then obtained as:

$$x_n = x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})}. \tag{8}$$

Possible divergence of the solutions, *ie* when $|x_0 - x_1| < |x_1 - x_2|$, indicates wrong selection of the initial value of $x = x_0$ and can be improved by introducing it again as a mean: $x_0^* = 0.5(x_0 + x_1)$.

Since the value of x, being in a sense a parameter of the sea surface state, does not depend on the wavelength of light, so the upward reflected radiance L_1 for the wavelength of interest may be calculated from equation (1a):

$$L_1 = \int_0^1 \bar{L}_0(\mu) G(\mu) x_n [F(\mu)]^{x_n} \mathrm{d}\mu \tag{9}$$

and now the value of the scattered radiance L_2 may be regarded as known ($L_2 = L_u - L_1$).

It should be pointed out, however, that the x (or σ^2) parameter does not have any strict dynamic meaning because, in the first place, the real distribution of wave slopes is not axially symmetrical (apart from the trivial case of a flat surface). The parameter discussed should only be regarded as an equivalent of the real distribution parameters. This is the equivalent describing a hypothetical water surface, related to the real surface by producing, in the same field of incident radiance, the same quantity of radiance reflected vertically upward (and only vertically). Of course, the last limitation is of no great importance as an obstacle in the method considered. In fact, only the vertical components of upward radiance field are looked for, and the parameter of the hypothetical slope distribution is introduced temporarily into the calculations, with the only aim to determine one of those vertical components.

3. Optical parameters of water

The next step now will be an extraction of the value of ratio η from equation (1b). In the first place, we should try to separate the diffuse reflection function R_D into a term dependent on the optical parameters of the water only, and a term independent of them. For this reason, it is possible to write the function R_D as (see the transfer function k_2 – Olszewski, 1981):

$$R_D = T_s(\mu, \sigma) X(\eta, p) \cong T_s(\mu) X(\eta, p), \tag{10}$$

where T_s denotes a total effective downward and upward transmission function, describing the changes of radiance when passing the water surface and it is assumed to be a weak function of the surface state.

The function sought for is the $X(\eta, p)$ function, which we can write now as:

$$X(\eta, p) = L_2 [\int_0^1 \bar{L}_0(\mu) T_s(\mu) d\mu]^{-1}. \tag{11}$$

The above expression may just be regarded as an exact solution of the inverse problem put at the beginning. However, the η parameter remains concealed in the X function. A reasonable approach is then to determine the analytic form of the function $X(\eta, p)$. This can be achieved by using some simplified solutions of the radiative transfer equation. The quasi-single scattering approximation (Gordon, Brown, Jacobs, 1975; Plass, Humphreys, Kattawar, 1978) was chosen here as one of the simplest solutions. It yields the values of the radiance L_2 in the following manner:

$$L_2 = \int_0^1 \bar{L}_0(\mu) f(\mu) \omega_0' p'(\gamma) d\mu, \tag{12}$$

where scattering phase function $p'(\gamma)$ can be assumed as:

$$p'\left(0 \leqslant \gamma < \frac{\pi}{2}\right) = 0,$$

$$p'\left(\frac{\pi}{2}\leqslant\gamma<\pi\right)=\frac{1}{2\pi}, \tag{13}$$

from which we have:

$$\omega_0'=\frac{b'}{a+b'}=\frac{b_b}{a+b_b}=\frac{\eta}{1+\eta}. \tag{14}$$

Returning to equation (12), we obtain:

$$L_2=\int_0^1 \bar{L}_0(\mu)\left[\frac{f(\mu)}{2\pi}\right]\left[\frac{\eta}{1+\eta}\right]\mathrm{d}\mu, \tag{15}$$

where:

$$\frac{f(\mu)}{2\pi}=T_s(\mu), \tag{16}$$

and the looked for function $X(\eta, p)$ is given by the expression:

$$X(\eta, p)=X(\eta)=\frac{\eta}{1+\eta} \tag{17}$$

and finally:

$$\eta=\frac{X}{1-X}, \tag{18}$$

which is even simpler for $\eta\ll1$, since then:

$$\eta\cong X. \tag{19}$$

Strictly, a physical meaning of the parameter η finally obtained differs somewhat from that of the real inherent property represented by the ratio b_b/a, due to a simplified method used to find it. In fact, it should be considered as an equivalent of the real ratio mentioned, yielding under the assumed simplified conditions the value of upward vertical radiance equal to that actually existing. The accuracy of the approximation can be slightly improved by introducing some shape factor for back part of the phase function $p'(\gamma)$, initially assumed to be an isotropic one. However, the other simplifications of the quasi-single scattering model remain unchanged and the second parameter to be determined will appear (*ie* the shape factor, which seems to be of not much importance in comparison with the ratio b_b/a–(Gordon, Brown Jacobs, 1975; Olszewski, 1985). Hence, the method presented would remain limited to one parameter characterization of the medium, but because of all the above remarks it is called an evaluation method rather than the method of determination of optical properties.

