

DEPARTMENT OF THE NAVY NAVAL INTELLIGENCE SUPPORT CENTER TRANSLATION DIVISION 4301 SUITLAND ROAD WASHINGTON, D.C. 20390 50 ADA 03688 UNCLASSIFIED CLASSIFICATION: APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED Study of the Polarization of Light Scattered by Seawater <</p> TITLE: Issledovaniye polyarizatsii sveta, rasseyannogo morskoy vodoy Ye. Kondrashev, S.Ye. AUTHOR (S) PAGES: 9 Optika okeana i atmosfery, Institute of Oceanology of the USSR Academy of Sciences, "Nauka" Publishing House, SOURCE: Leningrad, 1972 Pages 136-148 01700 MAR 15 1977 ORIGINAL LANGUAGE: Russian С TRANSLATOR: APPROVED 3894 NISC-TRANSTATION 1 February 1977 DAT 115 407682 :00 114,2409hf. Jet With Trott. COPY AVAILABLE TO DDC DOES NOT PERMIT FULLY LEGIBLE PRODUCTION DISTRIBUTION / AVAILABILITY CODES AVAIL Sed/or SPECIAL Qi21.

## STUDY OF THE POLARIZATION OF LIGHT SCATTERED BY SEAWATER

[Kondrashev, S. Ye., Issledovaniye polyarizatsii sveta, rasseyannogo morskoy vodoy, in: Optics of the Ocean and Atmosphere (Optika okeana i atmosfery), Institute of Oceanology of the USSR Academy of Sciences, "Nauka" Publishing House, Leningrad, 1972, pp. 136-148; Russian]

The state of a light beam is determined by the Stokes parameters, which will /136 be written as 1

$$S_1 = 1; S_2 = 1P \cos 2\Psi; S_3 = 1P \sin 2\Psi; S_4 = 1q;$$

where I is the intensity (brightness) of the light beam; P is the degree of polarization of the light beam;  $\Psi$  is the angle of rotation of the direction of "maximum" polarization with respect to the plane of scattering; q is the degree of ellipticity.

An arbitrary partially polarized light beam of intensity I may be represented as the sum of two incoherent beams: a completely polarized beam of intensity I' = rI

and a completely depolarized beam of intensity I'' = (1 - r)I. The quantity  $r = +\sqrt{p^2} + q$  is the degree of homogeneity of the light beam.

The scattering matrix, which is a linear operator of the transformation of Stokes parameters for light scattering by a volume of seawater, was experimentally /13 determined with a laboratory matrix meter.

The first column of the scattering matrix represents the scattering volume of a turbid medium exposed to completely depolarized (natural) light with Stokes parameters

$$S_1 = I, S_2 = S_3 = S_4 = 0,$$

The polarization parameters of the scattered light during exposure to natural light were obtained from the following formulas:

$$P_{\bullet} = \pm \sqrt{\tilde{f}_{21}^{*} + \tilde{f}_{31}^{*}};$$

$$\Psi_{\bullet} = \pm \left| \frac{1}{2} \operatorname{arctg} \left( \tilde{f}_{21} / \tilde{f}_{21} \right) \right| \text{ for } \tilde{f}_{21} > 0;$$

$$\Psi_{\bullet} = \pm \left[ \frac{\pi}{2} - \left| \frac{1}{2} \operatorname{arctg} \frac{\tilde{f}_{31}}{\tilde{f}_{21}} \right| \right] \text{ for } \tilde{f}_{21} < 0;$$

$$q_{\bullet} = \tilde{f}_{41};$$

$$r_{\bullet} = \pm \sqrt{\tilde{f}_{21}^{*} + \tilde{f}_{31}^{*} + \tilde{f}_{41}^{*}}.$$

$$(!)$$

In the formulas for  $\Psi_*$ ,  $\tilde{f}_{31} > 0$  has a (+) sign, and  $\tilde{f}_{31} < 0$  has a (-) sign. If  $\tilde{f}_{31} = 0$ , then for  $\tilde{f}_{21} > 0$ , angle  $\Psi_* = 0$ , and when  $\tilde{f}_{21} < 0$ , angle  $\Psi_* = \pi/2$ . If  $\tilde{f}_{21} = 0$ , then for  $\tilde{f}_{31} > 0$ , angle  $\Psi_* = +45^\circ$ , and when  $\tilde{f}_{31} < 0$ , angle  $\Psi_* = -45^\circ$ .

