The Nature of Optical Remote Sensing Coefficient

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ABSTRACT

The remote sensing coefficient or radiance reflection coefficient is a principal product of atmospheric correction algorithms applied to the remotely measured optical images of the ocean. This coefficient contains information about angular structure of light radiance, roughness of the ocean surface, and optical properties of the water. This presentation analyses remote sensing coefficient and presents it as a product of three physically different values or factors. The first factor depends on geometrical parameters of illumination and atmospheric optical properties, the second factor depends on roughness of the ocean surface, and the third one depends on the optical properties of seawater. The approach used to derive the third in-water factor is valid for all levels of water turbidity – from the clearest open waters to the most turbid waters of river mouths and extremely scattering waters of Yellow Sea type.

Keywords: seawater, light, reflection, remote sensing coefficient, brightness coefficient, radiance coefficient.

1. INTRODUCTION

This paper is devoted to derive remote sensing coefficient (RSC) or radiance reflection coefficient is a principal product of atmospheric correction algorithms applied to the remotely measured optical images of the ocean. The RSC contains information about angular structure of light radiance, roughness of the ocean surface, and optical properties of the water. This presentation analyses RSC and presents it as a product of three physically different values or coefficients. The first coefficient depends on geometrical parameters of illumination and atmospheric optical properties, the second coefficient depends on roughness of the ocean surface, and the third coefficient depends on the optical properties of seawater. The approach used to derive the third in-water coefficient is valid for all levels of water turbidity – from the clearest open waters to the most turbid waters of river mouths and extremely scattering waters of Yellow Sea type. It is shown that presented structure of RSC allows to increase precision of retrieving seawater optical properties from remotely measured optical images of the ocean.

2. REMOTE SENSING COEFFICIENT

By definition remote sensing coefficient (RSC) of the sea or ocean, or brightness/radiance coefficient of the sea or ocean (as it is defined in European literature), is a ratio of upward radiance L_u^+ to downward irradiance E_d^+ of light just above the water surface,

$$r_{rs} = L_u^+ \big/ E_d^+ . \tag{1}$$

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Equation (1) could be rewritten as

$$r_{rs} = \frac{L_u^+}{E_d^+} \equiv \frac{L_u^+}{L_u^-}\,\frac{E_d^-}{E_d^+}\,\frac{L_u^-}{E_d^-} = T_\uparrow^D\, T_\downarrow\, \rho(\theta) = \frac{T_\downarrow^D\, T_\downarrow}{n_w^2}\,\rho(\theta), \tag{2}$$

where L_u^- is upward radiance just below the water surface, E_d^- is upward irradiance just below the sea surface, $T_\uparrow^D = L_u^+ / L_u^- = T_\downarrow^D / n_w^2$ is a transmittance of diffuse light ascending from the water by the wavy surface, $T_\downarrow^D$ is a transmittance of atmospheric diffuse light by the wavy surface, n_w is the water index of refraction, $T_\downarrow = E_d^- / E_d^+$ is a transmittance of total atmospheric light by wavy sea surface, and $\rho(\theta) = L_u^- / E_d^-$ is radiance coefficient of water body of finite depth, and θ is a zenith angle. Here superscripts (+) and (-) denote, respectively, values above and below the water surface.

The total transmittance of water surface can be expressed as follows,

$$T_\downarrow = f\,T_f + (1-f)\left[(1-q_a)\,T_\downarrow^D + q_a\,T_\downarrow^S\right], \tag{3}$$

where f is a portion of the water surface covered by foam, $T_f = 1 - A_f$ is a foam transmittance, A_f is a foam albedo, q_a is a portion of downward irradiance in atmosphere just above the water surface that is due to a direct solar light, $T_\downarrow^S = 1 - R_F^S$ is a transmittance of direct solar light by the sea surface free of foam, and R_F^S is a Fresnel reflection coefficient of direct solar light by wavy water surface uncovered by foam.

