Use of a Spectralon panel to measure the downwelling irradiance signal: case studies and recommendations

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Field determinations of the remote sensing reflectance signal are necessary to validate ocean color satellite sensors. The measurement of the above-water downwelling irradiance signal $E_d(0+)$ is commonly made with a reference plaque of a known reflectance. The radiance reflected by the plaque (L_{dspec}) can be used to determine $E_d(0+)$ if the plaque is assumed to be near Lambertian. To test this assumption, basic experiments were conducted on a boat under changing sky conditions (clear, cloudy, covered) and with different configurations for simultaneous measurements of L_{dspec} and $E_d(0+)$. For all measurement configurations, results were satisfactory under a clear sky. Under cloudy or covered skies, shadow effects on the plaque induced errors up to 100% in the determination of $E_d(0+)$. An appropriate measurement configuration was defined, which enabled $E_d(0+)$ to be determined with an accuracy of better than ±15% regardless of the sky conditions. © 2004 Optical Society of America

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1. Introduction

Calibration and validation of remote sensing (satellite or airborne) ocean color data require regular and accurate field optical measurements. One of the main measured parameters is the water-leaving reflectance, commonly called remote sensing reflectance (R_{rs}, in sr^{-1}). This R_{rs} signal is defined as the ratio between the water-leaving radiance (L_w, in W m^{-2} nm^{-1} sr^{-1}) and the downwelling irradiance [$E_d(0+)$, in W m^{-2} nm^{-1}] just above the water surface.[1]

Protocols have been defined concerning the measurement of these two parameters.[2] Different techniques to determine L_w from above-water or underwater measurements have been widely discussed.[3–9] Most of these studies were focused on the uncertainty in L_w determinations, depending on instrumental characteristics and environmental variability, with only a small discussion concerning the techniques used to measure $E_d(0+)$ and its associated accuracy.[6] $E_d(0+)$ can be measured directly with an irradiance sensor or indirectly with a radiance sensor and a reference plaque (e.g., Spectralon) having a known bidirectional reflectance. In this case, the measured signal is the downwelling radiance (L_{dspec}) reflected by the plaque. Assuming the plaque to be near Lambertian,[10,11] $E_d(0+)$ is approximately determined as[2]

$$E_d(0+) = \frac{\pi}{R_g} L_{\mathrm{dspec}}, \tag{1}$$

where R_g (dimensionless) is the plaque's bidirectional reflectance function. The wavelength dependence of the parameters is omitted to simplify the notation. The L_{dspec} and R_g parameters also depend on the Sun and viewing geometry.[2]

This second technique is commonly adopted because it requires use of only one radiance sensor.[12–22]

Our purpose in this paper is to quantify the uncertainties in use of the reference plaque, depending on the configuration of the measurement (respective positions of the plaque and sensor) and illumination conditions (cloud cover). Different cases have been studied during fieldworks in the Plymouth coastal waters comparing $E_d(0+)$ determined with a radiance sensor and a Spectralon plaque system with $E_d(0+)$ measured with an irradiance sensor. Measurements were carried out from 350 to 950 nm (spectral resolution of 3.3 nm) with a Trios RAMSES-ARC hyperspectral radiance sensor (7° field of view) and a

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Trios RAMSES-ACC-VIS irradiance sensor. The reference plaque was a Labsphere white Spectralon panel (SRT-99-050) of dimensions 12.5 cm × 12.5 cm and 99% efficiency (i.e., $R_g \approx 99\%$). Results are presented and discussed, leading to some important practical recommendations.

2. Effects of Changing Sky Conditions

A. Objective and Method

The preliminary objective is to know how accurately $E_d(0+)$ can be determined with a radiance sensor and a Spectralon panel system under quite different illumination conditions (clear, cloudy, and covered skies). Notably, a specific objective is to estimate the errors committed during previous field optical measurements in the Gironde and Loire estuaries.[14]

To address this problem, measurements were carried out during two consecutive days in the Plymouth Sound and the mouth of the Tamar estuary (southwest UK). On 3 September 2003, optical data were collected from 11:15 to 17:00 Greenwich Mean Time (GMT). The sky was covered and almost homogeneous; from time to time, the Sun was visible behind the clouds. On 4 September 2003 data were collected from 09:15 to 15:45 GMT. The sky was perfectly clear, i.e., blue without any apparent cloud. On both dates, the sea surface was almost plane, resulting in slight movements of the boat.