\*Numbers in the right margin indicate pagination in the original text.

The second column of the scattering matrix represents the scattering volume of the turbid medium exposed to linearly polarized light beams: horizontally polarized  $\{S_1 = S_2; S_3 = S_4 = 0\}$  and vertically polarized  $\{S_1 = -S_2; S_3 = S_4 = 0\}$ .

The third column of the scattering matrix represents the scattering volume exposed to linearly polarized light beams with polarization angles  $\Psi = \pm 45\{s_1 = s_3; s_2 = s_4 = 0\}$ ,  $\{s_1 = -s_3; s_2 = s_4 = 0\}$ .

The fourth column of the scattering matrix represents the scattering volume exposed to light beams with circular polarization  $\{S_1 = S_4; S_2 = S_3 = 0\}$ ,  $\{S_{\uparrow} = -S_4; S_2 = S_3 = 0\}$ .

The polarization parameters of the scattered light during exposure to completely alternatively polarized light beams were determined from the following formulas:

$$\begin{split} \hat{r}_{j}^{*} &- \div \frac{\sqrt{(\tilde{f}_{21} \pm \tilde{f}_{2j})^{2} + (\tilde{f}_{31} \pm \tilde{f}_{3j})^{3}}}{1 \pm \tilde{f}_{1j}}; \\ \Psi_{j}^{*} &= \pm \left| \frac{1}{2} \arctan\left\{ \frac{\tilde{f}_{31} \pm \tilde{f}_{3j}}{\tilde{f}_{21} \pm \tilde{f}_{2j}} \right\} \right|, \text{for}(\tilde{f}_{21} \pm \tilde{f}_{21}) > 0; \\ \Psi_{j}^{*} &:= \pm \left[ -\frac{\pi}{2} - \left| \frac{1}{2} \arctan\left\{ \frac{\tilde{f}_{31} \pm \tilde{f}_{3j}}{\tilde{f}_{21} \pm \tilde{f}_{2j}} \right\} \right| \right] \text{for}(\tilde{f}_{2j} \pm \tilde{f}_{2j}) < 0; \\ q_{j}^{*} &= \frac{\tilde{f}_{41} + \tilde{f}_{4j}}{1 \pm \tilde{f}_{1j}}; \\ r_{j}^{*} &= \pm \frac{\sqrt{(\tilde{f}_{21} \pm \tilde{f}_{2j})^{2} + (\tilde{f}_{31} \pm \tilde{f}_{3j})^{2} + (\tilde{f}_{41} \pm \tilde{f}_{4j})^{3}}{1 \pm \tilde{f}_{1j}}. \end{split}$$
(2)

The (±) signs of the polarization parameters correspond to the irradiating beams with  $c{\pm S_i}$ , where j = 2, 3, 4.

In the formulas for  $\Psi_j$ ,  $(\tilde{f}_{31} \pm \tilde{f}_{3j}) > 0$  has a (+) sign, and  $(f_{31} \pm f_{3j}) < 0$  has a (-) sign. If  $(\tilde{f}_{31} \pm \tilde{f}_{3j}) = 0$ , then for  $(\tilde{f}_{21} \pm \tilde{f}_{2j}) > 0$ , angle  $\Psi = 0$ , and for  $(\tilde{f}_{21} \pm \tilde{f}_{2j}) < \Psi_j = \frac{\pi}{2}$ . If  $(\tilde{f}_{21} \pm \tilde{f}_{2j}) = 0$ , then for  $(\tilde{f}_{31} \pm \tilde{f}_{3j}) > 0$  angle  $\Psi_j = +45^\circ$ , and for  $(\tilde{f}_{31} \pm \tilde{f}_{3j}) < 0$ ,  $\Psi_j = -45^\circ$ .

In Eqs. (1) and (2),  $\tilde{f}_{ij}$  are the relative components of the scattering matrix.<sup>1</sup>

The experimentally obtained components of the scattering matrix of seawater have a smoother form than for monodisperse latex. The angular dependences of the components of the scattering matrix are more sensitive functions than the scattering indicatrices. Certain components of the scattering matrix, shown in Fig. 1, correspond to two samples of seawater with similar values of the scattering index. The samples were taken in the northeastern Black Sea in the summer of 1969, 1.5 miles from the shore at a depth of 10 m. The table shows data for membrane filtration, %.

