Measurement of water-leaving radiance on smooth water surfaces at different viewing angles using high-resolution spectroradiometer

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This letter describes a method for calculating water-leaving radiance on smooth surfaces at different angles based on Fresnel law and the polarized measurements using an ASD FS3 spectroradiometer. The spectroradiometer is mounted on a goniometer so that it views the water surface from a height of several decimeters at different viewing angles through a linear polarizing filter. The incident angles equal the viewing angles. The water-leaving radiance spectra acquired by other methods are compared with the polarized measurements from the smooth water surface, and the radiance spectra obtained by the proposed method are found to be consistent with the results of the reference methods. The current study provides another effective technique for measuring water-surface reflectance via remote sensing. Moreover, the method does not avoid the sun glint during the detection of water-leaving radiance in cases where the viewing geometric position is clear.

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A hyperspectral sensor provides information, such as high spatial resolution and spectral resolution, for water remote sensing. However, when the water radiation is tested by machine-carried or spaceborne systems, the testing process can be affected by other factors (such as the atmospheric radiation, Fresnel reflection, and so on). The most common influencing factor is the sun glint reflected by water waves.

When the sensor detects sunlight directly reflected by the water crest or wave slope, the information on the water and everything under it can be totally deteriorated. Hochberg *et al.*[1] indicated that when the time and viewing geometric position vary, the sun glints can be avoided. However, Mustard *et al.*[2] stated that the different features of the different outside local make this method unavailable. Kusrer *et al.*[4] pointed out that sun glints can be effectively eliminated at 760 nm. In fact, some radiation signals, such as benthic algal cover and seagrasses[3,5−8], always exist in the near-infrared part of the spectrum.

Surface waves mainly cause the extensive distribution of sun glints. Curran[9] stated that polarized measurements may provide some useful information for determining the state of a sea surface. Talmage *et al.*[10] summarized that applying partial polarized light into the sensor can illustrate the feasibility of the use of polarized measurements. Horváth[11] calculated the polarizing distribution of the smooth water surface and then measured the features of different water-polarizing reflections[12]. Moreover, Gal *et al.*[13] proved Horvath's theory using practical measurements. Meanwhile, Cunningham *et al.*[14] measured the water-leaving radiation degree of the sea surface at the Brewster angle using polarizing techniques. However, they did not prove the assumption that the polarization of water-leaving radiation can be zero.

On smooth water surfaces, the signals that the detector gets are only water-leaving radiation and sun glint signals instead of atmospheric scattered and space diffusing signals. In this letter, the degree of polarization of water-leaving radiance is assumed to be close to zero. The current study tests water-leaving polarization under this assumption and proposes a method for calculating the degree of polarization of the water-leaving radiation from different angles while avoiding sun glints based on the Fresnel law. Meanwhile, the feasibility of the proposed method is proven through laboratory measurements.

The polarization state can be calculated using the Stokes parameters as follows:

$$\begin{cases} I = E_{\mathrm{p}}^2 + E_{\mathrm{s}}^2 \\ Q = E_{\mathrm{p}}^2 - E_{\mathrm{s}}^2 \\ U = 2E_{\mathrm{p}}E_{\mathrm{s}}\cos\delta \\ V = 2E_{\mathrm{p}}E_{\mathrm{s}}\sin\delta \end{cases}, \tag{1}$$

$$\theta = \frac{1}{2}\arctan\left(\frac{U}{Q}\right), \tag{2}$$

where δ refers to the phase difference and θ refers to the polarization azimuth. V can be ignored after reflection. Light can be decomposed into parameters parallel (p) and perpendicular (s) to the incident plane, which is the plane formed by the normal direction and incident light. The degree of polarization P can be calculated as

$$P = \frac{\sqrt{Q^2+U^2}}{I} = \frac{\sqrt{(I_{\mathrm{p}}-I_{\mathrm{s}})^2+4I_{\mathrm{p}}I_{\mathrm{s}}\cos^2\delta}}{I_{\mathrm{p}}+I_{\mathrm{s}}}. \tag{3}$$

Polarization light mainly includes line, ellipse, and circle polarizations, which can all be presented using the ellipse equation. Generally, the θ (the polarization azimuth) of the principle axis and x-axis can be demonstrated by the ellipse equation

$$\cos\delta = \frac{I_\mathrm{s} - I_\mathrm{p}}{2\sqrt{I_\mathrm{s} I_\mathrm{p}}} \tan 2\theta. \quad (4)$$

E_s and E_p refer to the amplitudes of the x- and y-axes, respectively. Combining Eqs. (4) and (3) obtains

$$P = \frac{I_\mathrm{s} - I_\mathrm{p}}{|\cos 2\theta|\,(I_\mathrm{p} + I_\mathrm{s})}. \quad (5)$$

The reflection and refraction values can be obtained when the light is incident to the smooth water from the atmosphere. α and β refer to the incident and refraction angles, respectively. The following are Fresnel reflectance formulas:

$$r_\mathrm{p} = \frac{\tan(\alpha - \beta)}{\tan(\alpha + \beta)}, \quad r_\mathrm{s} = \frac{\sin(\beta - \alpha)}{\sin(\beta + \alpha)}, \quad (6)$$

where r_p and r_s represent the amplitude reflectances. Without considering the direction, Eq. (6) shows that when α=0° and r_s=r_p (the incident light is vertical), the reflection light has no polarization property. When $0° < \alpha < 90°$, where $r_\mathrm{p} < r_\mathrm{s}$, the parallel parameter of the reflection light electric vector is always less than the vertical parameter. Thus, the light reflected by the water after oblique incidence is the polarized light when the incident lights are natural.

