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AN ALGORITHM TO ESTIMATE CONCENTRATIONS OF SUSPENDED PARTICLES IN SEAWATER FROM SATELLITE OPTICAL IMAGES

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Abstract: A new method to retrieve concentrations of suspended organic and inorganic particles in seawater from satellite images is proposed. The method uses as input images of scattering and backscattering coefficients in several satellite channels as well as an image of concentration of chlorophyll. All these three properties are derived using an atmospheric correction algorithm and algorithms to derive inherent optical properties from remote sensing reflectance. The proposed method is based on several approaches developed previously by Twardowski *et al.*, van de Hulst, and Evans and Fournier and is based on Mie theory. The outputs to this method are images of concentrations of organic and terrigenic fractions of suspended matter in seawater.

1. Introduction

In this paper we describe an approach to estimate concentrations of suspended scattering particles in seawater using spectral information obtained in optical channels from a satellite. Modeling results by various authors (Forand and Fournier [1], Twardowski and others[2]) show that spectral dependence of particular scattering and extinction (attenuation) coefficients are closely connected with the shape of particle size distribution in seawater. In the first approximation the shape of size distribution may be represented in the form of Junge distribution. The spectral shape of scattering or particular extinction (or scattering) coefficient allows us to obtain a Junge parameter which is a key to compute an effective refractive index of seawater with suspended scattering particles. The value of effective refractive index allows us to estimate shares of organic and terrigenic fractions of scatterers. The total concentration of scattering matter is estimated through the total scattering coefficient and a scattering efficiency by arbitrary size particle averaged over restored size distribution (Evans and Fournier, [3] van de Hulst [4]). The actual realization of the approach is implemented as a FORTRAN code and tested with an optical satellite data of sea water reflection in the Gulf of Mexico (Mississippi Bight area).

The inputs to the proposed algorithm are images of particle extinction c_p, scattering b_p and backscattering b_{Bp} coefficients, and outputs are images of concentrations of organic C_p^{org} and terrigenic C_p^{ter} fractions of suspended matter. The input images are obtained from the images of remote sensing reflectance r_{rs} in several bands of a satellite optical sensor. We used algorithms of K. L. Carder [5] and R. A. Arnone [6] to obtain values of extinction, scattering and backscattering coefficients from the values of remote sensing reflectance. The spectral remote sensing reflectance [7] was obtained from the spectral values of radiances of the ocean-atmosphere system using an atmospheric correction algorithm developed by Howard R. Gordon [8].

2. Derivation of effective refractive index of water with scatterers

The first step in the algorithm is to obtain the slope γ in the spectral dependency of particular extinction coefficient $c_p \sim \lambda^{-\gamma}$ using a linear interpolation method in a log-log scale. The next step is to restore main properties of size distribution of particles suspended in seawater. While realistic particle size distributions $N(r)$ (where r is a particle radius) are quite unique and only in very rare cases may be described by some theoretical kind of size distribution, they are in general, if plotted on a log-log scale: *i. e.* $\log N(r)$ versus $\log(r)$, exhibit a linear behavior. It means, that in the first approximation they can be described as a Junge (hyperbolic) distribution, $N(r) \sim r^{-\nu}$, with positive value of parameter ν .

The extensive study of inherent optical properties of seawater with scatterers distributed according to Junge law was accomplished by Twardowski *et. al.* [2]. Among other results these authors obtain empirical relationship between slope of particular extinction coefficient and Junge parameter, as well as relationship that connects effective refractive index of seawater n_w with Junge parameter ν and backscattering b_{bp} coefficient. According to Twardowski *et al.* [2] the relationship between particular extinction slope γ and Junge parameter ν is linear:

$$c_p(\lambda) = A_c \lambda^{-\gamma}, \quad \nu = \gamma + 3, \quad r_{\min} = 0.006\mu\text{m}, \quad r_{\max} = 76\mu\text{m}, \tag{1}$$

here $r_{\min}$ and $r_{\max}$ are minimum and maximum radii in particles size distribution.

