Improving the description of sunglint for accurate prediction of remotely sensed radiances

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Abstract

The bidirectional reflection distribution function (BRDF) of the ocean is a critical boundary condition for radiative transfer calculations in the coupled atmosphere–ocean system. Existing models express the extent of the glint-contaminated region and its contribution to the radiance essentially as a function of the wind speed. An accurate treatment of the glint contribution and its propagation in the atmosphere would improve current correction schemes and hence rescue a significant portion of data presently discarded as “glint contaminated”. In current satellite imagery, a correction to the sensor-measured radiances is limited to the region at the edge of the glint, where the contribution is below a certain threshold. This correction assumes the sunglint radiance to be directly transmitted through the atmosphere. To quantify the error introduced by this approximation we employ a radiative transfer code that allows for a user-specified BRDF at the atmosphere–ocean interface and rigorously accounts for multiple scattering. We show that the errors incurred by ignoring multiple scattering are very significant and typically lie in the range 10–90%. Multiple reflections and shadowing at the surface can also be accounted for, and we illustrate the importance of such processes at grazing geometries.

1. Introduction

Sunglint is a persistent feature in satellite imagery. If the ocean surface were flat, a perfect image of the Sun’s disk would be observed in the specular direction. The effect of surface roughness is to spread the specular reflection over a wider range of angles; the glint region, as observed from typical satellite altitudes, often extends to several hundred kilometers, with associated reflectance values greater than 0.2 [1].

Programs such as the NASA’s Earth Observing System (EOS) aim at inferring accurate information about the atmosphere and the surface on a global scale. Exploitation of signals observed by sensors looking within regions affected by the high sunglint reflectance requires a stable response over a wide dynamical range. Since this requirement is seldom fulfilled, this problem is currently dealt with by tilting the sensor away or shutting it off completely. This strategy results in the periodic...
black swaths observed in composite images of the globe mapping ocean products. To analyze ocean color data obtained by instruments such as the Sea-viewing Wide Field of view Sensor (SeaWiFS, on-board SeaStar) or the MODerate-resolution Imaging Spectroradiometer (MODIS, deployed on both the Terra and Aqua spacecrafts), NASA has developed a comprehensive data analysis software package (SeaWiFS Data Analysis System, SeaDAS), which performs a number of tasks including cloud screening and calibration, required to convert the raw satellite signals into calibrated top-of-the-atmosphere (TOA) radiances. In addition, the SeaDAS software package has tools for quantifying and removing the atmospheric contribution to the radiance ("atmospheric correction") as well as the contribution due to the whitecaps and sunglint in the ocean [2].

The strong sunglint signal could conceivably be used for remote sensing of gaseous constituents [3,4], and to improve the retrieval of aerosol properties [5] in methods developed for simultaneous retrieval of atmospheric and marine parameters from TOA radiances [6]. In an image affected by sunglint, we can identify an area (usually along the rim of the glint patch) where the sunglint contribution to the radiance at the TOA is comparable to the water-leaving radiance. This area divides the portions of the image where sunglint radiance is too small to affect the retrieval from the central region of the glint where the contribution is too large to attempt an atmospheric correction.

In the SeaDAS correction scheme, a sunglint flag is triggered for a given pixel geometry when the predicted sunglint radiance is higher than a certain value (0.0001 in normalized units, i.e., for a solar irradiance \( F_0 = 1 \)) and lower than the threshold used for cloud screening (0.01). Pixels that fall into this category are then subjected to a glint-correction, which begins with a calculation of the TOA radiance based on the assumption that light is directly transmitted in both directions through the atmosphere. This directly transmitted radiance (DTR) is then subtracted from the measured radiance to arrive at the DTR-corrected TOA radiance [7].

