INDICATRICES OF LIGHT SCATTERING BY SEA WATER

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Abstract

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INDICATRICES OF LIGHT SCATTERING BY SEA WATER

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1. In work ([1]) it was indicated that, for transparent waters, the elongation of the scattering indicatrix $\beta(\gamma)/\beta(90)$ increases as the value of the scattering coefficient at an angle of $90°$—($\beta(90)$)—increases. It was suggested that the scattering indicatrix of particles of marine suspension is unchanged for all waters, and that the observed differences between the scattering indicatrices of sea water are explained by changes in the ratio between molecular scattering and scattering by suspended particles.

In the present work, the validity of this hypothesis was tested by analyzing scattering indicatrices measured on samples from the northern part of the Indian Ocean.* The indicatrices studied also belong to transparent waters (the mean value of the attenuation coefficient is 0.25**, which corresponds to a transparency of 78%) and are smooth curves without

Table 1

Type of indicatrix	Number of indicatrices of this type	Range of variation $\lg \beta(15)/\beta(90)$	$\lg \beta(15)/\beta(90)$	$\lg \beta(90)$	ε	σ	ε/σ
I	33.5*	1.5–1.8	1.690.076	−1.680.22	0.250.085	0.200.060	0.750.114
II	58.5*	1.8–2.0	1.930.045	−1.980.14	0.250.071	0.170.046	0.710.072
III	38	2.0–2.1	2.050.018	−2.090.19	0.250.090	0.170.055	0.780.135
IV	33	2.1–2.4	2.190.067	−2.140.16	0.300.103	0.180.046	0.660.139

* Indicatrices having boundary values between the ranges of $\lg \beta(15)/\lg(90)$ were counted in each of the adjacent types as 0.5 each.

any local maxima or minima, so characteristic of the scattering indicatrices of monodisperse suspensions. Between the curves, noticeable differences are observed, significant in the region of angles smaller than $70°$, and comparable

Fig. 1. Angular dependences of the absolute scattering coefficient, averaged for each of the four types

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with the values of the experimental errors for angles greater than 70°. Between the variation of $\lg \beta(\gamma)/\beta(90)$ for any fixed scattering angle from the range of angles 4—70° and the variation of this quantity for the angle 15°, chosen as the reference angle, a significant correlation is observed, and therefore it proves possible to use, as a parameter characterizing the shape of the indicatrix, the value of $\lg \beta(\gamma)/\beta(90)$ for the angle 15°.

For convenience of further analysis, all the curves studied were divided into four types, corresponding to four ranges of values of $\lg \beta(15)/\beta(90)$. Naturally, there is no sharp boundary between these types, and each of them passes smoothly into the neighboring one. In Fig. 1

* The material analyzed (163 scattering indicatrices) was obtained during the 31st voyage of the *Vityaz* (October 1960–March 1961) with the aid of the SPN-57 instrument ([2]). All measurements refer to the green region of the spectrum ($\lambda_{\text{eff}} = 545$ mµ).

** Values of attenuation and scattering coefficients are everywhere given in m^{-1} on the natural base.

presented are the dependences $\beta(\gamma)$, averaged for each of the four types, and in Table 1–the values of the optical characteristics of seawater, also averaged for each of the types. As is seen from Table 1, the transition from type I to type IV is accompanied by an increase in the elongation of the indicatrix and, at the same time, by a decrease in the absolute value of the scattering coefficient at an angle of 90°. The values of the other optical characteristics for all four types practically do not change.

Fig. 1. Angular dependences of the absolute scattering coefficient, averaged for each of the four types

The correlation coefficient between $\lg \beta(15)/\beta(90)$ and $\lg \beta(90)$ is -0.66; the correlation coefficient between $\lg \beta(15)/\beta(90)$ and any of the other three optical characteristics is less than 0.2. Statistically significant relations are also found between $\lg \beta(90)$ and the values of $\lg \beta(\gamma)/\beta(90)$ for other scattering angles smaller than 70°. Comparison of the regression coefficients calculated for these relations with the corresponding regression coefficients for the same relations calculated from the data of the 35th voyage of the R/V *Vityaz* shows that the derived relations are sufficiently representative for this region and are stable with respect to season.

As is seen from Fig. 1, the increase in the elongation of the scattering indicatrix in going from type I to type IV is explained by a decrease in the absolute scattering values in the region of angles greater than 30°, while the scattering value in the interval of angles 4–20° remains almost unchanged. There can be only one reason for such a change—a change in the qualitative composition of the suspension; namely, in going from type I to type IV the number of small particles decreases, whereas the coarse fraction in the suspension of the region under study remains sufficiently stable. Thus, for this region the assumption of invariability of the scattering indicatrix of particles of marine suspension proves to be incorrect.

