Vicarious Calibration of the POLDER Ocean Color Spectral Bands Using In Situ Measurements

Bertrand Fougnie, Pierre-Yves Deschamps, and Robert Frouin

Abstract—The radiometric sensitivity of the POLarization and Directionality of the Earth’s Reflectances (POLDER) instrument in the ocean color spectral bands (443, 490, and 565 nm) was checked vicariously by comparing top-of-atmosphere normalized radiances measured by the instrument with those computed for the same geometries using a radiative transfer model. In situ measurements of aerosol optical thickness and marine reflectance at the time of the satellite overpass were used as input to the model. The accuracy of the vicarious calibration coefficients was estimated to better than 3%. A large decrease in the POLDER instrument response was found in the blue, confirming the results previously obtained using alternative techniques.

Index Terms—In-situ measurements, POLDER, radiative transfer, radiometric calibration.

I. INTRODUCTION

POSTLANCE radiometric calibration of any ocean color space sensor is necessary to check for any change in the optics during launch and to monitor the degradation of the optics under the illumination by energetic ultraviolet photons. On-board devices such as lamps and solar diffusers, as well as alternative methods such as the method using molecular scattering [1]–[2], attempt to address the issue. Any on-board calibration device, however, has its own limits of accuracy. An accurate retrieval of the marine reflectances would require an absolute calibration accuracy better than 1% for the spectral bands in the blue region of the spectral spectrum. This is beyond the performance of any on-board device. The vicarious calibration method, presented and applied hereafter, makes use of in situ measurements and should be viewed as a backup solution to ultimately control the accuracy of the postlaunch calibration.

In the vicarious calibration method, the radiances measured by the sensor are compared with those computed by a radiative transfer model of the atmosphere-ocean system with, as inputs, the necessary geophysical parameters: ozone amount, wind speed, aerosol properties, and marine reflectances. For application to the POLDER instrument on board the advanced earth observation satellite (ADEOS) [3], ozone amount is taken from the Total Ozone Mapping Spectrometer (TOMS), also on board ADEOS, and the other parameters are obtained from in situ measurements performed at (or close to) the time of the satellite overpass.

II. MATERIAL AND METHODS

A. Concept

As explained above, we intend to compare the top-of-atmosphere (TOA) radiances measured by the POLDER instrument to those computed by a radiative transfer model making use of in situ measurements to describe the variable scattering/reflecting component of the earth’s atmosphere-ocean system. The radiative transfer computation is similar to the one performed in the atmospheric correction algorithm. Any error affecting the radiative transfer computation would affect the absolute accuracy of the TOA radiances, but nevertheless, the effect would be canceled at first order if the same error was made for the retrieval of the marine reflectance. This is the case, for example, for ozone absorption modeling. We used the total ozone content from the TOMS/ADEOS instrument. The lower boundary of the radiative transfer model, i.e., the ocean surface, is characterized by a diffuse reflectance \( \rho_{\text{water}}(\lambda) \) which is taken isotropic from (directional) radiometric measurements, either under water (MER instrument), or above water (SIMBAD instrument). The radiative transfer model also requires aerosol properties, namely optical thickness and type, which are derived from sun intensity measurements made from the sea surface by a SIMBAD radiometer or any other sun photometer (CIMEL, HHCRM). Wind speed, taken from the shiplog, is necessary to compute the glitter, direct solar radiation reflected by wave slopes, and the whitecap reflectance, which also define the bottom conditions of the atmosphere-ocean radiative transfer model.

Let us denote by \( \alpha_k \) the radiometric sensitivity of the POLDER instrument in the spectral band \( k \). Radiometric sensitivity characterizes the instrument response to incident radiance. The higher the radiometric sensitivity, the larger the digital count (for a given change in input radiance, the corresponding change in digital count is larger). The prelaunch \( \alpha_k \)’s were determined in the laboratory using Centre National d’Etudes Spatiales (CNES) integrating sphere [3]. In the
TABLE I  
In-situ CAMPAIGNS FOR POLDER OCEAN COLOR CALIBRATION AND VALIDATION