When the atmospheric scattering and water reflection signals are ignored, the reflected intensity that the detector gets is denoted as I. The reflection intensity includes the specular reflection light I_o and the water-leaving radiation I_l. However, the intensity of specular reflection is necessary for detecting water-leaving radiance. Considering that polarization is generated by specular reflection, the degree of polarization can be presented as

$$P = \frac{I_\mathrm{j}}{I_\mathrm{o}} = \frac{I_\mathrm{s} - I_\mathrm{p}}{|\cos 2\theta|\,(I_\mathrm{s} + I_\mathrm{p})}, \quad (7)$$

where I_j refers to the linearly polarized lights. The denominator in the formula is the summation of signals I. When I_l is unpolarized, it becomes half of that before polarization. The numerator in Eq. (7) is fixed. According to Fresnel law, another formula exists

$$\frac{I_\mathrm{s}}{I_\mathrm{p}} = \frac{|r_\mathrm{s}|^2}{|r_\mathrm{p}|^2} = \left(\frac{\cos(\alpha - \beta)}{\cos(\alpha + \beta)}\right)^2. \quad (8)$$

According to Eqs. (7) and (8), the intensity of specular reflection is denoted as

$$I_\mathrm{o} = \frac{|\cos 2\theta|\,[\cos^2(\alpha - \beta) + \cos^2(\alpha + \beta)]}{\cos^2(\alpha - \beta) - \cos^2(\alpha + \beta)}(I_\mathrm{s} - I_\mathrm{p}). \quad (9)$$

Equation (9) shows that only Q and U contribute to the reflected lights. Thus, the calculations can draw only the results of specular reflection instead of the water-leaving radiance. The refraction angle can be obtained using the refraction law, $n_1 \sin\alpha = n_2 \sin\beta$, where n_1 and n_2 refer to the refraction indexes of air and water, which are 1 and 1.3333, respectively. After calculating the intensity of specular reflection I_o, the water-leaving radiance I_l can be calculated by deducting I_o from the total intensity I.

The measurement system consists of a goniometer for measuring angles, a lamp with a 90° freedom of motion, which simulates the sun, and an ASD FS3 350 to 2 500 nm spectroradiometer. The apparatus is shown in Fig. 1.

The goniometer has a 1.2-m-long motor-driven arm that can travel 90° from the zenith using a stepping motor carried on a 1.2-m-diameter circular ring. The inner circle, which holds the sample material, has a diameter of 0.4 m and can rotate from 0° to 360° in the azimuthal direction. In the viewing direction, a bare fiber-optic cable is fixed in a metal tube that guides the reflected light to the spectrometer. A calcite Glan–Thomson prism allows free rotations from 0° to 360° in 1° increments to observe different polarization directions and to measure the polarization at a given wavelength (350 to 2 300 nm)[15].

For each measurement, the black columnar receptacle with diameter of 0.35 m and height of 0.4 m is filled with pure water. The radiance contribution from the container is negligible. Maignan *et al.*[16] reported that a few targets in the database, including small water bodies that reflect sunlight according to Fresnel laws, are very close to the specular direction (2° from the specular direction). The specular light may be calculated directly using Eq. (9) because the corrections for the diffused light are not needed for the lamp measurements[17].

In measuring the light reflections in water, a 350 to 850 nm wave band is selected as the main scale. According to Hochberg's method[1], without determining the incident direction, the degree of polarization of the water-leaving radiance can be calculated using Eq. (3), as shown in Fig. 2. As shown, the degree of polarization of the water-leaving radiance is so small that it can be assumed as zero. This result shows the feasibility of the assumption that the degree of polarization of the water-leaving radiance is close to zero.

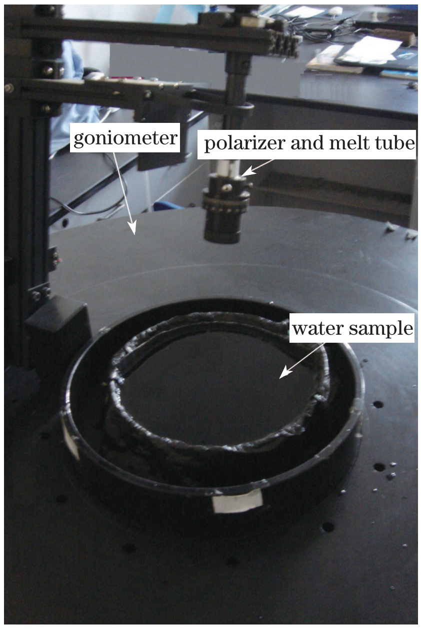

Fig. 1. Water sample, polarizer, and metal tube, which carried the bare fiber-optic cable and the goniometer.

