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# Experimental analysis of the measurement precision of spectral water-leaving radiance in different water types: reply

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**Abstract:** Reliable in situ water-leaving radiance ($L_w$) measurements are critical for calibrating and validating the ocean color products from remote platforms (e.g., satellite). In an experimental effort, Wei et al. [Opt. Express **29**, 2780 (2021)] reported that the on-water radiometry allows for high-precision radiance determination. Zibordi [Opt. Express **29**, 19214 (2021)] questioned the use of the "1% radiometry" term in the former and commented on the data collection with the sensor's optical window submerged in water. This reply responds to the comments and discusses the on-water data processing protocol, which shows the obtained $L_w$ is not affected by the questions raised therein.

## 1. Introduction

The on-water in situ measurement approach is a relatively new concept compared to the existing above- and in-water radiometric methods that have been in use for quite a long time. It employs a skylight-blocking apparatus or approach (SBA) [1–3], allowing for the derivation of water-leaving radiance ($L_w$) with minimal disturbance from the sea surface reflection.

Wei et al. [4] analyzed the radiance data from the on-water approach. Their results showed high measurement precision among different water types, suggesting a promising approach for ground-truth observation of this optical property. The paper by Zibordi [5] first commented on the use of "1% radiometry" and then pointed out an error appearing in the discussion in Wei et al. [4] (see Section 5.2 therein). The comment paper also argued that the radiance data from a submerged sensor might not be well separated from others. It stated that "(it is) difficult flagging those measurements performed with the optical window immersed, and the difficulty is expected to increase with sea state that rises the variability of $z$, and also to vary with wavelength and water type".

In this work, we responded to Zibordi [5] and explained the potential issues. As a follow-up analysis, we highlight the working mechanism and the effectiveness of the probability density function (PDF)-based data filtering protocol adopted for SBA measurements. We show that the comments do not invalidate the data processing protocol and that the results presented in Wei et al. [4] remain reliable.

## 2. Responses to the comments

### 2.1. 1% radiometry

The ocean color community has long recognized the necessity to obtain accurate ground-truth radiance data for satellite calibrations. McClain et al. [6] suggested that "the individual sources

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of uncertainty for the acquisition of ground-truth data must be on the order of 1–2%, or what is referred to more generally as simply '1% radiometry'". Wei et al. [4] referred to this concept in two places: Introduction and Conclusion sections. Two relevant statements in Wei et al. [4] are not accurate; explanations can be found in Zibordi [5].

### 2.2. Radiance observations

The primary comment, arising from a brief discussion in Section 5.2 of Wei et al. [4], is related to the observational scenarios encountered by a radiance sensor. For the on-water approach, ideally, the radiance sensor is in a position where the edge of the cone is slightly submerged in the water, while the glass window of the radiometer is still in the air (Fig. 1(a)). The cone eliminates the direct interference from the skylight and sunlight but introduces a self-shading error ($\varepsilon$). Thus, the radiance measured by a well-calibrated sensor ($L_w^m$) is equal to

$$L_w^m = L_u(0^-) \cdot [1 - \varepsilon] \cdot \tau_{wa}, \tag{1}$$

where $L_u(0^-)$ is upwelling radiance right below the water surface, and $\tau_{wa}$ is the upwelling radiance transmittance across the water-air interface ($\approx 0.54$) [7,8].

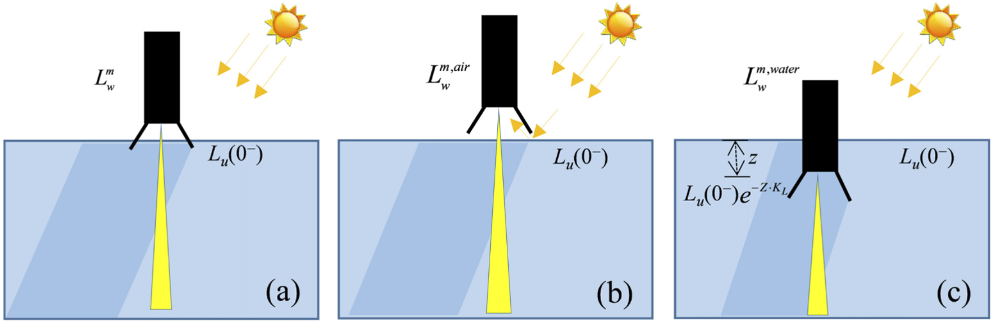

**Fig. 1.** One-dimensional schematic of on-water radiance determination under (a) ideal situation, (b) uplifted position, and (c) submerged case. $L_w^m$, $L_w^{m,air}$, and $L_w^{m,water}$ denote the radiances measured for three scenarios, respectively. The shadows from the instrument and the cone are depicted in dark blue shades.

