Improved method of Fournier-Forand marine phase function parameterization

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Abstract: Volume scattering functions (VSFs) and other optical seawater parameters were measured during a cruise in the Southern Baltic. Phase functions (PFs) calculated from VSFs were compared with Fournier-Forand phase functions parameterized with backscattering ratios. Due to significant divergences between experimental and modeled data a new method of Fournier-Forand phase function parameterization is proposed.

OCIS codes: (010.4450) Ocean optics; (290.1350) Backscattering; (290.5820) Scattering.

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1. Introduction

Modeling of light propagation in deep waters requires a function describing the angular distribution of scattered light intensity i.e. the phase function. Since scattering function measurements are difficult and until now have not been frequently made, several types of phase function models have been proposed for radiative transfer calculations. One of the most cited and used is the Petzold average phase function [1, 2], which is based on measurements performed in the early 1970's in San Diego Harbor waters. Several types of analytical phase functions have also been proposed. First of them was the Henyey-Greenstein phase function [3], originally used in astrophysics, which was quite popular because of its simple form. However, it did not have a backscattering maximum typical for marine scatterers. This was

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the reason Haltrin [4] developed his phase function which consisted of the sum of two Henyey-Greenstein ones with maximums for forward and back scattering. Therefore Haltrin's function is also called the Two-Term Henyey-Greenstein phase function. Another parameterized analytical phase function, created to fit the shape of Petzold's measured phase function is the Fournier-Forand (FF) phase function [5].

During a cruise on the R/V Oceania in May 2006, volume scattering functions (VSFs) of Southern Baltic seawater were measured. The scattering function meter (VSM) [6] designed and built at the Marine Hydrophysical Institute of the National Academy of Science in Sevastopol was used for the measurements. They were carried out at four wavelengths: 443, 490, 555 and 620 nm; the results were presented recently [7]. The angular resolution of the VSM is equal to 0.25 deg. It measures at 715 scattering angles (from 0.5 to 179 deg). For several stations, simultaneous measurements of absorption and attenuation coefficients were made using a Wetlabs ac-9 instrument. Spectral channels of the ac-9 are not coincident with the VSM channels. Fortunately they are very close for three cases. The ac-9 instrument makes measurements at wavelengths: 412, 440, 488, 510, 555, 650, 676 and 715 nm. Absorption coefficients for spectral channels used by the VSM were obtained by linear interpolation.

2. Materials and methods

Fournier and Forand (FF) gave an analytical expression for the phase function of Mie scatterers [5] with a hyperbolic (Junge-type) particle size distribution. The FF phase function is expressed by two parameters, real index of refraction *n* and slope of the Junge particle size distribution μ. The form of the function is given by [8]:

$$\beta(\theta) = \frac{1}{4\pi(1-\delta)^2 \delta^{\nu}} \left(\left[\nu(1-\delta) - (1-\delta^{\nu}) \right] + \frac{4}{u^2} \left[\delta(1-\delta^{\nu}) - \nu(1-\delta) \right] \right), \qquad (1)$$

where:

$$\nu = \frac{3-\mu}{2}, \quad \delta = \frac{u^2}{3(n-1)^2}, \quad u = 2\,sin(\theta/2).$$

Integration of the Eq. (1) provides a simple relationship between parameters *n*, μ and the particle backscatter fraction B_p:

$$\mu = 2\frac{\log\left(2B_p(\delta_{90}-1)+1\right)}{\log \delta_{90}} + 3 \qquad (2)$$

where δ_{90} is δ determined for scattering angle θ = 90 deg.

Because there is no direct method of obtaining relative refractive index *n* of oceanic suspension, the FF phase function has been used infrequently. However, in 2002 Mobley et. al [9] proposed a method of choosing the FF phase function using only one parameter B_p. Concerning the Petzold Average Phase Function they gave simple linear relationship between *n* and μ. According to Mobley et al parameters of the FF phase function are given by the intersection points of red dashed line (see Fig. 1.) with appropriate contours of B_p. Mobley's method, which has been cited almost 50 times, has been used by many authors [10-12].

