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A Model of Underwater Spectral Irradiance Accounting for Wave Focusing

Peter Gege

DLR, Earth Observation Center, Remote Sensing Technology Institute, Oberpfaffenhofen, 82234 Wessling, Germany (peter.gege@dlr.de)

Abstract. The downwelling irradiance in water usually shows very high short-time variability due to focusing and defocusing of the sun and sky light by the wave-modulated water surface. Since the direct and diffuse components are affected differently by wave focusing, not only intensity is highly variable, but also the spectral shape is fluctuating. A depth dependent analytic model was developed which calculates the direct and diffuse components separately. By assigning weights to the intensities of the two components, measurements performed at arbitrary surface conditions can be analysed using inverse modeling by treating the weights as fit parameters. The model was validated against Hydrolight and field measurements and implemented into the public domain software WASI for the simulation and analysis of downwelling irradiance measurements.

Keywords: Ocean optics, Irradiance, Wave focusing, Inverse modeling, Analytic model, WASI.
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INTRODUCTION

Measurements of downwelling irradiance in water, E_d, usually shows strong short-term variability, caused by the water surface (Figure 1a). Waves, ripples and foam alter steadily the refraction angle of the incident rays, leading to focusing and defocusing effects [1, 2]. Intensity varies typically by 20–40 % in the upper few meters [3, 4], but flashes can be an order of magnitude above average [5]. Since the spectral shapes of the direct and diffuse components are different (Figure 1b), the spectral shape of E_d is changing as well [6]. No model exists so far that can handle this variability for data analysis of single E_d measurements. The model presented here was developed for this purpose. The paper provides a brief overview; for details see [7].

PARAMETERIZATION OF IRRADIANCE

The effect of the water surface on downwelling irradiance in water is usually modeled using wind speed or slope distributions of the waves as parameters. These models are suited to describe the influence on irradiance as statistical averages. Since the goal here is the analysis of individual measurements, a different approach is chosen. E_d is split into a direct (E_{dd}) and a diffuse (E_{ds}) component as follows:

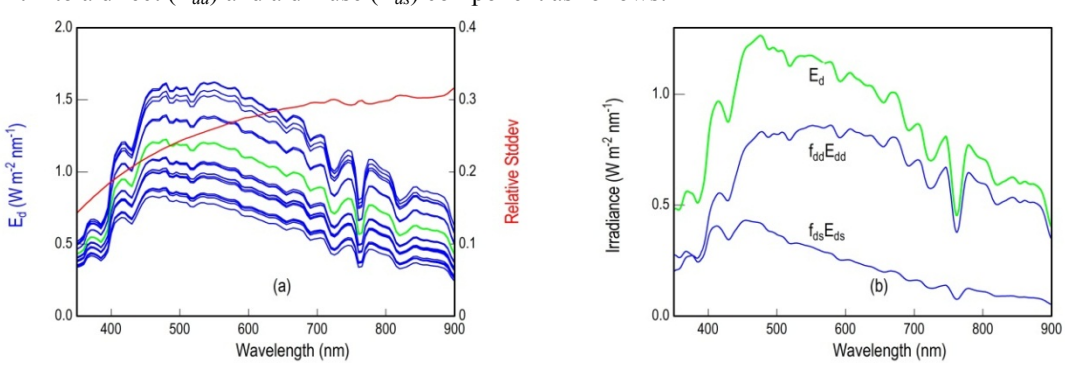

FIGURE 1. Illustration of downwelling irradiance in water. (a) Short-term variability of E_d. 19 measurements were made within 100 s just below the water surface. The standard deviation illustrates the associated changes of spectral shape. (b) Differences between the irradiance components. The described model was used to separate the direct (E_{dd}) and diffuse (E_{ds}) components for the green marked E_d measurement of panel (a). The relative intensities were $f_{dd} = 0.91$ and $f_{ds} = 0.92$.