4. Incident radiance

To complete the described method of remote sensing, one should present a possibility of the measurements of the angular distribution of incident radiance coming into calculations as averaged over the azimuthal angle. A proposal of such a measurement employs the definition of irradiance (Jerlov, 1976), from which the following relation may be obtained:

$$E(\mu)=2\pi \int_{\mu}^{1} L_0(\mu)\,\mu\,\mathrm{d}\mu\,, \tag{20}$$

which leads to the expression for $\bar{L}_0(\mu)$:

$$\bar{L}_0(\mu)=-\frac{1}{2\pi}\frac{\mathrm{d}E(\mu)}{\mu\,\mathrm{d}\mu}\,. \tag{21}$$

Thus, the determination of the radiance distribution $\bar{L}_0(\mu)$ requires the knowledge of variations of $E(\mu)$. An optical system (see Fig. 1) measuring this quantity consists of a flat irradiance collector of diameter d and a cylindrical collimator of diameter D with variable height h, limiting the collector field of view. The irradiance falling on the collector from the truncated solid angle, contained in the cone of height h and base diameters D and d, is recorded as a function of h, the latter being related to the zenith angle of the incident radiance.

The accuracy of reproduction of the real radiance distribution improves with the decrease of the ratio d/D. By a detailed analysis of the system it can be proved (Olszewski, 1984) that with the collector diameter about one order of magnitude smaller than that of a collimator, the system reproduces the needed radiance distribution quite satisfactorily. The only dependence necessary for the calculations is then the geometrical one, relating the cosine of view angle μ to an actual height (h) of the collimator:

$$\mu(h)=\cos\left[\operatorname{arctg}\left(\frac{D}{2h}\right)\right]. \tag{22}$$

The method of measurement of the incident radiance distribution has some influence on the means of solving all the introduced integrals. Generally, all of them could be solved using an arbitrary known method. But in the case of a discrete measurement of the radiance distribution, *ie* when:

$$\bar{L}_0(\mu)\cong\bar{L}_0[\mu(h_i)]=\bar{L}_0(\mu_i)=\bar{L}_{0i} \tag{23}$$

the method consisting in replacing the integrals of proper functions $\varphi(\mu)$ by the sums of discrete functions $\varphi_i=\varphi(\mu_i)$ can be employed.

5. Technique

To meet all the requirements discussed, a special meter has been designed and is under construction. It allows a spectral measurement of the atmospheric downward radiance distribution, averaged over the azimuth, as well as upward vertical radiance coming up from the sea. A schematic diagram of the instrument, shortly called the radiance distribution meter, is presented in Figure 1. A general outline of its optical system just has been described. As for some technical details, they are specified in figure caption.

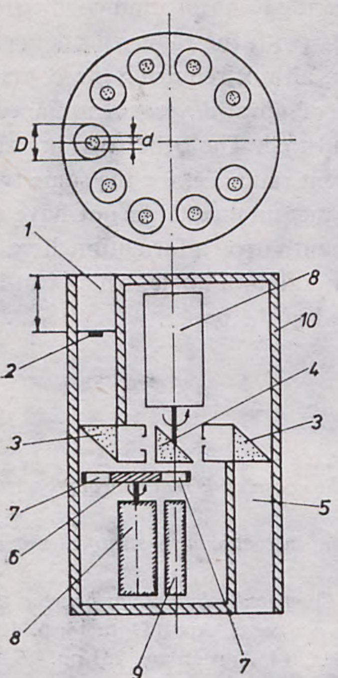

Fig. 1. Schematic diagram of a radiance distribution meter; upper part – downward view, lower part – vertical cross section
1 – downward irradiance collimators, **2** – downward irradiance collectors, **3** – fixed prisms, **4** – rotating prism, **5** – upward radiance collimator, **6** – rotating target with filters, **7** – interference filters, **8** – motors, **9** – photodetector, **10** – cable input

Some important parameters are as follows. The ratio of collector (*2*) to collimator (*1*) diameters d/D is fixed as 1 : 10. Collimator (*1*) height h is varied for every collimator. Due to this, the rotating prism (*4*) successively selects nine upward view angles $\vartheta = \arccos \mu$: 5°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 90°, plus one downward view angle: 5°. Changes of the angles occur with fast continuous rotation of the prism (*4*), so selection of the geometrically proper measuring moments has to be done electronically.

No such need occurs when the wavelength of light is changed, because this is performed by gradual movements of the disk (*6*). It stops, for an arbitrary time, every 60° of a turn, and then one of the six interference filters is placed between a prism (*4*) and a photodetector (*9*). The filters (*7*) in the disk can be exchanged if such a need arises.

In the single optical system for upward radiance (*5*) no lambertian collector is used. This diminishes the difference between the upward and downward radiance levels at the photodetector surface. A similar effect for the downward radiance field is obtained by increasing the distance of collectors (*2*) to a photodetector when the view angle increases.

Other data will be the subject of a separate paper, after completing and testing the apparatus.

6. Conclusions

On the basis of the above discussion one can conclude that the method presented above, apart from its all simplifying limitations, allows the quick and technically easy quantitative evaluation of the ratio of back-scattering to absorption coefficients of the sea water, under conditions of moderate winds (with the foam effects negligible). The set of four measurements is needed for it, all not requiring the contact with water. The two of them are the measurements of upward vertical radiances, one for the wavelength examined and one in near infrared. The other two are the measurements of the angular distribution of the incident radiance, for the same two wavelengths. In the method described the latter two measurements do not have to give a full angular distribution. The only needed quantitative information here is the distribution of incident radiance averaged over the azimuth angle, which can be performed automatically by an optical device described in the paper.

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