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Correlations between the Parameters of the Light Volume Scattering Functions in the Mediterranean Sea Surface Waters

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Purpose. The aim of the work is to study relationships between the parameters of the light volume scattering functions based on the data of their measurements in the Mediterranean Sea surface waters.
Methods and Results. The data of measurements of the light volume scattering functions in the water samples taken in a few regions of the southern Mediterranean Sea, namely from the Strait of Gibraltar to the Levant Sea, as well as in the central part of the Aegean Sea and near the Dardanelles Strait (May, 1998) were used. The following parameters of the volume scattering functions were calculated: total scattering coefficient, and asymmetry and variation coefficients. The maximum and minimum values of the scattering coefficient were 0.21 and 0.09 m^{-1}, respectively; and those for the asymmetry coefficient – 77.8 and 33.9. The variation coefficient of the angle scattering coefficients changed within 35–79%, its maximum and minimum values fell on the angles 7.5° and 162.5°, respectively. Obtained were the relations between the variation coefficient and the scattering angle, the asymmetry coefficient and the scattering coefficient, and the angle scattering coefficients and the total scattering coefficient. All of them possess high (more than 0.9) correlation coefficients. The coefficient value (51.7%) at the angle 2° does not correspond to general relation of the variation coefficient to the scattering angle. This fact is explained by different contributions of coarse and fine suspended matter to the light volume scattering function. At the angle 2°, the main contribution is made by a coarse (organic) suspended matter, whereas at the angles exceeding 7.5° – by a fine (mineral) suspension.
Conclusions. The values of the variation coefficient of the angle scattering coefficient at the angles equal to 2° and exceeding 7.5° demonstrate variability of the coarse and fine suspended matter in the Mediterranean Sea, respectively. The equation for the relation between the asymmetry coefficient of the light volume scattering functions and the total scattering coefficient obtained for the Mediterranean Sea waters is close to the analogous one obtained for the Atlantic Ocean tropical waters. The angle 3.5° is optimal for determining the total scattering coefficient using the angle scattering coefficient for the Mediterranean Sea functions.

Keywords: volume scattering function, parameters, asymmetry, variation, scattering coefficient, scattering angle, Mediterranean Sea

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Introduction

Ocean hydro-optics main task is to study the inherent hydro-optical characteristics of the area under consideration. The primary characteristics include physical quantities that characterize the optical properties of ocean water. These values do not depend on the illumination conditions, but are determined by the chemical composition of the water, the thermodynamic state and, the main thing, by the presence of optically active impurities in the water in the form of solutions and suspensions. The main inherent hydro-optical characteristics are the coefficients of absorption, scattering, attenuation, as well as the volume scattering function (angular distribution of light scattering).

Information on the light scattering characteristics is necessary to solve many problems related to ocean optics, for example [1–3]. Hence, the study the light scattering in waters of different regions of the World Ocean [4–15] is relevance. However, it is often difficult to find information on hydro-optical characteristics in a given area. In this case, low-parameter optical models are used, which link various inherent hydro-optical characteristics and permit to determine a number of others from one measured characteristic [16–20]. In [8], the light volume scattering functions obtained in the Mediterranean Sea and some of their characteristics are given. In the present work, based on the measurement data given in [8], the relationships between some parameters of the volume scattering function are considered.

Relationships between the parameters of the volume scattering function is of practical importance: it gives possibility to estimate another, according to one known parameter, having no necessary data [21]. Of particular practical interest is the relationship between the total scattering coefficient σ and angle scattering coefficient σ(θ), which permits to determine the total scattering coefficient by measuring not all values of the angular distribution function of scattering coefficient σ(θ) in the directions θ = 0–180°, but only the scattering coefficient in one of the directions σ (θ). Theoretical and practical research of this issue was carried out in works [22, 23]. In the present paper, such a study is carried out in relation to the Mediterranean Sea waters.

Research region and period

Measurements of the light volume scattering function in the Mediterranean Sea were carried out during the Marine Hydrophysical Institute expedition in the 2nd cruise of the R/V *Gorizont* (May 1998). Measurement areas were located in the southern part of sea from the Strait of Gibraltar to the Levant Sea and in the Aegean Sea (Fig. 1). Water samples, which the volume scattering function were measured in, were taken throughout the entire route of the vessel.