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$$E_d(\lambda, z) = f_{dd} E_{dd}(\lambda, z) + f_{ds} E_{ds}(\lambda, z). \quad (1)$$

where λ denotes wavelength. The parameters f_{dd} and f_{ds} describe the intensities of E_{dd} and E_{ds} relative to conditions with a plane water surface. f factors <1 correspond to intensity decrease, f factors >1 to intensity increase. The relationship of the f factors to the slopes of the wave facets is not relevant for the model, since it is used for data analysis, but not to predict E_d variations as a function of wind and waves. Data analysis is done using inverse modeling of wavelength-dependent E_d measurements, with f_{dd} and f_{ds} as wavelength-independent fit parameters.

The two E_d components incident on the water surface, $E_{dd}(\lambda, 0+)$ and $E_{ds}(\lambda, 0+)$, are calculated using the analytic model of Gregg and Carder [8]. Their database was extended using Modtran calculations to cover the spectral range 300–1000 nm at a spectral resolution < 1 nm. The major parameters are sun zenith angle, ozone scale height, water vapor scale height, aerosol optical depth, and Angström exponent of aerosol scattering. The irradiance components at depth z are related to those above the water surface as follows:

$$E_{dd}(\lambda, z) = E_{dd}(\lambda, 0+) \exp\left\{-\frac{K_{dd}(\lambda) z l_{dd}}{\cos\theta'_{sun}}\right\}(1 - \rho_{dd}), \quad (2)$$

$$E_{ds}(\lambda, z) = E_{dd}(\lambda, 0+) \exp\{-K_{ds}(\lambda) z l_{ds}\}(1 - \rho_{ds}). \quad (3)$$

where θ'_{sun} is the sun zenith angle in water. l_{dd} and l_{ds} are the average path lengths of the beams forming E_{dd} and E_{ds} relative to sensor depth, respectively. K_{dd} and K_{ds} are the average diffuse attenuation coefficients of the water layer between surface and depth z for E_{dd} and E_{ds}, respectively. ρ_{dd} and ρ_{ds} denote the reflectance factors of $E_{dd}(\lambda, 0+)$ and $E_{ds}(\lambda, 0+)$, respectively. They are calculated for a plane water surface as a function of the sun zenith angle.

The model is insensitive to wavelength-independent effects, for example erroneous sensor calibration or changes of ρ_{dd} or ρ_{ds}; the parameters f_{dd} and f_{ds} pick up such effects during inverse modeling.

PARAMETERIZATION OF ATTENUATION

A beam of light passing a water layer is attenuated by absorption and scattering processes along its path. Since irradiance sensors detect the forward scattered radiation, the backscattering coefficient b_b is the relevant parameter describing the fraction of attenuation caused by scattering processes. Hence, the following approximation is made:

$$K_{dd}(\lambda) = K_{ds}(\lambda) = \mathrm{a}(\lambda) + b_b(\lambda). \quad (4)$$

where a is the average absorption coefficient of the water layer between surface and depth z. The software HydroLight-EcoLight version 5.1 (HE5) [9] was used to analyze the parameter dependency of l_{dd} and l_{ds} for constant concentrations of the water constituents chlorophyll-a (C), suspended sediment (X), and CDOM (absorption at 440 nm, Y). Since irradiance is difficult to measure at depths larger than approximately 5 m due to low intensity, the simulations were restricted to the upper 5 m. It was found that l_{dd} is close to 1, while l_{ds} depends mainly on θ'_{sun} and weakly on z. For $C = 2$ µg/l, $X = 0.6$ mg/l, $Y = 0.3$ m^{-1} the relationships $l_{dd} = 1.000 \pm 0.004$ and $l_{ds} = 1.1156 + 0.5504$ $(1-\cos\theta'_{sun})$ were obtained.

