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# INTEGRAL PROPERTIES OF ANGULAR LIGHT SCATTERING COEFFICIENT MEASURED IN VARIOUS NATURAL WATERS

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**Abstract:** Empirical dependencies of integral properties of experimentally measured light scattering phase functions of sea water are presented. These integral properties include probability of backscattering or ratio of backscattering to scattering coefficients, average cosine, and, average square of cosine. These dependencies have been derived from about a thousand of *in-situ* measurements of angular scattering coefficient made in various open ocean and coastal waters, including two cases measured in waters of the lake Baikal. Proposed empirical dependencies may be used for enhancing underwater visibility algorithms, developing analytical models of sea water phase functions, and as inputs to radiative transfer models of light propagation in natural waters.

This work presents results of preliminary analysis of *in situ* measurements of angular light scattering coefficients (or volume scattering functions, VSF) measured by Petzold (15 phase functions [1]), Mankovsky (41 phase functions [2-4]), and M. E. Lee (818 phase functions [5-7]). The areas of measurement include such diverse water areas as open ocean waters of Atlantic, Indian and Southern oceans, Mediterranean and Black seas, Lake Baikal, [2, 3] and coastal and near-coastal waters of Atlantic [4] and Pacific oceans [1] with the total scattering coefficient $b$ varying between 0.008 and 10 $m^{-1}$. Basic parameters of all volume scattering function (VSF) measuring devices used in all four *in situ* experiments considered here are given in Table 1. The maximums of sensitivities of the VSF probes presented in Tab. 1 are different. The spectral sensitivities of Petzold and Mankovsky devices are very close: both devices measure VSFs in a blue-green range of spectrum (515 and 520 nm respectively), both have wide sensitivity channels (with 30 and 40 nm half-width) and both almost touch the green sensitivity maximum (550 nm)

Table 1. Basic parameters of VSF measuring devices. Here $\lambda$ is a center of measurement spectral band in nm, $\Delta\lambda$ is a half-width of measuring spectral band in nm, and $N_{ang}$ is a number of measuring angles.

| Author | $\lambda$,nm | $\Delta\lambda$ | Accuracy | Angular Range | $N_{ang}$ |
|---|---|---|---|---|---|
| T. J. Petzold [1] | 515 | 30 | 10% | 0.338°-170° | 21 |
| V. I. Mankovsky [2, 3] | 520 | 40 | 12% | 2°-162.5° | 33 |
| M. E. Lee, 2000 [5-7] | 550 | 10 | ~5% | 0.6°-177.3° | 590 |
| M. E. Lee, 2001 [5-7] | 550 | 10 | ~3-8% | 0.5°-178.5° | 607 |

of Lee's probe. According to the latest results of spectral measurements of VSFs in all SeaWIFs channels [8] and modeling using approach of the Ref. 9, the spectral variability of VSF is very weak. It means that results of Petzold and Mankovsky measurements (56 VSFs) may be included with corresponding weights into the database of 818 Lee's VSF without any noticeable reduction in the precision of the results that include all measurements.

One of the most important inherent optical properties are backscattering coefficient $b_B$ and probability of backscattering $B$ (normally referenced by experimentalists as a ratio of $b_B$ to $b$):

$$b_B = (b/2)\int_{\pi/2}^{\pi} p(\theta)\sin\theta\, d\theta, \qquad 0.5\int_0^{\pi} p(\theta)\sin\theta\, d\theta = 1, \tag{1}$$

$$B = b_B / b \equiv 0.5\int_{\pi/2}^{\pi} p(\theta)\sin\theta\, d\theta, \tag{2}$$

here $p(\theta) = \beta(\theta)/b$ is a phase function of scattering with $\beta(\theta)$ being a VSF and $\theta$ a scattering angle. Inherent optical properties $b_B$ and $B$ appear as parameters in approximate [12] and exact [13] analytical solutions to radiative transfer equation. Very important parameters in optical remote sensing of natural water basins, diffuse reflection $R$ and remote sensing reflection $r_{rs} \sim R$ coefficients, are functions of absorption $a$ and backscattering $b_B$ coefficients.

There are additional four parameters that define modulation transfer function (MTF) used for the estimation of underwater visibility [14-16]: average cosine and average square of cosine over scattering phase function:

$$\overline{\cos\theta} = 0.5\int_0^{\pi} p(\theta)\cos\theta \sin\theta\, d\theta, \qquad \overline{\cos^2\theta} = 0.5\int_0^{\pi} p(\theta)\cos^2\theta \sin\theta\, d\theta, \tag{3}$$

average scattering angle and average square of scattering angle over scattering phase function:

$$\bar{\theta} = 0.5\int_0^{\pi} p(\theta)\theta \sin\theta\, d\theta, \qquad \overline{\theta^2} = 0.5\int_0^{\pi} p(\theta)\theta^2 \sin\theta\, d\theta. \tag{4}$$

Below we present results of analysis of an extensive database of 869 volume scattering functions and related to them phase functions and give a number of regressions [17] that can be used for various problems of radiative transfer in natural waters, underwater visibility, and processing of optical remote sensing information.