The goal of this investigation is to demonstrate the need of a better description of sunglint radiances. For a wind-roughened ocean–atmosphere surface with a given parametrization of the wave-facet mean slope-square in terms of the wind speed, it is desirable to establish an efficient computation procedure to provide glint radiance values without the assumptions invoked by the DTR approach. Since the radiative transfer (RT) code employed in this study more accurately describes the physics of the problem, its inclusion in the atmospheric correction procedure enables more reliable calculation of the glint radiance for an extended portion of the glint-contaminated region, resulting in fewer pixels being rejected during retrievals.

It has been demonstrated that the errors due to the scalar approximation in atmospheric RT can be quite significant, especially in the case of Rayleigh scattering [8,9]. Instruments capable of measuring polarization are being included in the satellite payloads of oncoming missions such as Glory [10], with the explicit goal to look for aerosol signatures also in the glint region [11,12]. Even though the errors due to the scalar approximation are much smaller than those quantified in this study, further improvements in the glint description should take into account polarization effects.

In Section 2 we define sunglint and the rough-surface bidirectional reflection distribution function (BRDF) in relation to the boundary condition for RT in the atmosphere. We also summarize the straightforward DTR approach used in SeaDAS, and then describe a more accurate approach that accounts for multiply scattered radiances (MSR). In Section 3 we derive the inherent optical properties (IOPs) of the atmosphere which are input in a RT code. We then quantify the error incurred by the DTR approach invoked in SeaDAS, to demonstrate the need for an improvement (Section 4). Finally, in Section 5 we present some preliminary results on the effects of multiple surface reflections and shadowing. An accurate yet computationally efficient determination of the glint TOA radiance as a function of viewing geometry, surface roughness and atmospheric state can be accomplished with the use of look-up tables, serving as an interpolating grid to provide reliable radiance values whenever the sunglint flag is active in the correction scheme.

2. RT in the presence of a wind-roughened ocean surface

2.1. Basic equations

We define sunglint as the radiation field due to a direct beam reflected from the (ocean) surface. To quantify this contribution, we must solve the radiation transfer equation [13]:

\[
\frac{dL(\tau, \mu, \phi)}{d\tau} = L(\tau, \mu, \phi) - F_s \frac{\pi}{4} p(\tau, -\mu_0, \phi_0; \mu, \phi) e^{-\tau/\mu_0} - \frac{1}{4\pi} \int_0^{2\pi} d\phi' \int_0^\infty d\mu' p(\tau, \mu', \phi'; \mu, \phi) L(\tau, \mu', \phi')
\]

subject to the appropriate boundary condition at the air–water interface:

\[
L(\tau = \tau_s, \mu, \phi) = \frac{\mu F_s}{\pi} e^{-\tau_s/\mu_0} r_{\text{glint}}(-\mu_0, \phi_0; \mu, \phi) + \frac{1}{\pi} \int_0^{2\pi} d\phi' \int_0^\infty d\mu' r_{\text{glint}}(-\mu', \phi'; \mu, \phi) L(\tau_s, -\mu', \phi').
\]

Here \( \mu_0 = \cos \theta_0 \) and \( \mu = \cos \theta \) are the cosine of the solar (SZA) and sensor viewing zenith angles (SVA), respectively, and \( \phi \) and \( \phi_0 \) the corresponding azimuthal angles. In Eq. (1), the second term on the right-hand side is the single scattering term, whereas the third term is the multiple scattering term. In Eq. (2), the first term on the right-hand side is due to direct sunglint radiation, whereas the second accounts for the reflection of the diffuse downward component. The \( r \) is the ratio of the reflected radiance in the direction \( (\mu, \phi) \), around the solid angle \( d\omega_0 \), to the incident
irradiance from direction \((\mu_0, \phi_0)\):

\[
\rho = \frac{dL(\mu, \phi)}{L_0(\mu_0, \phi_0)d\Omega_0}.
\]