3. Results and discussion

VSF data measured in the Southern Baltic were processed to obtain measured Phase Functions (PFs). The latter were compared with FF phase functions obtained from Mobley's algorithm for known B_p. The difference D between analytical and experimental functions was defined as:

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$$D = \frac{\sum_{\theta}\left[PF(\theta) - FF(\theta)\right]^2 \sin\theta}{\sum_{\theta} PF(\theta)^2 \sin\theta} \tag{3}$$

where the sum was calculated over all 715 scattering angles θ, for which scattering intensities are known. This difference formula mimics the way an integral of the difference squared would be calculated if the phase functions were known for every scattering angle value.

The comparison gave significant discrepancy values. For some surface waters the difference D exceeded 25%, however for deep waters taken from depths 52 m and 82 meters D was higher than 55%. The authors of the VSM assure that the VSF is measured with 5% accuracy. That is why two parameter fitting of the FF functions to measured PF was made.

For known B_p and the set of refractive indices n, from 1.001 to 1.25 with step 0.001, a huge number of FF phase functions was calculated. The parameters n and μ were found for the FF function for which D was smallest. The algorithm was evaluated for each of over 30 measured PFs.

These pairs (n, μ) are presented in Fig. 1. (black circles). Contours of the backscattering ratios, obtained from Eq. (2) are also shown. The red dashed line which, according to Mobley et al., provides parameters n and μ is also marked. The red point describes the best fit of n and μ to the Petzold phase function. It is obvious that Mobley's method only fits well for a small amount of measured data. This is why a better parameterization method is needed.