Dependence between backscattering and scattering coefficients is very important for algorithms of processing optical remote sensing information. Until recently ocean optics community has only restricted database of 15 volume scattering functions measured by Petzold [1] near the California coast. In 2002 additional 41 phase functions of scattering measured all over the World Ocean have been released. [2, 3] The LEO-15 experiment added a significant number of VSFs [5, 7]. The analysis of this database, based on processing with DataDesk software and manual study of measurement conditions, allows us to divide all 869 phase functions into two categories: 1) Typical oceanic waters. They include a majority of Petzold and Mankovsky phase functions and a bulk of LE0-15 at 2000 phase functions; 2) Biologically stable oceanic waters. They include a majority of LE0-15 at 2001 phase functions plus some phase functions from another experiments. The second type of water exhibits different kind of relationship between backscattering and scattering coefficients. This type of water is ideally described by the model of

Ref. 9 and belongs to the category of biologically stable waters. The content of small inorganic particles in this kind of water is smaller than in a typical oceanic water due to processes of sedimentation and biological absorption of inorganic particles by phytoplankton. The rough weather conditions usually destroy biological equilibrium by releasing absorbed inorganic particles in open ocean and by raising terrigenic sediments from the bottom in shallow water. We derived two equations that relate backscattering and scattering coefficient for these two types of waters:

1) Typical oceanic waters (combination of Petzold, Mankovsky and LEO-00 type waters, $\lambda \approx 500 \div 560$ nm, 101 VSFs) :

$$b_B = b_B^w + 0.00618(b - b_w) + 0.00322(b - b_w)^2, \quad r^2 = 0.88, \quad 0.008 \le b \le 9.3\text{m}^{-1}. \qquad (5)$$

2) Biologically stable oceanic waters (LEO-01, 759 VSFs, $\lambda \approx 540 \div 560$ nm):

$$b_B = b_B^w + 0.00579 + 0.00462(b - b_w), \quad r^2 = 0.95, \quad 0.09 \le b \le 2.6\text{m}^{-1}. \qquad (6)$$

here $b_w$, a scattering coefficient by pure water; it is given by the following equation:

$$b_w = 0.005826\left(400/\lambda\right)^{4.322}. \qquad (7)$$

In practical situation sometimes it is very difficult to determine *a priori* the type of water. In this case it is preferable to use Eq. (5) over Eq. (6) because it covers larger range of variability of scattering and backscattering coefficients.

*In situ* measurements of oceanic optical properties in more than 99% of cases do not include measurements of VSF or backscattering coefficient. For that reason it is very important to have some reasonable estimates of these inherent optical properties. The estimation of scattering phase function based on measurements of $b$ and $c$ was proposed in Ref. 18. The estimation of backscattering coefficient based on a knowledge of VSF at 140° was proposed by Maffione and Dana [19].The relationship between $\beta(140°)$ and $b_B$ used in current estimations of $b_B$ is based primarily on theoretical estimates [19]. For that reason it is practically important to derive similar relationship based on our extensive experimental data. The plot of $b_B$ as a function of $\beta(140°)$ for all 869 VSFs is shown in Figure 1. The data presented in this figure is represented by the following linear regressions that do not show any significant distinction between two types of waters:

$$b_B = 7.233\beta(140°), \quad r^2 = 0.999, \text{ or } \int_{\pi/2}^{\pi} p(\theta)\sin\theta\, d\theta = 14.466\, p(7\pi/9). \qquad (8)$$

The first part of Eqs. (8) enhances the relationship similar to the one proposed in Ref. 19 with the values of estimated $b_B$ 6.6% higher than originally proposed by Maffione and Dana. The right part of Eqs. (8) could be used for adjustments of analytical models of marine phase functions similar to the procedure presented in Ref. 20. Average cosines over scattering phase function, that are given by Eqs. (3), determine modulation transfer function [14-16] which is used for image transfer modeling in sea water.

