Spectral sea surface reflectance of skylight

XIADONG ZHANG,1,* SHUANGYAN HE,1,2 AFSHIN SHABANI,1 PENG-WANG ZHAI,3 AND KEPING DU4

1Department of Earth System Science and Policy, University of North Dakota, 4190 University Ave, Grand Forks, ND 58202-9011, USA
2Ocean College, Zhejiang University, Hangzhou 310058, China
3Department of Physics, University of Maryland Baltimore County, Baltimore, MD 21250, USA
4State Key Laboratory of Remote Sensing Science, School of Geography, Beijing Normal University, Beijing 100875, China

*zhang@aero.und.edu

Abstract: In examining the dependence of the sea surface reflectance of skylight \( \rho_s \) on sky conditions, wind speed, solar zenith angle, and viewing geometry, Mobley [Appl. Opt. 38, 7442 (1999).] assumed \( \rho_s \) is independent of wavelength. Lee et al. [Opt. Express 18, 26313 (2010).] showed experimentally that \( \rho_s \) does vary spectrally due to the spectral difference of sky radiance coming from different directions, which was ignored in Mobley’s study. We simulated \( \rho_s \) from 350 nm to 1000 nm by explicitly accounting for spectral variations of skylight distribution and Fresnel reflectance. Furthermore, we separated sun glint from sky glint because of significant differences in magnitude, spectrum and polarization state between direct sun light and skylight light. The results confirm that spectral variation of \( \rho_s(\lambda) \) mainly arises from the spectral distribution of skylight and would vary from slightly blueish due to normal dispersion of the refractive index of water, to neutral and then to reddish with increasing wind speeds and decreasing solar zenith angles. Polarization moderately increases sky glint by 8 – 20% at 400 nm but only by 0 – 10% at 1000 nm. Sun glint is inherently reddish and becomes significant (>10% of sky glint) when the sun is at the zenith with moderate winds or when the sea is roughened (wind speeds > 10 m s\(^{-1}\)) with solar zenith angles < 20°. We recommend a two-step procedure by first correcting the glint due to direct sun light, which is unpolarized, followed by removing the glint due to diffused and polarized skylight. The simulated \( \rho_s(\lambda) \) as a function of wind speeds, sun angles and aerosol concentrations for currently recommended sensor-sun geometry, i.e., zenith angle = 45°, is available upon request.

©2017 Optical Society of America

OCIS codes: (010.4450) Oceanic optics; (280.0280) Remote sensing and sensors.

References and links

15. Z. Lee, N. Pahlevan, Y.-H. Ahn, S. Greb, and D. O’Donnell, “Robust approach to directly measuring water-leaving reflectance in and above-water, the above-water method has been widely used although each has its own advantages and disadvantages [3].

1. Introduction
Spectral water-leaving radiance \( L_w \) or its equivalent, remote sensing reflectance \( R_{rs} \), is a core quantity in interpreting ocean color observation and the subsequent retrieval of water constituents. Among the three observational schemes typically deployed in the field to measure \( L_w \) or \( R_{rs} \) [1], i.e., in-water, above-water, or a combination of in and above-water, the above-water method has been widely used [2] although each has its own advantages and disadvantages [3].

It has long been recognized [4] that the measured radiance \( L_v \) from an above-water sensor unavoidably includes surface-reflected skylight or glint, which has to be removed to derive \( L_w \), i.e.,

\[
L_w(\lambda; \Omega_v) = L_v(\lambda; \Omega_v) - \int_{2\pi} p(\Omega \to \Omega_v) r(\lambda; \Omega \to \Omega_v) L_v(\lambda; \Omega_v) d\Omega
\]  

Here, \( \Omega_v \) and \( \Omega \) are solid angles denoting the directions of the sensor’s field-of-view (FOV) and skylight respectively, \( r \) represents the Fresnel reflectance from directions \( \Omega \) to \( \Omega_v \), by the air-sea interface, \( p \) (sr\(^{-1}\)) the probability density function for the reflection from \( \Omega \) to \( \Omega_v \), to occur, \( L_v(\lambda; \Omega_v) \) the spectral skylight coming from direction \( \Omega_v \) and \( \lambda \) the wavelength. Since \( L_v \) includes direct sun beam, which is approximately 5-6 orders of magnitude greater than typical.
skylight radiance away from the sun, the experimental setup measuring $L_w$ is normally
arranged to minimize the probability of $p(Sun \rightarrow Sensor)$. For example, the sensor is typically
pointed away from the sun at a direction with the azimuth angle (relative to the sun plane) $\phi_s = 45 - 90^\circ$
and zenith angle $\theta_v = 35 - 45^\circ$ [2,3,5,6] (Fig. 1). If solar zenith angle is $\theta_v$, a sun
ray would point to ($\pi - \theta_v, \pi$), and the azimuthal angle difference, conventionally defined
between the sun ray vector and radiance vector measured by the sensor, is $\pi - \phi_s$. In the
following, we will use solid angle (e.g., $\Omega$) and polar coordinates (e.g., $\theta, \phi$) with or without a
subscript interchangeably in representing a direction.

![Fig. 1. Schematic diagram showing the typical experimental setup for above-water water-
leaving radiance measurements. As a convention, the sun is always placed in the X-Z plane.