The theoretical scattering indicatrix of spherical particles for a certain particle size distribution of the Young distribution type<sup>2</sup> is in good agreement with the experimental ones if one considers that scattering at angles greater than 15° is determined by particles with  $\rho \leq 6$  and a refractive index n = 1.15-1.20. At /13 smaller angles, the scattering is determined by particles with  $\rho > 6$  and refractive index n = 1.05. Assuming the particles to be spherical, we find according to

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Fig. 1. Some relative components of the scattering matrix for samples Nos. 1 and 2

Number of sample, characteristics	Particle diameter, µm						Total number	Suspension,
	1-2.5	2.5-5	5-10	10-25	25-50	>50	cles, m <sup>3</sup>	g/m <sup>3</sup>
No. 1 $\sigma = 0.047 \text{ m}^{-1}$ $\epsilon = 0.076 \text{ m}^{-1}$	70.5	7.3	7.1	11.5	3.5	0.1	873·10 <sup>6</sup>	0.62
No. 2 $\sigma = 0.051 \text{ m}^{-1}$ $\varepsilon = 0.09 \text{ m}^{-1}$	71.0	8.4	7.6	10.5	2.0	0.5	911·10 <sup>6</sup>	0.71

Shifrin<sup>3</sup> that the entire twice-refracted light is located within a cone with an apex angle of about 20° for n = 1.05. Since seawater contains up to 50-90% of fine particles not detectable by geologists, all the characteristics of the polarization curves at scattering angles greater than 15-20° depend on particles with  $\rho \leq 6$ , which in scattering theory correspond to the intermediate case between Rayleigh scattering and geometrical optics. At scattering angles up to 15-20°, the prin- /14 cipal polarization effects will be introduced by large particles with optical properties differing little from those of seawater.

Scattering of circularly polarized light (Figs. 2, 3, 4). To within a constant factor, the scattering matrix component  $\tilde{f}_{14}$  is equal to the difference of scattered light intensities from clockwise-polarized light and from counterclockwise-polarized light. We see from the shape of the  $\tilde{f}_{14}$  curve for sample No. 1 that the  $\tilde{f}_{14}$  values are positive at angles of about 6°, although their magnitude is small. In the remaining angular interval, to within the experimental errors,  $\tilde{f}_{14}$  may be taken to be equal to zero, with the exception of the angles 40-80°, where these values are negative (up to -0.2).



## Fig. 2. Ellipticity of scattered light from alternatively polarized irradiating light beams.

(No. 1), (No. 2) - numbers of samples in all the figures.

For sample No. 2, the value of the component  $\tilde{f}_{14}$  may always be assumed to be zero, with the exception of the angles from 130°, where  $\tilde{f}_{14}$  is negative.

The shapes of  $q_4$  curves for the two samples are very similar, with a certain shift of local maxima for sample No. 1 to larger scattering angles. No quantitative characteristic of any kind appears possible. At a scattering angle of 100°, the ellipticity disappears for both samples in the case of scattering of clockwisepolarized light.

The dissimilarity of the behavior of  $q_4^{\pm}$  curves in the 90° angle range may be explained by the anisotropy of the optical properties of the material of the scattering centers. A greater anisotropy is observed for sample No. 1.

Samples No. 1 and 2 differ very strongly in the behavior of the degree of linear polarization  $P_4^{\pm}(\phi)$ . The greatest dissimilarity between  $P_4^{\pm}$  and  $P_4^{-}$  is observed in sample No. 2. For example, for the 70° angle, R<sup>-</sup> ~ 0, and R<sup>+</sup> = 0.8 is the maximum value.

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The depolarizing properties of the scattering volume determine the shape of the  $r_4(\phi)$  curve. The curves show a certain regularity. Since the  $r_4$  curve represents the polydispersity of the scattering volume, it may be concluded that sample No. 2 is more polydisperse, but the largest minimum is characteristic of sample No. 1 at a scattering angle of 130°.

Scattering of alternatively polarized light beams with a polarization angle of  $\pm 45^{\circ}$  (Figs. 2, 3, 5). To within a constant coefficient, the behavior of the scattering matrix component  $f_{13}$  is equal to the difference of the total intensities of the scattered light beams from linearly polarized irradiating light beams with a /144 polarization angle of  $\pm 45^{\circ}$ . This value is rather insignificant for sample No. 1 and vanishingly small for sample No. 2.