NUMERICAL VALIDATION

HE5 was taken to analyze the accuracy of the model for a plane water surface. Corresponding spectra of $E_d(\lambda,z)$, $E_{dd}(\lambda,z)$ and $E_{ds}(\lambda,z)$ were calculated for 99 combinations of depth (range: 0–5 m) and the sun zenith angle (range: 0–80°). The concentrations of water constituents were chosen as before. The standard deviation of the ratio in the range 400–700 nm was taken to quantify relative differences of spectral shape. The average was 0.3 % for E_d, 0.4 % for E_{dd}, and 0.3 % for E_{ds}. The average ratios in the range 400–700 nm were taken to quantify absolute differences of intensity. These are shown in Figure 2. The average is 1.002 for E_d, 0.998 for E_{dd}, and 1.006 for E_{ds} for θ_{sun} ranging from 0 to 70°. Consequently, the model agrees well with HE5.

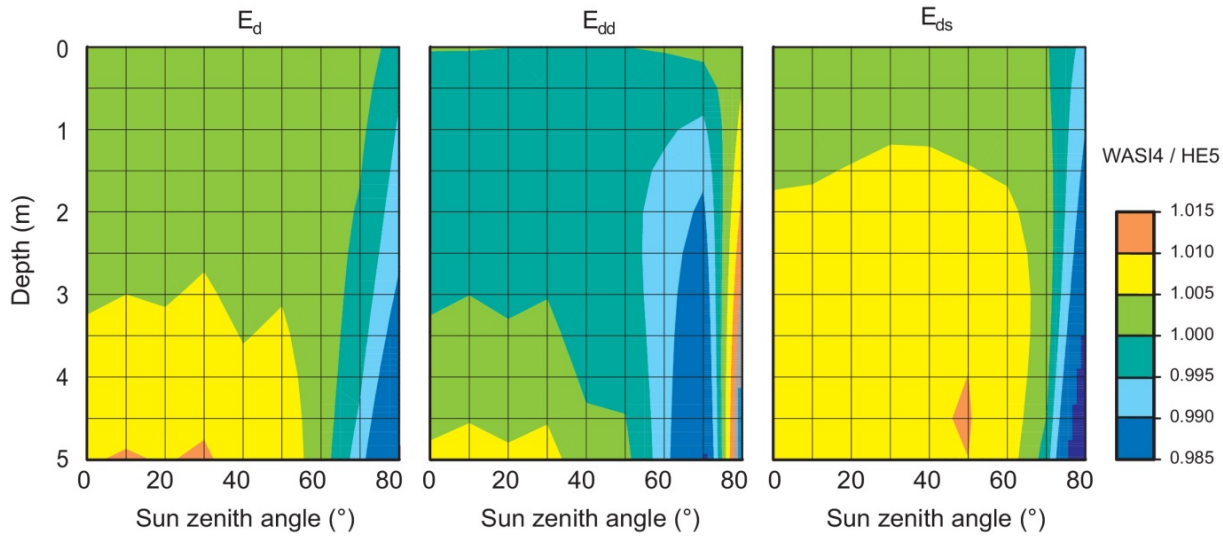

FIGURE 2. Ratios of the average irradiances in the range 400–700 nm between the analytic model (WASI4) and HE5.

EXPERIMENTAL VALIDATION

The HE5 simulations shown before confirm a good correspondence between the simple analytic model and a physically more complete treatment of the radiative transfer. However, this validation is principally restricted to a plane water surface since HE5 can model the effects of wind-roughened surfaces on E_d only as statistical averages, but not for single E_d measurements of short integration time. To validate the analytic model for real measurements which are affected by wave focusing, a number of E_d depth profiles were collected at 5 days in the range 0–2.8 m at the German lake Starnberger See with a Trios RAMSES-ACC-VIS spectrometer [10]. At each depth, at least 30 individual E_d measurements were made to capture the variability due to wave focusing. The measurements were performed at relatively smooth water surface with wave heights between 3 and 10 cm, for which the wave focusing effect is most pronounced [11, 12]. They covered a wide range of sun zenith angles (27–90°) and included both clear and overcast sky conditions (see Table 1).