To aid correction of surface-reflected skylight, skylight coming from the direction ($\theta', \phi'$)
that would be specular-reflected into the sensor by a flat surface is often measured (Fig. 1). With the measured $L_s(\lambda; \theta', \phi')$, the skylight correction is performed as:

$$L_w(\lambda; \Omega_v) = L_s(\lambda; \Omega_v) - \rho_s(\lambda)L_s(\lambda; \theta', \phi'),$$

(2)

where from Eq. (1) $\rho_s(\lambda)$ should be [7]:

$$\rho_s(\lambda) = \frac{\int p(\Omega \rightarrow \Omega_v) r(\lambda; \Omega \rightarrow \Omega_v) L_s(\lambda; \Omega) d\Omega}{L_s(\lambda; \theta', \phi')}.$$  (3)

Apparently $\rho_s$ varies with the sun positions and atmospheric condition (both affecting $L_s$),
sea states (affecting $\rho$ and $r$), sensor geometry (affecting every item in Eq. (3)), and wavelength
(through $L_s$ and $r$). However, since $\rho_s$ cannot be measured directly, its values have to be
estimated. Carder and Steward [8] used a value of 0.021 by Austin [9] for flat sea surface and
Mobley [5] simulated $\rho_s$ as a function of environmental conditions and recommended $\rho$
=0.028 with $\theta_v$ $\approx 40^\circ$, $\phi_s$ $\approx 45^\circ$ for wind speeds $< 5$ m s$^{-1}$ or overcast sky at all wind speeds,
and higher values for other conditions (referring to Fig. 9 in [5]).

Mobley [5] assumed the angular pattern of sky radiance ($L_s$ in Eq. (3)) and water refractive
index ($r$ in Eq. (3)) are independent of wavelength, and hence so is $\rho_s$. Spectrally invariant $\rho_s$
is also assumed in some other studies [e.g., 10,11]. Lee et al. [7] pointed out that $\rho_s$ should
vary spectrally because diffused sky radiance and direct sunlight both have spectral shapes
different from $L_s(\lambda; \theta', \phi')$. By comparing measured $L_s(\lambda; \theta_v, \phi_v)$ and $L_s(\lambda; \theta', \phi')$ with
simulated $L_s(\lambda; \theta_v, \phi_v)$, Lee et al. [7] also showed that $\rho_s$ could increase from 400 to 800 nm
by a factor of up to eight. However, it is still unclear how the spectral behavior of \( \rho_s \) varies with sensor setup, sky condition, sun angles, or sea states.

Effect of skylight polarization on \( \rho_s \) was recently investigated [12,13] and found to be significant. For example, for the viewing geometry shown in Fig. 1, both Harmel et al. [12] and Mobley [13] found that \( \rho_s \) at 550 nm would be underestimated by up to 25 – 30% depending on solar zenith angles and aerosol concentration if polarization of skylight was not accounted for. However, if and how polarization affects the spectral variation of \( \rho_s \) has not been studied yet.

The main objective of this study is to numerically investigate the spectral variation of \( \rho_s \) as a function of solar zenith angle, wind speeds and aerosol concentrations. Our approach has improved over the earlier studies (e.g., [5,7]) in three areas: First, the spectral variation of \( L_s \) distribution was explicitly considered. Second, we separated sun glint from sky glint. Since it is impossible to completely eliminate sun glint in above-water radiometry regardless of the setup, it is of interest to know how much the sun glint contributes to the sky glint [14]. Third, we accounted for the spectral variation of the refractive index of water, which increases toward shorter wavelength through normal dispersion and results in \( \sim10\% \) increase of Fresnel reflectance from 700 nm to 400 nm. Also, we explored the possible effect of skylight polarization on spectral variation of \( \rho_s \).

2. Methodology

2.1 Theoretical basis

We assume that for skylight or sun light coming from an arbitrary direction, capillary wave facets within the surface area subtended by the sensor’s FOV have an orientation that reflect this incident light into the sensor. The probability of the facets having such orientation is determined by the slope distribution of facets which, in turn, is a function of wind [15]. The probability-weighted sum of reflected light coming from every direction within the sky dome represents the glint component that a sensor measures. Also, we explicitly separate direct sun beam (\( L_{sun} \)), considered a mathematical singularity, from the rest of skylight (\( L_{sky} \)), i.e., \( L_s = L_{sky} + L_{sun} \). With this, Eq. (3) becomes:

\[
\rho_s(\lambda) = \rho_{sky}(\lambda) + \rho_{sun}(\lambda),
\]

and

\[
\rho_{sky}(\lambda) = \frac{\int_{2\pi-4\pi} p(\Omega \rightarrow \Omega') r(\lambda; \Omega \rightarrow \Omega') L_{sky}(\lambda; \Omega)d\Omega}{L_{sky}(\lambda; \theta, \phi')}, \tag{5}
\]

\[
\rho_{sun}(\lambda) = \frac{\int_{4\pi} p(\Omega \rightarrow \Omega') r(\lambda; \Omega \rightarrow \Omega') L_{sun}(\lambda; \Omega)d\Omega}{L_{sun}(\lambda; \theta, \phi')}, \tag{6}
\]