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Date</th>
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<th>Atmospheric</th>
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<td></td>
<td>Nov. 14, 1996</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Hawaii Islands</td>
<td>Nov. 18, 1996</td>
<td>MOCE</td>
<td>HICRM</td>
</tr>
<tr>
<td>RONSARD</td>
<td>LeHavre-Nouméa</td>
<td>Dec. 10, 1996-</td>
<td>SIMBAD</td>
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<td>Jan. 15, 1997</td>
<td></td>
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<td>CALCOFI-9702</td>
<td>S. Calif. Coast</td>
<td>Feb. 1, 1997-</td>
<td>MER</td>
<td>CIME1</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CALCOFI-9704</td>
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<td>Apr. 2, 1997-</td>
<td>MER/</td>
<td>SIMBAD</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Eq. Atlantic</td>
<td>Jun. 6, 1997-</td>
<td>SIMBAD</td>
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<tr>
<td></td>
<td></td>
<td>Jun. 30, 1997</td>
<td></td>
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<td>ACE-2</td>
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<tr>
<td></td>
<td></td>
<td>Jun. 30, 1997</td>
<td></td>
<td></td>
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</table>

following, we shall examine the change in \( \alpha_k \) after launch, expressed as

\[
A_k = \frac{\alpha_k(\text{postlaunch})}{\alpha_k(\text{prelaunch})}.
\]

B. POLDER Data

The POLDER radiometer [4] is basically a spectral camera which takes spectral images of the earth at regular time intervals while its satellite platform ADEOS is moving along the orbit. Consequently, a target at the surface is viewed by the POLDER radiometer, forward and backward, under 12–14 different angles during a single orbit overpass.

We have analyzed POLDER Level 1 data, processed by CNES at the Centre de Production POLDER (CPP), Toulouse, France, and calibrated using the prelaunch calibration, at ocean color wavelengths, i.e., the POLDER spectral bands at 443, 490, 565, 670, and 865 nm. Level 1 were corrected by CPP for the optics polarization and stray light, and they were geometrically resampled on the POLDER earth reference grid. Level 1 data are normalized radiances, i.e., the spectral radiances, times \( \pi \), divided by the (spectral) solar constant corrected for the sun-earth distance variations. This is convenient because a Lambert white reflector with an albedo of one would have a reflected normalized radiance of one for a sun at zenith, 0.5 for a solar zenith angle of 60°, thus the interpretation of multispectral behavior is more straightforward.

After the launch of ADEOS on August 18, 1996, the POLDER instrument was continuously turned on from October 30, 1996, and systematic data acquisition started until the loss of the ADEOS platform on June 30, 1997; a global eight-month ocean color data set was acquired. Thus, the object of our vicarious method is the calibration of Level 1 normalized radiances to be used in the processing of the POLDER Level 2 data. Note that one in situ measurement (latitude and longitude) corresponds to one POLDER pixel (line, column) and up to 14 POLDER views as described by [4], i.e., up to 14 geometries (solar zenith angle, viewing zenith angle, relative azimuth angle, and consequently scattering angle).

C. In-situ Measurements

A program of in-situ measurements was conducted in order to calibrate the POLDER radiances and to validate the derived products, marine reflectances, and phytoplankton pigment concentration. Atmospheric optics as well as marine optics are necessary to characterize the geophysical conditions of the earth-atmosphere system at the time of POLDER observation. The various cruises that provided useful in-situ measurements

Fig. 1. Normalized response of the spectral bands of POLDER and SIMBAD radiometers.
Fig. 2. Location of the in-situ campaigns.

during the eight months of the POLDER data acquisition are listed in the Table I, and location is shown in Fig. 2. The underwater MER radiometer and the CIMEL sunphotometer have been used for these measurements, as well as the SIMBAD radiometer specifically designed to perform both these observations quasi-simultaneously.

1) SIMBAD Dataset: The SIMBAD radiometer was originally designed and realized by the Laboratoire d’Optique Atmosphérique, University of Lille, France, for the radiometric calibration of the POLDER instrument and the validation of the POLDER products. The same SIMBAD radiometer works as a sunphotometer when aiming at the sun, and makes above-water measurement of the marine reflectance when aiming at the sea. For the latter measurement, the instrument is equipped with a polarizer to reduce reflected sky radiance and glitter when the measurement is made at a viewing angle close to the Brewster zenith angle [5]. The wavelengths of the five SIMBAD spectral bands, centered at 443, 490, 560, 670, and 870 nm, fit the POLDER ocean color spectral bands (Fig. 1). The aerosol optical thickness in five spectral bands, and the marine reflectances in the 443, 490, and 565 nm POLDER bands are derived from the measurements. The aerosol model is deduced from the spectral dependence of the aerosol optical thickness between 443 and 870 nm. Note that during some of the campaigns, a prototype of the SIMBAD radiometer was used, and spectral band centered at 490 nm was not available. The reflectance measured by the SIMBAD radiometer at 560 nm is used to compute the TOA radiance at 565 nm. Measurements were made only when the sun was not obscured by clouds and the cloud coverage was estimated to be less than 30%.