The similar result was obtained earlier by Forand and Fournier [1] who implied a Junge distributions of scatterers with infinite limits. They obtained the similar result for the case of particular scattering coefficient:

$$b_p(\lambda) = A_b \lambda^{-\tilde{\gamma}}, \quad \nu = \tilde{\gamma} + 3, \quad r_{\min} = 0, \quad r_{\max} = \infty. \tag{2}$$

We tested both regressions (1) and (2) and found that regression (1) produces more reliable results.

The effective refractive index of suspended particles is connected with backscattering probability by particulate matter $B_p = b_{bp} / b_p$, where b_{bp} is a particular backscattering coefficient, by the following regression [2] obtained from results of modeling using Mie theory:

$$n_p(B_p, \gamma) = 1 + B_p^{0.5377 + 0.4867\gamma^2}\left[1.4676 + 2.2950\gamma^2 + 2.3113\gamma^4\right]. \tag{3}$$

So, the equations (1) and (3) allow us to restore the parameter of the size distribution ν and effective refractive index of scatterers.

3. Estimation of concentration of organic and terrigenic fractions of scatterers

The total concentration of particular matter C_p could be found from the following relationships:

$$C_p = C_v \rho, \quad C_v = N_{tot} \overline{V}_p, \tag{4}$$

here C_v is a volume concentration of particular matter, ρ is a mass density of particles, N_{tot} is a total number of particles per unit volume, $\overline{V}_p$ is an average volume of one scattering particle which can be obtained using the following equation:

$$\overline{V}_p = \frac{4}{3}\pi\int_{r_{\min}}^{r_{\max}} r^3 f(r)\,dr, \qquad \int_{r_{\min}}^{r_{\max}} f(r)\,dr = 1, \tag{5}$$

here $f(r)$ is a normalized size distribution of particles.

Taking into account that total number of scattering particles can be expressed through the particular scattering coefficient [4],

$$N_{tot} = b_p \Big/ \left[\pi\int_{r_{\min}}^{r_{\max}} Q_{sc}(n_w, x)\, r^2 f(r)\,dr\right], \tag{6}$$

where Q_{sc} is a scattering efficiency. We can rewrite Eqs. (4)-(6) as follows:

$$C_v = \frac{4}{3} b_p \frac{S_v}{S_q}, \quad S_v = \int_{r_{\min}}^{r_{\max}} r^3 f(r)\,dr, \quad S_q = \int_{r_{\min}}^{r_{\max}} r^2 f(r) Q_{sc}(r)\,dr. \tag{7}$$

Integrals S_v and S_q also may be used to obtain a specific scattering coefficient of particular matter:

$$b_p^0 = \frac{b_p}{C_p} = \frac{3}{4\rho}\frac{S_q}{S_v}. \tag{8}$$

The scattering efficiency Q_{sc} of particles suspended in seawater depends on effective refractive index n_w of seawater and size parameter, $x = 2\pi r/\lambda$, where λ is a wavelength of light in vacuum. The value Q_{sc} can be computed numerically using Mie theory [4]. This approach while having superior accuracy is not good for our purposes due to its slowness. For that reason we have chosen to use an analytic expression for Q_{sc} proposed by Evans and Fournier [3]:

$$Q_{sc}(n_w, x) = \frac{Q_R}{\left[1 + \left(Q_R / Q_v T\right)^{\mu}\right]^{1/\mu}}, \tag{9}$$

here

$$Q_R(n_w, x) = \frac{8}{3} x^4 \left(\frac{n_w^2 - 1}{n_w^2 + 2}\right)^2, \tag{10}$$

$$Q_v(n_w, x) = 2\left[1 - \frac{2}{\overline{\rho}}\left(\sin\overline{\rho} - \frac{1 - \cos\overline{\rho}}{\overline{\rho}}\right)\right], \quad \overline{\rho} = 2x(n_w - 1), \tag{11}$$

$$T(x) = 2 - \exp(-x^{-2/3}), \tag{12}$$

$$\mu(n_w,x)=\frac{1}{2}+(n_w-1)+(n_w-1)^2+\frac{1}{x}\left[\frac{3}{5}-\frac{3}{4}(n_w-1)^{1/2}+3(n_w-1)^4\right]. \tag{13}$$

Equations (9)-(13) give us a very good approximation to scattering efficiency, especially when used later for monodispersed scatterers. The testing of algorithm to restore concentrations of scatterers based on Eqs. (4)-(13) proves that it is stable and reliable.