where \( \Omega_s \) is the solid angle subtended by the sun as seen from the Earth. Let \( L_{sky}(\lambda; \theta_m, \phi_m) \) represent \( p(\Omega \rightarrow \Omega') r(\lambda; \Omega' \rightarrow \Omega) \)-weighted average of \( L_{sky} \) over the sky dome (\( 2\pi-\Omega_s \)) and \( L_{sun}(\lambda; \theta_m, \phi_m) \) the average radiance of the direct sun beam, and Eqs. (5) and (6) become:

\[
\rho_{sky}(\lambda) = \frac{L_{sky}(\lambda; \theta_m, \phi_m)}{L_{sky}(\lambda; \theta, \phi')} \int_{2\pi-4\pi} p(\Omega \rightarrow \Omega') r(\lambda; \Omega \rightarrow \Omega') d\Omega' = R_{sky}(\lambda)r_{sky}(\lambda), \tag{7}
\]

\[
\rho_{sun}(\lambda) = \frac{L_{sun}(\lambda; \theta_m, \phi_m)}{L_{sky}(\lambda; \theta, \phi')} \int_{4\pi} p(\Omega \rightarrow \Omega') r(\lambda; \Omega \rightarrow \Omega') d\Omega = R_{sun}(\lambda)r_{sun}(\lambda), \tag{8}
\]
where \( R_{\text{sun}}(\lambda) \), \( R_{\text{sky}}(\lambda) \) and \( r_{\text{sun}}(\lambda) \), \( r_{\text{sky}}(\lambda) \) represent the ratio and integral terms in Eqs. (7) and (8), respectively. The reason for further separating \( p_{\text{sky}}(\lambda) \) into \( R_{\text{sky}}(\lambda) \) and \( r_{\text{sky}}(\lambda) \), and \( p_{\text{sun}}(\lambda) \) into \( R_{\text{sun}}(\lambda) \) and \( r_{\text{sun}}(\lambda) \) is to gain a better understanding of \( p_c \). \( r_{\text{sky}}(\lambda) \) represents the mean reflectance for uniformly distributed skylight and \( R_{\text{sky}}(\lambda) \) represents the scaling factor dependent on how the actual skylight deviates from the uniform distribution. \( r_{\text{sun}}(\lambda) \) represents the reflectance from the direction of the sun to the sensor. Both \( r_{\text{sky}} \) and \( r_{\text{sun}} \) are a property of the surface, depending only on sea states or winds for a given observation geometry.

2.2 Simulation

Following Mobley [5], the sky dome hemisphere surrounding the sensor FOV is partitioned into quads, except for the polar cap (i.e., \( \theta = 0^\circ \)) which is represented by a cone defined by its half angle. Radiance is assumed to be constant within each quad. Instead of partitioning the sky dome into quads of equal angular spacing (i.e., each quad is defined by the same same \( \Delta \phi \) and \( \Delta \theta \)), the quads in our partition are of equal area; each quad is defined by the same \( \Delta \phi \) and \( \Delta \theta \), where \( \phi = \cos \theta \). In other words, each quad subtends the same solid angle, which, in our study, is set to be equal to \( \Omega_s \). With an average sun-earth distance of \( 1.496 \times 10^8 \) km and the sun’s diameter of \( 1.393 \times 10^9 \) km, the half angle of the sun disk is \( \alpha_{0.5} = 0.2668^\circ \), which gives \( \Omega_s = 6.8096 \times 10^{-3} \) sr. Therefore, in partitioning the sky dome, the half angle is \( \alpha_{0.5} \) for the polar cap; and \( \Delta \phi = 9.3084 \times 10^{-3} \) rad and \( \Delta \theta = 7.3155 \times 10^{-3} \) rad for non-polar quads. With this equal solid-angle partition, the weighting of reflected skylight from each quad depends only on the orientation probability of capillary wave facets. If using the equal-angle partition, the weighting factor for each quad depends on both orientation probability and the solid angle that this quad subtends. Also, with the solid angle of each quad being the same as the sun’s, the contribution of the direct solar beam can be easily assessed by simply replacing skylight from the sun’s direction with solar radiation.

We used the coordinate system defined in Fig. 1 with the sun in the x-z plane. Let \( (\theta, \phi) \) be the polar coordinate (zenith and azimuth angles, respectively) of an arbitrary point on the \( i \)th quad and \( \mathbf{s} \) the unit Cartesian vector representing incoming skylight from this point so that \( \mathbf{s} = (-\cos \phi, \sin \theta, -\sin \phi, \sin \theta, -\cos \theta) \). Let \( \mathbf{r} \) be the unit Cartesian vector representing the reflected light entering the sensor’s field of view, the unit vector \( \mathbf{n} \) normal to the wave facets that would reflect \( \mathbf{s} \), into \( \mathbf{r} \) is \( \mathbf{n} = \frac{\mathbf{r} - \mathbf{s}}{|\mathbf{r} - \mathbf{s}|} \). The angle of reflection \( \theta = \cos^{-1} |\mathbf{s} \cdot \mathbf{n}| \). The polar coordinate for \( \mathbf{n}_i \), \( (\theta_{ni}, \phi_{ni}) \) = \( (\arccos z_{ni}, \arctan y_{ni}/x_{ni}) \), where \( x_{ni}, y_{ni}, \) and \( z_{ni} \) are \( \mathbf{n}_i \)'s Cartesian x-, y-, and z- coordinates, and the slope of these wave facets is \( \tan \theta_{ni} \). As \( (\theta, \phi) \) moves around on this quad, the corresponding \( \mathbf{n}_i \) also changes, defining ranges of \( \theta_{ni,\text{min}} \leq \theta_{ni} \leq \theta_{ni,\text{max}} \) and \( \phi_{ni,\text{min}} \leq \phi_{ni} \leq \phi_{ni,\text{max}} \). Assuming independence of wind directions, the probability density \( (p_i) \) of wave facets having the orientations that would reflect skylight coming from the \( i \)th quad into the sensor is [16]:

\[
p_i = \frac{p_x \times p_y}{\sum_{z_k} p_{i_k}} , \quad (9)
\]

\[
p_y = \exp\left( -\frac{\tan^2 \theta_{ni,\text{min}}}{2\sigma^2} \right) - \exp\left( -\frac{\tan^2 \theta_{ni,\text{max}}}{2\sigma^2} \right) , \quad (10)
\]

\[
p_y = \frac{\phi_{ni,\text{max}} - \phi_{ni,\text{min}}}{2\pi} , \quad (11)
\]

where \( \sigma^2 \) is the mean square slopes of capillary wave facets following Cox and Munk [15] and \( \sum_{z_k} p_i \) represents the sum of \( p_i \) over the entire hemispheric sky dome.
The same procedure was followed to find the probability of reflecting direct sunlight (or skylight coming from the polar cap) into the sensor except in this case the shape of the grid is not a quad but a cone. The Cartesian unit vector representing incoming sun beam from the peripheral of the sun is

\[
\begin{bmatrix}
-\cos \theta_{\text{sun}} \sin \alpha_{0.5} \cos \beta - \sin \theta_{\text{sun}} \cos \alpha_{0.5} \\
-\sin \alpha_{0.5} \sin \beta \\
\sin \theta_{\text{sun}} \sin \alpha_{0.5} \cos \beta - \cos \theta_{\text{sun}} \cos \alpha_{0.5}
\end{bmatrix},
\]

where \( \beta = [0, 2\pi] \). To represent the incoming light from the polar cap is equivalent to setting \( \theta_{\text{sun}} = 0 \) in Eq. (12).

In computing the Fresnel reflectance, we used the refractive index of seawater following [17]. Skylight radiance distributions \( L_{\text{sky}}(\lambda, \theta, \phi) \) and direct solar radiance \( L_{\text{sun}}(\lambda, \theta_{\text{sun}}) \) for various solar zenith angles are simulated using MODTRAN [18] with a 1976 US standard atmosphere and standard maritime aerosol model with an aerosol optical depth at 550 nm \( (\tau_a) \) of 0.05 (~23 km visibility).

3. Results

We will present the results computed for the sensor-sun geometry that is currently recommended using the coordinate system defined in Fig. 1 \((\theta_{\text{sun}} = 0)\): for the sensor, \((\theta_v, \phi_v) = (40°, 45°)\); and for skylight to be measured, \((\theta', \phi') = (40°, 225°)\).

Fig. 2. The contours of logarithmic probability density \( p \) (sr\(^{-1}\)) as a function of skylight direction \((\theta, \phi)\) at wind speeds of 0, 5, 10 and 15 m s\(^{-1}\). In each polar plot, the center represents the sensor’s FOV, zenith angles \((\theta)\) vary from 0 to 90° in radial direction, and azimuth angles \((\phi)\) are defined relative to the sun. The \( \star, \square \) and \( + \) symbols denote the directions of the sun \((\theta_{\text{sun}}, \phi_{\text{sun}}) = (30°, 0)\), the sensor \((\theta_v, \phi_v) = (40°, 45°)\) and specular point of the sensor \((\theta', \phi') = (40°, 225°)\), respectively.

3.1 Spatial distribution of \( p, r \) and \( L_{\text{sky}} \)

The estimated probability density function \( p \) are shown in Fig. 2 for wind speeds \( U = 0, 5, 10 \) and 15 m s\(^{-1}\) and for sun zenith angle \( \theta_{\text{sun}} = 30° \). For low wind \((U = 0 \text{ m s}^{-1})\), the skylight reflected into the sensor \( (\square \text{ in Fig. 2}) \) is mainly from directions immediately surrounding the sensor’s specular point \((\theta', \phi')\) \( (+ \text{ in Fig. 2}) \). As wind speeds increase, the chances of the existence of wave facets with an orientation that would reflect skylight coming from directions other than \((\theta', \phi')\) increase [15]. With a roughened surface, it is possible for the sensor to see reflected skylight coming from almost any direction. However, the probability remains the highest in the directions around \((\theta', \phi')\) and decreases in other directions with the lowest probability in the directions behind the sensor and near the horizon. The probability of the sensor seeing the sun \((\star \text{ in Fig. 2})\) with a zenith angle of 30° increases by three orders of magnitude from \( -2 \times 10^{-6} \) (sr\(^{-1}\)) for \( U = 5 \text{ m s}^{-1} \) to \( -8 \times 10^{-3} \) (sr\(^{-1}\)) for \( U = 15 \text{ m s}^{-1} \). For measurements taken with near-nadir sun (zenith < 10°), the probability of seeing sun glint remains > 0.1 sr\(^{-1}\) as long as \( U > 5 \text{ m s}^{-1} \).
The mean reflectance angles and the corresponding Fresnel reflectance \( (r) \) at 532 nm for each quad are shown in Fig. 3. No dependence on wind speeds was found for either of the two variables, which is expected because the slope distribution for wave facets has a zero mean \([15]\) regardless of wind speeds. For the sensor setup examined here, the reflectance angles for incoming skylight are limited to \(< 65^\circ\), increasing towards the directions opposite to the sensor and towards the horizon. The corresponding Fresnel reflectance at 532 nm varies between 0.021 to 0.089, relatively invariant for reflectance angles \(< 40^\circ\) and increasing rapidly following the trend observed in Fig. 3(a) for reflectance angles \(> 40^\circ\).