The total radiance (or brightness) coefficient of water body $\rho(\theta)$ is connected with the total diffuse reflection coefficient $R = E_u^- / E_d^-$ by the following relationship [1],

$$R = 2\pi \int_0^1 \rho(\theta)\cos\theta\sin\theta\, d\theta, \qquad 0 \le R \le 1. \tag{4}$$

For Lambertian reflector, $\rho(\theta) = \rho = \text{const}$ and $R = \pi\,\rho$.

The total radiance coefficient $\rho(\theta)$ can be split into two parts, the radiance coefficient for diffuse light ρ_D, and radiance coefficient for direct solar light ρ_S,

$$\rho(\theta) = (1-q_w)\,\rho_D(\theta) + q_w\,\rho_S(\theta), \tag{5}$$

where q_w is a portion of downward irradiance in water just below the water surface [1-3]. The value $q_w = E_S^w / (E_D^w + E_S^w)$ can be expressed through the similar value q_a as follows. The downward diffuse and direct irradiance just below the water surface are,

$$E_D^w = f\,(1-A_f)(E_D^a + E_S^a) + (1-f)\,E_D^a\,T_\downarrow^D, \qquad E_S^w = (1-f)\,E_S^a\,T_\downarrow^S, \tag{6}$$

consequently,

$$q_w = (1-f)\,\frac{T_\downarrow^S}{T_\downarrow}\,q_a. \tag{7}$$

By combining Eqs. (2), (5) and (7) we have,

$$\begin{aligned} r_{rs} &= \frac{T_\downarrow^D}{n_w^2}\left\{T_\downarrow \rho_D - q_a(1-f)T_\downarrow^S\left[\rho_D - \rho_S(\theta)\right]\right\} \\ &\equiv \frac{T_\downarrow^D}{\pi n_w^2}\left\{f(1-A_f)+(1-f)\left[(1-q_a)T_\downarrow^D + q_a T_\downarrow^S\, \eta_S(\theta)\right]\right\}R, \end{aligned} \tag{8}$$

here we assumed that $\rho_D = R/\pi$ and denoted $\eta_S(\theta) = \rho_S(\theta)/\rho_D$. The value η_S is dependent on a zenith angle θ. and inherent optical properties of seawater The diffuse transmittance $T_\downarrow^D$ is a transmittance of direct light $T_\downarrow^S$ averaged over zenith angle θ with the weight proportional to the sky radiance:

$$T_\downarrow^D = \left\langle T_\downarrow^S \right\rangle_\theta, \tag{9}$$

so, Eq. (8) can be rewritten as follows:

$$r_{rs} = \frac{\left\langle T_\downarrow^S \right\rangle_\theta}{\pi n_w^2}\left\{f(1-A_f)+(1-f)\left[(1-q_a)\left\langle T_\downarrow^S \right\rangle_\theta + q_a T_\downarrow^S\, \eta_S(\theta)\right]\right\}R, \tag{10}$$

where R is a diffuse reflection coefficient of the water body illuminated by diffuse light.
According to [2, 3] solar to sky light ratio parameter q_a is only a function of atmospheric parameters,

$$q_a = \left(1 + \frac{B_a \tau_a}{\mu_s}\right) e^{-\tau_a/\mu_s}, \tag{11}$$

where τ_a is a total atmospheric optical thickness, B_a is a probability of backscattering of light in atmosphere, and $\mu_s = \cos Z_S$, with Z_S as a solar zenith angle. The foam fraction f is a function of a wind speed. According to [1] it is expressed through the wind speed u as follows:

$$f = \begin{cases} 1.2\cdot 10^{-5}\, u^{3,3}, & u \le 9\,\mathrm{m/sec}, \\ 1.2\cdot 10^{-5}\, u^{3,3}(0.221u - 0.99), & u > 9\,\mathrm{m/sec}. \end{cases} \tag{12}$$