Ignoring shadowing and multiple reflections, the sunglint reflectance can be shown to be [14, 15]

\[
\rho_{\text{glint}}(\mu_0, \mu, \Delta \phi) = \frac{\pi P(z', y')\mu_F(n_w, \mu_0, \mu, \Delta \phi)}{4\mu_0\mu_0 \cos^4 \beta},
\]

where \(\mu_F(n_w, \mu_0, \mu, \Delta \phi)\) is the Fresnel reflection coefficient, \(n_w\) the index of refraction of water and \(\beta\) is the tilt angle between the vertical and the normal to the surface element. A widely accepted empirical expression for the wave-slope probability distribution was provided by Cox and Munk [14, 16, 17]:

\[
P(z', y') = \frac{1}{2\sigma_z \sigma_y} \exp \left[ -\frac{1}{2} \left( \frac{z^2}{\sigma_z^2} + \frac{y^2}{\sigma_y^2} \right) \right] \left[ 1 - \frac{C_{21}}{2} \left( z^2 - 1 \right) y - \frac{C_{03}}{6} \left( \eta^2 - 3 \right) y + \frac{C_{40}}{24} \left( \eta^4 - 6 \eta^2 + 3 \right) \eta \right].
\]

Here \(\eta = z' / \sigma_z\) and \(\eta = z' / \sigma_y\), where \(\sigma_z\) and \(\sigma_y\) are the crosswind and upwind root mean squares components to the total variance of the slope distribution, \(z_r\) and \(z_y\) are the components of slope; a prime indicates that the axes are oriented along the crosswind and upwind directions. The coefficients of the distribution as provided by Cox–Munk are \(C_{21} = 0.01 - 0.0086 U\), \(C_{03} = 0.04 - 0.03 U\), \(C_{40} = 0.40\), \(C_{22} = 0.12\) and \(C_{44} = 0.23\). These coefficients show that the distribution is roughly Gaussian with a variance increasing linearly with the wind speed \(U\).

2.2. The directly transmitted (DTR) approach

The sunglint radiation is expressed as a function of the following variables:

\[ L_{\text{TOA}}^{\text{glint}} = L_{\text{TOA}}^{\text{glint}}(\mu_0, \mu, \Delta \phi, \text{AM}, \tau_{\text{TOT}}, U, \lambda). \]

The angles \(\mu_0, \mu\) and \(\Delta \phi\) define the Sun–satellite geometry, \(U\) is the wind speed and \(\lambda\) the wavelength. The atmosphere is parametrized through choice of an aerosol model (AM) and the total optical depth \(\tau_{\text{TOT}}\).

The SeaDAS algorithm activates the sunglint flag for a given pixel when the reflection coefficient, as calculated from the Cox–Munk distribution (5), exceeds a certain threshold. The TOA radiance is then computed assuming that the direct beam and its reflected portion only experience exponential attenuation through the atmosphere [7]. Thus, in SeaDAS the direct TOA Sunglint radiance is

\[
L_{\text{TOA}}^{\text{glint}}(\mu_0, \mu, \Delta \phi) = F(\lambda)T_{0}(\lambda)T(\lambda)L_{\text{GN}}.
\]

\[ T_{0}(\lambda)T(\lambda) = \exp \left\{ -[\tau_{\text{TM}}(\lambda) + \tau_{\text{A}}(\lambda)] \left[ \frac{1}{\mu_0} + \frac{1}{\mu} \right] \right\}. \]

The normalized sunglint radiance \(L_{\text{GN}}\) would be the value of sunglint radiance if there were no atmosphere, and the solar irradiance were \(F_{0}(\lambda) = 1\). \(\tau_{\text{TM}}\) and \(\tau_{\text{A}}\) (\(\tau_{\text{TM}} + \tau_{\text{A}} = \tau_{\text{TOT}}\)) are the Rayleigh (air molecules) and aerosol optical thicknesses.

It is clear that multiple scattering processes are not taken into account: every photon removed from the direct path (absorbed or scattered) has no further chance to reach the detector. In other words, a scattered photon is treated as an absorbed photon.

