Spectral reflectance of sea foam in the visible and near-infrared: In situ measurements and remote sensing implications

Robert Frouin
Scripps Institution of Oceanography, University of California San Diego, La Jolla

Myriam Schwindling and Pierre-Yves Deschamps
Laboratoire d’Optique Atmosphérique, Université des Sciences et Technologies de Lille I
Villeneuve d’Ascq, France

Abstract. The spectral reflectance of sea foam was measured at the Scripps Institution of Oceanography Pier, La Jolla, California, by viewing the sea surface radiometrically in a region of breaking waves. Foam reflectance was found to decrease substantially with wavelength in the near-infrared, contrary to the findings of previous studies, theoretical as well as experimental. Values in the visible (0.44 μm) were reduced by typically 40% at 0.85 μm, 50% at 1.02 μm, and 85% at 1.65 μm. The spectral effect was explained by the nature of the foam, which is composed of large bubbles of air separated by a thin layer of water (foam stricto sensu) and of bubbles of air injected in the underlayer. The presence of bubbles in the underlayer enhances water absorption and thus reduces reflectance in the near-infrared. For ocean color remote sensing, affected by the presence of foam and aerosols, the consequences of neglecting the spectral dependence of foam are dramatic. With only a small amount of foam, in the presence of aerosols or not and thus irrespective of aerosol type, the errors in the retrieved water reflectance at 0.44 μm are above 0.01, which does not meet the accuracy goal of 0.001 for biological applications. Since under normal conditions the effect of foam may have the same magnitude as the effect of aerosols, atmospheric corrections will be inaccurate (and useless) in many cases, even taking into account the spectral dependence of the foam reflectance. Space observations potentially contaminated by an effective foam reflectance (product of reflectance and fractional coverage) above 0.001, i.e., corresponding to wind speeds above 8 m s⁻¹, should be eliminated systematically. Utilization of near-infrared wavelengths above 0.9 μm for atmospheric corrections of ocean color, possible with the moderate-resolution imaging spectrometer (MODIS), would aggravate the problem. The measurements also indicated that foam significantly affects the retrieval of aerosol turbidity at 0.85 and 1.02 μm for wind speeds above 10 m s⁻¹ but impacts minimally turbidity estimates at 1.65 μm. Over the oceans the spectral range above 1 μm is definitely recommended for remote sensing of tropospheric aerosol load and type from space.

1. Introduction

The influence of foam, whitecaps, and streaks on the optical properties of the ocean has been recognized for many years [Maul and Gordon, 1975; Gordon and Jacobs, 1977] and has potentially large effects on the solar energy, radiance or irradiance, reflected by the ocean-atmosphere system. The calculations of Gordon and Jacobs [1977] have shown that at small Sun zenith angles the planetary albedo of a clear ocean may double in the presence of an amount of foam of 4%, assuming that the foam is totally reflective. At large Sun zenith angles the foam produced less dramatic changes in the top-of-atmosphere albedo because of increased atmospheric contribution. Such an amount of foam (i.e., 4%) would exist for wind speeds of 14 m s⁻¹ or so [e.g., Koepke, 1984]. Sea foam reflectance actually is smaller than 1 [Austin and Moran, 1974] and might depend on water composition and foam thickness [Whitlock et al., 1982], but the effect on the planetary albedo remains significant for typical wind speeds.

The presence of foam at the ocean surface is important, not only for radiation budget studies (less solar energy absorbed by the ocean, more solar energy reflected back to space), but also for aerosol and ocean color remote sensing from space [Tas- san, 1981; Koepke and Quenzel, 1981; Whitlock et al., 1982; Gordon and Wang, 1994a]. Koepke and Quenzel [1981] studied the effect of 0–1% foam coverage (wind speeds of 1.4–7 m s⁻¹) on the upwelled radiance at the top of the atmosphere. They concluded that the optimum wavelengths for monitoring aerosol turbidity over the oceans were located below 1.05 μm. In their simulations they assumed that the foam reflectance was constant with wavelength, which may not be true, especially above 0.9 μm, as shown by Whitlock et al. [1982] from laboratory measurements. Whitlock et al. [1982] suggested that wave-
lengths above 1.2 $\mu m$ were preferable. Regarding ocean color, Gordon and Wang [1994a] characterized the effect of whitecaps on atmospheric correction of radiances measured from space. Using the experimental results of Whitlock et al. [1982] and the theoretical calculations of Stabeno and Monahan [1986], which indicated negligible (<3%) whitecap reflectance, and no spectral dependence of this reflectance, between 0.6 and 0.9 $\mu m$, respectively, they found that for wind speeds less than 10–12 m s$^{-1}$ the effect of whitecaps on the retrieval of the water-leaving radiance in the blue was quite small (<0.001 in reflectance), especially when the aerosol scattering was weakly dependent on wavelength (maritime aerosols). They further examined the errors resulting from uncertainties in the models relating effective whitecap reflectance (the product of fractional coverage and reflectance) to wind speed [Koepeke, 1984; Monahan and O'Muircheartaigh, 1980], concluding that for maritime aerosols the existing models were sufficiently accurate to meet the sea-viewing wide-field-of-view sensor (SeaWiFS) accuracy goal for biological applications. For aerosols exhibiting scattering properties that are strongly dependent on wavelength (e.g., continental aerosols), however, the accuracy goal would be met only if the whitecap reflectance were underestimated.