Fig. 3. The reflectance angle (a) and Fresnel reflectance at 532 nm (b) estimated for each quad. The polar axes and symbols are the same as in Fig. 2.

The ratio of \( L_{skycl}\) to \( L_{skycl}' \) simulated using MODTRAN are shown in Fig. 4 for \( \theta_{sun} = 10, 30, \) and \( 50^\circ \) and for wavelength = 400 and 700 nm. The region with relatively low sky radiance is in the directions opposite to the sun (location with lowest sky radiance is indicated by the star symbol), and this relatively dim region expands with decreasing \( \theta_{sun} \). Also, the sky radiance at \( (\theta', \phi') \) (‘+’ in Fig. 4) is generally low, only \(< 20\%\) brighter than the lowest sky radiance. There is a clear spectral variability in the skylight distribution; sky radiance at 400 nm is distributed relatively more uniform at non-solar directions than that at 700 nm, which tends to increase with a stronger gradient towards the sun.

Fig. 4. The normalized sky light distribution, \( L_{skycl}(\theta,\phi) / L_{skycl}(\theta',\phi') \), as a function of \( \theta_{sun} \) (10, 30 and 50\(^\circ\)) and wavelengths (400 and 700 nm). The yellow contour line, if shown, has a value of 16. The polar axes and symbols are the same as in Fig. 2. The ⭐ indicates the direction in the sky with the lowest radiance.

Having examined the spatial variations of \( \rho, r, \) and \( L_{skycl} \) individually, we will now examine their combined effect on \( \rho_s \) under various environmental conditions, particularly by accounting for the spectral variations of Fresnel reflectance and skylight distribution.

3.2 Spectral \( r_{sky} \), \( R_{sky} \) and \( \rho_{sky} \)

As expected, \( r_{sky} \) depends only on winds (Fig. 5(a)). Under calm conditions, \( r_{sky}(\lambda) \) is close to (but always greater than) the Fresnel reflectance by a flat surface reflecting skylight coming...
from \((\theta', \phi')\) (dotted line in Fig. 5(a)). The probability for the sensor to see skylight coming from directions other than \((\theta', \phi')\) that have higher reflectance (Fig. 3) increases significantly with wind speeds (Fig. 2). As a result, \(r_{sk}\) increases by about 8-10% as wind speeds increase from 0 to 15 m s\(^{-1}\) (Fig. 5(a)).

Because \(L_{sk}(\lambda; \theta'; \phi')\) is generally dimmer than sky radiance in other directions and only < 20% brighter than the lowest sky radiance (Fig. 4), the ratio of average sky radiance \(L_{sk}(\lambda; \theta_n, \phi_m)\) to \(L_{sk}(\lambda; \theta', \phi')\), i.e., \(R_{sk}(\lambda)\), are mostly > 1 (Fig. 5(b)). \(R_{sk}(\lambda)\) is nearly spectrally flat under calm conditions with values \(\approx 1\). With low winds, reflected skylight come from a very limited direction around \((\theta', \phi')\) (Fig. 2(a)), where skylight is relatively uniform (Fig. 4). With winds, \(R_{sk}(\lambda)\) typically increases towards longer wave lengths (Fig. 5(b)) because skylight in other directions are normally richer in longer wavelengths than \(L_{sk}(\lambda; \theta', \phi')\) (Fig. 4). Generally, the spectral slope is greater the stronger the wind and closer the sun is to the zenith.

\(\rho_{sk}\) increases with wind speeds (Fig. 5(c)), which affect both \(r_{sk}\) and \(R_{sk}\); \(\rho_{sk}\) increases with decreasing solar zenith angles, which only affect \(R_{sk}\). It can be easily derived from Figs. 5(a) & (b) that \(\rho_{sk}\) is always greater than the flat surface Fresnel reflectance. The spectral shapes of \(\rho_{sk}\) also change with wind speeds, from slightly blueish to relatively neutral to increasingly reddish as wind speeds increase (Fig. 5(c)). For example, the values of \(\rho_{sk}\) for \(\theta_{sun} = 30^\circ\) (dotted lines in Fig. 5(c)) are 0.0274 and 0.0246 at 350 nm and 1000 nm for \(U = 0\) m s\(^{-1}\), 0.0293 and 0.0302 for \(U = 5\) m s\(^{-1}\), and 0.0315 and 0.0377 for \(U = 10\) m s\(^{-1}\).

