DETERMINATION OF SENSOR DEPTH FROM DOWNWELLING IRRADIANCE MEASUREMENTS

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ABSTRACT

The wave focusing effect causes measurements of under water downwelling irradiances E_d to be extremely variable in intensity and spectral shape. A new analytical model for E_d has been developed recently, which can deal with the induced variability by treating the direct and diffuse components of E_d separately. This paper presents a method to determine the current sensor depth from under water downwelling irradiance measurements using that model combined with improved parameterizations for the direct and diffuse downwelling attenuation coefficients. The average relative deviation of sensor depth for a data set containing over 1400 measurements under various illumination conditions and depths is on the order of 5 %.

***Index Terms*—** Downwelling Irradiance, Wave Focusing, Sensor Depth, WASI

1. INTRODUCTION

In situ measurements are essential for the validation of water remote sensing algorithms. For shallow waters, the bottom reflectance has a significant influence to the remotely sensed signal. To calculate bottom reflectances accurately, the downwelling irradiance E_d has to be measured under water. Under water measurements of E_d can also be used to determine water constituent concentrations [1]. However, because of the wave focusing effect, measurements of E_d are extremely variable [2]. A new analytical model by Gege [3] can correct for the wave focusing effect by treating the direct and diffuse components of E_d separately. To improve the characterization of the attenuation for the direct and diffuse components of E_d within that model, parameterizations for the direct (K_{dd}) and diffuse (K_{ds}) fractions of K_d have been developed by Groetsch [4]. By fitting the model parameters to under water downwelling irradiance spectra, an accurate estimation of the current sensor depth can be retrieved. Typically, E_d sensors designed for under water measurements have a pressure sensor included to estimate the current sensor depth. However, those measurements usually have a resolution on the order of tens of centimeters, which can be critical for shallow water applications. Furthermore, the depth estimation from pressure sensors does not account for waves in the field of view of the E_d sensor, which can change the optical path length considerably.

The method presented in this paper solely relies on the spectral information recorded in under water E_d measurements and therefore offers redundancy to potentially existing depth information retrieved from pressure sensors. In this paper a data set, covering a variety of measurement conditions and sensor depths, is used to validate the developed models and to show the applicability of a sensor depth retrieval from under water E_d measurements.

2. MATERIALS AND METHODS

2.1. Measurements

For the validation of the E_d model by Gege [3] and the K_{dd} and K_{ds} parameterizations by Groetsch [4], a dataset of E_d field measurements was collected with a *Trios*[1] RAMSES ACC VIS (wavelength range 320 - 900 nm, spectral sampling interval 3.3 nm, SN: 806f) spectroradiometer. Additionally, measurements of the upwelling radiance and irradiance, L_u and E_u were performed, but not used for this publication. The spectral calibration of the instrument was carried out by the

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[1] http://www.trios.de

sensor manufacturer (*Carl Zeiss MicroImaging GmbH*, Jena, Germany). The radiometric calibration was performed by *Trios* with a NIST-traceable FEL lamp (DXW-1000W, 120V) which is calibrated by *Gigahertz-Optik GmbH* (Türkenfeld, Germany) according to NIST standards. Because the radiometric calibration of the used irradiance sensor (RAMSES ACC-VIS, serial number: 806f) was carried out more than two years before the field measurements, the calibration was validated with a NIST-traceable FEL lamp (GAMMA SCIENTIFIC 5000-16C, serial number: GS1033, calibrated 16. Oct 2009). In the range of 400 - 800 nm used for this study, the spectral differences were below 4 %, which is considered negligible. As the absolute intensities are of no importance for the fit of sensor depth (section 2.2, [2]), the spectral and radiometric calibration by *Trios* was used for the data evaluation.

The measurements were performed in Lake Starnberg, which is located south of Munich, Germany. With an area of about 60 km^2 and a north-south extent of more than 20 km it is the fifth biggest lake in Germany. The measurements were taken at two sites, a jetty in Starnberg (N 47.9963°, E 11.3495°: 'Mole Starnberg') at the northern shore and a jetty in Seeshaupt (N 47.8214°, E 11.3208°: 'Lido Seeshaupt') at the southern shore. The setup in figure 1, consisting of a cantilever arm build onto a mobile construction, allowed for the successive submersion of the sensor mount into the water column. The mount is balanced out in the water, so that the sensors are aligned normally to the water surface. The entry optics of the up- and downwards measuring sensors are aligned in one horizontal plane. A measuring tape connects the cantilever arm with the sensor mount to have reliable, independent readings of the actual sensor depth. A source of error is the determination of the offset between the entry optics of the E_d sensor and the the measuring tape, which is assumed to be on the order of 1 cm. Currents may tilt the sensor mount and bulge the measuring tape. However, only little influence from currents was observed during the measurements and the corresponding uncertainty is estimated to be on the order of 1 cm.

