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A SUBMERSIBLE PROBE TO MEASURE SPECTRAL DIFFUSE ATTENUATION AND DIFFUSE REFLECTANCE OF LIGHT BY NATURAL WATERS

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ABSTRACT

This article presents schematics and principles of operation of a new submersible spectral probe to measure both diffuse attenuation and diffuse reflection coefficients of visible light by natural oceanic and lake waters. This probe directly measures the following properties of light field in water: spectral downwelling irradiance, spectral upwelling irradiance, and spectral diffuse attenuation coefficient of light. By processing these basic light field quantities this probe outputs values of diffuse reflectance of water mass below the instrument, spectral light attenuation and backscattering coefficients.

INTRODUCTION

The diffuse attenuation coefficient and diffuse reflection of light are two major apparent properties of natural waters. These properties may be used to estimate light propagation and visibility inside natural marine and lake waters. The diffuse reflection coefficient is a major component that defines values of remote sensing reflectance of natural water basins.

This article explains schematics and principles of operation of a new submersible spectral probe to measure both diffuse attenuation and diffuse reflection coefficients of visible light by natural oceanic and lake waters (Chepyzhenko, 1999). This probe actually measures the

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following four properties of light field in water: two spectral downwelling irradiances E_d at depths z_1 and $z_2 > z_1$, and two upwelling irradiances E_u at the same depths, here $z_2 = z_1 + \Delta z$, where Δz is a variable base of the probe (for definitions of E_d and E_u see Haltrin 1998a). The diffuse reflectance $R(z)$, downwelling $k_d(z)$, and upwelling $k_u(z)$ diffuse attenuation coefficients are defined according to the following basic equations:

$$R(z) = \frac{E_u(z)}{E_d(z)}, \quad k_d(z) = -\frac{1}{E_d(z)}\frac{d\,E_d(z)}{dz}, \quad k_u(z) = -\frac{1}{E_u(z)}\frac{d\,E_u(z)}{dz}, \tag{1}$$

here z is a depth of measurement. For our probe we define the depth as $z = 0.5(z_1 + z_2)$.

BASIC EQUATIONS OF THE PROBE

The layout of the probe is shown in Figure 1. The probe has the following technical characteristics: spectral range: 380-700 nm; spectral resolution: 5 nm; time of full spectrum scan: 50 μs; range of optical base Δz adjustments: 0-2 m; range of absorption coefficient estimation: 0.005-0.5 1/m; type of integrating light collectors: cosine; errors of measurements: 5%; range of measured natural light fields variation: 10,000,000; maximum depth of measurements: 200 m.

In order to adjust definition for diffuse reflectance given by Eqs. (1) to our probe, we used the following equations:

$$R(z) = 0.5\left[R(z_1) + R(z_2)\right], \quad R(z_1) = \frac{E_u(z_1)}{E_d(z_1)}, \quad R(z_2) = \frac{E_u(z_2)}{E_d(z_2)}. \tag{2}$$

The similar procedure for diffuse attenuation coefficients gives the following results:

$$k_d(z) \cong -\frac{2}{E_d(z_2) + E_d(z_1)}\frac{E_d(z_2) - E_d(z_1)}{(z_2 - z_1)}, \tag{3}$$

$$k_u(z) \cong -\frac{2}{E_u(z_2) + E_u(z_1)}\frac{E_u(z_2) - E_u(z_1)}{(z_2 - z_1)}. \tag{4}$$

Because in an asymptotic regime both coefficients given by Eqs. (3) and (4) obtain the same value, $k_d(z)\big|_{z\to\infty} = k_u(z)\big|_{z\to\infty} = k_\infty$, we accept the following approximate equation for the asymptotic diffuse attenuation coefficient: k_∞