2.3. The MSR approach

The DTR approach only accounts for the direct beam (Beam 2 in Fig. 1). In contrast, the MSR approach computes the TOA radiance by solving the radiative equation (1) subject to the appropriate boundary condition (2), therefore allowing multiple scattering processes to be included in the computation. For consistency with the definition of sunglint, radiation reflected from the surface after being scattered (Beam 1) is removed by setting the downward diffuse term in Eq. (2) to zero.

The complete solution of Eqs. (1) and (2) gives the total TOA radiance, \(L_{\text{TOA}}^{\text{tot}}(\mu_0, \mu, \Delta \phi)\). \(L_{\text{TOA}}^{\text{tot}}\) also consists of photons scattered in the instrumental field of view without having hit the surface (Beam 4). We denote this contribution \(L_{\text{TOA}}^{\text{bs}}(\mu_0, \mu, \Delta \phi)\), since it can be calculated considering a black (i.e., totally absorbing) surface (\(\rho_{\text{glint}} = 0\) in Eq. (2)). To isolate the glint contribution we must subtract this “black-surface” component from the complete radiation field:

\[
L_{\text{TOA}}^{\text{glint}}(\mu_0, \mu, \Delta \phi) = L_{\text{TOA}}^{\text{tot}}(\mu_0, \mu, \Delta \phi) - L_{\text{TOA}}^{\text{bs}}(\mu_0, \mu, \Delta \phi).
\]

This expression properly includes multiply scattered reflected radiation, but ignores sky radiation undergoing reflection (Beam 3). Thus, it guarantees that the difference between the DTR and MSR approach is solely due to that component of the TOA radiance reaching the detector after being scattered along the path from the surface to the detector (Beam 3). We may now quantify the error introduced by the DTR assumption. In doing this, we neglect the effect of whitecaps as well as the
wavelength dependence of the index of refraction. Moreover, only the Gaussian part of the Cox–Munk wave-slope distribution is retained.

We use the LIDORT RT model [18] for our scattering calculations. This is a fully coupled ocean–atmosphere discrete ordinate code with a facility for simultaneous generation of radiances and analytic weighting functions. For radiances, LIDORT has a similar scope to the plane parallel DISORT code [19,20]. The model has a full BRDF treatment for a variety of land surfaces [18]. The ocean-glitter BRDF model for a randomly rough surface is based on the Cox–Munk slope distribution, and there are additional enhancements for the shadowing effect and for multiple reflections by surface facets (these effects are considered in Section 5). Besides accounting for surface reflectance and multiple scattering processes as in other codes [21,22], LIDORT is capable of exact treatments of direct-beam surface reflections and atmospheric single scattering. As in DISORT, the LIDORT code requires as input total IOPs, the construction of which is considered in the next section.

It has been shown that curved-atmosphere solar beam attenuation plus plane-parallel single and multiple scattering gives accurate radiance results (up to 1%) for solar angles up to 89° provided the SVA is less than 30° [23,24]. For SVAs greater than 30° and up to 70°, it is necessary to treat also the line-of-sight path attenuation in a curved atmosphere in order to generate a more precise single scattering contribution [24–27]. The advantages of LIDORT include a pseudospherical approximation for the treatment of the solar and outgoing beam attenuation in a curved atmosphere.