The irradiance sensor was fixed to a vertical bar on the top of the boat, viewing the zenith. Concerning the radiance sensor and the Spectralon panel, the configuration adopted during previous field optical measurements in the Gironde and Loire estuaries was reproduced. The Spectralon plaque was held horizontally by a person on the back extremity of the boat, at a distance of 4 m from the cockpit. The dimensions of the cockpit are 4 m (width) × 2 m (height) × 6 m (length). The same person was pointing the radiance sensor vertically toward the middle of the Spectralon plaque. A minimum distance of 20 cm was respected between the sensor and the plaque.

On 4 September 2003, under a clear blue sky, the plaque was presented in front of the Sun to avoid any direct shadow effect. On 3 September, under a covered sky, the plaque was presented to the clearest part of the sky, where the Sun was hidden by the clouds. At each station, the irradiance and radiance signals were recorded simultaneously five consecutive times. Ten stations were completed on 3 September; the same ten stations (i.e., same geographical positions) were completed on 4 September.

The five consecutive radiance and irradiance scans were inspected and then averaged. Whatever the sky conditions, the recorded irradiance spectra showed slight variations [typically ±4% of the mean value, highest difference observed in the near infrared (700–900 nm)]. The five recorded radiance spectra systematically showed higher variations [up to ±12% of the mean value, highest difference observed at low wavelengths (400–500 nm)]. These higher variations certainly resulted from the movements of the boat, inducing movements of the radiance sensor plus the Spectralon panel system. Because of these movements, the sensor was not always viewing the same surface of the plaque with the same angle. These first observations logically indicate a better stability of the signal measured with the irradiance sensor.

Then the mean values of the radiance and irradiance signals were considered, respectively noted as E_d and L_{dspec}. Their ratio was calculated as

$$r_{\mathrm{spec}} = \frac{R_g E_d}{L_{\mathrm{dspec}}} \tag{2}$$

in steridians. According to Eq. (1), it was expected to obtain π sr.

The difference between the measured $E_d(0+)$ and the $E_d(0+)$ signal derived from the measurement on the plaque, assumed to be Lambertian, was calculated as

$$\mathrm{diff}_{\mathrm{spec}} = \frac{\pi R_g^{-1} L_{\mathrm{dspec}} - E_d}{E_d} \times 100 \tag{3}$$

in percent. The variations of r_{spec} and $\mathrm{diff}_{\mathrm{spec}}$ were observed as a function of wavelength.

B. Results

We first present the results obtained under a clear blue sky on 4 September 2003 (Fig. 1). As expected, the obtained r_{spec} ratios [Fig. 1(a)] show values rather close to π. Low spectral variations are observed from 400 to 900 nm, except at specific wavelengths corresponding to gaseous absorption peaks (e.g., absorption by oxygen at 687 and 762 nm).[23] At these wavelengths, the observed slight variations certainly result from slight differences in the spectral calibration of the two Trios sensors. However, the observed differences between the measured $E_d(0+)$ signal and the one derived from Eq. (1) are significant [Fig. 1(b)]. As can be seen, $\mathrm{diff}_{\mathrm{spec}}$ ranges between -20% and $+25\%$ and is typically positive with a mean value of $+10\%$. Thus, assuming the reliability and accuracy of the irradiance sensor, use of a Spectralon reference plaque leads to a slight overestimation of the actual $E_d(0+)$ signal. Spectral variations are also observed around 762 nm for the reasons explained above and in the blue domain (400–430 nm). These blue wavelength variations may be due to the calibration of the Trios optical sensors.[24] Under a clear blue sky and on the basis of the adopted configuration, results are therefore globally satisfactory although not highly accurate.

Under a covered sky, results are quite different (Fig. 2). r_{spec} is systematically higher than π, with significant variations from 3.7 to approximately 6.7 sr [Fig. 2(a)]. However, spectral variations remain low, excluding peaks around 762 nm [Fig. 2(b)]. In terms of a difference between the measured and the derived $E_d(0+)$, $\mathrm{diff}_{\mathrm{spec}}$ is always negative, which means that $E_d(0+)$ derived from Eq. (2) is systematically underestimated. $\mathrm{diff}_{\mathrm{spec}}$ ranges from -10% to

