Evaluation of SIMBADA measurements of marine reflectance and aerosol optical thickness during ACE-Asia and AOPEX

Robert Frouin*, Hubert Loisel**, Antoine Poteau***

*aScripps Institution of Oceanography, La Jolla, California, USA
**Laboratoire d’Océanologie et Géosciences, Wimereux, France
***Laboratoire d’Océanographie de Villefranche, Villefranche-sur-mer, France

ABSTRACT

The SIMBADA radiometer was designed to check the radiometric calibration of satellite ocean-color sensors and evaluate the atmospheric correction of ocean-color imagery. It measures marine reflectance and aerosol optical thickness in 11 spectral bands covering the spectral range 350 to 870 nm. Aerosol optical thickness is obtained by viewing the sun disk and marine reflectance by viewing the ocean surface through a vertical polarizer that minimizes sun glint and reflected skylight. The measurements made by SIMBADA during ACE-Asia (March-April 2001, Japan Sea) and AOPEX (July-August 2004, Mediterranean Sea) are compared with those made concomitantly by other ocean radiometers and sun photometers, i.e., MER, PRR, SPMR, Trios, TSRB, and BOUSSOLE instruments for marine reflectance and CIMEL and Microtops for aerosol optical thickness. Agreement is generally good between the various measurements or estimates. The SIMBADA aerosol optical thickness is within ±0.02 of the values obtained by other sun photometers. The SIMBADA marine reflectance, after correction for bi-directional effects (Q factor), does not exhibit biases when compared with estimates by other radiometers, which generally agree within ±10%. In some cases larger discrepancies exist, and they are largely explained by differences in solar irradiance. More accurate SIMBADA estimates may be obtained by improving the radiometric calibration, the correction for angular geometry and water body polarization, the calculation of incident solar irradiance, and the selection of data minimally affected by sky reflection.

Keywords: Ocean color radiometry, SIMBADA, marine reflectance, aerosol optical thickness, ACE-Asia, AOPEX

1. INTRODUCTION

Several large-swath satellite ocean-color sensors are now in orbit, and others are scheduled to fly during the next few years. They include the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the MODerate resolution Imaging Spectrometer (MODIS), the Medium resolution Imaging Spectrometer (MERIS), the Polarization and Directionality of the Earth’s Reflectance (POLDER), the Ocean Color Monitor (OCM), the Visible Infrared Imager Radiometer Suite (VIIRS) (scheduled for 2011 and 2014), the Ocean Land Colour Instrument (OLCI) (scheduled for 2013), and the Second-Generation Global Imager (SGLI) (scheduled for 2014) (see http://www.iocccg.org). These sensors have been designed to provide large-scale, long-term views of phytoplankton abundance for studies of biogeochemical cycles. They possess adequate spectral bands to retrieve the concentration of plant pigments and, for some sensors, other variables such as the concentration of colored dissolved organic material, and important ocean carbon pool.

* SIO/UCSD, Climate, Atmospheric Science, and Physical Oceanography Division, 9500 Gilman drive, La Jolla, California 92039-0224; rfrouin@ucsd.edu; phone 1 858 534 6243; **Hubert.Loisel@univ-littoral.fr; phone 33 321 99 6420; ***Antoine.Poteau@obs.vlfr.fr; phone 33 493 76 3912
The passage from satellite radiance to biological variables is generally accomplished in two steps, namely (1) correction of atmospheric effects to retrieve normalized water-leaving radiance, and (2) application of bio-optical algorithms to the retrieved normalized water-leaving radiance. If the first step is not accomplished successfully, the bio-optical algorithms are useless. One fundamental activity, therefore, is to make sure that the normalized water-leaving radiance is retrieved within the acceptable uncertainty limits for scientific applications. This includes not only comparing estimates of normalized water-leaving radiance with in situ measurements, but also evaluating the atmospheric correction scheme and verifying the radiometric calibration of the ocean-color sensor.

Retrieving normalized water-leaving radiance from satellite radiance is not an easy task, because typically 90% or more of the top-of atmosphere (TOA) signal at ocean-color wavelengths is composed of photons that have not interacted with the water body. Some atmospheric effects are straightforward to correct (molecular scattering, ozone absorption), others more difficult to take into account (aerosol scattering and absorption). The current, standard atmospheric correction schemes (e.g., Gordon, 1997) experience difficulties in the presence of absorbing aerosols (desert dust, pollution-type particles), whitecaps, and high sediment loads (non-zero water-leaving signal in the near infrared). In the coastal zone, adjacency effects and influence of the bottom may also yield erroneous normalized water-leaving radiance. These conditions, therefore, must be sampled in validation activities.

One approach to evaluation of normalized water-leaving radiance is to organize dedicated experiments in specific environments, especially those that are likely to experience atmospheric correction problems (Clark et al., 1997), during which both normalized water-leaving radiance and aerosol optical properties are measured. The aerosol measurements are needed to interpret differences between satellite and in situ values of normalized water-leaving radiance and, eventually, to adjust atmospheric correction schemes. These experiments are generally costly. They cannot be carried out over the full range of expected oceanic regimes and atmospheric types.