2) Other Datasets: The second set of in-situ measurements involves underwater radiometers used for the calibration and validation of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Data were obtained from a MODIS Ocean Characterization Experiment (MOCE) cruise in the vicinity of Hawaii Islands (courtesy of Dennis Clark, NOAA, [6]) and from CALifornia COoperative Fisheries Investigation (CALCOFI) cruises using a MER underwater radiometer (courtesy of Gregg Mitchell, Scripps Institution of Oceanography). These instruments sample the vertical profile of upwelling radiance and of downwelling irradiance at different depths, from typically 100 m to the surface. The (spectral) marine reflectance is determined from the ratio of the (spectral) upwelling radiance to the (spectral) downwelling irradiance extrapolated just below the surface, and adjusted for the transmission factor of the surface. The MER spectral bands are centered at 443, 490, 555, 570, and 665 nm, and a linear interpolation between MER data at 555 and 570 nm is done to estimate the marine reflectance at 565 nm. During the MOCE cruise, the high spectral resolution spectrometer Marine Optical System (MOS) made acquisitions at 443, 490, 565, and 670 nm. The CIMEL and HHCRM sunphotometers were used during two of the cruises (Table I). The CIMEL spectral bands are centered at 440, 670, and 870 nm, and the HHCRM ones at 440, 490, 560, and 670 nm. All the measurements were made in the Northern Pacific (Fig. 2).

During each cruise, surface wind speed and direction and surface atmospheric pressure were taken from the shiplog. The surface pigment concentration was also measured, except during the MS TOUCAN transect. We assume that the small dataset given in Table I is representative of different seasons (November to June), oceanic waters (Atlantic and Pacific), and aerosols contents.

D. Computation of TOA Radiances

The TOA normalized radiances are computed using a radiative transfer code based on the successive orders of scattering (SOS) method [7] applied to the earth’s atmosphere-ocean system. This code considers multiple scattering and polarization into the atmosphere [7] and reflection by the wavy surface. The atmosphere-ocean system is described by geophysical inputs from in-situ measurements, i.e., marine reflectances at 443, 490, and 565 nm, aerosol optical thickness at 865 nm, aerosol model, and surface wind speed. The computations are made for the geometry of all the (14) view directions and for the five POLDER spectral bands centered at 443, 490, 565, 670, and 865 nm.
The atmosphere scattering is described by a mixture of aerosol particles and molecules, with concentrations decreasing exponentially with altitude and a scale height of 2 and 8 km, respectively. The atmospheric molecular optical thickness, as a function of wavelength, follows the law given in Gordon et al. [8] from Hansen and Travis [9]. This law is weighted by the spectral response of the POLDER spectral bands, and by the solar extraterrestrial spectral irradiance, see values given in Table II. The molecular optical thickness has been adjusted to the actual surface air pressure at the time of measurement. The aerosol amount is characterized by the aerosol optical thickness measured \textit{in situ} at 870 nm. We select an aerosol model in the aerosol model set defined by Gordon and Wang [10] for SeaWiFS, based on the work by Shettle and Fenn [11], as the one giving the best fit of the wavelength dependence of the measured aerosol optical thicknesses. The aerosol optical thicknesses used in the computation at the short wavelengths is the extrapolation of the measured optical thickness at 870 nm for the identified aerosol model. An absorbing ozone layer is added above the molecular and aerosol scattering layer. Ozone absorption affects the spectral bands centered at 490, 565, and 670 nm and is computed for the total ozone content obtained from TOMS on ADEOS. Other gaseous absorption is neglected.

The surface reflection at the bottom of the scattering atmosphere is described by Fresnel’s law; the wave slope statistics are computed as a function of wind speed using the Cox and Munk’s model [12] (this gives intense specular reflection at low wind speed, otherwise known as glitter). To this surface reflection component is added the marine diffuse reflectance. The water body is assumed to be Lambertian, and the marine reflectance is taken from the measurements.

Finally, the outputs of the code are the TOA normalized radiances.

### E. Comparison Between TOA Measured and Computed Normalized Radiances

**Matchup Data Set:** A matchup is considered when:

1. POLDER data have been acquired, i.e., data are available at the time of this study;
2) POLDER data show clear sky condition, i.e., the visual inspection of the 865-nm spectral band data does not show any cloud in a 10 by 10 pixel square centered on the matchup pixel;

3) *in-situ* measurements, marine reflectances, and aerosol optical thicknesses exist on the same day and within 3 h of the satellite overpass;

4) the *in-situ* measurements correspond to high solar elevation (above 55°);

5) the *in-situ* optical thickness is less than 0.1 at 865 nm;

6) the *in-situ* wind speed is less than 10 m s⁻¹.