Though experimental studies of sea foam reflectance have been made [e.g., Austin and Moran, 1974], very little is known about spectral characteristics and nothing about bidirectional properties. The only published data on the spectral reflectance of foam are those of Whitlock et al. [1982], and they were obtained from laboratory measurements. The experimental setup of Whitlock et al. [1982] was carefully designed, yet it might not have generated realistic foam, i.e., foam encountered in nature. In the laboratory the foam patches, obtained by vigorously stirring a tank where air under high pressure was added to the water, were dense and concentrated near the surface. Furthermore, the measurements were made in fresh water, and detergent was used to stabilize the foam. Over the ocean, depending on the age of the foam and the wave conditions, the concentration of air bubbles might fall off with depth less rapidly than it did in the experiment of Whitlock et al. [1982], which could cause a pronounced spectral dependence of the foam reflectance, at least in principle. If the spectral dependence between 0.6 and 0.9 $\mu m$ is actually larger than the dependence measured by Whitlock et al. [1982], considering sea foam as a gray body in atmospheric correction schemes for ocean color remote sensing (e.g., the scheme proposed by Gordon and Wang [1994b]) might result in inaccurate estimates of water-leaving radiances and hence erroneous estimates of phytoplankton pigment concentrations.

In the present study we report on measurements of the spectral reflectance of sea foam made at the Scripps Institution of Oceanography (SIO) Pier in La Jolla, California, where we installed several radiometers to view the sea surface in a region of breaking waves. We take into account in the modeling of the radiometric signal the effect of water and bottom scattering. We compare the results with those of Whitlock et al. [1982] and Stabeno and Monahan [1986], and we discuss the differences. We quantify the effect of foam on the retrieval of water-leaving radiance (or equivalently, reflectance) in the blue by (1) using the spectral reflectance of sea foam obtained from the measurements and (2) assuming no spectral dependence of the foam reflectance (the generally assumed gray model). We assess, for ocean color remote sensing purposes, the impact of neglecting the spectral dependence of the foam reflectance in atmospheric correction algorithms. We also reexamine, in view of our measurements, the conclusions of Whitlock et al. [1982] about optimum wavelengths for aerosol remote sensing.

2. Measurements

2.1. Instrumentation

The instruments selected to investigate sea foam reflectance included a Sun photometer–sky radiometer system developed by CIMEL Electronique [Holben et al., 1994] for the monitoring of aerosol optical properties and two radiometers built by the Laboratoire d’Optique Atmosphérique of the University of Lille and referred to as the MIR system. The CIMEL system, when used in sky mode, measured radiances in four spectral bands centered at 0.44, 0.67, 0.87, and 1.02 $\mu m$. Radiometric sensitivity was adapted to measure sky radiance and the sometimes weaker ocean signal. The bandwidth was 0.01 $\mu m$ for all spectral bands, and the field of view was 1.2°. The MIR system measured radiances in spectral bands centered at 0.44, 0.55, 0.65, and 0.85 $\mu m$ (MIR-7), and 0.85 and 1.65 $\mu m$ (MIR-8). The bandwidth was 0.04 $\mu m$ for all spectral bands except the 0.44 and 1.65-$\mu m$ bands (only 0.01 $\mu m$), and the field of view was 2°.

Data acquisition was accomplished differently depending on the type of system (CIMEL or MIR). In the case of the CIMEL system the data were read sequentially in the four spectral bands, and it took a few seconds to complete a measurement cycle. During this time the sea state might have changed, which needs to be considered in the measurement protocol and in the data processing (see below). In the case of the MIR system the data were acquired simultaneously in all the spectral bands.

2.2. Experimental Setup and Procedures

The experiment took place at the SIO Pier, La Jolla on February 9, 1994, around 2100 UT (early afternoon). The radiometers were installed on the pier with their optical heads manually oriented toward the ocean surface. To avoid glint contamination and shading effects, we positioned the optical heads so that the viewing zenith angle and the relative azimuth angle (between the solar and viewing directions) remained around 45° and 180° (backscattering), respectively.

The radiometers viewed the ocean surface in a region of breaking waves. Photographs taken from the SIO Pier (Figure 1) show the typical aspect of the ocean surface when a wave breaks (Figure 1, top) and after a wave has broken (Figure 1, bottom). Breaking of the waves occurred where the water was a few meters deep, and sediment particles from the sandy bottom were present in the water column. In an attempt to minimize the effect of nonsimultaneity in the CIMEL data acquisition, the sea foam observations were made when the surface was well covered by foam. Sky conditions were clear, and the aerosol optical thickness in the four CIMEL bands was measured before and after the ocean surface was observed.