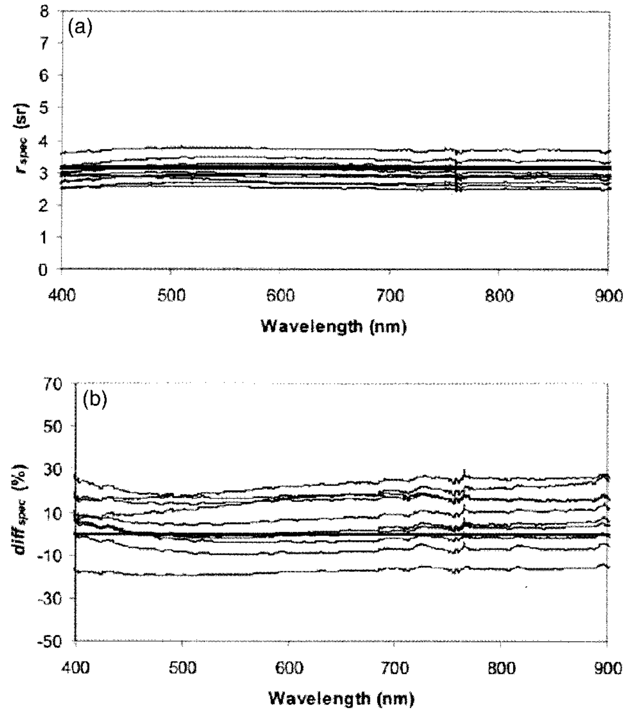

Fig. 1. Spectral variations of (a) r_{spec} and (b) $\text{diff}_{\text{spec}}$. Measurements were taken under a clear blue sky on 4 September 2003 from 09:15 to 15:45 GMT in the Plymouth Sound (southwest UK).

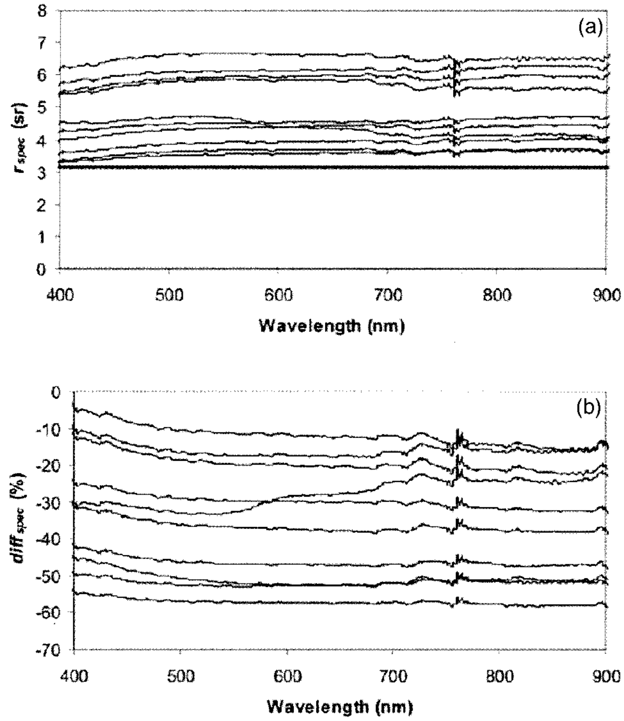

Fig. 2. Spectral variations of (a) r_{spec} and (b) $\text{diff}_{\text{spec}}$. Measurements were taken under a covered sky on 3 September 2003 from 11:15 to 17:00 GMT in the Plymouth Sound (southwest UK).

up to more than -60% and tends to increase (in absolute values) from low to high wavelengths. These results are definitely not satisfactory. They indicate that, under a covered sky and on the basis of the adopted configuration, errors up to a factor of 2 may be committed when $E_d(0+)$ is determined from Eq. (2) compared with the R_{rs} signal.

This certainly explains the observations made by Doxaran *et al.*[14] These authors compared R_{rs} spectra (400–1000 nm) recorded in the turbid Loire estuarine waters during two consecutive days. The sky was blue the first day and covered homogeneous the second day. At equivalent turbidity (i.e., suspended matter concentrations) they observed R_{rs} amplitude variations up to a factor 2 from one day to the other, the spectra recorded under a covered sky that was systematically higher than the ones recorded under a clear sky. These variations were attributed to possible significant variations of the bidirectional effects of the R_{rs} signal, namely, the f/Q ratio.[25–28] In fact, they were most probably due to large errors committed when L_{dspec} was measured under a covered sky.

On the basis of these first experiments, under a clear blue sky, a reference Spectralon plaque can be used to estimate $E_d(0+)$ with an acceptable accuracy; but this is not the case under a covered sky. At this stage, two explanations can be proposed:

(1) The Spectralon plaque that we used is not Lambertian under diffuse incident light conditions.

(2) The measurement configuration is not appropriate and induces shadow effects on the Spectralon plaque, especially under diffuse incident light conditions.

The second hypothesis can be easily verified by means of improving the measurement configuration.