3. Optical property setup in the atmosphere

We consider a standard molecular atmosphere (mid-latitude summer) up to a height of 100 km with a uniform aerosol distribution below 2 km, as depicted in Fig. 2. Thus, below 2 km we add the molecular (τM) and aerosol (τA) optical thicknesses, each composed of the scattering (superscript s) and an absorption (superscript a) part:

\[ τ_{\text{TOT}} = τ_M + τ_A = (τ_M^s + τ_M^a) + (τ_A^s + τ_A^a). \]  (9)

The phase function is expanded in Legendre polynomials \( P_l(\cos θ) \):

\[ p(τ, \cos θ) = \sum_{l=0}^{2M-1} (2l+1)P_l(τ)P_l(\cos θ). \]  (10)

The optical properties of each aerosol component, including the Legendre expansion coefficients of the phase function, are computed by a Mie-code [28]. The optical properties of a multi-component mixture are then obtained as the concentration-weighted average of the optical properties of each aerosol component [29].
The $l$-th expansion coefficient $\chi^l$ is calculated, at each layer $m$, by combining the molecular and aerosol moments with weights $b_m$, given by the ratios of the molecular scattering optical depth to the total scattering optical depth:

$$ b_m = \frac{\tau_{m,m}^\lambda}{\tau_{A,m}^\lambda + \tau_{M,m}^\lambda}. \quad (11) $$

Here we recall that the Rayleigh phase function has zero moments except from $\chi^0_R = 1$ and $\chi^2_R = 0.1$. Thus, the phase function moments are specified as follows:

$$ \chi^0_m = 1, \quad (12) $$
$$ \chi^1_m = (1 - b_m)\chi^1_A, \quad (13) $$
$$ \chi^2_m = 0.1b_m + (1 - b_m)\chi^2_A, \quad (14) $$
$$ \chi^l_m = (1 - b_m)\chi^l_A, \quad l > 2. \quad (15) $$

Over the ocean, the aerosol size distribution is typically bimodal, consisting of a large and a small mode. In this paper we consider AMs generated [30] as a combination of two limiting cases: (1) small particles typical of tropospheric conditions, at 50% of relative humidity ($T50$); (2) large particles typical of ocean areas with a high humidity content ($O99$). The optical properties of the bimodal mixture are parametrized in terms of the mixing ratio $f$ (number-density fraction of large-mode particles) and the total number density $N$ as follows:

$$ N = N_{T50} + N_{O99}; \quad N_{O99} = fN; \quad N_{T50} = (1 - f)N, \quad (16) $$

$$ k_{\text{MIX}} = (1 - f)k_{T50} + fk_{O99}. \quad (17) $$
Here $k(\lambda)$ is the extinction coefficient, $\omega(\lambda)$ the single scattering albedo, $\sigma(\lambda) = \omega(\lambda)k(\lambda)$ the scattering coefficient and $\chi(\lambda)$ the Legendre moment (expansion coefficient for the phase function). Large particles have a heavier weight in determining the optical properties. A typical maritime scenario comprises a mixture of 1% of large particles and 99% of small particles [31]. The extinction coefficient curves for each AM depend on the particle number density. The aerosol load in the atmosphere model is set by specifying the desired total aerosol optical depth at 865 nm ($\tau_{865}$). This defines the coefficient $s_t$ used to rescale the optical depth of the aerosol mixture at 865 nm, $\tau_{865}^{\text{MIX}}$, as well as at all the other channels:

$$s_t = \frac{\tau_{865}^{\text{MIX}}}{H},$$

(20)

$$\tau_{\text{Am}} = s_t \tau_{865}^{\text{MIX}} h_m.$$  

(21)

Here $H$ is the total depth of the portion of the atmosphere loaded with aerosols and $h_m$ is the depth of the $m$-th layer.

4. Quantifying the error in the DTR approach

To evaluate the potential for improving retrievals in glint areas, we examined the approach of Wang and Bailey [7], who added a simple procedure to the SeaDAS algorithm to raise the threshold above which the sunglint flag is triggered. Their method is based on the DTR assumption, and therefore ignores multiple scattering in the path between the surface and the detector (and from the TOA to the surface as well).