To take into account the scattering by the water and the sandy bottom, measurements were also made at the end of the pier where the surface was almost free of foam. For both foam-covered and foam-free observations, viewing geometry was similar. The difference in the depth of the water at the end of the pier and in the middle of the pier (where the foam observations were made) was a few meters, which was assumed to have a negligible impact on the corrections for water and bottom scattering (see section 3.3).

Because of a problem in one of the MIR acquisition units, it was not possible to make MIR-7 and MIR-8 measurements simultaneously. Each radiometer was connected successively to
Figure 1. Typical aspect of the ocean surface, as seen from the Scripps Institution of Oceanography Pier, when a wave breaks (top) and after a wave has broken (bottom).
Thus simultaneous measurements were only made at 0.44, 0.55, 0.65, and 0.85 μm (MIR-7) and at 0.85 and 1.65 μm (MIR-8).

3. Data Processing

3.1. Radiometric Calibration

The instruments were calibrated in the laboratory by using an integrating sphere delivering a known radiance (CIMEL, MIR) and in the field by using a plate of known reflectance properties (CIMEL). The laboratory calibration was performed on December 1, 1993, at the University of Lille and the field calibration on January 16, 1994, at Stephenson Peak (altitude 1896 m), Laguna Mountains, California. For the field calibration the reflective plate was placed horizontally in the Sun and viewed vertically. The downward irradiance on the plate, including the contribution of photons that had interacted with the surface and the atmosphere, was computed using the successive orders of scattering code of Deuzé et al. [1989] and measurements of the aerosol optical thickness at the calibration site. Assumptions were made about the surface reflectance and aerosol type, but the resulting errors were minimized since the aerosol optical thickness was low and only a small fraction of the photons reflected by the surface reached the plate. The laboratory and field calibration coefficients (i.e., for each wave band the values of K in the equation \( L = K(CN) \) relating digital count \( CN \) to radiance \( L \)) agreed to within ±10% and were averaged to yield the final calibration coefficients. The coefficient at 1.02 μm was corrected for the significant dependence upon temperature of the detector response at that wavelength.

3.2. Transformation Into Reflectance

The bidirectional reflectance measured in any wave band is defined as

\[
\rho(\mu_s, \mu_v, \varphi) = \frac{\pi L(\mu_s, \mu_v, \varphi)}{E(\mu_s)} \tag{1}
\]

where \( E \) is the downwelling irradiance at the surface, \( L \) is the measured radiance, \( \mu_s \) and \( \mu_v \) are the cosines of the solar and viewing zenith angles, respectively, and \( \varphi \) is the relative azimuth angle. The irradiance \( E \) can be expressed as a sum of direct and diffuse components:

\[
E(\mu_s) = \mu_s E_d(\mu_s) \exp(-\tau/\mu_s) + t_s(\mu_s) E_d(\mu_s) \tag{2}
\]

where \( t_s \) is the transmittance for gas absorption (mostly affected by ozone), \( E_d \) is the extraterrestrial solar irradiance, \( \tau \) is the optical thickness of the atmosphere, and \( E_d \) is the diffuse sky irradiance.

The atmospheric optical thickness \( \tau \) was measured before and after the ocean observations using the CIMEL radiometer in Sun mode. The averaged values, i.e., 0.332 at 0.44 μm, 0.121 at 0.67 μm, 0.074 at 0.87 μm, and 0.070 at 1.02 μm, were interpolated or extrapolated to the MIR-7 and MIR-8 wavelengths. Extrapolation to 1.65 μm was achieved by taking into account the spectral dependence of the molecular and aerosol contributions. For aerosol optical thickness the averaged values were 0.101 at 0.44 μm, 0.08 at 0.67 μm, 0.059 at 0.87 μm, and 0.063 at 1.02 μm. The spectral dependence between 0.44 and 1.02 μm (Angström exponent of 0.65) was assumed to be valid between 1.02 and 1.65 μm.

The diffuse irradiance \( E_d \) was simulated using the code of Deuzé et al. [1989]. The measured optical thicknesses and the aerosol model C70 of Shettle and Fenn [1979] were used in the calculations. Since the Sun zenith angle varied from 48° to 52° during the experiment, the simulations were performed at these extreme angles. The two \( E_d \) values were close, and the average was taken for \( E_d \).

Because the surface is surely not a perfect Lambertian reflector, the estimates of the sea foam reflectance depend on sky conditions. The isotropic component of \( E_d \), however, is small (the aerosol scattering phase function has a large forward peak), of the order of 10% of \( E \) at 0.44 μm and 1% at 0.87 μm, and the reflectance obtained using (1) remains very close to the actual (intrinsic) reflectance of the target.

Glitter was negligible for the geometric conditions of the experiment, but specular reflection of skylight by the surface contaminated the measurements. The effect, however, was not corrected for because it was relatively small (see section 4), and it affected similarly the observations of the foam-free and foam-covered surface and therefore was not of any significant consequence in the determination of the spectral variations in the foam reflectance in the following section.