The transmittance of direct light by wavy sea surface is expressed through the Fresnel reflection coefficient R_F^0 of a flat surface and wind speed as follows [4]:

$$T_\downarrow^S(Z_S,u) = 1 - a_0(u) - R_F^0(Z_S)\left\{a_1(u) + R_F^0(Z_S)\left[a_2(u) + a_3(u) R_F^0(Z_S)\right]\right\}, \qquad 0 \le u < 12\,\mathrm{m/sec}, \tag{13}$$

here

$$R_F^0(Z_S) = \frac{1}{2}\left[\left(\frac{\cos Z_S - \sqrt{n_w^2 - \sin^2 Z_S}}{\cos Z_S + \sqrt{n_w^2 - \sin^2 Z_S}}\right)^2 + \left(\frac{n_w^2 \cos Z_S - \sqrt{n_w^2 - \sin^2 Z_S}}{n_w^2 \cos Z_S + \sqrt{n_w^2 - \sin^2 Z_S}}\right)^2\right], \tag{14}$$

is a Fresnel reflection coefficient of directed light from clear water, and coefficients a_i $(i = 0,\ldots 3)$ are given by the following equations:

$$a_0(u) \; = \; 0.001\left(6.944831 - 1.912076\,u + 0.03654833\,u^2\right), \tag{15}$$

$$a_1(u) \; = \; 0.7431368 + 0.0679787\,u - 0.0007171 u^2, \qquad (16)$$

$$a_2(u) \; = \; 0.5650262 + 0.0061502\,u - 0.0239810\,u^2 + 0.0010695\,u^3, \qquad (17)$$

$$a_3(u) \; = \; -0.4128083 - 0.1271037\,u + 0.0283907\,u^2 - 0.0011706\,u^3. \qquad (18)$$

The equation for transmittance of diffuse light by wavy sea surface according to Eqs. (9) and (13) is,

$$T_{\downarrow}^{D}(u) = \left\langle T_{\downarrow}^{S} \right\rangle_{\theta} \equiv 1 - a_0(u) - \left\langle R_F \right\rangle \left\{ a_1(u) + \left\langle R_F \right\rangle \left[a_2(u) + a_3(u) \left\langle R_F \right\rangle \right] \right\}, \qquad 0 \le u < 12\,\mathrm{m/sec}, \qquad (19)$$

where

$$\left\langle R_F \right\rangle = \frac{1}{2} \int_0^{\pi/2} R_F^0(\theta)\, F(\theta)\, d\theta, \qquad \int_0^{\pi/2} F(\theta)\, d\theta = 1, \qquad (20)$$

here $F(\theta)$ is a normalized radiance distribution of the sky (without including the direct sunlight). For Lambertian sky $F(\theta) = 2/\pi$ we have the following equation for diffuse transmittance:

$$T_{\downarrow}^{D}(u) = 1.367 \cdot 10^{-5} (46.434 - u)(1410 + 20.6\,u + u^2), \qquad 0 \le u < 12\,\mathrm{m/sec}. \qquad (21a)$$

For overcast sky $F(\theta) = 2(1 + 2\cos\theta)/(4 + \pi)$ (cardioid distribution) we have a different equation for diffuse transmittance:

$$T_{\downarrow}^{D}(u) = 6.123 \cdot 10^{-6} (59.3 - u)(2564 + 33.74\,u + u^2), \qquad 0 \le u < 12\,\mathrm{m/sec}. \qquad (21b)$$

The difference between values of transmittance given by Eq. (21a) and (21.b) is about 10%. The average of transmittance values given by both equations is about $\left\langle T_{\downarrow}^{D}(u) \right\rangle_u \approx 0.9$. The more elaborate procedure to average Fresnel reflection coefficient should include an actual radiance distribution of the sky which is dependent on atmospheric optical properties.

3. NONLINEARITY OF APPARENT OPTICAL PROPERTIES IN RESPECT TO GORDON'S PARAMETER

Remote sensing coefficient, as we show below, is proportional to diffuse reflection coefficient. Both these values are apparent optical properties, that is they are dependent not only on inherent optical properties, but also on conditions of illumination and geometrical and optical structure of the surface and bottom of the sea.

