Reports of the Academy of Sciences of the USSR

1962

SovietRxiv

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Abstract

Full Text

Reports of the Academy of Sciences of the USSR

1962. Volume 147, No. 3

GEOPHYSICS

V. A. TIMOFEEVA

DEGREE OF POLARIZATION OF NATURAL LIGHT IN THE SEA

(Presented by Academician V. V. Shuleikin on 21 VI 1962)

As has already been noted ([1]), measurements of the polarization of natural light in the sea have until now been carried out almost exclusively in the horizontal direction. As for the spatial distribution of the polarization characteristics, essentially no data have been available up to the present time.

The aim of the present work was to study the spatial distribution of the polarization of natural light in the sea at different depths and in different parts of the visible region of the spectrum.

For measuring the polarization of natural light in the sea, a marine photoelectric polarimeter was designed and built at the Black Sea Department of the Marine Hydrophysical Institute of the Academy of Sciences of the Ukrainian SSR. The polarimeter makes it possible to measure both the brightness and the polarization characteristics of underwater daylight in practically all directions (over the sphere), in three spectral regions and in "white" light, down to a depth of 100 m. Only 11 min are required to carry out all measurements at each horizon. The accuracy with which the degree of polarization is determined by the polarimeter is quite sufficient for solving the problem posed.

Fig. 1. Dependence of the degree of polarization on the angle A for different ζ at $\tau = 11$

Measurements of the polarization of natural light in the sea were carried out from the expedition vessel *Mikhail Lomonosov*. During the measurements the

Fig. 2. Polar diagrams of the distribution of the degree of polarization by zenith angles of the polarimeter at $\tau = 8$.

Figure 2: Fig. 2. Polar diagrams of the distribution of the degree of polarization by zenith angles of the polarimeter at $\tau = 8$.

sea state was 1-2 points, the sky was cloudless, and the altitude of the Sun was about 29°. Let us consider the results obtained.

We introduce the following notation: A is the angle between the vertical of the Sun and the vertical of the polarimeter (the vertical plane passing through the optical axis of the polarimeter) (the angle A is measured clockwise from the vertical of the Sun); ζ is the zenith angle of the polarimeter (the angle between the optical axis of the polarimeter and the direction toward the zenith); φ is the scattering angle (the angle between the optical axis of the polarimeter and the refracted solar ray); P is the degree of polarization; τ is the optical depth (the product of the extinction coefficient and the geometrical depth).

Figure 1 gives examples of curves showing the dependence of the degree of polarization on the angle A for optical depth 11. As was to be expected, the curves are symmetric with respect to the direction toward the Sun.

Taking into account the natural scatter of the experimental points, it may be said that a change in the angle A causes a systematic change in the degree of polarization for any, but fixed, ζ. The magnitude of this change ranges from 10 to 50%.

The angle $A_{\max}$, at which the degree of polarization is maximal for a given ζ, does not remain constant as ζ changes. At small ζ this angle is close to 180° (i.e., in the direction away from the Sun), whereas in the direction toward the Sun the degree of polarization is minimal. With increasing zenith angle, the direction in which the degree of polarization is maximal begins gradually to approach the direction toward the Sun. At ζ = 140-160°, for all the depths investigated, the degree of polarization is maximal in the direction toward the Sun and minimal in the opposite direction.

The curves obtained by us for $\zeta = 90°$ show good qualitative agreement with the curves of Waterman and Westell ([2]). The maximum degree of polarization for this zenith angle does indeed lie near $A = 90$ and 270°, and the minimum near $A = 0$ and 180°. In some cases, however, there are rather large deviations (up to 30°). The principal cause producing periodic changes in the degree of polarization (Fig. 1) should apparently be regarded as the change in the scattering angle when A changes; however, there is undoubtedly also the influence of other secondary factors which so far cannot be taken into account. Curves for ζ different from 90° have been obtained by us for the first time, and therefore there is as yet nothing with which to compare them.

Fig. 2. Polar diagrams of the distribution of the degree of polarization by

Fig. 3. Spatial distribution of the degree of polarization at optical depths 7 (left) and 13 in green rays.

Figure 3: Fig. 3. Spatial distribution of the degree of polarization at optical depths 7 (left) and 13 in green rays.