F i g. 1. Route of R/V *Gorizont* in the Mediterranean Sea

Instrumentation and measurement technique

Light volume scattering function were measured with a nephelometer [1] in water samples taken from the sea surface. Table 1 shows the technical characteristics of the nephelometer.

T a b l e 1

Technical characteristics of a nephelometer

Characteristic	Value
Angles of measurements σ(θ), °	2; 7.5; further in 5 to 162.5
Spectral range of measurements, nm	520 (±40)
Error of measurements σ(θ), %	10

Measurements of the scattering coefficient in the nephelometer are carried out in the range of angles 2–162.5°. The scattering coefficients in the region of small angles were found by extrapolating the scattering function to this region using the equation $\lg\sigma(\theta) = A + B\theta + C\theta^2$. To determine the coefficients A, B and C, the σ(θ) values measured at angles 2; 7.5 and 12.5° were used. As a result, the scattering coefficients at the angles: 0.25; 0.75; 1.25; 1.75; 2.5; 3.5; 4.5; 5.5; 6.5° were calculated. At angles exceeding 162.5°, σ(θ) = const was taken.

Light volume scattering function parameters

As a characteristic of light scattering in hydro-optics, the angular distribution function of the scattering coefficient σ(θ) in the directions θ = 0–180° is used. In the light scattering theory, the volume scattering function is the function $\chi(\theta) = 4\pi\sigma(\theta)/\sigma$, where σ is the scattering coefficient [24]. The χ(θ) function shows the light scattering probability in different directions. In this work, the term "volume scattering function" is applied to the function σ(θ), which shows the amount of scattered light in different directions.

The following integral parameters of the volume scattering function were calculated:

– scattering coefficient σ, m^{-1}, according to the formula

$$\sigma = 2\pi \int_{0}^{180} \sigma(\theta) \sin\theta d\theta;$$

[1] Man'kovskiy, V.I., 1981. [Marine Pulse Nephelometer]. In: B. N. Malinovsky and V. T. Cherepin, Eds., 1981. [*Instruments for Scientific Research and Automation Systems in the Academy of Sciences of the Ukrainian Soviet Socialist Republic*]. Kiev: Naukova dumka, pp. 87-89 (in Russian).

– asymmetry coefficient K, according to the formula $K = \dfrac{\int_0^{90} \sigma(\theta)\sin\theta d\theta}{\int_{90}^{180} \sigma(\theta)\sin\theta d\theta}$

Measurement results and their discussion

A total of 32 volume scattering function were measured. The maximum and minimum values of the volume scattering function parameters observed in the Mediterranean Sea were 0.21 and 0.09 m^{-1} for the scattering coefficient; 77.8 and 33.9 for the asymmetry coefficient, respectively.

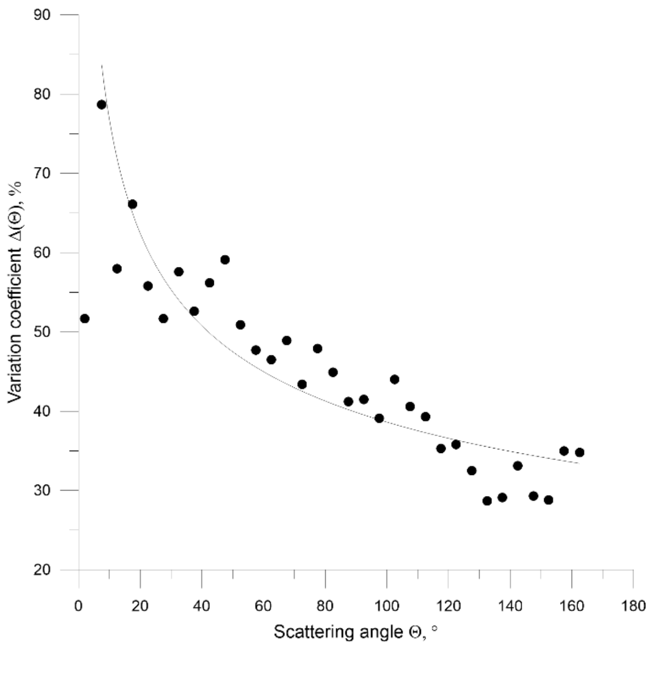
The σ(θ) *variations.* For the entire array of volume scattering function, variation coefficients of scattering coefficients (Δ(θ), %) were calculated at different angles:

$$\Delta(\theta) = \delta[\sigma(\theta)] / < \sigma(\theta) >,$$

where δ[σ(θ)] is the standard deviation: < σ(θ) > is the mean value.