Diffuse reflection coefficient (DRC) of water body is an informative part of remote sensing reflectance [5] of light by the ocean. DRC contains information on content of dissolved and suspended substances in seawater. DRC is an apparent optical property that depends not only on inherent optical properties of the seawater, but also on the parameters of illumination. The dependence on inherent optical properties is expressed through the dependence on Gordon's parameter, *i.e.* the ratio of backscattering coefficient b_B to the sum of absorption a and backscattering coefficient, $g = b_B / (a + b_B)$. In the open ocean DRC is linearly proportional to g. This linear equation is very good for the Type I open ocean waters [6]. It is also acceptable for about 90% of coastal waters. Theoretical and numerical analysis show that the linear relationship can be adequately used only when Gordon's parameter g is relatively small, *i.e.* $g < 0.1$. This criterion is always satisfied in open ocean waters. The available database of experimental measurements

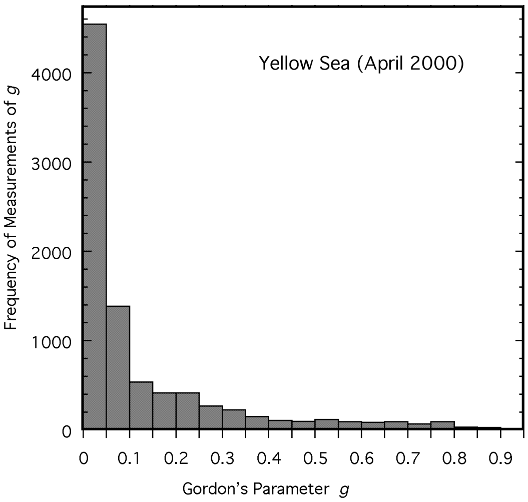

Figure 1. Distribution of occurrences of measured Gordon's parameter in Yellow Sea in 2000 [7].

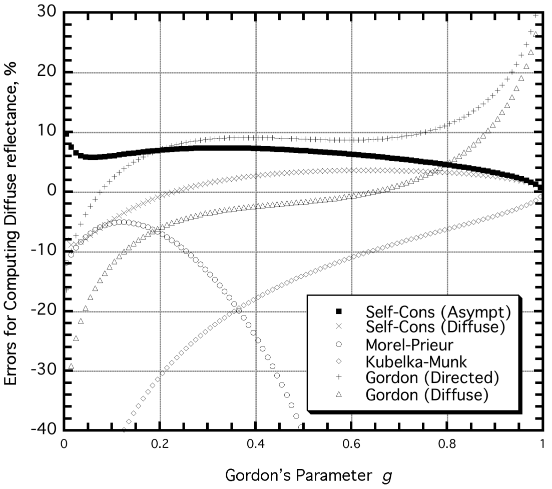

Figure 2. Dependence of diffuse reflectance coefficient errors on Gordon's parameteter [7].

show that in coastal waters Gordon's parameter may exceed this critical value of 0.1. In some very turbid coastal waters it can even reach values higher than 0.95. For example, in waters of Yellow Sea or coastal waters close to river estuaries the percentage of cases when $g > 0.1$ can reach 50% or more.

Until recently we had no significant cases of *in situ* measurements that show existence of sea waters with high cases of Gordon's parameter g exceeding 0.1. Relatively recent measurements made in 2000 by NRL researches with collaboration of Korean scientists in Yellow Sea shows that these highly scattering waters exhibit these characteristics [7]. Figure 1 shows a histogram of the frequency of measurements of Gordon's parameter in this expedition. In this case more than 50% of measurements correspond to Gordon's parameter exceeding critical limit of linear approach. It means that processing of such data should involve nonlinear equations connecting DRC with g. For that reason we will use a self-consistent radiative transfer approach that takes into account non-linearity of inherent optical properties on Gordon's parameter [8-10].