![Fig. 5. Variations of \(r_{sk}\), \(R_{sk}\) and \(\rho_{sk}\) with wind speeds (\(U = 0, 5, 10\) and 15 m s\(^{-1}\)) and solar zenith angles (\(\theta_{sun} = 0\) and 30\(^\circ\)). Note that the blue solid line (\(U = 0\) m s\(^{-1}\), \(\theta_{sun} = 0^\circ\)) and blue dotted line (\(U = 0\) m s\(^{-1}\), \(\theta_{sun} = 30^\circ\)) overlap each other in (b) and (c). The dotted line in (a) represents Fresnel reflectance for reflectance angle of 40\(^\circ\) and the dashed line in (b) and (c) represents the values computed if the skylight distribution is assumed to be spectral-invariant and simulated using the Harrison and Coombes [19] model \(U = 10\) m s\(^{-1}\) and \(\theta_{sun} = 30^\circ\).](image)

### 3.3 Spectral \(r_{sun}\), \(R_{sun}\) and \(\rho_{sun}\)

The probability of the sensor seeing the sun glint increases rapidly with increasing wind speeds and decreasing solar zenith angles; so does \(r_{sun}\) (Fig. 6(a)). The values of \(r_{sun}\) vary over a wide range with maximums on the order of \(10^{-7}\). As can be expected, direct sun beam is typically 5 – 6 orders of magnitude greater than \(L_{sk}(\theta', \phi')\), and due to Rayleigh scattering, \(R_{sun}\) always exhibit a strong reddish hue (Fig. 6(b)). As a result, \(\rho_{sun}\) always increases towards longer wavelengths. However, unlike \(\rho_{sk}\) which is always greater than the flat surface Fresnel reflectance expected for the given observation geometry, \(\rho_{sun}\) varies widely from negligible to significant as compared to \(\rho_{sk}\) (Fig. 6(c)). Its significance is mainly decided by \(r_{sun}\). Under most conditions (open circles in Fig. 6(d)) \(\rho_{sun}\) is negligible, with values < 1% of \(\rho_{sk}\). For sun
glint to be significant (average $\rho_{\text{sun}}(\lambda)/\rho_{\text{sky}}(\lambda) > 10\%$), $r_{\text{sun}}$ should be greater than $-0.2 \times 10^{-7}$, which corresponds to the conditions where the sun is at the zenith with moderate winds or the sea is much roughened ($U > 10 \text{ m s}^{-1}$) with $\theta_{\text{sun}} < 20^\circ$ (black circles in Fig. 6(d)).

Spectral $\rho_s (\rho_{\text{sky}} + \rho_{\text{sun}})$ is examined in Fig. 7 for various wind speeds and solar zenith angles. We roughly partitioned $\rho_s(\lambda)$ into three groups depending on the significance of sun glint. The first group of $\rho_s(\lambda)$ (Fig. 7(a)) represents the cases when $\rho_{\text{sun}}$ is negligible as compared to $\rho_{\text{sky}}$ and corresponds to the conditions denoted by open circles in Fig. 6(d). In this group, $\rho_s(\lambda)$ are typically $< 0.04$ for $350 < \lambda < 1000 \text{ nm}$ and exhibit negligible spectral variation (the spectral slopes are between $-0.1$ and 0.1). The second group represents the intermediate cases (grey circles in Fig. 6(d)), where $\rho_{\text{sun}}$ account for between 1 and 10% of $\rho_{\text{sky}}(\lambda)$. In this group, $\rho_s(\lambda)$ remain $< 0.05$ but show increasing spectral signature with slopes range between 0.1 and 0.3 (Fig. 7(b)). The third group represents the cases when sun glint amounts to $> 10\%$ of $\rho_{\text{sky}}(\lambda)$, corresponding to the conditions denoted as black circles in Fig. 6(d). In this group, $\rho_s(\lambda)$ (Fig. 7(c)) are generally greater in magnitude and steeper in spectral slope towards longer wavelengths than are the other two groups. The spectral slopes in the 3rd group vary between 0.4 and 0.8. In general, $\rho_s$ increases with increasing wind speeds and decreasing solar zenith angles.
4. Discussion and conclusions

Results shown in Figs. 2–4 explain the logic behind the experiment setup currently recommended for above-water radiometry for ocean color: (i) $\phi_v \approx 45^\circ$ reduces the probability of a sensor seeing sun glint while still avoiding seeing the sun-cast shadow (Fig. 2); (ii) $\theta_v = 40^\circ$ minimizes Fresnel reflectance (Fig. 3); and (iii) skylight coming from $(\theta', \phi') \approx (40^\circ, 225^\circ)$ has relatively low radiance (Fig. 4). A combination of these factors ultimately reduces the sky- and sun-glint though it cannot be completely eliminated and their correction requires the knowledge of $\rho_s$ (Eq. (3)). The variables in Eq. (3) that vary spectrally include incoming sky and direct sun light $L_s(\lambda)$ and Fresnel reflectance $r(\lambda)$. Due to normal dispersion of the refractive index of water, Fresnel reflectance at a given angle increases with decreasing wavelength within the visible and near infrared wavelengths. Although this spectral change small and probably won’t be detected by an above-water radiometer, it is opposite to the spectral change of $\rho_s$ that has been observed to increase towards the longer wavelengths [7,20]. Therefore, the observed spectral variation of $\rho_s$ must arise from $L_s(\lambda)$.