The profile measurement starts with the sensors above the water surface to capture the incident radiation ($E_d(0^+)$) followed by a measurement just below the surface ($E_d(0^-)$). Consequently, measurements in fixed depth intervals are taken until the sensor mount touches the ground. The last measurement is a second take of $E_d(0^+)$ to check if the illumination conditions remained stable during the acquisition. Each measurement consists of at least 30 individual data takes to capture the present variability due to the wave focusing effect. In table 1 the details of the measurements are listed. The listed wave heights were taken as the uncertainty in the reading of the sensor depth from the measuring tape. The data set comprises a large variety of illumination conditions, concerning sun zenith angle and cloud cover. As the measurements were carried out from a jetty close to the shore, the maximal sampling depth was restrained by the local bathymetry to 2.77 m.

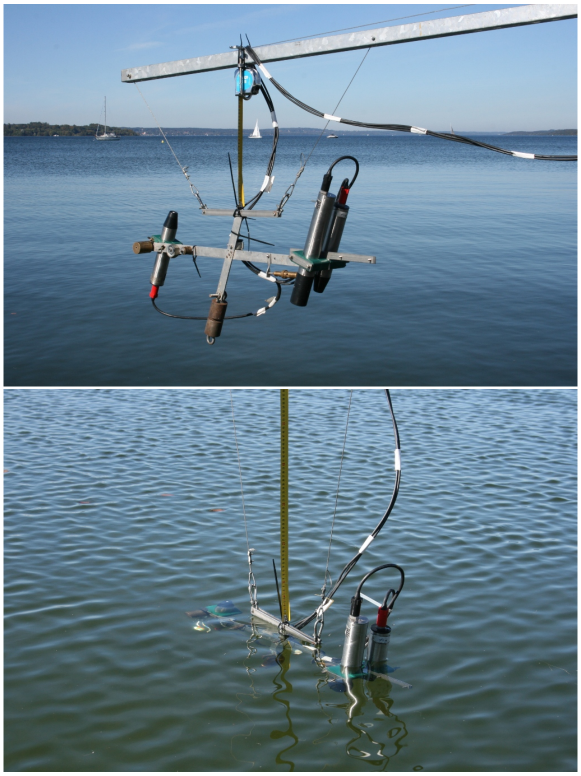

Fig. 1. Measurement setup: sensor mount (top), sensor mount partially submersed (bottom)

2.2. Processing

The new analytical E_d model by [3] and the parameterization for K_{dd} and K_{ds} by [4] are implemented to the public domain software WASI [5]. Using WASI, the developed models were fitted to the measured E_d spectra. The sensor depth is one of the parameters determined during those fits. The validation of the models was then carried out with the independent field measurements of sensor depth. The model used for the calculation of the downwelling irradiance just above the water surface is the analytic model of Gregg and Carder [6]. It assumes a cloudless, marine standard atmosphere. To achieve an optimal fit of the sensor depth, the atmospheric parameters in the Gregg and Carder model have to be adjusted to the the above water spectra. Those parameters are: ozone scale height H_{oz}, Angström exponent α, turbidity coefficient β and water vapor concentration WV. The determined values are averaged over all above water spectra and set constant for the subsequent under water fits. These were performed with the following parameters and start values:

- Concentration of phytoplankton class no. 4 (dinoflagellates) $C[4] = 2.0$ mg m^{-3}

Table 1. Details of measurements at location 'Mole Starnberg' (M) and 'Lido Seeshaupt' (L)

Parameter	M1	M2	M3	L1	L2
Date, [dd-mm-yy]	11-10-10	16-06-11	28-06-11	04-10-10	17-05-11
Local Time, [hh:mm]	14:15-15:45	14:00-15:30	19:45-21:15	15:30-16:30	11:30-13:30
Depths, [cm]	0-277	0-243	0-193	0-131	0-117
Depth steps, [cm]	30	30	30	30	50
Measurements, [#]	360	276	329	230	251
Cloud cover, [%]	0	100	0	0	100
Sun zenith angle, [°]	57-65	27-37	78-90	61-68	29-34
Wave height, [cm]	5	3	3	5	10
Bottom type	macroph.	sediment	macroph.	macroph.	sediment

- Suspended matter concentration $C_X = 0.6$ g m^{-3}
- Gelbstoff concentration $C_Y = 0.3$ m^{-1}
- Spectral slope of Gelbstoff absorption $S = 0.016\,\text{nm}^{-1}$
- Depth $z = 2.0$ m
- Fraction of direct radiation ${f_{dd}}^2 = 1.0$
- Fraction of diffuse radiation $f_{ds} = 1.0$

The sun zenith angle for each measurement was calculated automatically, based on location and local time. The values for the Q-factor and the water temperature were set to $Q = 5$ and $\text{T}_w = 20.0\,°\text{C}$. The fits were performed in a wavelength range of 400 to 800 nm and an interval of 3 nm. The quantity minimized during the fit procedure was set to least squares. The fit of the sensor depth is slightly dependent on the yellow substance exponent S. As independent measurements of S were not performed within this study, S was included as a fit parameter.