Because the POLDER pixel size is 7 by 7 km², we have to assume that the pixel is homogeneous, i.e., that the *in-situ* measurements, marine reflectances, and aerosol optical properties are constant inside the pixel. This approximation appears reasonable for most of the open sea but may become hazardous near the coast. This explains why a few coastal matchup data had to be rejected.

Nine matchup data sets are finally selected. The corresponding geophysical parameters are given in Table III and matchup location is shown in Fig. 2.

During overpass, the POLDER instrument views 12–14 times the same point on the ocean surface. Therefore, from one
Fig. 4. Viewing geometries of the four matchups of Fig. 3. In each polar plot, the radius represents the viewing zenith angle $\theta_v$ and the polar angle $\phi$ the azimuth relative to the sun direction. The solid circle indicates the specular direction, and each open circle indicates one direction of POLDER observation for (a) November 11, 1996, (b) February 13, 1997, (c) May 9, 1997, and (d) June 27, 1997. The selected POLDER views are identified by a cross. The scattering angle $\Theta$ is given for some of the directions of observation.

III. RESULTS

Computed and measured TOA radiances normalized to the extraterrestrial solar irradiance are presented in Fig. 3(d) for four of the matchups. The TOA normalized radiances are plotted versus the scattering angle (the angle between the solar incident direction and the viewing direction) in order to identify the multi-angular observations, and for 443, 565, 670, 865, and 490 nm when available. The selected matchups illustrate various viewing geometries, and the different shapes in the dependence with scattering angle observed can be usefully interpreted with the help of Fig. 4. In this figure, the directions of POLDER observation (open circle) close to the direction of specular reflection (solid circle) are susceptible to be contaminated by glitter. Fig. 3(a) and (b) corresponds to cases of large solar zenith angle and a viewing to the west; these cases are mostly uncontaminated by glitter, except marginally [Fig. 3(a)]. Fig. 3(c) and (d), on the other hand, corresponds to cases of small zenith angle and a viewing to the east, and for several directions of observation there is a variable and significant glitter contamination [Fig. 4(c) and (d)]. The glitter-contaminated observations are rejected because an accurate glitter modeling would be extremely difficult. Only the observations corresponding to a POLDER reflectance (i.e., the normalized radiance observed by POLDER divided by the cosine of the solar zenith angle) of less than 0.02 at 865 nm are retained for the comparison. These observations correspond mainly to the backward scattering directions. For convenience, the scattering angles of the selected directions are marked by an interval on the $x$-axis of Fig. 3 and are identified by crosses in Fig. 4. Assuming that the postlaunch calibration at 865 nm has changed by 5% from its prelaunch value, as reported by Hagolle et al. [2], a Lambertian white normalized radiance $R_w$ is added to the surface signal in order to adjust the computed TOA normalized radiances at 865 nm in the selected directions. In doing that, the geophysical model determined in situ from the ship or the buoy (Table III) is adjusted for all the POLDER pixels ($7 \times 7$ km): in particular, whitecap and subpixel cloud effects, which are difficult to estimate for all the pixels [13] are indirectly assessed from the 865-nm
Fig. 5. Ratio of prelaunch- and postlaunch-calibrated (this study) POLDER normalized radiances $A_k(\lambda)$ as a function of scattering angle for the spectral bands centered at 443, 490, and 565 nm, and for the whole matchup data set.

observation. The $R_c$ values for each of the selected matchups are reported Table III. The fact that computed normalized radiances at shorter wavelengths are systematically superior to those obtained using prelaunch calibration coefficients (i.e., loss of radiometric sensitivity) is not surprising as we generally expect some degradation of the optics during and after launch.

A systematic discrepancy exists between computed and prelaunch-calibrated normalized radiances at 443, 490, and 565 nm. This is best shown by forming the ratio of the prelaunch-calibrated and computed normalized radiances (Fig. 5). The $A_k$ values are more or less independent of the viewing geometry expressed by the scattering angle. All the selected POLDER observations correspond to scattering angle between 85 and 170°. Table IV gives the mean and standard deviation of the $A_k$ estimates, as well as the number of estimates. The smaller $A_k$ values (larger decrease of sensitivity) are obtained in the blue region, which is generally expected. The standard deviation of the $A_k$ estimates is about 0.03 or less, whatever the wavelength.