To better understand this causal relationship, we separated direct sun beam $L_{sun}(\lambda; \theta_{sun})$ from the rest of skylight $L_{sky}(\lambda; \theta, \phi)$. Figure 4 shows that the distribution of skylight does vary with wavelengths. To examine the possible effect of ignoring the spectral component of skylight distribution, we followed [5] using the Harrison and Coombes [19] model to compute skylight distribution, which is assumed to be spectrally invariant, for $U = 10$ m s$^{-1}$ and $\theta_{sun} = 30^\circ$. The estimated $R_{sky}(\lambda)$ is a constant (dashed line in Fig. 5(b)) and $\rho_{sky}(\lambda)$ (dashed line in Fig. 5(c)), which has the same spectral shape as $r_{sky}(\lambda)$ but of higher values, differ significantly from the result (yellow solid line in Fig. 5(c)) computed under the same wind speed and solar zenith angle but with a skylight distribution that varies spectrally. This confirms that the observed spectral behavior of $\rho_s$ increasing towards longer wavelengths is largely due to the spectral variation of skylight.

Our simulation has been focused on the recommended above-water radiometry setup, i.e., $(\theta_v, \phi_v) = (40^\circ, 45^\circ)$. The effects on $\rho_s$ of changes in the sensor’s orientation and azimuthal positions were examined for $U = 10$ m s$^{-1}$ and $\theta_{sun} = 30^\circ$ and the results are shown in Fig. 8. For $\theta_v$ changing from $40^\circ$ to $30^\circ$, $\rho_{sky}$ decreases (blue vs. yellow dotted lines in Fig. 8), but $\rho_{sun}$ increases (blue vs. yellow dashed lines). For $\phi_v$ changing from $45^\circ$ to $90^\circ$, $\rho_{sky}$ decreases (blue vs. red dotted lines in Fig. 8), but $\rho_{sun}$ increases (blue vs. red dashed lines). This interesting contrast between $\rho_{sky}$ and $\rho_{sun}$ results in less dramatic but still observable changes in $\rho_s$ because the changes in $\rho_{sun}$ are greater. For example, $\rho_s$ varies by $\sim 20\%$ from 0.031 at 350 nm to 0.038 at 900 nm for $(\theta_v, \phi_v) = (40^\circ, 45^\circ)$ (blue solid line), but varies by $\sim 60\%$ from 0.030 at 350 nm to 0.048 at 900 nm for $(\theta_v, \phi_v) = (30^\circ, 90^\circ)$ (purple solid line). The recommended setup, i.e., $(\theta_v, \phi_v) = (40^\circ, 45^\circ)$ not only lowers the value of $\rho_s$ but reduces its spectral variation as well. For a station near Hawaii with $U = 8$ m s$^{-1}$, $\theta_{sun} = 31^\circ$, $(\theta_v, \phi_v) = (30^\circ, 90^\circ)$, Lee et al. [7] estimated $\rho_s$ by comparing measured reflectance with simulated water-leaving reflectance. They found $\rho_s$ increasing from about 0.03 – 0.04 at 400 nm to 0.08 – 0.25 at 800 nm. The spectral increases of $\rho_s$ they derived are much greater than our simulated results (purple solid line in Fig. 8), probably due to noises in the simulated water-leaving reflectance in the longer wavelengths or due to instantaneous and random variabilities above water (e.g., clouds), in water (e.g., bubble or phytoplankton patches), or on the surface (e.g., foam) that the models could not account for. Regardless, part of their estimated spectral variation of $\rho_s$ is due to stronger sun-glint contamination with smaller $\theta_v$ and larger $\phi_v$ (purple dashed line in Fig. 8) than the recommended observation geometry.
So far, the results are based on maritime aerosol with an optical depth $\tau_a = 0.05$ at 550 nm. Spectral variation of skylight distribution is expected to vary with aerosol loads, and this effect is examined in Fig. 9, showing the changes in $\rho_{sky}(\lambda)$, estimated as a ratio to $\rho_{sky}(\lambda; U = 10 \text{ m s}^{-1}; \tau_a = 0.05)$, for various wind speeds and aerosol optical depths. $\rho_{sky}$ becomes slightly more reddish with increasing aerosol concentrations (red dotted lines in Fig. 9). However, for $\tau_a$ varying between 0 – 0.3, which is greater than typical seasonal variability of aerosols (~0.2) [21], its effects (< 5%) is very limited, particularly in comparison with the effect due to winds (about 5-10% for $\Delta U = 2 \text{ m s}^{-1}$; blue lines in Fig. 9).