4. RADIANCE REFLECTANCE RATIO AND DIFFUSE REFLECTANCE OF WATER

According to the theory of Ref. [8-10] we can write the radiance reflectance ratio as:

$$\eta_S(\theta) = \frac{\rho_S(\theta)}{\rho_D} = \frac{\kappa^2}{2\left(1+\kappa\cos\theta\right)\left[\kappa - \ln(1+\kappa)\right]}, \tag{22}$$

where

$$\kappa = \frac{\bar{\mu}(3-\bar{\mu}^2)}{1+\bar{\mu}^2}, \quad \bar{\mu} = \sqrt{\frac{1-g}{1+2g+\sqrt{g(4+5g)}}}\ , \quad g = \frac{b_B}{a+b_B}, \tag{23}$$

a is an absorption coefficient of water, b_B is a backscattering coefficient of light by water, g is a Gordon's parameter, and $\bar{\mu}$ has physical meaning of average cosine of diffuse light inside water, and θ is a zenith angle measured inside water body. If we want to express Eq. (22) through a zenith angle ϑ outside water, we should use the Snellius law,

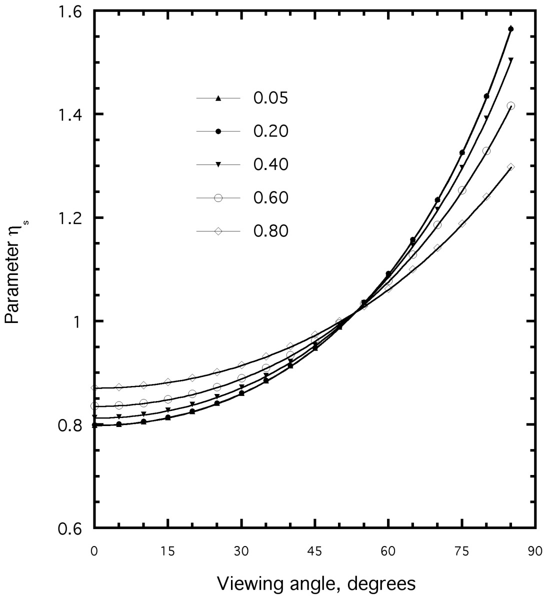

Figure 3. Dependence of parameter η_S on viewing angle for different values of Gordon's parameter.

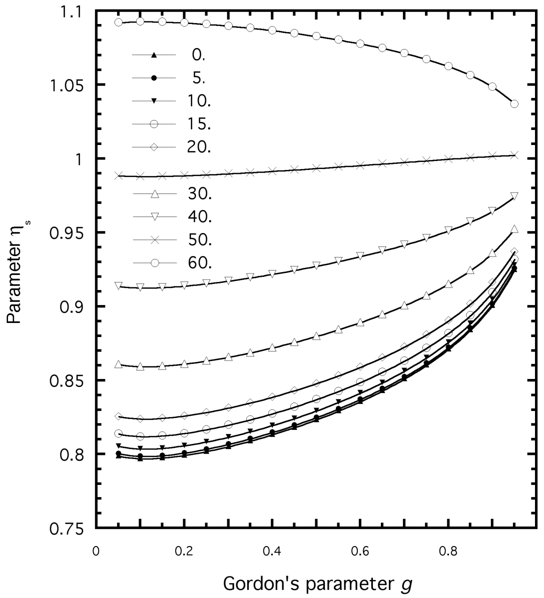

Figure 4. Dependence of parameter η_S on Gordon's parameteter for different viewing angles.

$\sin\vartheta = n_w \sin\theta$, which results in substitution in Eq. (22): $\cos\theta \to \sqrt{1-\sin^2\vartheta/n_w^2}$. Function $\eta_S(\theta)$ is normalized as follows:

$$2\int_0^{\pi/2} \eta_S(\theta)\cos\theta\sin\theta\,d\theta = 1. \tag{24}$$

The dependence of factor η_S on viewing angle and Gordon's parameter is shown in Fig. 3 and 4.