If the cone pops out of the water surface, the skylight and sunlight reflected off the water surface can enter the field-of-view (FOV) of the detector (Fig. 1(b)). One may readily conclude that such measured radiance, $L_w^{m,air}$, is greater than $L_w^m$ especially in the red to near-infrared wavelengths where $L_u(0^-)$ is close to 0 for most clear natural waters.

When the sensor's window is submerged in water, it views radiance with a different solid angle (Fig. 1(c)). The radiance values recorded by such a sensor submerged at depth $z$, $L_w^{m,water}$, becomes the following (also see Ref. [5]),

$$L_w^{m,water} = L_u(0^-) \cdot \exp[-z \cdot K_L] \cdot (1 - \varepsilon'') \cdot \tau_{wga}, \tag{2}$$

where $K_L$ the diffuse attenuation coefficient for upwelling radiance, $\tau_{wga}$ stands for the light transmittance from water through glass to air, and $\varepsilon''$ is the self-shading error for the submerged sensor. Assume $\varepsilon$ and $\varepsilon''$ are comparable, the ratio of Eq. (2) to Eq. (1) can be simplified as $L_w^{m,water}/L_w^m \approx \tau_{wga} / \tau_{wa} \cdot \exp[-z \cdot K_L]$. Zibordi [5] is right on this ratio that is slightly larger than unity ($\approx 1.05$). The original discussion in Section 5.2 of Wei et al. [4] miscalculated it.

It is noteworthy that the above discussion has excluded the impacts of surface waves on the radiance field in the air-water boundary layer. The radiances from a submerged sensor can be variable and exceed ±(5%–10%) of their median values, depending on wind speeds and solar-zenith angle, etc. As a result, the measured ratios of $L_w^{m,water}$ to $L_w^m$ can significantly deviate from 1.05, either positively or negatively.

## 3. Discussion on radiance data processing

The protocol for the radiance data processing is based on the fact that most of the measurements from an on-water instrument represent $L_w^m$, not $L_w^{m,air}$ or $L_w^{m,water}$. It uses a PDF filter to identify and remove questionable spectral measurements. In the following, we employ examples to show the working mechanism of this filtering approach. In Fig. 2, the data were obtained from mesotrophic coastal waters under two-foot seas (~0.6 m high). The simultaneous above-water irradiance ($E_s$) was stable with a coefficient of variation (CV) lower than 5% between 410–650 nm.