3.3. Extraction of the Foam Reflectance

The foam reflectance was extracted from the measurements by applying three different methods. These methods vary in the way the ocean reflectance in the presence of foam was modeled.

In the first method (method 1), foam was assumed to form a semitransparent, uniform layer overlying a second layer consisting of the water and bottom. This method does not account for a partial coverage of the surface by foam. If \( \rho_o \) denotes the reflectance of the water and bottom, the measured reflectance \( \rho \) can be written

\[
\rho = \rho_f + \rho_o/(1 - \rho_o \rho_f) \tag{3}
\]

where \( \rho_f \) is the foam reflectance. Solving (3) for \( \rho_f \) yields

\[
\rho_f = (\rho - \rho_o)/(1 + \rho_o - 2 \rho_o) \tag{4}
\]

In the second method (method 2), foam was assumed to be opaque and to cover the water partially, with a fractional coverage \( A \). Therefore the measured reflectance is

\[
\rho = A \rho_f + (1 - A) \rho_o \tag{5}
\]

and \( \rho_f \) becomes

\[
\rho_f = [\rho - (1 - A) \rho_o]/A \tag{6}
\]

Examining (6), the problem is to determine the fractional coverage \( A \). Since our study focuses on the spectral dependence rather than the absolute value of the foam reflectance, \( A \) was calculated assuming that the foam reflectance was 0.5 at 0.44 μm (a typical value found in the literature). With this assumption, \( A \) is obtained from the following equation:

\[
A = (\rho_{0.44} - \rho_{0.44f})/(0.5 - \rho_{0.44f}) \tag{7}
\]

where the subscript 0.44 refers to the 0.44-μm wavelength.

In the third method (method 3) we combine the assumptions made in methods 1 and 2. Foam overlays the water with a fractional coverage \( A \) and obeys (3). Further neglecting interactions between the fractional areas covered and not covered by foam, \( \rho \) can be expressed as

\[
\rho = A(\rho_f + \rho_o(1 - \rho_f)^2/(1 - \rho_o \rho_f)) + (1 - A) \rho_o \tag{8}
\]
or, after rearranging:

$$\rho = \frac{A p_f [1 - \rho_o]^2 (1 - \rho_o p_f)] + \rho_o}{(1 - \rho_o p_f)} \quad (9)$$

Taking $\rho_f, 0.44 = 0.5,$ (9) can be solved for $A$:

$$A = \frac{[2(\rho_o 0.44 - \rho_o 0.44) - \rho_o 0.44 \rho_o 0.44 + \rho_o 0.44]}{(1 - \rho_o 0.44^2)} \quad (10)$$

At the other wavelengths, $\rho_f$ is obtained by solving (9); that is,

$$\rho_f = \frac{(\rho - \rho_o)[A(1 - \rho_o)^2 + \rho_o (\rho - \rho_o)]}{1 - \rho_o^2} \quad (11)$$

Unlike method 1, methods 2 and 3 require that the measurements be performed simultaneously at all wavelengths (the measurements at 0.44 $\mu$m are used to determine $A$, which is then used to determine $\rho_f$ at the other wavelengths). This was not possible with the CIMEL system (see section 2.2). Thus Methods 2 and 3 were only applied to the MIR-7 data, since the MIR-8 does not have a spectral band centered at 0.44 $\mu$m.

4. Results

A total of 51 and 10 data sets, or series of measurements in four spectral bands (0.44, 0.67, 0.87, and 1.02 $\mu$m), were acquired by the CIMEL system in the presence and absence of foam, respectively. The measurements in the presence of foam were made between 2054 and 2115 UT and those in the absence of foam between 2122 and 2126 UT. More data sets were acquired by the MIR system: 472 data sets between 2053 and 2109 UT (foam-covered surface) and 39 data sets between 2131 and 2132 UT (foam-free surface) using MIR-7, and 146 data sets between 2109 and 2115 UT (foam-covered surface) and 42 data sets between 2134 and 2136 UT (foam-free surface) using MIR-8. In the case of MIR-7 a data set also comprises data in four spectral bands (0.44, 0.55, 0.65, and 0.85 $\mu$m). In the case of MIR-8 a data set is composed of a single measurement at 1.65 $\mu$m (the 0.85-$\mu$m band was not used).

Figure 2 depicts typical time series of measurements obtained with MIR-7 over a foam-free surface (Figure 2a) and a foam-covered surface (Figure 2b). The reflectance of the foam-free surface is fairly constant with time, varying spectrally from 0.07 at 0.44 $\mu$m to 0.008 at 0.85 $\mu$m (Figure 2a). These values correspond to the water reflectance, specular reflection of diffuse skylight, and residual foam reflectance. At 0.44 $\mu$m the effect of specular reflection has been estimated using a single scattering model and is about 0.03; the few per cent remaining must be attributed to the water reflectance of a turbid medium with some influence of the reflectance of a sandy bottom. At 0.85 $\mu$m the water reflectance is negligible, the effect of surface reflection is about 0.003, and the few tenths of a per cent remaining are attributed to residual foam. Thus water reflectance and surface specular reflection contribute little to the measured values of foam, even at 0.44 $\mu$m.