3. RESULTS

Figure 2 shows the results of a linear regression analysis of the independently measured sensor depths and the WASI-determined depths. Each point in the graph corresponds to the mean over several data takes (usually 30) at a distinct depth. The errorbars correspond to the standard deviation of those data takes. The linear regression results in a R^2 of 0.99 with a slope of 0.98 and an intercept of 6.49 cm (p <0.01, standard error = 0.02 cm). In table 2 the absolute and relative standard deviations as well as the absolute and relative deviations from the measuring tape readings are listed. The same analysis has been performed with the widely used K_d model by Gordon [7], which resulted in an average relative standard deviation of 30 % and an average relative deviation of 29 %. The atmospheric parameters, determined by fitting the atmospheric model in WASI to the above water measurements, are listed in table 3.

Table 2. Comparison of the WASI fit results with the measuring tape readings.

Site	abs. STD [cm]	rel. STD [%]	abs. dev. [cm]	rel. dev. [%]
L1	6.58	8.65	5.23	5.44
L2	2.62	3.51	4.53	1.42
M1	5.95	6.41	-1.96	-2.58
M2	5.51	3.44	0.15	-0.46
M3	4.14	4.45	17.68	16.31
Abs. mean	4.96	5.29	5.91	5.24

Table 3. Atmospheric parameters derived with WASI from above water E_d measurements.

	M1	M2	M3	L1	L2
H_{oz}, [cm]	0.276	0.662	0.337	0.225	0.535
α, [-]	-0.170	0.070	-0.207	0.522	0.038
β, [-]	0.455	1.598	0.461	0.226	1.837
WV, [cm]	0.157	1.977	0.804	0.659	1.103

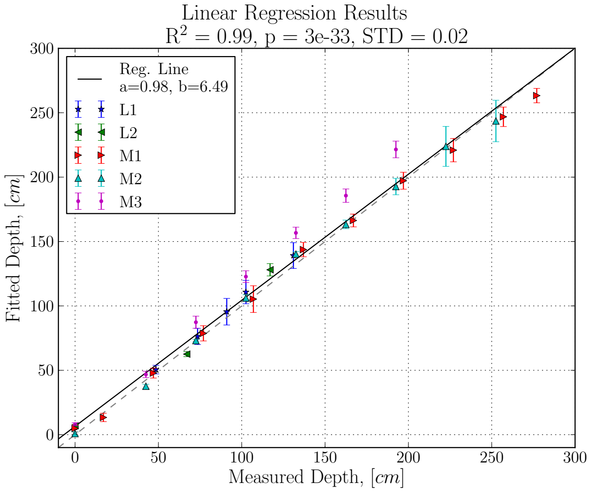

Fig. 2. Validation of WASI fits: Fit results for sensor depth plotted against measured sensor depth.

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[2] as explained in [3]

4. DISCUSSION

The low average relative standard deviation on the order of 5 % indicates that variabilities in E_d, introduced by the wave focusing effect, are correctly interpreted by the model. The low average absolute deviations, on the order of 5 cm, suggest that the method is suitable for the determination of the sensor depth from E_d spectra. Even for the high sun zenith angle case M3, reasonable results are obtained. Considering the wave heights of 3-10 cm for the collected data set, an error of the same order of magnitude is expected for the independent readings of sensor depth from the measuring tape. As this error is of the same order of magnitude as the observed deviations, it can be regarded as an upper limit for the real uncertainty of the presented method. This conclusion is supported by the results of the linear regression analysis with a squared coefficient of correlation of 0.99, a slope close to one and an interception on the order of the average wave heights. Those results make the method suitable for sensor depth dependent applications in shallow as well as in optically deep waters. It has to be stressed that a reliable sensor depth estimation cannot be achieved with conventional K_d models, such as the widely used Gordon model, considering the resulting high standard deviations and deviations (both on the order of 30 % in the analysis of the current data set).

As all the measurements were taken in the same lake, the optical properties of the sampled water columns are similar. Therefore a repetition of the presented validation measurements in highly turbid as well as extremely clear waters would be of interest. The maximal sampling depth of 2.77 m can be considered as sufficient for the investigated water bodies. However, for clear waters considerably higher sampling depths would be necessary to validate the model. An interesting consecutive application is the determination of inertial optical properties (IOPs) from E_d spectra and even more, their change with depth.

5. CONCLUSION

The presented method for the determination of sensor depth from downwelling irradiance measurements has been proven to produce accurate results for various illumination conditions and sensor depths for the investigated water bodies. In contrast to sensor depths acquired from pressure sensors, the method does not require additional instrumentation and is sensitive to the actual optical path length as wave heights are taken into account. Those accurate measurements of sensor depth are important for the determination of water constituent concentrations and inherent optical properties from E_d spectra and indispensable for calculating bottom reflectance, which is a key quantity in shallow water remote sensing applications.

6. REFERENCES

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