The next final touch to our algorithm is to separate organic and inorganic components of suspended matter.

The final step in this algorithm is to separate organic and terrigenic fractions of suspended matter. The simplest approach is to assume that scattering particles consist of two fractions, organic and terrigenic, with different refractive indices and the same size distributions. In this case an effective refractive index of suspended particles is determined by

$$n_p=\alpha^{org}n^{org}+(1-\alpha^{org})n^{ter}. \tag{14}$$

here α^{org} is a share of organic matter in suspended scattering fraction. Consequently,

$$\alpha^{org}=\frac{n^{ter}-n_p}{n^{ter}-n^{org}}. \tag{15}$$

And, correspondingly, the concentrations of organic and inorganic fractions of suspended matter are:

$$C_p^{org}=\alpha^{org}\rho^{org}C_v, \qquad C_p^{ter}=(1-\alpha^{org})\rho^{ter}C_v. \tag{16}$$

According to Refs. [2, 9, 10] relative refractive index of organic fraction can be accepted as $n^{org}=1.04$ (phytoplankton cells), and for terrigenic fraction as $n^{ter}=1.157$ (quartz-like inorganic matter), and mass densities: $\rho^{ter}=2\cdot 10^3\,\mathrm{g/dm^3}$ (or g/l), $\rho^{org}=10^3\,\mathrm{g/dm^3}$ (or g/l).

Figures 1-4 show results of sample computation using proposed algorithm. Figures 1 and 2 represent 300x300 pixels SeaWIFs images of two input parameters, remote sensing reflectance r_{rs} in Band 3 (490 nm) and scattering coefficient of particles b_p the same spectral band. Figures 3 and 4 display output images of the share of organic matter α^{org} and concentration of terrigenic part of the scatterers C_p^{ter} generated using proposed algorithm.

4. Conclusion

We proposed here a new method to retrieve concentrations of suspended organic and inorganic particles in seawater from satellite images. The method uses as input values of extinction, scattering and backscattering coefficients in several satellite channels. The outputs to this method are concentrations of organic and terrigenic fractions of suspended matter in seawater.

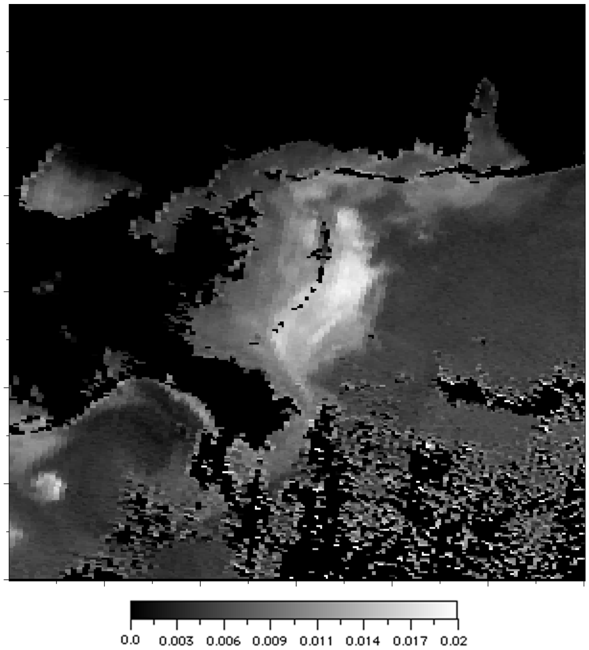

Figure 1. Remote sensing reflectance (490 nm).