Unlike the reflectance measurements without foam, the measurements in the presence of foam exhibit large temporal variations (Figure 2b). The reflectance increases sharply when the waves start to break and then decreases somewhat exponentially until the next wave breaks. A characteristic feature of Figure 2b is the similar reflectance values at 0.44, 0.55, and 0.65 $\mu$m but the substantially lower reflectance values at 0.85 $\mu$m.

The instantaneous values of foam reflectance, derived by application of method 1 to the data of Figure 2, are depicted in Figure 3a. Foam reflectances of Figure 3a are very close to the measured values in Figure 2b, and the correction applied using the foam-free reflectance in method 1 is very small.

Figure 3b summarizes the spectral reflectances derived using method 1, in the spectral range 0.44–1.65 $\mu$m. They are mean spectral values, averaged over all the data sets, and the associated standard deviations. The results obtained with the CIMEL system are also shown in Figure 3b, since method 1, unlike method 2 or 3, is also applicable to data not collected simultaneously in all the spectral bands (see section 3 for more details). The measurements from the two instruments overlap in the spectral range 0.4–1 $\mu$m and give similar spectral reflectances within their standard deviations. Foam reflectances from the CIMEL measurements are systematically above the ones from MIR measurements by a small factor. This may be due to the different procedures of acquisition by the two instruments: The MIR system was activated continuously and averaged the signal from the foam of the wave crests and troughs, while the CIMEL system acquisition was activated visually to measure the maximum of the sea foam. The foam reflectance, while remaining fairly constant between 0.45 and 0.65 $\mu$m on average, decreases conspicuously between 0.65 and 0.85 $\mu$m. Average values are 0.40 at 0.65 $\mu$m and 0.25 at 0.85 $\mu$m. Lower values are observed at higher wavelengths, reaching 0.06 at 1.65 $\mu$m.

Figure 3c shows the spectral reflectance values of Figure 3b normalized to unity at 0.44 $\mu$m. They are presented in this
data were partitioned into four $\rho_f$ ranges, namely, $\rho_f < 0.25$, $0.25 < \rho_f < 0.4$, $0.4 < \rho_f < 0.55$, and $\rho_f > 0.55$. The mean values and standard deviations of $\rho_f$ in the four ranges are given in Figure 4a. The spectral dependencies of the foam reflectance are also given in Figure 4b after normalization at 0.44 $\mu$m. The decreases of the spectral reflectances between 0.65 and 0.85 $\mu$m (Figure 4a) remain fairly constant when normalized to the 0.44-$\mu$m reflectance (Figure 4b), except for the lowest values of the foam reflectance (range 1), which show a more rapid decrease in the near-infrared.

In terms of spectral dependence, the results obtained using method 2 or 3 are similar to those obtained using method 1. Figure 5 shows that by taking constant the foam reflectance at 0.44 $\mu$m and varying the foam coverage, the derived foam reflectance at the other wavelengths does not change as a function of time (within model and instrument errors), i.e., when the waves start breaking and after they are broken. On the other hand, the derived reflectances using method 2 or 3 must be interpreted in terms of a spectral dependence rather than absolute values. In Figure 3c, where the spectral dependencies of the estimated foam reflectances normalized to unity using the three methods were compared, one notes that the spectral change in foam reflectance between 0.65 and 0.85 $\mu$m manner to better illustrate and compare the spectral dependencies derived from the two instruments using different methods.

In order to check whether the spectral dependence of the foam reflectance depends on the amount of foam or, more precisely, on the absolute value of the foam reflectance $\rho_f$, the
is about 39% of the foam reflectance at 0.65 μm using methods 2 and 3 and that this compares well with the 37% value obtained using method 1. One can conclude that the choice of a particular method to process the data does not affect the retrieval of the spectral dependence of the foam reflectance.

5. Discussion

5.1. Physical Interpretation of the Results

The results show a rapid darkening of the spectral reflectance of foam with wavelength in the near-infrared. The value of the reflectance in the visible is decreased typically by 40% at 0.87 μm, 50% at 1.02 μm, and 85% at 1.65 μm. This spectral effect is larger than the one reported by Whitlock et al. [1982], the only other experimental reference found on the subject. Whitlock et al. [1982] measured the reflectance of a foam artificially produced in a water tank. Figure 2 of Whitlock et al. [1982] shows foam reflectance decreased by 5% at 0.85 μm, 10% at 1.02 μm, and 50% at 1.65 μm. The spectral measurements by Whitlock et al. [1982] have been widely cited to support the idea that the foam reflectance has no significant spectral dependence in the near-infrared up to 1 μm [e.g., Koepke, 1984]. In addition, the atmospheric correction algorithms for ocean color remote sensing are based on the hypothesis that foam is white spectrally [Gordon et al., 1994b]. Our measurements, made in situ, contradict this hypothesis.