Fig. 4. Spatial distribution of the degree of polarization at optical depth $\tau \cong 14$ (from left to right) in the blue, green, and red parts of the spectrum

Figure 4: Fig. 4. Spatial distribution of the degree of polarization at optical depth $\tau \cong 14$ (from left to right) in the blue, green, and red parts of the spectrum

zenith angles of the polarimeter at $\tau = 8$.

Let us give polar diagrams of the distribution of the degree of polarization by zenith angles ζ for different values of A (indicated in Fig. 2 inside the curves) at optical depth $\tau = 8$. The arrow indicates the direction of the refracted solar rays (beneath the sea surface) in the solar vertical.

The diagrams clearly show that: 1) near the solar rays (i.e., at small ζ and A) the degree of polarization is minimal and changes hardly at all with changing ζ; 2) the direction in which the degree of polarization is maximal changes with changing angle A; and 3) the diagrams are asymmetric with respect to the refracted rays or the vertical (with the exception of $A = 90^{\circ}$). Polar diagrams of the type shown in Fig. 2 were used by us subsequently to construct figures characterizing the spatial distribution of the degree of polarization at different depths.

Fig. 3. Spatial distribution of the degree of polarization at optical depths 7 (left) and 13 in green rays.

Figure 3 shows a photograph of such spatial figures for optical depths 7 and 13 in green rays. The arrows, as before, indicate

direction of the refracted solar rays beneath the sea surface. As we see, the distribution body of the degree of polarization of natural light in the sea at each of these depths (and also at depth 11) is asymmetric with respect to the vertical or to the refracted rays; apparently, symmetry should occur only at those depths at which the light is ultimately scattered and where, consequently, the influence of the asymmetry of illumination of the sea is no longer felt. Thus, for example, under vertical illumination of the medium (i.e., under normal incidence of the solar rays on the water surface), in laboratory conditions we obtained a figure for the distribution of the degree of polarization that was, naturally, strictly symmetric with respect to the vertical. In this same direction (i.e., toward decreasing asymmetry—Fig. 3) an increase in the Sun' s altitude, cloudiness, and increased turbidity of the water should act.

Fig. 4. Spatial distribution of the degree of polarization at optical depth $\tau \cong 14$ (from left to right) in the blue, green, and red parts of the spectrum

Comparison of the spatial distribution of the degree of polarization at depths 7 and 13 shows that the degree of polarization at depth 13 is considerably smaller in all directions than at depth 7. This is in complete agreement with the results of our laboratory studies ([1]), as well as with what was obtained by Ivanov and Uterman ([3]) in the sea in the horizontal direction. Moreover, as was to be expected, Fig. 3 shows that at depth 13 the asymmetry of the body with respect to the vertical is less than at depth 7.

Let us consider the influence of the wavelength of light on the degree of polarization. Earlier ([1]), on the basis of laboratory studies, we put forward the supposition that in the sea the degree of polarization should be smaller for the most penetrating rays and larger for the short-wavelength and especially the long-wavelength parts of the spectrum (the influence of the scattering indicatrix was not considered in this case). This supposition is now confirmed by the material of field measurements. Figure 4 presents the spatial distribution of the degree of polarization at depth $\tau \cong 14$ in the blue, green, and red parts of the spectrum. The ratio of the extinction coefficients at this depth was respectively 1.1; 1.0 and 1.4.

From Fig. 4 it is evident that, indeed, the degree of polarization of natural light in the sea for different directions in the green rays is smaller than in the blue and, especially, in the red. Ivanov and Uterman ([3]) came to an analogous conclusion regarding the degree of polarization of underwater daylight in the horizontal direction.

Unfortunately, the results obtained cannot yet be compared, even approximately, with theoretical calculations, because of the complexity of the theory of light propagation in scattering turbid media (including the sea). Moreover, the scattering matrix required for such a comparison is not yet known under real conditions.

In conclusion, I express my gratitude to M. N. Kaigorodov, who took part in the measurements of polarization in the sea with a polarimeter.

Black Sea Division
of the Marine Hydrophysical Institute
of the Academy of Sciences of the Ukrainian SSR

Received
3 III 1962

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