The Δ(θ) value at different scattering angles are shown in Fig. 2. In the range of angles 7.5–162.5°, the variation coefficient is approximated by the function $\Delta(\theta) = 152{,}6\ \theta^{-0.3}$ ($R = 0.91$).

The maximum value of Δ(θ) is observed at a scattering angle of 7.5° and is Δ(7.5°) = 79%. With an increase in the scattering angle, the variation coefficient decreases and at an angle of 162.5° is Δ(162.5°) = 35%.



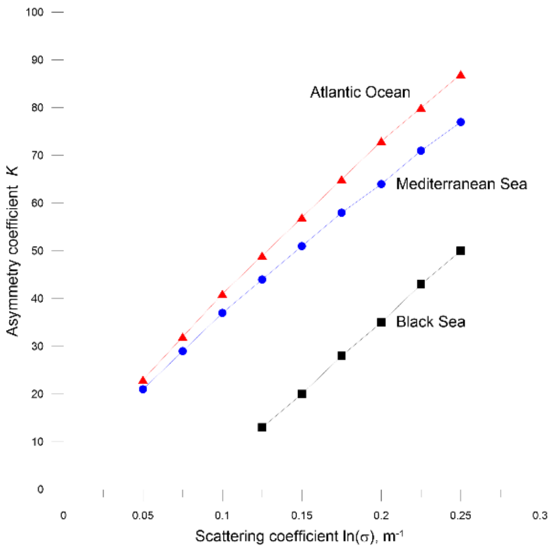
F i g. 2. Variation coefficient of the scattering coefficient depending on direction of scattering

The variation coefficient $\Delta(2°)$ = 51.7% does not correspond to the general relationship (Fig. 2). This is explained by the different contributions to the volume scattering function from coarse and fine suspended matter [25]. At small angles, the main contribution to light scattering is made by a coarse suspension. Thus, at θ = 2°, the contribution of the coarse suspension is three times greater than the one of the fine suspension. At θ = 7.5°, the fine suspension contribution is 4 times higher than the coarse suspension contribution, at θ = 15° – 30 times and at θ = 162.5° – about 100 times. That is, in the Mediterranean Sea, the variation coefficients at an angle of 2° reflect the variability of the coarse (organic) suspended matter concentration, and at angles θ > 7.5° – of fine (mineral) suspended matter one.

Relationship between the asymmetry coefficient and the scattering coefficient. In the Mediterranean Sea, like in other water basins, the following relationship between the asymmetry coefficient of the volume scattering function and the scattering coefficient was observed: with an increase in the scattering coefficient, the asymmetry coefficient increases.

According to the data of [13], the equation $K = f(\sigma)$ in the Mediterranean Sea has the form $K = 232\sigma^{0.8}$ (R = 0.95). In [26] it was shown that the coefficients of relationship $K = f(\sigma)$ depend on the suspension composition in the water of a given water basin and have a regional character.

When comparing the equations $K = f(\sigma)$ in the Mediterranean Sea and in other water basins [9, 11, 26], it was found that the equations describing the relationship for the Mediterranean Sea and for the polygon in the tropical Atlantic Ocean [11] are close (Fig. 3). This is obviously due to the fact that Atlantic waters enter the Mediterranean Sea through the Strait of Gibraltar [27], moving eastward in the southern part of the sea where the light volume scattering functions were measured.