What can explain the larger decrease of the foam reflectance that we observed in the near-infrared? Obviously, it is caused by a larger water absorption through a longer photon path in the fluid. During our experiment we observed that the breaking of the waves not only produced a foam stricto sensu, i.e., large patches of the waves not only produced a foam stricto sensu, i.e., large

Figure 5. Time series of the derived foam reflectances at 0.55, 0.65, and 0.85 μm, from the MIR measurements of Figure 2 using method 2.

...
Table 1a. Error on Water Reflectance at 0.443 μm for Several Combinations of $p_a$ and $p_f$ at 0.865 μm ($p_a + p_f = 0.02$) and Some Values of the Ångström Exponent $\alpha$

<table>
<thead>
<tr>
<th>$\rho_f/(p_a + p_f)$</th>
<th>$\alpha$</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
<td>-0.00021</td>
<td>-0.00098</td>
<td>-0.00263</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Foam behaves as a gray body (no spectral dependence of reflectance).

### 5.2. Impact on Remote Sensing of Ocean Color

The strong spectral dependence of the foam reflectance may significantly impact the atmospheric correction of ocean color measurements from space. To evaluate the effect, a simplified model is used. In this model the radiance measured at the top of the atmosphere, normalized by the extraterrestrial solar irradiance, is expressed as

$$\rho_f = \rho_{w} + \rho_{m} + \rho_{m} + \rho_{f}$$

where $\rho_{w}$ is the water body reflectance, i.e., the parameter to retrieve from the measurements, $\rho_{m}$ and $\rho_{f}$ are the scattering reflectance for molecules and aerosols, respectively, $\rho_{f}$ is the foam reflectance, and subscript $i$ denotes a wavelength or a spectral band. For the sake of simplicity, in (12) the multiple interactions (coupling) between molecules, aerosols, and foam are neglected. These simplifications, though drastic, will not change the order of magnitude of the estimated errors. It is also assumed in (12) that the geometry conditions are not favorable to glitter (the glitter effect is neglected). In the calculations the wavelengths selected are 0.443, 0.67, and 0.865 μm, the equivalent wavelengths of the spectral bands of future ocean color sensors like the SeaWiFS [Hooker and Esaias, 1993] and the polarization and directionality of the Earth’s reflectance (POLDER) instrument [Deschamps et al., 1994].

The atmospheric correction algorithm computes $\rho_{m}$ at all wavelengths, which is then subtracted from the measurements. It is assumed that $\rho_{m}$ is computed exactly, without errors. The ocean is assumed black ($\rho_{w} = 0$) at 0.67 and 0.865 μm, and the objective is to retrieve $\rho_{w}$ at 0.443 μm (after subtraction of the molecular scattering contribution, indeed).

Simulations and application of aerosol models indicate that to a first approximation, the aerosol reflectance $\rho_{a}$ varies with wavelength following a regular power law in $\lambda^{-\alpha}$ (in terms of spectral variations of the aerosol optical thickness, $\alpha$ is referred to as the Ångström exponent). This power law is used to perform the extrapolation to 0.443 μm.

The foam reflectance, on the other hand, is a perturbing element that has its own spectral dependence. The perturbing effect on the retrieved water reflectance at 0.443 μm is evaluated using two spectral laws of variation of the foam reflectance, namely (1) no spectral change with wavelength (gray model) and (2) a spectral change deduced from the observations, that is, 0.6 at 0.865 μm and 1 at 0.67 and 0.443 μm (normalized values), and four values of the aerosol exponent, $\alpha = 0, 0.5, 1.0,$ and $1.5$. Several mixtures of the $p_a$ and $p_f$ reflectances at 0.865 μm are considered. The value of $(\rho_a + \rho_f)$ is fixed at 0.02, and the ratio $\rho_f/(\rho_a + \rho_f)$ is taken equal to 0 (no foam), 0.5, and 1 (no aerosols). In the absence of foam $(\rho_f = 0)$, the value of 0.02 for $(\rho_a + \rho_f)$ and thus $\rho_a$ at 0.865 μm corresponds to typical aerosols having an optical thickness of 0.2 and to observations at 90°–120° scattering angles (minimum values of the aerosol volume scattering phase function).