Another approach is to use long-term buoys, such as MOBY (Clark et al., 1997) and BOUSSOLE (Antoine et al., 2004, 2008), or permanent offshore platforms, such as the Venice Tower (Zibordi et al., 2002), equipped with automatic instrumentation. One major advantage is that long-term time series can be collected systematically and operationally, but a drawback is that the data is limited to a few locations. This is a serious issue in the coastal zone, where biological diversity is large and water composition complex and highly variable, and where complicated mixtures of aerosols may occur.

A complementary approach, developed during 1997-2003 as part of the SIMBIOS project, exploits cruises of opportunity by research vessels or merchant ships. This approach requires instrumentation that can provide quality data of both normalized water-leaving radiance and aerosol optical thickness (i.e., the basic ocean-color variables) from a moving platform at sea without interfering with the other ship activities. The requirements led to the concept of the SIMBAD field radiometer (Deschamps et al., 2004) and its advanced version, SIMBADA (Bécu, 2003).

In the following, the basic features of the SIMBADA radiometer are summarized, and the radiometric calibration and data processing are described. SIMBADA measurements of marine reflectance and aerosol optical thickness are then compared with those made by other instruments (i.e., SPMR, PRR, MER, BOUSSOLE radiometers, and TSRB for marine reflectance; CIMEL and Microtops for aerosol optical thickness) during ACE-Asia (16 March to 17 April 2001, Northwest Pacific Ocean and Japan Sea) and AOPEX (31 July to 17 August 2004, Western Mediterranean Sea). Improvements in data processing that may lead to more accurate SIMBADA estimates are finally discussed.
2. THE SIMBADA RADIOMETER

The portable SIMBADA radiometer (Figure 1) is an advanced version of the SIMBAD radiometer (Deschamps et al., 2004). It was designed to provide measurements of both marine reflectance and aerosol optical thickness in spectral bands approximately 10 nm wide centered at 350, 380, 350, 380, 412, 443, 490, 510, 565, 620, 670, 750, and 870 nm.

Aerosol optical thickness is obtained by viewing the Sun, and marine reflectance by viewing the ocean surface at a nadir angle of 45 degrees and a relative azimuth angle of 135 degrees. The measurements are made through a vertical polarizer which, when viewing the surface, reduces substantially sunlight reflected in the instrument field-of-view (Fougnie et al., 1999; Deschamps et al., 2004). Data is only collected in clear sky situations, i.e., when satellite ocean-color retrievals are made.

Same optics and detectors, but different electronic gains are used in Sun- and ocean-viewing modes. The measurements are made simultaneously in all the spectral bands (one collimator and detector for each band), but viewing the Sun and the ocean surface is accomplished sequentially. Field-of-view is 3 degrees. Frequency of measurements is 10 Hz. Data is only collected in clear sky situations, i.e., when satellite ocean-color retrievals are made.

The instrument also acquires data on viewing angles (inclinometer, magnetometer) and internal control parameters, i.e., time, geographical location (GPS), temperature, and atmospheric pressure. These data are used in the processing of the raw data into geophysical variables.

![Figure 1: The SIMBADA radiometer and its spectral bands.](image-url)

3. RADIOMETRIC CALIBRATION

The radiometric calibration of the instrument, including characterization of noise and and detector linearity, is performed using a 0.5 m diameter integrating sphere with a 0.2 m aperture (Figure 2). Illumination is achieved by two (internal and external) tungsten lamps and one (external) Xenon lamp. Attenuators allow for variable radiance levels. Stability is better than 1%.
The integrating sphere can only be used to calibrate the SIMBADA radiometer in ocean-viewing mode (high detector gain), because its radiance is too low for measurements in Sun-viewing mode (low detector gain). The calibration in Sun-viewing mode, therefore, is performed in the field, on top of Mount Laguna (1896 m), California, using the Bouguer-Langley method.

The calibration coefficient in ocean-viewing mode, $K_h$, can also be estimated from the calibration coefficient in Sun-viewing mode, $K_s$, using the ratio of the electronic gains, $g$, and the solid angle, $Ω$, of the instrument angular aperture ($3.456 \, 70.028$ degrees), i.e., $K_h = K_s/(Ω \cdot g)$. The ratio of the electronic gains can be obtained by viewing a Spectralon plaque illuminated by the Sun in Sun- and ocean-viewing modes. If $CN_s$ and $CN_i$ denote the respective numerical counts, then $g = CN_s/CN_i$. This alternative calibration method, which does not rely on an artificial source of light, is practical in the field.

4. DATA PROCESSING

Processing the raw SIMBADA data into aerosol optical thickness and marine reflectance involves a number of steps and corrections (Deschamps et al., 2004; Bécu, 2003).

The passage to aerosol optical thickness, which only uses the highest numerical counts, is straightforward. The vertical polarizer has minimum influence since direct sunlight is not polarized.