### Table IV

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>443 nm</th>
<th>490 nm</th>
<th>565 nm</th>
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<tbody>
<tr>
<td>Mean $A_k(\lambda)$</td>
<td>0.8954</td>
<td>0.9495</td>
<td>1.0296</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.0155</td>
<td>0.0216</td>
<td>0.0307</td>
</tr>
<tr>
<td>N of $A_k(\lambda)$ estimates</td>
<td>60</td>
<td>27</td>
<td>60</td>
</tr>
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</table>

### IV. DISCUSSION AND CONCLUSION

We have found a large decrease of the sensor response after launch in the blue spectral bands (443 and 490 nm). This decrease has also been observed by Hagolle et al. [2] using alternative techniques; the $A_k$ values found by Hagolle et al. are 0.970 at 443 nm, 0.995 at 490 nm, and 1.035 at 565 nm. If our results are in agreement with those of Hagolle et al. [2] for the 565-nm spectral band (small bias of 3%), they reveal a larger decrease in sensor response in the blue part of the spectrum, i.e., for the 443-nm (bias of about 10% instead of 3%) and 490-nm (bias of about 5% instead of 0.5%) spectral bands.

The matchup data set is limited, particularly for the 490-nm spectral band, making it difficult to investigate further the discrepancies. There does not appear to be any residual effect linked to the geometry (the scattering angle or the viewing zenith angle), the wind speed, aerosol optical thickness, or to the Lambertian white normalized radiance $R_c$.

We tried to assess the accuracy of the computed TOA normalized radiances by altering several steps of our processing, i.e., by introducing

1) a 5% bias error on the POLDER calibration of the spectral band centered at 865 nm, used to assess the whitecap and subpixel cloud normalized radiance $R_c$;
2) a 10% bias error on the measured marine reflectances;
3) a 0.01 bias error on the measured optical thickness at 865 nm;
4) a 0.2 bias error on the measured aerosol Ångström coefficient. This bias error was calculated for the matchup of May 9, 1997, for which the aerosol optical thickness was 0.06 at 865 nm.

In Table V, we display the resulting errors on the estimated $\bar{A}_k$. The specified errors of 0.01 on aerosol optical thickness and of 0.2 on aerosol Ångström coefficient correspond to accurate SIMBARD [14] or CIMEL [15] measurements, and they affect the $\bar{A}_k$ determination by less than 0.008 at 443 and 490 nm and by about 0.01 at 565 nm. The error of 10% on the measured marine reflectances at 443, 490, and 565 nm is typical for the SIMBARD above-water technique as shown in [14], and for the classic underwater techniques (see [16]). This error on the marine reflectance includes the calibration error of the radiometers, typically 5–6% for those three wavelengths, as well as the processing error due to varied corrections (see [14] and [16]). This error has the largest effect on the $\bar{A}_k$ determination at 443 nm, i.e., about 0.01. The POLDER interband calibration accuracy at 865 nm also affects the $\bar{A}_k$ determination, especially at 490 and 565 nm, and the resulting error on $\bar{A}_k$ is typically 0.01 or less for all the spectral bands. Thus, the postlaunch calibration change and necessary adjustment documented above and summarized in Table IV should be accurate to about 2–3%.

Inaccurate adjustment of the radiometric sensitivity of the POLDER instrument will result in erroneous marine reflectances and, ultimately, phytoplankton pigment concentration. The vicarious method applied here would be preferred to alternative methods (i.e., those of Hagolle et al. [2]), because it makes use of the same radiative transfer model as the atmospheric correction algorithm. We propose the adjustment of the radiometric sensitivity with the $\bar{A}_k$’s coefficient of Table IV to generate the POLDER Level 2 ocean color products.

ACKNOWLEDGMENT

The authors would like to thank J.-M. Nicolas from the Laboratoire d’Optique Atmosphérique, Université des Sciences et Technologies de Lille, for his contribution to computations and POLDER data accessibility, and everybody involved in the in situ measurements and its collection including G. Mitchell, M. Kahrur, D. Clark, D. Bakker, S. Carlier, D. Frutel, C. Tosca, C. Menzié, Y. Dandonneau, and the crews of MS Ronsard, MS Toucan, R/V Roger Revelle, R/V David Starr Jordan, R/V Vodyanitskyi, and RRS J. Clark Ross.

REFERENCES


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Robert Frouin received the Ph.D. degree in physics (radiative transfer/molecular spectroscopy) from the University of Lille, Lille, France, in 1983.

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