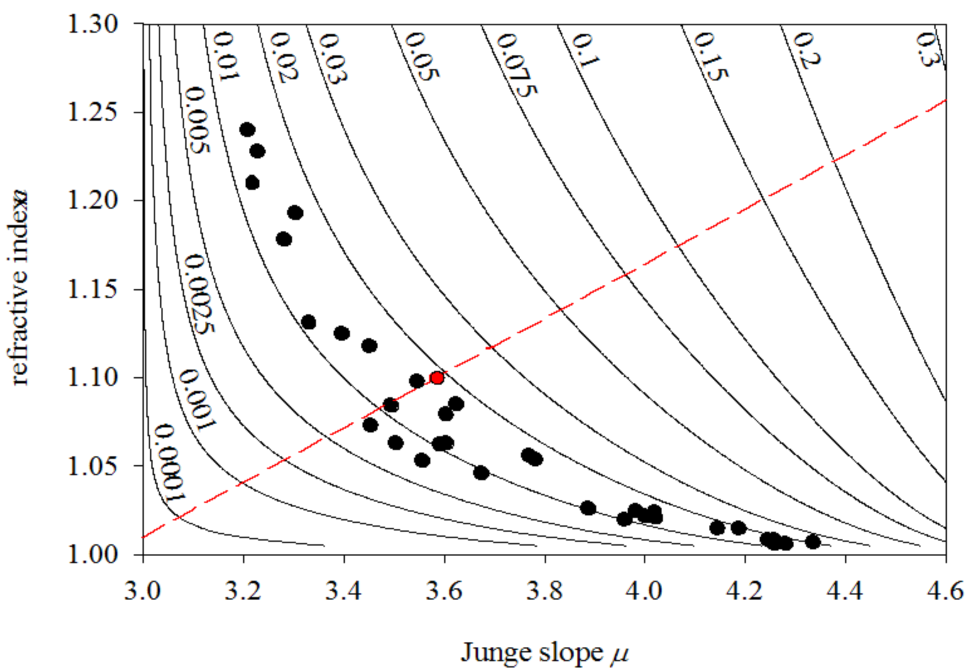
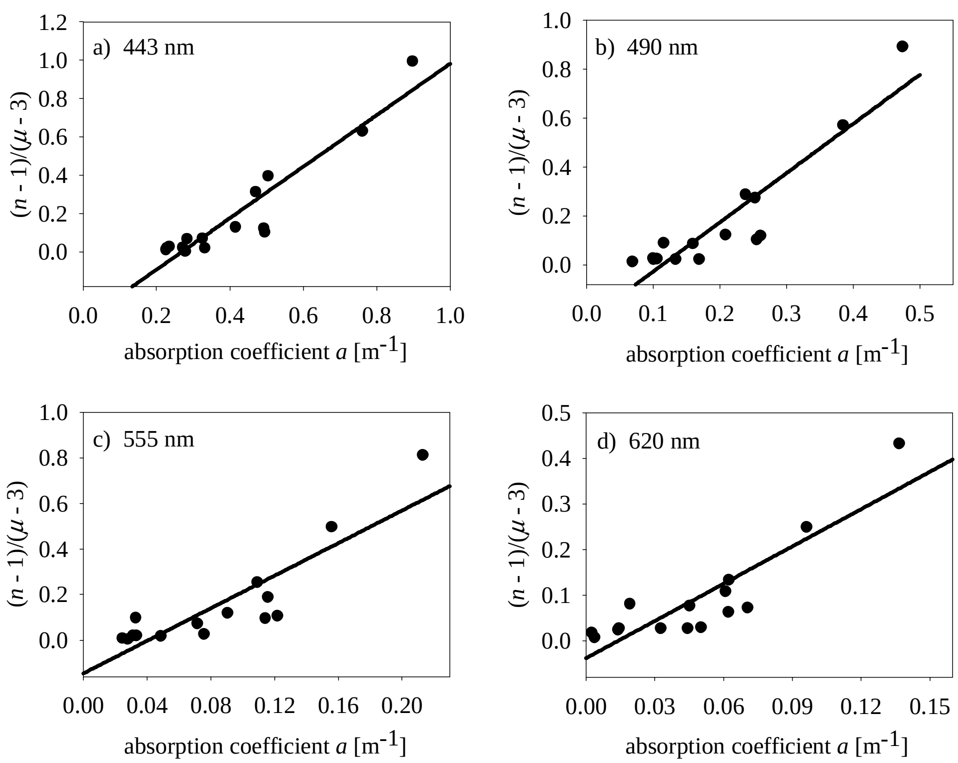


Fig. 1. Contours of the backscatter fraction B_p determined by Eq. (2). Black points denote parameters of the FF phase functions obtained from the best fit of the FF shape to measured VSF at wavelength 443nm. Red dashed line is Mobley's way to obtain parameters n and μ when B_p is given. The red circle shows parameters n and μ for the best fit to Petzold phase function.

We found that the parameters of fitted FF functions (black points in the Fig. 1.) can be grouped according to the place of measured PFs origin. Phase functions from clean waters deeper than 10 meters are found in the lower right corner of the plot. Points in the middle of Fig. 1. are from phase functions from the surface of open Baltic seawaters. Points in the upper left corner of the plot come from more turbid coastal waters. Our experimental data show that parameters n and μ are only weakly dependent on B_p. That is why we propose to draw a linear function $n(\mu)$, as Mobley et al. proposed, but with changing slope. We checked that the absorption coefficient a, measured by the mean of ac-9 values, would be a good characteristics of the linear slope of $n(\mu)$. Similarly to Mobley et al., we assumed that this linear function should intersect the point $n = 1$ and $\mu = 3$. That is why the slope of line is given by $(n - 1)/(\mu - 3)$. In Fig. 2 factors $(n - 1)/(\mu - 3)$ are plotted with absorption coefficients a for all wavelengths for which VSFs were measured.

