Pergamon

0042-6989(94)00254-1

Vision Res. Vol. 35, No. 12, pp. 1651–1666, 1995
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0042-6989/95 $9.50 + 0.00

Underwater Refraction–Polarization Patterns of Skylight Perceived by Aquatic Animals Through Snell's Window of the Flat Water Surface

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Received 8 November 1993; in revised form 17 June 1994; in final form 7 October 1994

The grass shrimp (*Palaemonetes vulgaris*) orients itself by means of the polarization pattern of the sky visible through Snell's window of the water surface. The celestial polarization pattern viewed from water is distorted and modified because of refraction and repolarization of skylight at the air–water interface. This work provides a quantitative account of the repolarization of skylight transmitted through a flat water surface. The degree and direction of linear polarization, the transmissivity and the shape of the refraction–polarization oval are calculated at the air–water interface as functions of the polarization characteristics and the incident angle of partially linearly polarized incoming light. Two-dimensional patterns of linear polarization ellipses and of the degree and direction of polarization of skylight are presented for different zenith distances of the sun. The corresponding underwater refraction–polarization patterns are computed. Transmissivity patterns of a flat water surface are calculated for unpolarized light of an overcast sky and for partially polarized light of clear skies as a function of the zenith distance of the sun. The role of these refraction–polarization patterns in orientation and polarization vision of the grass shrimp (*P. vulgaris*) and rainbow trout (*Oncorhyncus mykiss*) is reviewed. The effects of cloud cover, surface waves and water turbidity on the refraction–polarization patterns are briefly discussed.

Refraction polarization of skylight Snell's window Underwater polarization vision Sun compass navigation *Palaemonetes vulgaris* *Oncorhyncus mykiss*

1. INTRODUCTION

The eyes of several terrestrial and semi-terrestrial species are sensitive to the plane of polarization of light. They can use the polarization of blue sky for sun compass navigation when the sun is occluded (Waterman, 1981). The situation is less clear in aquatic animals although many—e.g. Cladocera (Baylor & Smith, 1953), salmon (Groot, 1965), crab (Shaw, 1966), teleosts (Forward & Waterman, 1973), goldfish (Hawryshyn & McFarland, 1987)—can discriminate E-vector direction and perform polarotactic responses. Several functions have been proposed for underwater polarization sensitivity, including contrast enhancement of underwater objects against the background (Lythgoe & Hemmings, 1967), vertical migration (Umminger, 1968), maintenance of body position (Bardolph & Stavn, 1978) and goal-directed orientation (Waterman, 1988).

The optical properties of the air–water interface play an important role in the theory of radiative transfer in the earth's atmosphere (Coulson, 1988) and hydrosphere (Jerlov, 1976). Refraction of light is associated with polarization according to Fresnel formulae; unpolarized direct sunlight penetrating the water becomes partially linearly polarized. The pioneer measurements of Waterman (1954) demonstrated that underwater light is substantially polarized in all directions, mostly linearly but with some ellipticity just beyond the edge of Snell's window (Ivanoff & Waterman, 1958a).

From just under the water surface to a depth of about 50 m in the clearest water, the distribution and quality of light are strongly influenced by refraction. Through a flat water surface an aquatic animal sees the entire celestial over-water hemisphere condensed into Snell's window with an angular extent of 97 deg. Light from Snell's window in shallow waters contains most of the components of the spectrum available to terrestrial animals. Outside Snell's window the light from deeper layers is reflected, it is dim and its spectral range is restricted especially in open waters. At the boundary of Snell's window light from near the above-water horizon is split into a rainbow due to dispersion (Jerlov, 1976). An object above-water directly overhead suffers little

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