The ellipticity for both samples never exceeds 0.35. Approximately the same shape of  $q_3^+$  and  $q_3^-$  curves is observed, as if with a parallel shift of one of the curves relative to the other, and a slight deformation. The moderate values of q over the entire range of scattering angles suggest that the material of the suspension is a dielectric with very low losses. The homogeneity of the scattered light



Fig. 4. Degree of polarization P and polarization angle  $\Psi$  of scattered light from alternatively circularly polarized irradiating light beams. For sample No. 2: from 0.5 to 10 and from 20 to 130°  $\Psi_4 = \pi/2$ ; for  $\phi = 15$  and 145°  $\Psi_4^+ = 0$ ; from 0.5 to 50°  $\Psi_4^- = 0$ ; from 70 to 145°  $\Psi_4^- = \pi/2$ .

 $r_3(\phi)$  for sample No. 1 is higher. The angular shape of the polarization angle curve /1 makes it possible to assume a greater uniformity of the forms of the scattering centers, but with a marked deviation from sphericity. A greater uniformity with a smaller  $\rho$  characterizes sample No. 1.

Scattering of horizontally and vertically polarized light beams (Figs. 2, 3, 6). Concerning the  $\tilde{f}_{12}$  component, the same may be said as for the  $\tilde{f}_{13}$  and  $\tilde{f}_{14}$  components. Its shape is somewhat similar to the shape for scattering centers in the form of spheres, but with a maximum smaller by 30-40%. The maximum for sample No. 1 is diffuse from 80 to 110°, and for sample No. 2, the maximum falls on  $\phi = 100^{\circ}$ .

The greatest ellipticity is that of samples at a 90° scattering angle for a horizontally polarized beam. For sample No. 1, this ellipticity of  $q_2$  is very pronounced. For scattering of the vertically polarized light beam, the ellipticity for both samples is insignificant over the entire range of scattering angles.

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Fig. 5. Degree of polarization P and polarization angle  $\Psi$  of scattering light from alternatively linearly polarized irradiating light beams at an angle of ±45°.





The dissimilarity in the behavior of  $q_2$  indicates an appreciable anisotropy of the properties of the scattering centers. For sample No. 1, this anisotropy is higher.

The behavior of the r<sub>2</sub> curve once more confirms the view that the polydispersity of sample No. 2 is higher.

Scattering of natural light (Figs. 3, 7, 8). To within a constant factor, the  $f_{11}$  component of the scattering matrix gives the intensity of the scattered light when a volume of turbid medium is exposed to natural light. Figure 7 shows the scattering indicatrices for these two water samples. Many papers have discussed the analysis of the suspension using the form of the scattering indicatrix. It is always assumed that the suspension is spherical in shape. On the basis of the form of the scattering indicatrix, one can select the particle size distribution function. No data on the shape, optical properties, anisotropy of the scattering particles, and their orientation in space can be obtained from data on the indicatrix.



Fig. 7. Light scattering indicatrices for two samples of seawater, Nos. 1 and 2, with similar values of the scattering index.

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In the scattering of natural light, there appears a slight ellipticity characteristic of particles of nonspherical shape, or inhomogeneity of the optical properties of the scattering centers. To within the experimental errors, the ellipticity may be considered the same for both samples. The degree of linear polarization  $P_*$  for sample No. 2 from 30 to 145° has a polarization angle of 90°, and at smaller angles, this angle is zero. Such behavior of the degree of polarization indicates a deviation from sphericity of the scattering centers that is smaller than for sample No. 1. The size spectrum for sample No. 2 is wider, as indicated by lower values of the degree of homogeneity  $r_*$ .

The above-discussed angular dependences of the polarization characteristics of scattered light with similar values of the scattering index  $\sigma$  make it possible to detect a difference in the composition of the suspension in the samples studied.



Fig. 8. Degree of polarization P and polarization angle  $\Psi$  of scattered light from a natural irradiating light beam. For sample No. 2: for  $\phi$  up to 30°  $\Psi_{\star}$  = 0; for  $\phi$  from 30 to 145°  $\Psi_{\star}$  =  $\pi/2$ .

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