Straight-line approximation of four scatter plots shown in Fig. 2. gives four simple equations, which describe relationships between refractive index n and Junge slope μ.

$$\begin{aligned} n(443\text{nm}) &= (1.34 \cdot a - 0.36)(\mu - 3) + 1 \\ n(490\text{nm}) &= (2.01 \cdot a - 0.23)(\mu - 3) + 1 \\ n(555\text{nm}) &= (3.57 \cdot a - 0.15)(\mu - 3) + 1 \end{aligned} \tag{4}$$



$$n(620\text{nm}) = (2.72 \cdot a - 0.04)(\mu - 3) + 1$$

Fig. 2. Factors $(n - 1)/(\mu - 3)$ plotted with absorption coefficients a for wavelengths: a) 443nm, b) 490 nm, c) 555nm, d) 620nm.

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One must solve the system of Eqs. (2) and (4) in order to use this improved method of Fournier-Forand phase function parameterization. The absorption coefficient *a* in Eq. (4) and the particle backscatter fraction B_p in Eq. (2) are also required. The solution of the system of equations gives the real index of refraction *n* and the slope of the Junge particle size distribution μ, which are needed to plot Fournier Forand phase functions.

If the parameterization must be limited to one parameter only, it is better to assume that B_p in Eq. (2) is constant. We took the following average values of B_p, for Southern Baltic waters, which were measured in the same cruise by mean of the VSM: B_p(443nm) = 0.0136, B_p(490nm) = 0.0132, B_p(555nm) = 0.012 and B_p(620nm) = 0.0119.

The differences D between the FF functions obtained from Mobley's method and the measured functions were calculated using Eq. (3). These differences were calculated for over 30 stations. Similarly the differences D for FF functions obtained from our algorithms were calculated. They are determined for only 14 stations, for which simultaneously PF and absorption coefficients *a* are known. Averaged differences D calculated for all available stations are collected in table 1.

Tab. 1. Average differences D (in %) between measured PF and calculated FF for three algorithms.

	Mobley's method (for known B_p)	Our 2 parameters algorithm (for known *a* and B_p)	Our 1 parameter algorithm (for known *a* and single B_p)
λ=443 nm	17.5	7.6	7.9
λ=490 nm	16.9	13.5	13.7
λ=555 nm	18.3	10.0	10.2
λ=620 nm	18.0	8.0	8.7

The average difference D for Mobley's method, for all measured stations and four wavelengths, is equal to 18%, whereas our algorithms gives mean difference D only 10%. For surface waters the mean differences are 11% (Mobley) and 7% (our method), and for deep waters respectively 35% and 21%.

4. Conclusions

Our parameterization potentially covers a wider range of cases than the one proposed by Mobley et al. It is based on actual measurements done at sea. We do not claim we have reached a universal parameterization which can be used in any region of the world ocean at any time. This is not plausible if one remembers that we used data from only one cruise. Especially, using absorption to parameterize scattering phase functions is certainly not the ultimate solution. Generally, there is no reason why phase functions should depend on absorption: for example changes in concentration of any highly absorbing but weakly scattering substance (like CDOM) will hardly change the average phase function. We believe that our data show dependence of phase function on absorption only because absorption co-varied with other optical properties, most probably because of quite uniform phytoplankton species composition in the rather limited area and period our measurement were limited to. For every wavelength, absorption correlated better than scattering with (n-1)(μ-3), while beam attenuation (being their sum) had a correlation coefficient in between. At the same time, all the three IOPs were highly correlated with each other. Therefore, we believe that choosing the one (absorption) best correlating with the phase function parameter rather than a less correlated one (scattering) or their linear combination (beam attenuation) is the optimal choice for parameterization, at least for our dataset.

However, the results presented here clearly show that the Mobley et al. phase function parameterization is clearly insufficient. It is obvious that many more phase function measurements, performed in different water types in different seasons, are needed before we will be sure we are able to provide robust parameterizations of marine phase functions. Such spectral parameterization is needed for radiative transfer modeling, remote sensing inverse problem solving or correction of the scattering error of absorption measurements, to mention only three problems of marine optics which solution would be greatly helped by improvement

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of our knowledge on the variability of spectral phase functions of marine scatterers. The parameterization we propose here is only the first step in this direction.

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