3. Improved Measurement Configuration

A. Objective and Method

The objective was to define an appropriate measurement configuration, minimizing as much as possible any shadow effect influencing the Spectralon plaque. The appropriate measurement configuration would permit us to obtain r_{spec} ratios equal or close to π sr whatever the illumination conditions (i.e., cloud cover).

Possible origins of shadow effects on the plaque are the cockpit of the boat, the person holding the plaque, and the radiance sensor. Different configurations were tested to minimize these influences under cloudy and covered skies. The plaque was placed successively on the back extremity of the boat, on the back of the boat close to the cockpit, and on the top of the boat (i.e., on the cockpit roof). The person holding the sensor was successively above and then below the plaque. Finally, the distance of the sensor above the plaque varied from 5 to 50 cm. The viewing angle (relative to nadir) also varied from 0° (nadir viewing) to 45°, with the plaque facing the clearest part of the sky. Under stable illumination conditions [$E_d(0+)$ variations lower than 3%], the variability of L_{dspec} was observed.

A second set of optical measurements were carried out in the Plymouth Sound on 13 November 2003 under a dark heterogeneous sky (ten stations completed from 13:00 to 14:00 GMT) and then on 19 November 2003 under a highly cloudy heterogeneous sky (ten stations completed from 11:00 to 12:00 GMT). On both dates, the swell resulted in significant movements of the boat. The same procedure was followed concerning the acquisition and processing of the recorded $E_d(0+)$ and L_{dspec} spectra:

- acquisition of a minimum of five consecutive spectra,
- calculation of the $E_d(0+)$ and L_{dspec} mean values,
- quantification of the variations around the mean value, and
- calculation of the r_{spec} and $\text{diff}_{\text{spec}}$ parameters.

B. Results

The different configurations showed that significant shadow effects on the plaque were induced by the cockpit when measurement took place on the back of the boat. These effects were obviously amplified with the proximity of the cockpit, and L_{dspec} decreased by up to 50%. Therefore placing the plaque on the cockpit roof appeared to be the appropriate solution. Significant shadow effects were also induced by the sensor placed at a distance lower than 10 cm above the plaque (L_{dspec} decreasing by up to 15%). These shadow effects became almost insignificant when a distance higher than 20 cm was considered (L_{dspec} variations lower than 3% without regard to sign). Considering a distance higher than 20 cm, the influence of the viewing angle (ranging from 0° to 45° relative to nadir) appeared almost insignificant (L_{dspec} variations lower than 2% without regard to sign). For practical reasons, a nadir-viewing angle was adopted.

The best results (lowest $\text{diff}_{\text{spec}}$ values) were observed with the following configuration:

- the Spectralon plaque placed horizontally on the top of the boat (i.e., on the roof) to remove the shadow effects induced by the cockpit and
- the person holding the radiance sensor remaining below the plaque.

Only the radiance sensor was obviously placed above the plaque, at a distance of 30 cm, and may have induced shadow effects. A distance higher than 30 cm would have been more appropriate but was difficult to assess because of the limited dimensions of the plaque and the movements of the boat.

Results are globally satisfactory with this configuration. Regardless of the sky conditions, r_{spec} values close to π are obtained, ranging between 2.7 and 3.6 sr from 400 to 900 nm [Fig. 3(a)]. However, a spectral dependency is also observed, resulting in a slight increase of r_{spec} with increasing wavelength. Specific spectral variations are still observed in the blue (400–450 nm) and notably around 762 nm.

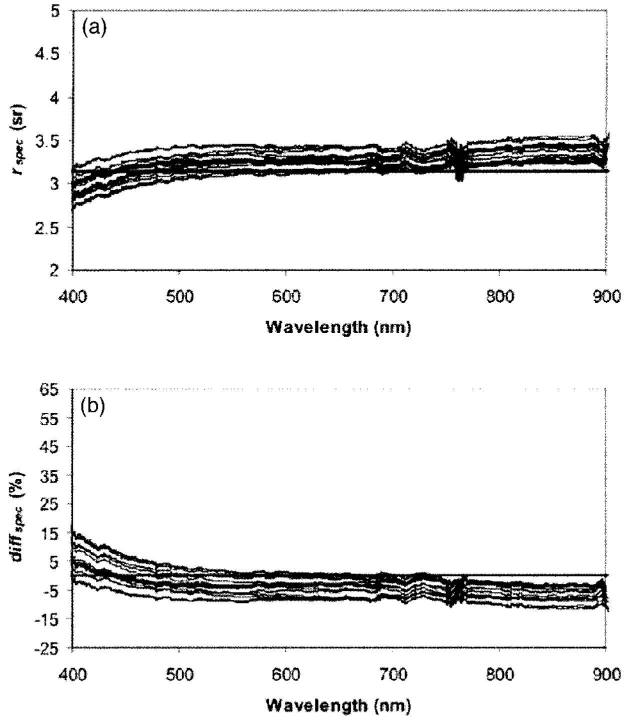

Fig. 3. Spectral variations of (a) r_{spec} and (b) $\text{diff}_{\text{spec}}$. Measurements were taken under various cloudy and covered skies on 13 November 2003 (13:00 to 14:00 GMT) and on 19 November 2003 (11:00 to 12:00 GMT) in the Plymouth Sound (southwest UK).