2. It was possible to select a particle-size distribution of the suspension for which the calculated theoretical curves agree sufficiently well with the measured ones. Figure 2 presents four experimental indicatrices having values of $\lg \beta(\gamma)$ close in magnitude to the mean values for each of the types and thus representing typical curves. The solid lines show theoretical indicatrices calculated under the assumption that the suspended particles are "soft" and spherical and obey a Junge-type distribution:

$$f(r) = A/r^5, \quad r_{\min} < r < \infty, \qquad f(r) = 0, \quad 0 < r < r_{\min}, \tag{1}$$

where r is the particle radius [3]. In doing so, molecular scattering by the water itself was taken into account:

$$\beta(\gamma) = \beta_{\text{particles}}(\gamma) + \beta_{\text{water}}(\gamma). \tag{2}$$

The values of $\beta_{\text{water}}(\gamma)$ were taken from [4].

The transition from the type I curve to the type IV curve is characterized by an increase in the limiting particle size: for type I $r_{\min} = 0.05\,\mu$; for type II, $0.075\,\mu$; for type III, $0.10\,\mu$; for type IV, $0.11\,\mu$.

The refractive index of the particles was taken to be 1.15 [5]. The particle concentrations N were calculated by equating the theoretical and experimental values of the scattering coefficient at an angle of 90°:

$$\beta_{\text{meas}}(90) - \beta_{\text{water}}(90) = \beta_{\text{theor}}(90). \tag{3}$$

* These data (29 indicatrices) refer to the same region of the Indian Ocean, but were obtained in another season (July–November 1962).

Knowing the particle concentration, one can find the distribution constant $A = 4Nr_{\min}^4$ and calculate the weight content and the granulometric composition of the suspension corresponding to the given scattering indicatrices (see Table 2). The particle density was taken to be 2.65 g/cm^3 ([5]).

Since simultaneous measurements of the optical characteristics and the composition of the suspension were not carried out, the results obtained were compared

Fig. 2. Comparison of measured indicatrices (dashed) and calculated ones (solid curves)

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with geological data available in the literature for the given region ([6]). The calculated suspension concentrations proved to be somewhat underestimated

Fig. 2. Comparison of measured indicatrices (dashed) and calculated ones (solid curves)

in comparison with the literature data, chiefly for the fraction $50 \div 10$ μ, where, according to the literature data, there is a local concentration maximum. This difference is apparently explained by the influence of the biogenic component of the suspension, which has a size distribution different from distribution (1).

Table 2

Indicatrix type	N, particles/m^3	Total suspension content, g/m^3 ($r > r_{\min}$)	Amount of suspension collected by geologists, g/m^3 ($r > 0.4\mu$)	$r > 100\mu$	100–50	50–10	10–5	5–1	$< 1\mu$
I	$91 \cdot 10^{12}$	0.506	0.063	0.00025	0.00025	0.0020	0.0025	0.020	0.038
II	$9.8 \cdot 10^{12}$	0.183	0.034	0.00014	0.00014	0.0011	0.0014	0.011	0.020
III	$2.9 \cdot 10^{12}$	0.127	0.032	0.00013	0.00013	0.0010	0.0013	0.010	0.019
IV	$1.9 \cdot 10^{12}$	0.113	0.028	0.00011	0.00011	0.0009	0.0013	0.009	0.017

The underestimation by distribution (1) of the number of these large particles is also indicated by the underestimated, in comparison with experimental values, values of the scattering index $\beta(\gamma)$ in the angular region 4–30° for theoretical indicatrices of types II, III, and IV (see Fig. 2), and, as a consequence of this, by the calculated values of the total scattering index σ for these types being

Fig. 3. Distribution of types of scattering indicatrices in the northern part of the Indian Ocean

Figure 3: Fig. 3. Distribution of types of scattering indicatrices in the northern part of the Indian Ocean

smaller than the measured ones*. In all probability, distribution (1) for $n = 5$ and the corresponding values

* The total scattering index was calculated by the formula given for a Junge-type distribution with $n = 5$ in ([7]). The following values of σ were obtained: for type I 0.24; II 0.12; III 0.10; IV 0.09.

$r_{\min}$, can be taken as the coarse structure of the composition of the marine suspension in the given region. Complete agreement between the measured and calculated values can be achieved by introducing the appropriate corrections to this distribution; however, for a detailed analysis and assessment of these corrections, simultaneous measurements of the optical characteristics and of the biological and geological composition of seawater on the same samples are necessary.

Fig. 3. Distribution of types of scattering indicatrices in the northern part of the Indian Ocean

3. Analysis of transparency maps for the surface horizons of the northern part of the Indian Ocean shows that, against the background of a generally uniform distribution of transparency, zones of turbidity stand out, exactly coinciding with the position of the zones of division between currents.

A definite connection is also traced between the distribution of types of indicatrices over the water area and the zones of currents and the boundaries between them (Fig. 3). If for the monsoon current the mean value of $\lg \beta(15)/\beta(90)$ is 1.93 (type II), then for the Countercurrent this value is 2.07 (type III), and for the Trade-Wind Current 2.14 (type IV), for the West Australian Current 2.00 (types II–III). Although at present it is difficult to explain the regularities of this distribution, owing to the absence of data on suspension and plankton measured simultaneously with the optical characteristics of the waters under study, nevertheless the results obtained indicate the possibility of using the scattering indicatrix as an additional optical criterion for investigating the dynamic structure of waters.

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Note: Figure translations are in progress. See original paper for figures.