$$k_\infty(z) \approx 0.5\left[k_d(z) + k_u(z)\right]. \tag{5}$$

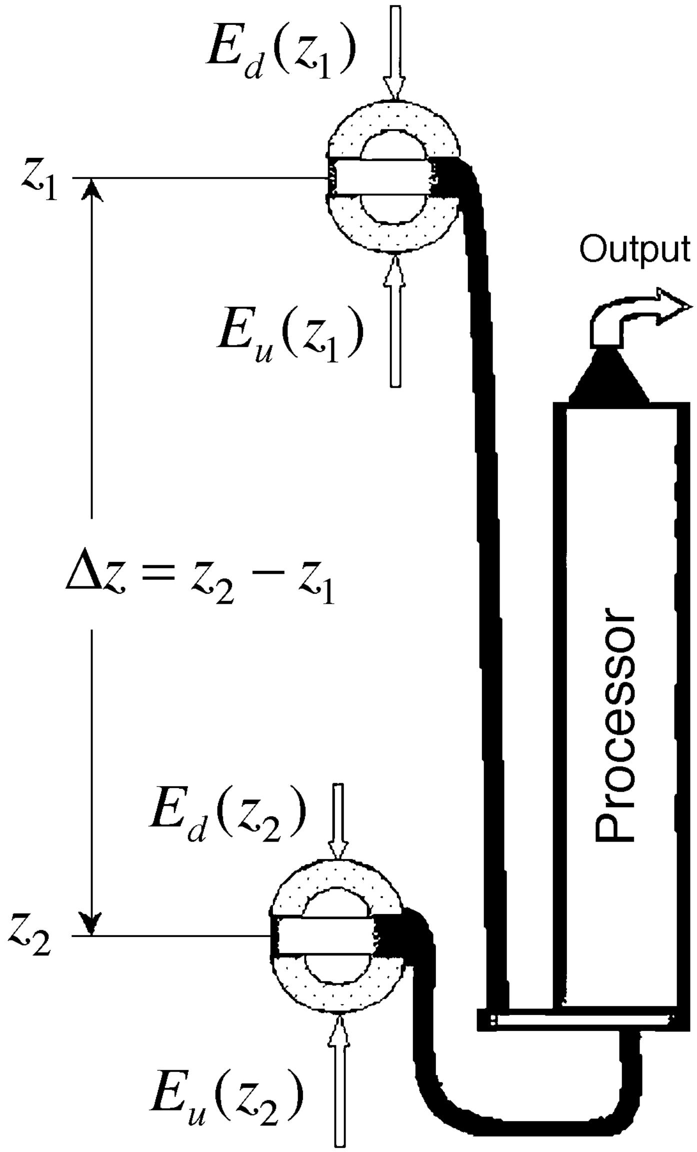

Figure 1. The layout of the submersible spectral probe to measure upwelling and downwelling irradiances in natural waters..

Consequently, our probe measures three very important properties of sea water: diffuse reflection coefficient, downwelling diffuse attenuation coefficient and upwelling diffuse attenuation coefficient. We also can estimate “generic” diffuse attenuation coefficient that represents an analog of asymptotic diffuse attenuation coefficient in the upper level of absorbing and scattering layer.

EXTRACTION OF INHERENT OPTICAL PROPERTIES

The radiative transfer theory shows that knowledge of diffuse reflection and diffuse attenuation coefficients allow us to estimate absorption and backscattering coefficients.

The basic equation for this task is the Gershun's equation that connects diffuse attenuation coefficient k_∞ with average cosine $\bar{\mu}$ over radiance angular distribution $k_\infty = a/\bar{\mu}$ and absorption coefficient a:

$$k_\infty = a/\bar{\mu}\,. \tag{6}$$

According to Haltrin (1998a, 1998b), an average cosine $\bar{\mu}$ can be expressed through diffuse reflection coefficient R and irradiances as follows:

$$\bar{\mu} = \frac{1-\sqrt{R}}{1+\sqrt{R}} \equiv \frac{\sqrt{E_d}-\sqrt{E_u}}{\sqrt{E_d}+\sqrt{E_u}}\,. \tag{7}$$

A combination of Eqs. (5), (6) and (7) gives us the following estimate for the true absorption coefficient of sea or lake water:

$$a \cong 0.5\left(k_d + k_u\right)\left(\frac{1-\sqrt{R}}{1+\sqrt{R}}\right). \tag{8}$$

Because the diffuse reflection coefficient R depends only on absorption a and backscattering b_b coefficients, we could estimate backscattering coefficient using the following equation:

$$b_b = a\frac{(1-\bar{\mu}^2)^2}{2\bar{\mu}^2(3-\bar{\mu}^2)}, \qquad \bar{\mu} = \frac{\sqrt{E_d}-\sqrt{E_u}}{\sqrt{E_d}+\sqrt{E_u}}\,. \tag{9}$$

Equations (7)-(9) presented above are quite precise, but they are still approximate. Some uncounted multiple scattering effects are present in these equations and should be eliminated from the results of measurements. In addition, the four used integrating hemispheres (see Fig. 1) are not ideally cosine, and some shadowing effects are present. All these imperfections are corrected in a processor block that uses look-up calibration tables generated for various sets of optical properties with the backward Monte Carlo procedure BMC3D developed by C. Mobley (2000).

CONCLUSIONS

The proposed submersible spectral probe to measure *in situ* diffuse reflectance and diffuse attenuation profiles can be used to estimate absorption and backscattering profiles in natural water basins. Used in a combination with the device to measure angular scattering coefficient (Haltrin, Lee, et. al., 1997a, 1997b) the presented probe constitutes a suite of instruments to measure a complete set of inherent optical properties of natural waters.

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