F i g. 3. Relation between the asymmetry coefficient and the scattering coefficient in the waters of the Mediterranean and Black seas, and the Atlantic Ocean

Note that the relation $K = f(\sigma)$ in the Black Sea, shown in Fig. 3, differs from similar dependences in the Mediterranean Sea and in the waters of the tropical Atlantic by significantly lower values of the asymmetry coefficient of the volume scattering function. This can be explained by the high values of fine (mineral) suspended matter concentration in the Black Sea waters. The asymmetry coefficients of the volume scattering function on such particles are much smaller than the volume scattering function for large (organic) particles.

Relationship of angle scattering coefficients with total scattering coefficient. In [22, 23, 28], the issue of the possibility of total scattering coefficient determination by measuring not the entire volume scattering function, but only the scattering coefficient at some fixed angle $\sigma(\theta)$, was considered. To that end, the angle what angle the error in calculating σ from $\sigma(\theta)$ will be the smallest at should be established.

In [28], the standard deviation of the function $\sigma(\theta)/\sigma$ was calculated at different scattering angles. The scattering coefficients $\sigma(\theta)$ in [28] were measured at 4, 15, 30, 45, 60, 75, 90, 105, 120, 135°. According to measurements in different regions of the World Ocean, the minimum standard deviation of the function $\sigma(\theta)/\sigma$ was observed at an angle of 4°.

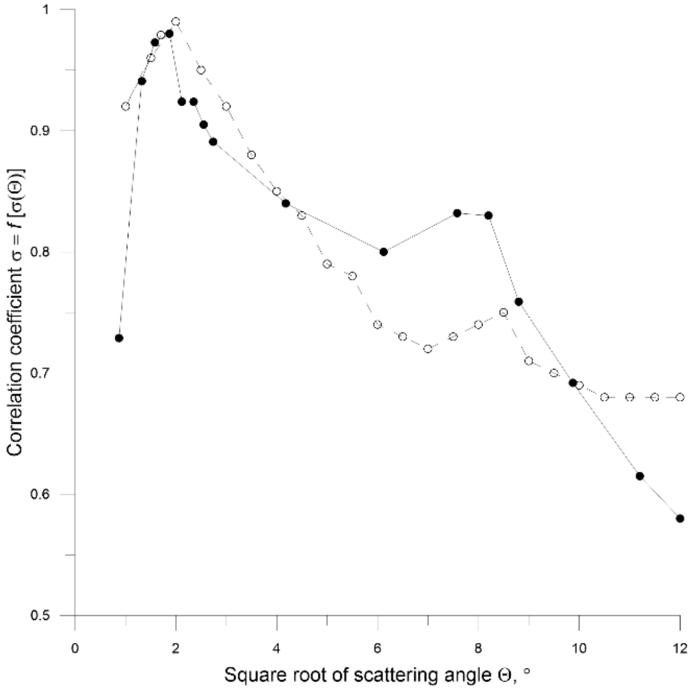
However, in this question, the range of angles θ from 4 to 15° and less than 4° remained undefined. This range of angles was studied in [22, 23]. The scattering coefficients in the range of small angles in [22, 23] were determined by the method described in this paper. The correlation coefficient σ with the values $\sigma(\theta)$ was calculated. The results are presented in Table 2.

Table 2

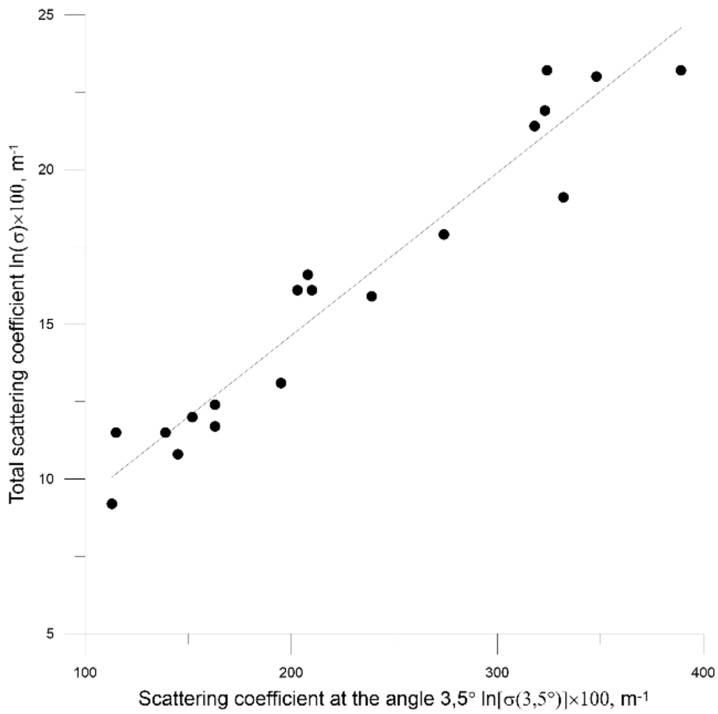
Maximums of correlation coefficient between the total scattering coefficient σ and the scattering coefficient at different angles σ(θ) [22]