The diffuse reflectance of shallow sea of arbitrary turbidity and absorption is represented by the following equation [8]:

$$R = \frac{R_\infty(1-A_bR_0) + (A_b - R_\infty)e^{-\nu z_b}}{(1-A_bR_0) + (A_b - R_\infty)R_0\,e^{-\nu z_b}}, \tag{25}$$

where

$$R_\infty = \left(\frac{1-\bar{\mu}}{1+\bar{\mu}}\right)^2, \qquad R_0 = \left(\frac{2+\bar{\mu}}{2-\bar{\mu}}\right)R_\infty, \qquad \nu = 2\bar{\mu}\,(a + b_B), \tag{26}$$

A_b is an albedo of a bottom, and z_b is a bottom depth, and R_∞ is a diffuse reflectance of optically deep sea illuminated by diffuse light.

Equations (22) and (25) take into account multiple scattering of light inside water and multiple reflection of light from the bottom. It is valid for arbitrary depths ($0 \le z_b \le \infty$), arbitrary bottom albedo $0 \le A_b \le 1$, and arbitrary inherent optical properties of water, $0 \le a \le \infty$, and $0 \le b_B \le \infty$.

5. CONCLUSION

The result of this paper is an equation that expresses remote sensing reflection coefficient as a function of twelve parameters:

$$\begin{aligned} r_{rs}(B_a,\tau_a,u,A_f,Z_S,n_w,\vartheta,a,b_B,z_b,A_b,\lambda) = \\ = \frac{T_{\downarrow}^{D}(u)}{\pi\, n_w^2}\Big\{ f(u)[1-A_f(\lambda)] + [1-f(u)][\{1-q_a(B_a,\tau_a)\}\, T_{\downarrow}^{D}(u) + \\ + q_a(B_a,\tau_a)\, T_{\downarrow}^{S}(Z_S,u)\ \eta_S(a,b_B,\vartheta)]\Big\} R(a,b_B,z_b,A_b), \end{aligned} \tag{27}$$

where B_a is a light backscattering probability in atmosphere,

$$B_a = \int_{\pi/2}^{\pi} p_a(\cos\theta)\sin\theta\, d\theta \Big/ \int_0^{\pi} p_a(\cos\theta)\sin\theta\, d\theta \tag{28}$$

(here p_a is an atmospheric light scattering phase function, and θ is a scattering angle), τ_a is a total optical thickness of atmosphere, u is a wind speed at the level of water surface, A_f is an albedo of a wind generated foam or whitecaps, Z_S is a solar zenith angle, n_w is a refraction index of water, ϑ is a viewing zenith angle of an optical receiver, a is an absorption coefficient of light in water, b_B is a backscattering coefficient of light in seawater, z_b is a water depth, A_b is a bottom albedo, and λ is a wavelength of light. Equation (27) shows spectral (wavelength) dependence of RSC only through the foam albedo. In reality, the following parameters also have spectral dependence on the wavelength of light: absorption and backscattering coefficients of water, bottom albedo, backscattering probability and total optical thickness of atmosphere, and, to some extent, refraction index of water. These dependencies are not shown in the right side of Eq. (27) in order to make it less bulky. The transmittivity of diffuse light by the wavy water surface $T_{\downarrow}^{D}$ is expressed by Eqs. (21), or can be calculated from Eq. (19) using current atmospheric properties. The share of water surface covered by foam f is computed using Eq. (12). The share of direct sunlight in the total light radiance on the water level q_a is computed using Eq. (11). The transmittance of direct light by the wavy surface $T_{\downarrow}^{S}$ is computed with Eqs. (13)-(18). The ratio of direct light reflectance to the reflectance of diffuse light η_S is given by Eqs. (22)-(23). And, finally, the diffuse reflectance coefficient of diffuse light by the shallow water body is given by Eqs. (25)-(26). Equation (27) is derived to be valid in the whole range of variabilities of optical properties of the water body and atmosphere and for arbitrary depth of the water. It is intended to be used in algorithms of remote processing of optical data, including derivation of water optical properties, water depth and bottom albedo.

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