4.1. Rayleigh-scattering atmosphere

Fig. 3 presents an example of DTR and MSR and relative errors in the sunglint TOA radiances for a purely Rayleigh scattering atmosphere, induced by ignoring multiple scattering along the path between the surface and the detector. The incident solar flux is set to 1 so that the radianse shown here, and in all subsequent figures, is the Sun-normalized sunglint (SNS) TOA radiance. In computing the reflection of the direct beam the wavelength dependence of the refractive index of water was ignored ($n = 1.333$ throughout). The surface is also considered to be non-absorbing. The left panel in the figure
shows the radiance components in the principal plane for an SZA of 40° and a wind speed of 5 m s⁻¹. We show results for SeaWiFS channels 1 and 8, at the extremes of the instrument spectral range: 412 nm (thick curves) and 865 nm (thin curves), respectively. For each channel, the dash-dotted line represents L_{\text{TOA}}^{\text{tot}}$, whereas the dotted line pertains to the black surface calculation. Both curves show the expected brightening toward the horizon resulting from scattering processes [32].

The dashed line is the difference L_{\text{TOA}}^{\text{tot}} - L_{\text{TOA}}^{\text{bs}}$, which is to be compared with the solid curve representing the DTR result.

At 865 nm, the DTR and MSR curves are almost overlapping, except at very high (> 80°) SVAs. As expected, the error incurred in the DTR approximation is larger at shorter wavelengths due to the dependence of the molecular scattering on the inverse fourth power of the wavelength, which also lowers the peak radiance. At 412 nm the DTR and MSR curves are clearly distinguishable. It is important to note that Fig. 3 represents a best-case scenario for the DTR approximation, because Rayleigh scattering is comparatively isotropic. Larger discrepancies are expected in presence of aerosols, because of asymmetries resulting from preferential scattering in the forward direction.

In the following we consider the representative channel at 490 nm, important for the retrieval of aerosol properties. The right panel in Fig. 3 depicts the DTR and MSR curves (solid and dashed lines as before) at 490 nm and the relative error |(L_{\text{DTR}} - L_{\text{MSR}})/L_{\text{MSR}}| (dotted line), whose values are to be read on the right vertical axis.

Wang and Bailey [7] base their approach on the assumption that the strength of the sunglint signal is such that the radiance effectively penetrates and propagates through the atmosphere mainly along the direct beam direction. While this assumption might be adequate very close to the specular direction, it severely fails at the rim of the sunglint patch, exactly where the correction is applied. These retrieval regions (0.0001 ≤ L_{\text{TOA}}^{\text{tot}} ≤ 0.01 in normalized radiance units) are highlighted in the figure by vertical dashed thick lines, and the error curve within these boundaries has also been thickened. It is striking how, already in this optically very thin atmospheric scenario, errors start at about 5% and grow quickly to 40% at low SVAs and to 95% at large SVAs.

4.2. Examples with aerosols at 490 nm

To illustrate the impact of aerosol scattering, we examine the results for the 490 nm channel for two typical SZAs and for different wind speeds, choosing limiting cases for the aerosol load and composition. Figs. 4 and 5, for SZAs of 15° and 40°, respectively, are both composed of four panels corresponding to different aerosol loads, set through the parameter $c_{\text{a}}^{865}$ (see Eq. (21)). The upper panels refer to small aerosol particles (T50) with $c_{\text{a}}^{865} = 0.03$ (left) and $c_{\text{a}}^{865} = 0.3$ (right). The panels in the bottom rows pertain to large aerosol particles (O99). The DTR curves are shown for three different wind speeds (1, 5 and 10 m s⁻¹). For clarity, only the MSR curve at 5 m s⁻¹ is displayed as a reference.

In both Figs. 4 and 5 the two left panels are similar, largely because the aerosol type does not influence the results significantly when only a small amount of aerosol is present. Error ranges are similar to those already found in the Rayleigh scattering case, growing quickly from 6–8%, in proximity of the cloud screening threshold, L_{\text{TOA}}^{\text{tot}}, to ~85–90%. The TOA radiance curves vary greatly when the atmosphere is heavily loaded with aerosols (right panels). Nonetheless, the errors span similar ranges even though the lower limit, ~20%, is significantly higher than that noted in Fig. 3.