Polarization of skylight has been found to exert a considerable impact on $\rho_{sky}$ [12,13]. However, it is still unknown how this impact varies spectrally. As an exploratory investigation, we computed $\rho_{sky}(\lambda)$ using a vector radiative transfer model [22] with a roughened surface based on [15] and a maritime aerosol. Figure 10 shows the comparison of $\rho_{sky}(\lambda)$ estimated with and without polarization for $\tau_a = 0$ and 0.2 and the viewing geometry shown in Fig. 1. Clearly, ignoring polarization would lead to an underestimation of $\rho_{sky}(\lambda)$, consistent with the prior results [12,13]. For a hypothetical molecules-only atmosphere with wind speeds = 10 m s$^{-1}$, Mobley [13; Fig. 19] estimated the ratios of $\rho_{sky}$ with polarization to $\rho_{sky}$ without polarization at 550 nm are highest (~1.3-1.4) when $\theta_{sun} = 30 - 40^\circ$, agreeing in general with our results (yellow solid lines in Fig. 10). The impact of polarization on $\rho_{sky}$ decreases with increasing aerosol loads and wind speeds, because increased scattering by aerosols and roughened surface would further depolarize the skylight. Spectrally, the impact of polarization generally decreases towards longer wavelengths. On average, accounting for polarization would increase $\rho_{sky}(\lambda)$ by about 8-20% at 400 nm to 0-10% at 1000 nm (dashed black lines in Fig. 10), which implies that our results shown in Fig. 5(c) have underestimated
$\rho_{\text{sky}}(\lambda)$ by the similar amounts. Apparently, the spectral effect due to polarization is opposite to the spectral effect due to skylight distribution. Comparison of Figs. 10 and 5(c) indicates that under situations where $\rho_{\text{sky}}(\lambda)$ exhibits strong spectral variation towards longer wavelengths, e.g., the yellow solid line in Fig. 5(c) for $U = 10$ m s$^{-1}$ and $\theta_{\text{sun}} = 0^\circ$, the polarization effect is the weakest, e.g., the yellow lines in Fig. 10(a). On the other hand, the polarization effect is relatively strong (Fig. 10(b) and 10(c)) when $\rho_{\text{sky}}(\lambda)$ exhibits weak spectral variation (see dashed lines in Fig. 5(c)). While results of $\rho_{\text{sky}}(\lambda)$ shown in Fig. 5 are still valid in general, polarization needs to be accounted for conditions with low wind speeds or larger solar zenith angles. Also, the effect of aerosol becomes much more significant through polarization than what is shown in Fig. 9 when polarization is ignored.

![Fig. 10. Ratios of $\rho_{\text{sky}}(\lambda)$ simulated with and without polarization for various solar zenith angles ($\theta_{\text{sun}}$), wind speeds ($U$) and aerosol optical depth ($\tau$). The mean of the ratios is shown as black dotted line in each panel.](image-url)

While clouds’ impact was not simulated in this study, it is not difficult to postulate that with increased scattering by clouds, skylight would become more uniform spatially and spectrally, which in turn would diminish the spectral variation of $R_{\text{sky}}(\lambda)$ and $\rho_{\text{sky}}(\lambda)$. Take an extreme case as an example. If skylight is isotropic over the entire sky dome, which applies more or less for overcast conditions, then $R_{\text{sky}}=1$ and $\rho_{\text{sky}}(\lambda)$ is effectively the same as $r_{\text{sky}}(\lambda)$ (Fig. 5(a)), which would probably appear spectrally flat for field observations. This is consistent with the results of Cui et al. [20] who estimated $\rho_{\text{sky}}$ almost spectrally flat between 400 and 800 nm for overcast or mostly cloudy atmosphere conditions.

Sun glint could make significant contributions to the surface-reflected light in windy and high-sun conditions that are often encountered in field experiments (Fig. 6(d)) because the probability of a sensor seeing sun glint increases considerably under these conditions (Fig. 2). Sun glint affects skylight correction by increasing the overall value of $\rho_s$ and further shifting its spectra favoring longer wavelengths (Fig. 6(c)). Since direct sun light is unpolarized, we recommend taking a two-step approach by first removing sun glint using Fig. 6(c) followed by skylight glint correction using Fig. 5(c) and Fig. 10.

In this study, the glint probability is computed directly from the distribution of capillary wave slopes and in the study by Mobley [5], it is estimated by the Monte Carlo method. For either method, one underlying assumption is that the entire hemispheric sky dome is sampled (e.g., see Eq. (10)). For field measurements, this means that the integration time of the sensor is long enough, the FOV is large enough, or both such that the capillary wave facets inside the FOV would cover enough variability during the integration time that light reflected from every direction in the sky (including the sun) are sampled. For sensors with short integration time ($10^{-3} - 10^{-2}$ s) or small FOV (< 100 cm$^2$), skylight is under-sampled (lower $\rho_{\text{sky}}$) and sun glint, if by any chances is recorded, may appear as spikes. In this case, measurements with outlier $L_t$ values may need to be filtered out [1,2]. For measurements with presumably fully sampled sky dome, $\rho_{\sun}$ is typically less than $\rho_{\text{sky}}$ (Figs. 5(c) and 6(c)), meaning sun-glint contaminated measurements do not necessarily appear as outliers and need to be removed separately as we outlined here.
A recently suggested sky-blocking method allows $L_w$ to be measured directly from above the sea surface by blocking surface-reflected light with a screen that extends into the water [23,24]. This would eliminate the need for sky- and sun-glint correction, but requires self-shading correction and sensors to be placed very close to the surface. Also, a majority of above-water measurements are taken from a fixed platform, for which reflected skylight and/or direct sun light is an unavoidable part and needs to be corrected.

**Funding**

National Aeronautics and Space Administration (NASA) (NNX13AN72G and NNX15AC85G); National Science Foundation (1355466 and 1458962). National Natural Science Foundation of China (41471284 and 41431176)

**Acknowledgment**

The manuscript has been greatly improved by addressing the thoughtful and constructive comments and suggestions made by two anonymous reviewers, whom we would like to thank for their time and efforts.