The results obtained with both foam models (the gray model and the model based on the SIO Pier observations) are presented in Tables 1a and 1b, respectively. The tabulated error is the difference between the "aerosol-foam" reflectance derived at 0.443 μm, using the power law extrapolation from 0.865 and 0.67 μm, and the actual one. A positive value of the error corresponds to an overestimation of the correction or an underestimation of the water reflectance. Using the gray model, the extrapolation scheme generally introduces small errors, which have practically no impact on the retrieval of $\rho_{w}$ at 0.443 μm. The errors only reach the critical value of 0.001 in reflectance when aerosols have an $\alpha$ exponent above 1. These results concur with those of Gordon and Wong [1994a], who performed calculations for varied geometries. Using the spectrally dependent model, however, the errors become catastrophic as soon as there is even a small amount of foam, mixed or not with aerosols, thus irrespective of aerosol type. Values are above 0.01, which is not acceptable, since the accuracy objective for $\rho_{w}$ at 0.443 μm is 0.001. The errors are 1 or 2 times higher than the aerosol radiance to correct at 0.443 μm, and it might be inaccurate or useless to perform atmospheric corrections in the presence of foam, even when taking into account the spectral dependence determined experimentally. At this stage, without measurements over the open ocean, a safe way to proceed would be to eliminate all cases potentially affected by a foam effective reflectance (product of foam reflectance and area covered by foam) above 0.001, i.e., wind speeds above 8 m s$^{-1}$ according to the formula derived from Koepke [1984]:

$$\rho_f = 6.49 \times 10^{-7} U^{5.2},$$

where $U$ is the wind speed in meters per second.

### 5.3. Impact on Remote Sensing of Tropospheric Aerosols

Remote sensing of tropospheric aerosols may be seriously affected by a strong decrease of the spectral reflectance of foam in the near-infrared, as observed at the SIO Pier. Our results concur with the previous statement by several authors [e.g., Whitlock et al., 1982] that remote sensing of tropospheric aerosols, using their scattered radiance, is optimum at higher wavelengths in the near-infrared (i.e., 1.6 μm and above); at those wavelengths, water reflectance and molecular scattering are negligible and foam reflectance is strongly reduced. Our results show that the foam reflectance at 1.6 μm is far less a problem than previously thought, so that the remotely sensed estimates of aerosols at wavelengths of 1.6 μm as well as 2.2 μm should be of very good quality. However, analysis of data measured at a single wavelength of 1.6 μm would only give us...
the aerosol optical depth or loading if we know the aerosol type.

Figure 6 is an illustration of the error \( \Delta \tau_{ao} \) produced by the foam reflectance on the retrieval of the aerosol optical thickness, \( \tau_{ao} \), from observations at different wavelengths between 0.4 and 1.65 \( \mu \)m and wind speeds of 10 and 15 \( \text{m s}^{-1} \). Assuming a single scattering approximation, the aerosol scattering reflectance, \( \rho_a(\lambda) \), is expressed as

\[
\rho_a(\lambda) = \frac{\tau_a(\lambda) \rho / 4 \mu \mu_v}{4 \mu \mu_v / p}
\]  

where \( p \) is the volume scattering phase function and \( \mu_s \) and \( \mu_v \) are the cosines of the solar and view zenith angles, respectively. We assume that most of the spectral variation of \( \rho_a(\lambda) \) is due to the aerosol optical thickness, which follows the power law \( \tau_a(\lambda) \sim (\lambda/\lambda_0)^{-\alpha} \), and that \( p / 4 \mu \mu_v \) has a typical value of 0.1 (\( p = 0.2 \) in the backward directions, \( \mu_v \mu_v \sim 0.5 \)).

The error \( \Delta \tau_a(\lambda = 1 \mu \text{m}) \), on the estimated aerosol optical thickness at \( \lambda = 1 \mu \text{m} \), after normalization using the above power law, is given by

\[
\Delta \tau_a(\lambda = 1 \mu \text{m}) = \frac{4 \mu \mu_v \rho(\lambda) \lambda^\alpha / p}{10 \rho(\lambda) \lambda^\alpha}
\]

with \( \lambda \) expressed in micrometers.

Figure 6a compares the errors due to the foam reflectance, assuming a gray model, or the spectral dependence of this study. It is derived for a sea foam reflectance of 0.009 in the visible (\( U = 15 \text{ m s}^{-1} \)) and an aerosol exponent \( \alpha \) of 1. Using the gray model, one would conclude that the error increases in the near- and shortwave infrared. Using the spectral value of this study, one finds, on the contrary, that the aerosol optical thickness is less perturbed by sea foam using observations at 1.6 \( \mu \text{m} \).

Figure 6b compares the errors obtained for different wind speeds and aerosol exponents. The error decreases when the aerosol exponent increases. At wind speeds of 10 \( \text{m s}^{-1} \) and below, the sea foam does not affect significantly the accuracy of the derived aerosol optical thickness, and the error is less than 0.01 in the near-infrared. Above a wind speed of 10 \( \text{m s}^{-1} \), the error rapidly increases with the wind speed, reaching an unacceptable value of 0.05 at \( U = 15 \text{ m s}^{-1} \), making it more necessary to use observations in the shortwave infrared at 1.6 \( \mu \text{m} \).

Figures 6a and 6b show that the effect of foam on the retrieved optical signal becomes important at wind speeds above 10 \( \text{m s}^{-1} \) and that this effect can only be reduced in the near-infrared, at 1 \( \mu \text{m} \) and above. Errors due to atmospheric molecular scattering and water reflectance have not been evaluated here, but it is clear that they are also decreased in this spectral range.