Moving to a SZA of 40° (Fig. 5), we again find similar error ranges but the lower solar elevation gives rise to two intervals in the forward scattering half-hemisphere (0° ≤ SVA ≤ 90°) where the correction is applied. The error curves are not symmetric and in the interval closer to zenith (with respect to the radiance peak) they start from smaller values, 6–8% with a small amount of aerosol and 17–23% with a large loading (but also 29% for T50, $c_{\text{a}}^{865} = 0.3$ at 10 m s⁻¹). Closer to the horizon, these values are much higher (10–38%), as a consequence of the longer optical path. In any case, the errors rise to over 90% close to the lower threshold (L_{\text{TOA}}^{\text{tot}} ≥ 0.0001). In Fig. 6 we examine the azimuthal dependence of the error in the TOA radiance. To this end we consider a typical maritime scenario with a mixture of T50 and O99 in a 0.98:0.02 ratio, with a loading $c_{\text{a}}^{865} = 0.1$. Fig. 6 shows the sunglint TOA peaks computed along the principal plane (left panel), 40° (center) and 90° of viewing azimuth (right). As found already, the errors depend weakly on the wind speed, and grow from 9% to 93%. Note, however, that at low wind speeds the narrow radiance peak quickly decays as we move away from the specular direction of reflection. It is also noteworthy that the weak dependence of the DTR errors on the wind speed is an expected result, since the errors themselves arise from processes in the atmosphere rather than being connected to the surface condition. In other words, the wind speed only affects the angular position and extent of the sunglint patch (and of the retrieval region), whereas the errors depend on the particular values of radiance chosen as thresholds.

These figures demonstrate that inclusion of multiple scattering allows for more accurate simulations of the sunglint radiance than the simplistic DTR approximation currently employed in SeaDAS.

5. Shadowing and multiple reflections

In this section, we look at the influence of shadowing [33] and multiple surface-facet reflections. Shadowing occurs as a consequence of surface elevation, when a slope intercepting the optical path prevents the beam from reaching the point of incidence chosen as the origin of the reference system (see Fig. 7). In the ocean-glitter BRDF treatment in LIDORT, shadowing is implemented according to the widely used correction due to Sancer [34] (see also [35]), where the basic glint
reflectance $\rho_{\text{glint}}$ in Eq. (4) is multiplied by the factor:

$$S(\Omega_0, \Omega, \alpha^2) = \frac{1}{1 + A(\cot \theta_0) + A(\cot \theta)}$$

(22)

with $\Omega_0 = (\mu_0, \phi_0)$, $\Omega = (\mu, \phi)$ and

$$A(x) = \frac{1}{2} \left[ \sqrt{\frac{2}{\pi}} \frac{\sigma}{x} \exp \left( -\frac{x^2}{2\sigma^2} \right) - \text{erfc} \left( \frac{x}{\sqrt{2}\sigma} \right) \right].$$

(23)

Multiple reflections occur instead in presence of steep slopes, when the incident beam is redirected toward another portion of wave for further reflection before leaving the surface. The treatment here follows that in Jin et al. [36]. The complete contribution to the glint is

$$R_{\text{tot}}(\Omega_0, \Omega) = \sum_{j=0}^{\infty} R_j(\Omega_0, \Omega),$$

(24)

where

$$R_j(\Omega_0, \Omega) = \int_{\Omega'} R_{j-1}(\Omega_0, \Omega') R_0(\Omega', \Omega) \, d\Omega'$$

(25)

and $R_0(\Omega_0; \Omega)$ is the basic, single-facet glint reflectance in Eq. (4). In general, only the first order of facet scattering (after the initial reflection) is significant. The hemispherical integrals are done by double Gaussian quadrature over the azimuth direction and the polar half-space.
In Fig. 8 we consider SZAs of 60° and 70°, to show the increasing importance of shadowing and multiple reflections at high solar angles. These results are of relevance for the glint measurement mode of the Orbiting Carbon Observatory (OCO) instrument [37], scheduled for launch in late 2008. OCO will join NASA’s A-train and will take across-track glint measurements for SZA values up to 75°.