The difference observed between the measured and the derived $E_d(0+)$ is also greatly minimized. $\text{diff}_{\text{spec}}$ ranges between -10% and $+15\%$ [Fig. 3(b)]. Typically, $\text{diff}_{\text{spec}}$ is positive in the blue [leading to a slight overestimation of $E_d(0+)$ from 400 to 450 nm], close to zero from 500 to 700 nm, and then negative in the near infrared [leading to a slight underestimation of $E_d(0+)$].

Consequently, it can be concluded that shadow effects were at the origin of the erroneous measurements carried out in September on the back of the boat; the Lambertian properties of the Spectralon plaque are not dependent on the sky conditions. Shadow effects, induced by the cockpit of the boat and by the person holding the sensor, resulted in a high inaccuracy of measurement. However, these effects can be greatly minimized. Adopting an appropriate measurement configuration, $E_d(0+)$ can be accurately estimated with a radiance sensor and a Spectralon plaque, whatever the illumination conditions.

4. Conclusions and Recommendations

The objective of this study was to know how $E_d(0+)$ can be accurately estimated from measurements of the downwelling radiance signal reflected by a Spectralon plaque (L_{dspec}). Basic experiments were conducted, measuring $E_d(0+)$ and L_{dspec} simultaneously on a boat under different illumination conditions (clear, cloudy, covered skies) and with different measurement configurations.

Under a clear sky, it was observed that presenting the plaque horizontally in front of the Sun is sufficient to obtain a correct L_{dspec} signal. This signal, multiplied by π sr (i.e., assuming that the plaque is a Lambertian reflector), provides a good estimation of $E_d(0+)$ ($\pm 10\%$ mean accuracy).

Under a diffuse incident light (i.e., cloudy or covered sky), obtaining a correct L_{dspec} signal is more complicated. In fact, shadow effects induced by the cockpit of the boat, by the person or system holding the radiance sensor, and by the radiance sensor itself can dramatically modify the measured L_{dspec} signal. Errors up to 100% can easily be committed when a Spectralon plaque is used on the deck of a boat under a covered sky. These errors related to L_{dspec} measurements can induce errors up to 100% on the determined R_{rs} signal. This certainly explains most of the R_{rs} variations observed by Doxaran *et al.*[14] in the Loire estuary with changing sky conditions. Thus, in these conditions, special care must be taken to minimize the shadow effects. The Spectralon plaque must be placed on the top of the boat (on the roof), above any object or holding system. It is recommended that the radiance sensor, viewing the plaque, be placed as far as possible from the plaque. Such recommendations may be difficult to respect on a boat with a rough sea surface, but are necessary to avoid large errors. Numerous measurements of L_{dspec} and $E_d(0+)$ were carried out respecting this configuration with a minimum plaque–sensor distance of 30 cm under various cloudy and covered skies. The measured L_{dspec} signal, multiplied by π sr, provides a good estimation of $E_d(0+)$ (accuracy better than $\pm 15\%$). This accuracy may logically be improved by use of a plaque of large dimensions and by an increase in the distance between the plaque and the radiance sensor. It can be compared with the uncertainty in L_w determinations: typically 8–18% in case 1 waters,[6,8,9] considering different techniques (above- and in-water optical measurements) and processing and correction methods. In turbid coastal (case 2) waters where use of in-water measurement techniques is limited and above-water techniques are influenced by surface reflection effects, imperfect corrections for the Sun and sky glint may result in significantly higher errors.[6,7] Therefore the uncertainty in $E_d(0+)$ must be taken into account when the percentage of error associated with R_{rs} measurements is assessed.

Regardless of the illumination conditions and the induced shadow effects, the ratio between the measured L_{dspec} and $E_d(0+)$ signals showed slight spectral variations from 400 to 900 nm. Consequently, errors committed when a Spectralon plaque is used to estimate the $E_d(0+)$ signal, then the R_{rs} signal, can be significantly minimized by use of a ratio between two wavelengths.

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