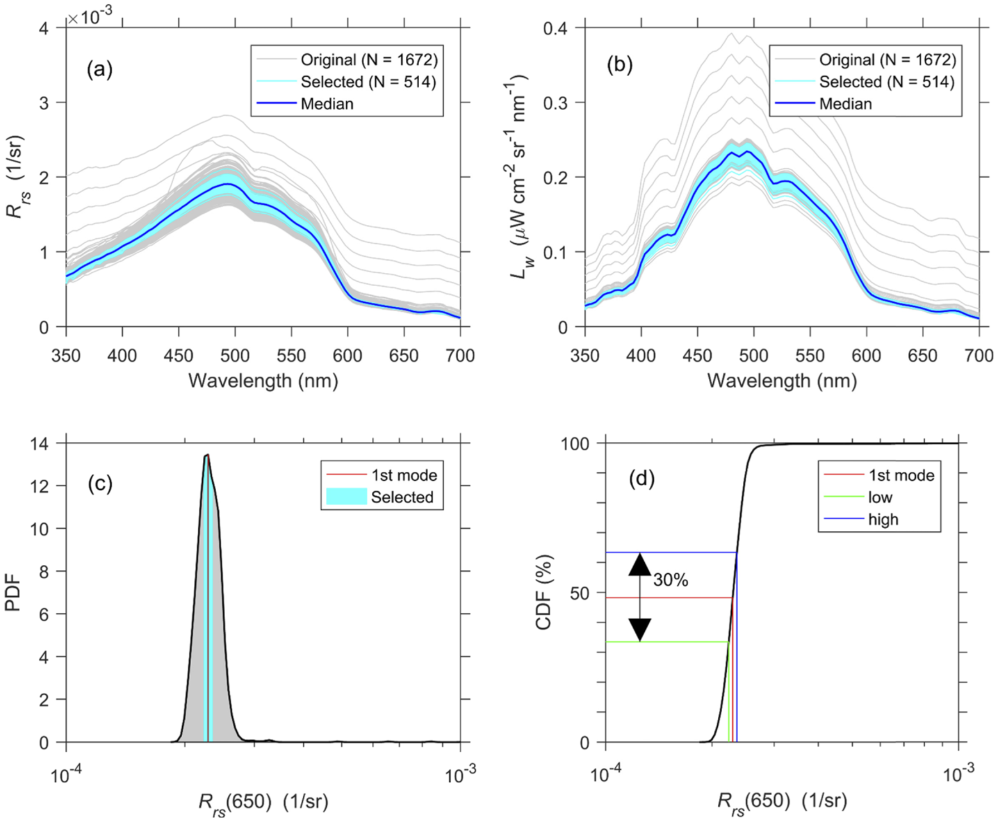

**Fig. 2.** On-water radiometric data processing for (a) $R_{rs}$ and (b) $L_{\mathrm{w}}$ in mesotrophic coastal waters (coordinates: 42.4050°N, −70.5469°W; sky: clear; sea condition: 0.6 m waves). The PDF and CDF functions of (c) and (d) are given for the original $R_{rs}(650)$ time series data, which are characteristic of tilt < 7°. The "selected" data refer to those passing the filtering criteria; in this case, they represent those within ±20% in terms of the probability distribution centered around the first mode of $R_{rs}(650)$ data. See more explanations in the text.

The processing starts with remote sensing reflectance ($R_{rs}$) from such time series measurements, not $L_w$. The use of $R_{rs}$ data is of practical advantage because the $R_{rs}$ spectra are relatively insensitive to the variation of $E_s$. The PDF function is derived for the "original" $R_{rs}$ time series at a single red band, e.g., 650 nm. Specifically, a MATLAB function *ksdensity* was used for the processing to generate the log-normal PDF for $R_{rs}(650)$ measurements. The first mode of the

PDF is close (but not necessarily equal) to the 50% probability. This first mode is regarded as the best estimate for the true $R_{rs}(650)$. The true $R_{rs}$ should be the most common observations in a time series data set if the water and bottom properties do not change during the measurement period. With the determination of the first model, we further located two $R_{rs}(650)$ values from the corresponding cumulative distribution function (CDF), which encompass ±15% probability from the first mode. The $R_{rs}$ spectra, with $R_{rs}(650)$ values falling within this range, were selected for subsequent analysis. The $L_w$ time series data corresponding to such selected $R_{rs}$ spectra can be readily identified. It is observable that the selected $R_{rs}$ and $L_w$ spectra still vary, resulting from the sea waves and sensor's orientation, etc. As a final step, we derived the median spectral values from the above-filtered $R_{rs}$ and $L_w$ spectra. Such derived median spectrum, which represents the final product, is subject to the minimal influence of the wave effects and submerging of the sensor.

## 4. Concluding remarks

We agree that the "1% radiometry" term should not be confused with the total uncertainty of the radiance measurements. We also confirm that the relevant statement in Wei et al. [4] (Discussion section 5.2 therein) on the relationship between the radiances from a submerged sensor and the true $L_w$ was not accurate. As a response to the comment, the issues discussed will not invalidate the data processing protocol and the obtained final products remain reliable. Lastly, we demonstrate how the present filtering protocol identifies the most plausible $R_{rs}$ and $L_w$ spectra from their time series measurements, which has minimized the influence of waves.

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