Since multiple reflections and shadowing are exclusively linked to the surface geometrical realization, we simply consider a Rayleigh scattering atmosphere. The plots in the figure are arranged in columns relative to the same wind speeds (1, 5 and 10 m s⁻¹). In each plot the dashed thick curve represents the sunglint TOA radiance computed within the MSR approach, when corrections neither for multiple reflections nor for shadowing are applied. The remaining curves show the results when either one or both the flags are switched on, the latter case being displayed with a thick solid line.

First we note that surface roughening always produces a shift of the radiance peak toward the horizon. This phenomenon has been observed experimentally [38] and explained theoretically as an accumulation of contributing mirroring facets toward the horizon [39].

Differences between the uncorrected and corrected radiances already become discernible at 60°, due to multiple reflections at low wind speeds but also to shadowing at higher wind speeds.

Shadowing of facets diminishes the radiance, whereas multiple reflections can redirect into the field of view rays that would otherwise be lost, therefore enhancing the signal. Note that the effects are not additive, since shadowing has a non-linear dependence on the wind speed.

6. Conclusions

We have shown the possibility of improving the description of sunglint through the use of an accurate radiative transfer treatment accounting for multiple scattering, a process normally ignored in current atmospheric correction schemes. The errors incurred by ignoring multiple scattering in the path from the surface to the sensor are high, typically ranging from 10% to 90% at 490 nm. These error ranges are determined by the radiance threshold values that mark the retrieval
region boundaries; the errors are smaller closer to the specular reflection peak (higher threshold). Surface roughness only affects the angular location and extent of the retrieval region where these errors occur. The minimum errors grow significantly in an atmosphere with a heavy aerosol loading, and asymmetries are found close to the horizon, especially in the presence of large (coarse-mode) particles.

We also computed the azimuthal dependence of the errors in a typical maritime situation. Since in general errors grow as the radiance decreases (away from the specular direction), the high directionality of the radiance peak at low wind speeds causes larger minimum errors away from the principal plane.

Finally, we presented some preliminary results on the importance of multiple reflections and shadowing. Corrections for these effects, dependent on the surface morphology, are needed at high Sun–satellite angles.

Whenever the sunglint flag is activated, retrieval of aerosol and surface parameters from satellite imagery can benefit from more accurate calculations which account for multiple scattering in the atmosphere, multiple surface reflections and shadowing effect. For an efficient determination of TOA radiances, look-up tables could be compiled as a function of viewing geometry, wind speed, aerosol model and aerosol optical depth.

Fig. 6. Azimuthal dependence of the Sun-normalized sunglint TOA radiance and relative error bands for an atmosphere containing an aerosol mixture \( T_{50}:O_{99}=0.98:0.02 \) and \( \tau_{865}=0.1 \). The three panels are relative to the principal plane (left), 40° (center) and 90° of azimuth (right). Note the different range of ordinates in the rightmost panels. An explanation of the legend is provided in Figs. 4 and 5.

Fig. 7. Sketch illustrating the geometrical effects of shadowing and multiple reflections. Ray \( R \) experiences simple surface reflection, whereas rays \( SH \) and \( MR \) suffer shadowing and multiple reflections, respectively.

Fig. 8. Effect of multiple reflections and shadowing on the Sun-normalized sunglint TOA radiance in a Rayleigh scattering atmosphere, computed along the principal plane of reflection for SZAs of 60° (upper row) and 70° (bottom row). From left to right, the plots pertain to wind speeds of 1, 5 and 10 m s⁻¹.

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References