Data analysis was done by inverse modeling of the individual E_d measurements using the software WASI, which is a tool for the simulation and inverse modeling of different types of spectral measurements in deep and shallow waters [13, 14]. The analytic E_d model has been implemented into WASI version 4 (ftp://ftp.dfd.dlr.de/pub/WASI/).

The first step of data analysis was the determination of the atmospheric parameters ozone scale height, water vapor scale height, aerosol optical depth, and Angström exponent of aerosol scattering by inverse modeling of the above-water E_d measurements that were made before each depth profile. The second step was inverse modeling of each individual in-water E_d measurement. Fit parameters were f_{dd}, f_{ds}, z, C, X, Y and the spectral slope of CDOM absorption, S. Third step was the statistical analysis of the fit parameters. Since at least 30 E_d measurements were made at each sensor position, the standard deviation (σ) could be calculated for each fit parameter.

The Table summarizes the standard deviations of z. Sensor depth could be derived with low standard deviation in the order of 5 %. Independent measurements confirmed the results of inverse modeling: the differences were in most cases below 1σ (Figure 3). Larger deviations were observed at site M3, where the sun was near the horizon.

TABLE (1). Summary of measurement conditions and uncertainties of derived sensor depth [10].

Site	Depth range (m)	Wave height (cm)	Cloud cover (%)	θ_{sun} (deg)	σ_z (%)	σ_z (cm)
L1	0 – 2.3	5	0	61 – 68	8.65	6.58
L2	0 – 2.5	10	100	29 – 34	3.51	2.62
M1	0 – 2.8	5	0	57 – 65	6.41	5.95
M2	0 – 2.4	3	100	27 – 37	3.44	5.51
M3	0 – 1.9	3	0	78 – 90	4.45	4.14

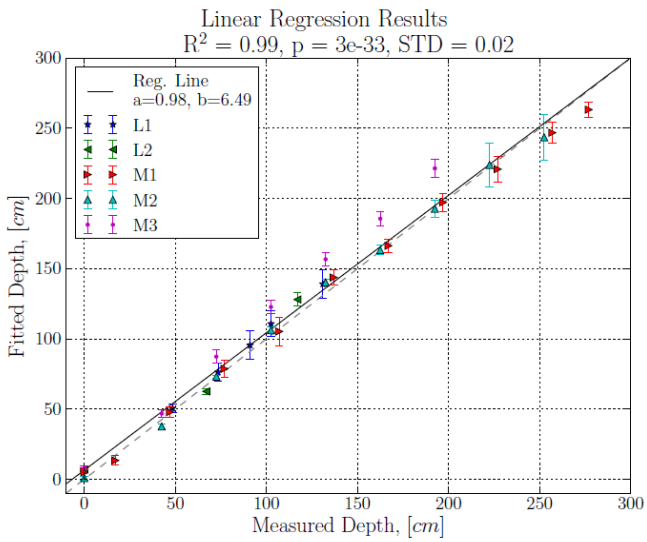

FIGURE 3. Experimental validation of sensor depth obtained from inverse modeling of E_d measurements. The error bars show the standard deviation of z estimates from subsequent E_d measurements at the same sensor position. From [15].

CONCLUSIONS

An analytic model of downwelling irradiance in water was developed which calculates the direct and diffuse components separately. This separation can handle the large variability at typical field conditions, and it allows us to account for the different path lengths of the two components. The model has been included in the software WASI 4 for forward and inverse modeling. It was validated numerically for a plane water surface against Hydrolight and experimentally for a wide range of sun zenith angles by comparing the derived sensor depth with independent measurements.

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Nicole Pinnel's measurements and discussions initiated the study, Curtis Mobley adapted EcoLight to 2° angular resolution, and Philipp Grötsch validated the model experimentally.

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