Considering that the assumption is tenable, the radiation can be obtained from different polarization angles. Then, the total intensity of the specular reflection lights can be calculated using Eq. (9). Next, this intensity is deducted from the total intensity detected by the spectrometer from the specular direction. Finally, the water-leaving radiance is illustrated in Fig. 3, which shows the different water-leaving radiances from different viewing zenith angles. The reference water-leaving radiance was taken from the works of Hochberg *et al.*[1,14]. Cunningham *et al.* used a polarizing technique for measuring the water-leaving radiance at the Brewster's angle. The results of these two works correspond with each other. The uncertainty of the water-leaving radiance reversed using the polarization technique (with the proposed method) is less than 5%. This method avoids the sun glint from the smooth water surface, as concluded by Kusrer *et al.*[4].

Figure 4 shows the different water-leaving radiances detected from different viewing angles. 0° represents 20°, 30°, 40°, 50°, and 60°. Taking 20° as an example, +0.5° means that the viewing zenith angle is 20.5° and –0.5° indicates that the detecting zenith angle is 19.5°. However, the incident angle remains to be 20°. When the viewing angle changes in the scale of 4°, the variety of the water-leaving radiance is inconspicuous. In other words, the water-leaving radiance can be detected using the polarized measurements with the angle range based on Maignam's conclusion[16].

In conclusion, under smooth water conditions, the signals that the detector gets are only water-leaving radiation and sun glint signals. This paper has proposed a method for calculating the water-leaving radiance based

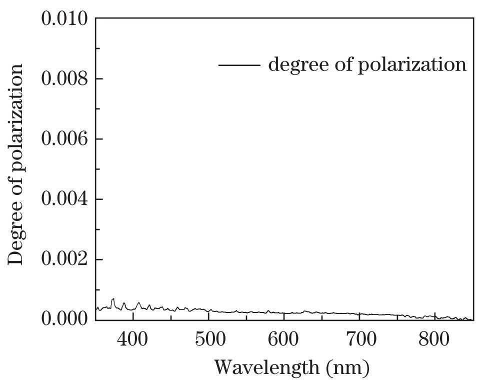

Fig. 2. Degree of polarization of water-leaving radiance.

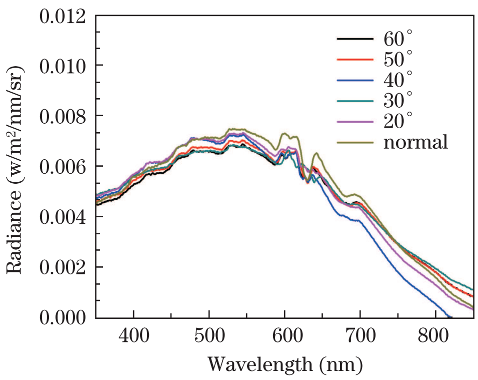

Fig. 3. Calculated water-leaving radiances and the standard value ("normal").

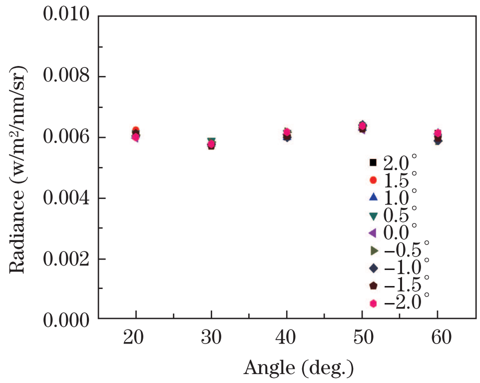

Fig. 4. Water-leaving radiance at different viewing angles at 630 nm. The degrees in the legend represent the variation of the viewing angles.

on the Fresnel law. Meanwhile, the proposed method has been tested by using pure water as the research target. The results show the feasibility of the assumption that the degree of polarization of water leaving is close to zero. The results obtained using the proposed technique are consistent with the measurements of Cunningham *et al.*[14]. When the sunlight incident direction is certain and the viewing angle is 2° more or less than the incident angle, without avoiding the direct reflection direction, the polarized technique is effective in measuring the degree of water-leaving radiation. The current method supplements the remote sensing technique and provides additional effective methods for monitoring the optical properties of water. Moreover, it extends the viewing scale of detecting the water-leaving radiance, and thus, it may reduce the limitations of the viewing space and time. In practical measurements, the influence of the atmosphere and the diffused sky radiation can be excluded according to the methods of Cunningham *et al.*[14,18]. However, in the current experiment, the influence of the water waves, shoal water area, suspended matter in the water, and so on, cannot be ignored and, hence, will be the topic of future research.

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