Figure 7 is an illustration of the error \( \Delta \alpha \) on the retrieval of the aerosol wavelength exponent \( \alpha \), assessed as follows. A set of wavelengths, typical of SeaWiFS, POLDER instrument, and MODIS [Ardanuy et al., 1991], has been used, namely at 0.44, 0.565, 0.67, 0.765, 0.865, 1.02, 1.22, 1.65, and 2.2 \( \mu \text{m} \). At these wavelengths the aerosol-foam reflectance signal has been computed using the same modeling as used previously for Figure 6: the aerosol reflectance is 0.02 at 1 \( \mu \text{m} \), and its spectral variation is defined by its wavelength exponent, \( \alpha \). The sea foam reflectance varies in the visible according to \( \rho_f = 6.49 \times 10^{-7} \times U^{3.52} \), and its spectral variation is represented by two models, the gray model, i.e., no spectral variation, or a spectral model derived from this study, Figure 3c.

Figure 7a compares the results for the gray model and the spectral one derived in this study, at \( U = 15 \text{ m s}^{-1} \) and \( \alpha = 1 \). The gray model gives errors that systematically underestimate the aerosol wavelength exponent. Using this study, however, the resulting effect of the sea foam is an overestimation of the aerosol wavelength exponent in the near- and shortwave infrared.

Figure 7b shows the error on the retrieved aerosol wavelength exponent, using the sea foam spectral model of this study, for different values of the wind speed and \( \alpha \). The error, \( \Delta \alpha \), is less than 0.1 at a wind speed of 10 \( \text{m s}^{-1} \) and below, which is acceptable, as was the case for the error on the retrieved aerosol optical thickness, \( \Delta \tau \) (Figure 6a). The error, \( \Delta \alpha \), however, is about 0.3 and not negligible at a wind speed of
the foam stricto sensu dissipated, the underwater bubbles became more apparent, enhancing the water absorption effect. In the open ocean, depending on wave height and thus wind speed, the concentration of air bubbles injected in the upper layers may vary, suggesting that the spectral effect should change with wind speed. Measurements in the open ocean therefore are necessary to confirm our findings and to characterize the spectral dependence of the foam reflectance as a function of wind speed/sea state.

The impact of our results on remote sensing of ocean color from space is large. Neglecting the spectral dependence of the foam reflectance in atmospheric correction schemes using 0.865- and 0.67-μm wavelengths (e.g., Gordon and Wang [1994b] for SeaWiFS) may introduce, even in the presence of a small amount of foam, errors above 0.01 on the water reflectance retrieved in the blue (0.44 μm). These errors do not meet the 0.001 accuracy requirement for biological applications; they are an order of magnitude higher. Since few measurements are presently available (to our knowledge the data presented in this study are the first in situ data on the spectral reflectance of foam ever collected) and since there are still questions to address (dependence on wind speed, bidirectional effects), it is recommended that for now, all satellite observations affected by an effective reflectance of foam above 0.001 in the 0.4- to 0.9-μm spectral range should be eliminated. On the basis of the study of Koepke [1984], this threshold corresponds approximately to wind speeds above 8 m s⁻¹. Using spectral bands centered at 1.2 and/or 1.6 μm to better estimate the aerosol reflectance in the blue (case of MODIS) would increase the errors on water reflectance estimates in the blue. This aggravated error is due to the spectral variation of the foam reflectance, which owing to water absorption, is larger between 0.44 and 1.1 or 1.6 μm than between 0.44 and 0.9 μm.

Regarding remote sensing of aerosols from space, our findings are in agreement with those of Whitlock et al. [1982], who showed that optimum wavelengths for retrieving optical thickness are 1.6 μm and above. Our results further suggest that because of the enhanced absorption effect due to underwater bubbles, the presence of foam is a much smaller problem at those wavelengths. Assuming that foam is a gray body would impact significantly the determination of the spectral dependence of aerosol thickness in the 0.67- to 0.865-μm range,
leading to inaccurate size distribution and thus incorrect description of aerosol type. Over the oceans the spectral range above 1 μm is definitely recommended for remote sensing of aerosol amount and type.

Present algorithms, used to retrieve aerosol properties from ocean color measurements, assume that sea foam is gray and will not work properly if our results prove robust. These algorithms are configured to utilize estimates of wind speed from numerical weather models and therefore have the potential to perform good corrections for wind speeds above 8 m s⁻¹. The question, however, is how accurately the foam reflectance, whatever its spectral variation, can be estimated from such data, even if the spectral nature of the foam reflectance is a function of wind speed. The issues raised here deserve timely attention because the next generation of ocean color/aerosol sensors, SeaWiFS, POLDER, MODIS, etc., will soon provide data.

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P.-Y. Deschamps and M. Schwindling, Laboratoire d’Optique Atmosphérique, Université des Sciences et Technologies de Lille I, 59655 Villeneuve d’Ascq, Cedex, France.

R. Frouin, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92033.

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