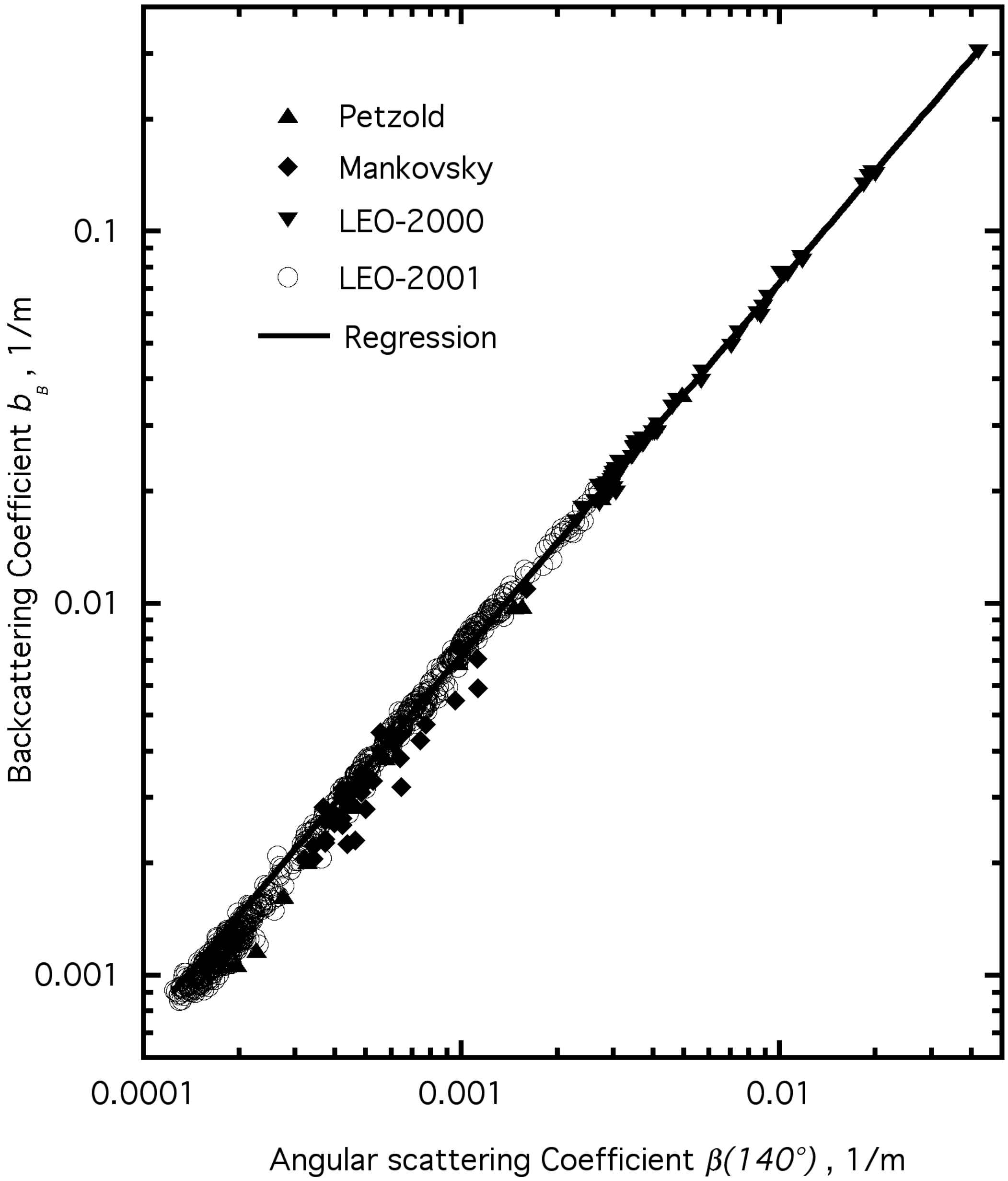


Figure 1. Relationship between volume scattering function at 140 degrees and backscattering coefficient.

The relationships between average cosines and $B$ based on 874 data sets has the following form:

$$\overline{\cos\vartheta} = \frac{1-4B^2}{1.0144+2.6307B-1.2772B^2}, \quad r^2 > 0.82, \quad 0.0022 < B < 0.146, \tag{9}$$

$$\overline{\cos^2\vartheta} = (6-14B^2)/[6(1+3.6213B)], \quad r^2 > 0.845, \quad 0.0022 < B < 0.146. \tag{10}$$

Due to higher variability of forward parts of VSFs relationships between average scattering angles and $B$ are not as good as relationships (9) and (10). The relationships between average scattering angle and square of scattering angle and average cosine have the following form:

$$\overline{\theta} = 0.29119\sqrt{1-\overline{\cos\theta}} + 2.5913\left(1-\overline{\cos\theta}\right), \qquad r^2 \sim 0.7, \quad 0.0022 < B < 0.146, \qquad (11)$$

$$\overline{\theta^2} = 2.4328\left(1-\overline{\cos\theta}\right), \qquad r^2 = 0.99, \quad 0.0022 < B < 0.146. \qquad (12)$$

***Conclusion:*** A number of regressions between inherent optical properties of sea water and integral parameters of marine volume scattering phase functions are established. These regressions are based on 869 experimental measurements of natural water volume scattering functions and represent a broad spectrum of oceanic and sea waters in the range between very clear open and very turbid coastal waters. Presented regressions may be used for modeling light transfer in ocean and lake waters, optical remote sensing algorithms, and for solving problems of visibility and image transfer in natural water basins.

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17. The extinction, absorption, scattering and backscattering coefficients, and also angular scattering coefficient or VSF used in this paper are expressed in units of $\mathrm{m}^{-1}$. In order to be consistent with requirements of physical dimensions all equations that include $b$, $b_B$, $b_w$ $b_B^w$, *etc.,* actually mean: $b = b / b_0$, $b_B = b_B / b_0$, $b_w = b_w / b_0$, and $b_B^w = b_B^w / b_0$, with $b_0 = 1\,\mathrm{m}^{-1}$.
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