Region	The angle corresponding to the maximum of correlation coefficient $\theta(R_{max})$, °	Maximum of the correlation coefficient R_{max}
Mediterranean Sea	3.0	0.99
North Atlantic	4.0	0.98
Black Sea	5.0	0.97
Average	4.5	0.96

Similar calculations were carried out in this study based on the results of measurements of volume scattering function in the Mediterranean Sea. Fig. 4 shows the relationship between the correlation coefficient σ and the value of $\sigma(\theta)$ as the scattering angle function. The maximum correlation coefficient $R_{max} = 0.98$ falls on the angle θ equal to 3.5°. Before, in [22], it was found: θ (R_{max}) = 3.0°. The difference is small and may be due to different statistics used in the calculations.



F i g. 4. Coefficient of correlation between the total scattering and the angle scattering at different angles of scattering in the Mediterranean Sea (solid line) and based on the model volume scattering function (dashed line)



F i g. 5. Relation between the total scattering coefficient and the scattering coefficient at the angle 3.5° in the Mediterranean Sea waters

For comparison Fig. 4 also shows graph of the correlation coefficient $\sigma = f[\sigma(\theta)]$, calculated from the model volume scattering functions [29]. The maximum correlation coefficient for model volume scattering function falls at an angle θ equal to 4.0°. It is noteworthy that for the experimental and model volume scattering functions, the correlation coefficient gradually decreases with increasing scattering angle, except for the range of angles of 50–80°, which its slight increase is observed in.

In fig. 5 for the Mediterranean Sea waters, the relationship between the total scattering coefficient and the scattering coefficient in the direction θ = 3.5° is shown. Equation is $\sigma = 0{,}053\sigma(3.5°)^{0.8}$, correlation coefficient $R = 0.97$.

Conclusion

Analysis of the interrelationships between some parameters of the volume scattering function in the surface waters of the Mediterranean Sea, considered in the work, shows the following.

1. The coefficient variation of the angle scattering coefficient Δ(θ) for the volume scattering function of sea varies within 35–79% with a maximum at 7.5° and a minimum at 162.5°. General dependence Δ(θ) on the scattering angle θ does not correspond to the value Δ(2°) = 51.7%. This is explained by the different contributions to the volume scattering function of light scattering from coarse and fine suspended matter. At an angle θ equal to 2°, the main contribution is made by a coarse (organic) suspension, at θ angles greater than 7.5° – by a fine (mineral) suspension. Accordingly, the Δ(θ) values at these angles show variations in the coarse and fine suspended matter concentration in the Mediterranean Sea.

2. Comparison of the relationship between the asymmetry coefficient of the volume scattering function with the total scattering coefficient $K = f(\sigma)$ in the Mediterranean Sea waters with the data known in the literature on such a relationship in the waters of other water basins showed that it is close to the relationship in the tropical Atlantic Ocean. This can be explained by the fact that Atlantic waters enter the Mediterranean Sea through the Strait of Gibraltar, moving eastward in the southern part of the sea, which the light volume scattering functions were measured in.

3. The optimal angle for determining the total scattering coefficient σ from the value of σ(θ) for the Mediterranean Sea volume scattering functions is the angle θ equal to 3.5°.

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Contribution of the co-authors:

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Ekaterina V. Mankovskaya – selection and analysis of literature, presentation of data in the text and their analysis, preparation of graphic and text materials, article correction

All the authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.