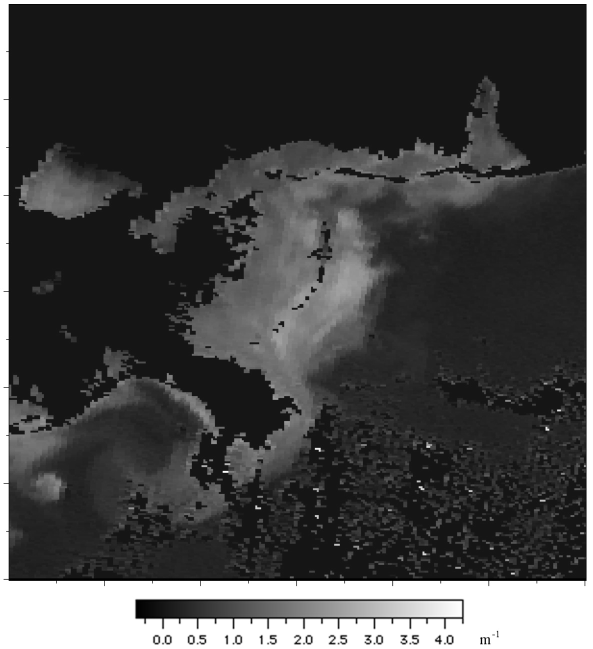

Figure 2. Scattering coefficient (490 nm).

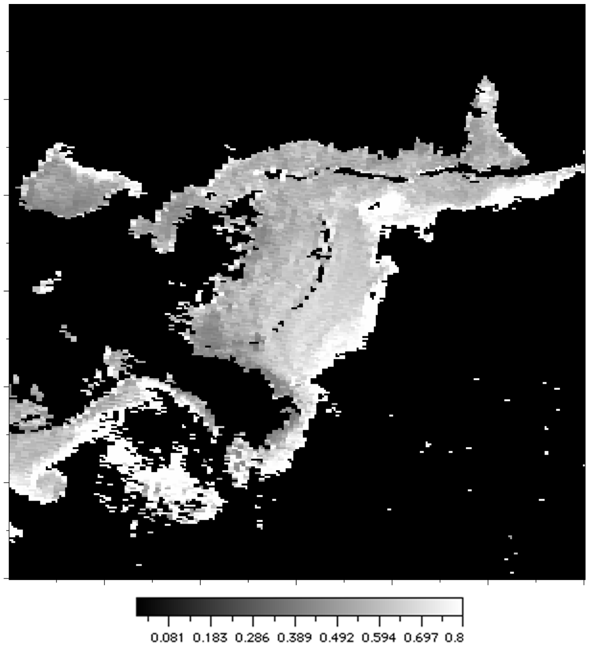

Figure 3. Share of organic matter.

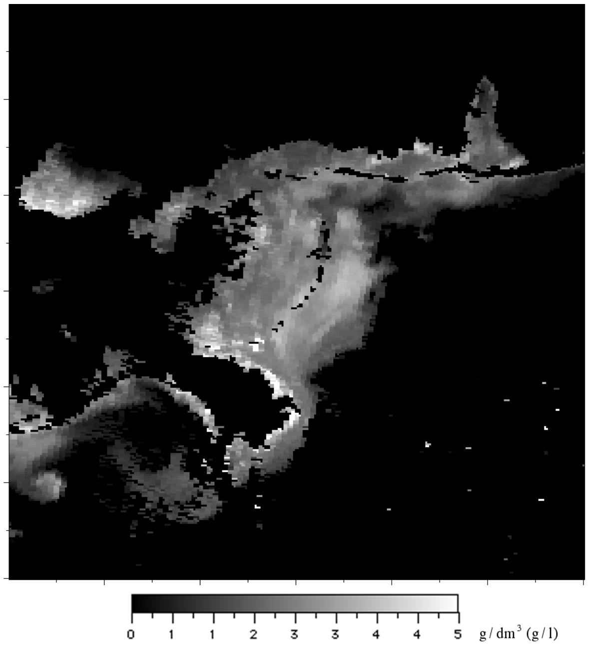

Figure 4. Concentration of terrigenic matter.

5. Acknowledgments

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