Reflection-Polarization Pattern at Water Surfaces and Correction of a Common Representation of the Polarization Pattern of the Sky

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Many hydrophilous insects recognize water by the polarization of the reflected light [1]. When the water is illuminated by diffuse, unpolarized sky light, the animals have a relatively simple polarization pattern to identify; all the e vectors in the reflected light are horizontal. But when the sky is clear and visibility good, very complicated polarization patterns can develop due to superposition of the polarization characteristics of the water surface and the partially reflected polarization pattern of the sky.

We have calculated such patterns for an ideal water surface, and present them here. We also present a revised picture of the polarization of sky light. The drawing of the sky polarization pattern published in 1959 by Stockhammer [2], which has been reproduced in many review articles and textbooks (e.g. [3-6]), and the two-dimensional representation of the sky polarization pattern published by Wehner [7,8] contain an error in the directions of the e vectors. Here we correct this error. For the calculations of reflection polarization the sky polarization pattern was slightly idealized; the lines of equal polarization were assumed to form exact circles around the position of the sun, as in Wehner's [9] three-dimensional polarization pattern, and the e vectors were assumed to be exactly aligned with these circles. Departures from this regular pattern in the vicinity of the sun (Babinet and Brewster neutral point) were disregarded. These departures are negligible because here the stronger polarization of the water surface predominates. The degree of polarization was approximated by \( d = d_{\text{max}} \sin \left( \frac{1}{2} \alpha \right) \) (see [10], p. 288; \( \alpha \) is the angular distance from the sun).

For sun elevations of 0° (sun at the horizon), 30°, 60°, and 90°, \( d_{\text{max}} \) was taken to be 77, 70, 63, and 56%, respectively (see [10], p. 295). To calculate the reflection of the sky polarization pattern the appropriate Fresnel formulas were used ([11], p. 332).

With an ideal water surface under diffuse, unpolarized sky light, all the e vectors in the reflection-polarization pattern are arranged concentrically around the center of the pattern; that is, from the viewpoint of an observer they appear horizontal (Fig. 1a). Polarization is maximal at the Brewster angle \( \theta = 53° \) (dotted line representing a degree of polarization \( d = 100% \)). The relative intensity of the reflected light is not shown in the figures. For unpolarized incident light it is 2% at \( \theta = 0° \) (in the center of the pattern) and 7.6% at the Brewster angle; the amount of light reflected rises rapidly for \( \theta > 60° \), reaching 100% at \( \theta = 90° \) (at the edge of the pattern).

With a clear, cloudless sky the polarization pattern visible over the water surface is considerably more complicated, because the polarization pattern of the sky itself contributes, to some extent,
to the reflection-polarization pattern. Figure 2a shows the sky polarization pattern for a sun elevation of 30°. This is the corrected form of Stockhammer’s pattern (Fig. 2b; see also legend). When the sun is at the zenith, the band of strongest polarization in the sky polarization pattern, 90° away from the sun, is parallel to the horizon; the e vectors in this zone are now horizontal and add to the polarization with horizontal e vectors in the reflection-polarization pattern, even in regions apart from the Brewster angle (Fig. 1b). The closer the sun comes to the horizon, the steeper is the slope of the band of strongest polarization in the sky, and the greater the departure of the e vectors from horizontal in the polarization pattern of the water surface. In the extreme case, when the sun is at the horizon (Fig. 1d), vertical (radial in Fig. 1) e vectors can appear. However, such discrepancies from the otherwise dominant horizontal e-vector orientation occur only in regions apart from the Brewster angle – regions in which the band of strongest polarization is reflected by the water surface and at the horizon (at the periphery of the pattern). Here the degree of polarization is lower than in the region of the Brewster angle.

1 Stockhammer based his polarization pattern on the data of Sekera, Sekera (cf. [13]) represented the e-vector directions in a rather obscure way, as lines of equal deviation of the plane of polarization from the vertical plane. In transferring the angles so indicated to the radii of polar-coordinate paper, Stockhammer reversed the direction of rotation. As a result, all the e-vectors appear reflected about the radial coordinates. Although Wehner [9] represented the sky polarization pattern correctly and in the first easy understandable form, with three-dimensional diagrams, some of the two-dimensional polarization patterns he published later [7, 8] exhibit the same peculiarities as Stockhammer’s pattern. Here the source of error was that the e-vector directions were determined by looking up at the dome of the sky, but then plotted in a polar-coordinate system that shows the dome as if it were viewed from above (Wehner, personal communication). Again, the result is a reflection of the e vectors at the meridians. Differences about the orientation mechanism of bees are not affected by this plotting procedure in any way, because the bee’s internal representation of the polarization pattern takes the same form.

For a long time it has been considered unlikely that animals could orient to the polarization of light reflected from shiny, nonmetallic surfaces, because “this reflection polarization varies too much in space and time” (22), see also [10]. Many hydrophilous insects do orient to reflection-polarization, however, at least to the extent that it guides them to their habitat [1]. The more complicated pattern associated with low elevation of the sun causes no great problems, for the following reason. It has been shown for Notonecta [12] that a polarizing horizontal surface with vertical e-vector direction is entirely ignored. Reflecting surfaces are interpreted as water when the horizontal e-vector component predominates. Over bodies of still water such zones are present even when the sun is low, at least on the side toward the sun and on the opposite side.

We thank Prof. D. Burkhardt for critically reading the text, Dr. M. A. Biedermann-Thornson for translating the text into English, the Bayerisches Staatsministerium für Unterricht, Kultur, Wissenschaft und Kunst for a grant given to G. Horváth and the Deutsche Forschungsgemeinschaft for financial support (Proj. E3, SFB4).

Received August 28, 1992

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