For marine reflectance, $R_w$, the numerical counts, after subtraction of the dark signal, are transformed into radiance (using the calibration coefficients for ocean-viewing measurements) and reflectance (using an estimate of the downward solar irradiance). Downward solar irradiance, $E_s$, is calculated as a function of solar zenith angle, aerosol optical thickness (determined from the SIMBADA measurements), and ozone amount (obtained from satellite data), which is accurate for cloudless skies.

Only ocean surface measurements made within ±5 degrees of the 45-degree nadir angle are kept, and the smallest values over a series of measurements (i.e., 100 measurements in 10 seconds) are selected. A correction is made for
the residual skylight (the surface is not completely flat), as a function of aerosol optical thickness and type (i.e., Angström exponent), and wind speed. This correction, in terms of reflectance, is typically 0.0007 at 350 nm and 0.00005 at 870 nm.

To account for eventual contamination by whitecaps, ship reflection, and eventually sun glint (i.e., other perturbations than reflected skylight), the reflectance at 870 nm is subtracted from the reflectance in the other spectral bands. This assumes that the water body reflectance is null at 870 nm (a good assumption, except in very turbid waters), and that the contamination does not depend on wavelength. However, this correction is not performed when the raw reflectance at 870 nm is above 0.004. Beyond this threshold, the data are discarded.

Finally, the polarized reflectance values are transformed into total reflectance, which includes correcting the measurements for polarization by water molecules and particles. The correction, relatively small at the scattering angles of interest, typically 150 degrees below water (degree of polarization is less than 15%), is performed assuming that the water body contains only molecules.

The final marine reflectance is generally close to the raw reflectance (i.e., the residual effects of skylight reflection and water body polarization are small). This attests of a good radiometer concept. The uncertainty budget for marine reflectance is ±0.0015 to ±0.0010 (ultraviolet to blue), ±0.0004 (green), and ±0.0002 (red). The uncertainty budget for aerosol optical thickness, mainly due errors in the Bouguer-Langley calibration, is ±0.02 (ultraviolet to green) and ±0.01 (red to near infrared).

5. EVALUATION DURING ACE-ASIA AND AOPEX

Measurements of marine reflectance and aerosol optical thickness made by SIMBADA radiometers during ACE-Asia (16 March to 17 April 2001, Northwest Pacific Ocean and Japan Sea) and AOPEX (31 July to 17 August 2004, Western Mediterranean Sea) were compared with those by other instruments (i.e., SPMR, PRR, MER, BOUSSOLE radiometers, and TSRB for marine reflectance; CIMEL and Microtops for aerosol optical thickness). Q factors (Mueller et al., 2003) were used, with the relevant geometry and chlorophyll concentration measured from filtered samples (HPLC, fluorometry), to transform, when applicable, the marine reflectance measurements into nadir values, i.e., into $R_n = \pi L_n(\theta_s, \theta_v = 0)/E_s$. For ACE-Asia, the data from the various instruments, including SIMBADA, were mapped to the SeaWiFS wavelengths. For AOPEX only the measurements obtained when the ship was at the Boussole site are used in the comparisons.

The aerosol optical thickness comparisons are displayed in Figure 3 (ACE-Asia) and Figure 5 (AOPEX). The values obtained by all instruments agree within theoretical errors, mainly due to uncertainties in the Bouguer-Langley calibration, estimated at about ±0.02 in the visible and ±0.01 in the red and near infrared.

Marine reflectance, after correction for bi-directional effects, does not exhibit biases between various estimates, which generally agree within ±10%. The Q factor correction makes the SIMBADA estimates closer to the other estimates. In some cases, for example on 17 and 30 March 2001 during ACE-Asia, discrepancies are larger, which is partly or principally explained by differences in $E_s$ values (not shown here). Some compensation may occur, however, for example on 15 April 2001 during ACE-Asia (both MER $E_s$ and $L_n$ values are relatively lower than the PRR, SIMBADA, and SIMBAD values). This may be due to the presence of clouds at the time of measurements by the underwater radiometers, but not at the time of the SIMBADA measurements.
Figure 3: Comparison of SIMBADA, SIMBAD, and Microtops aerosol optical thickness measurements during ACE-Asia.

Figure 4: Comparison of SIMBADA, SIMBAD, PRR, and MER marine reflectance ($R_w$) measurements during ACE-Asia.
Figure 5: Comparison of SIMBADA and CIMEL aerosol optical thickness during AOPEX (ship at the BOUSSOLE site).

Figure 6: Comparison of SIMBADA, SPMR, Boussole, and TSRB marine reflectance ($R_w$) during AOPEX (ship at the BOUSSOLE site).
5. CONCLUSIONS

The SIMBADA radiometer is a useful concept to check the radiometric calibration of ocean color sensors and evaluate ocean color products. Since the instrument measures not only marine reflectance but also aerosol optical thickness, it allows an interpretation of discrepancies between satellite-derived and measured marine reflectance, which may guide the development of improved atmospheric correction algorithms. SIMBADA measurements complement those made onboard fixed platforms (MOBY, Boussole, and AERONET-OC), since they can be made in varied oceanic and atmospheric regimes (they are not limited to a specific site), allowing ocean color data to be collected over the global oceans.

The theoretical accuracy of the SIMBADA measurements has been evaluated experimentally in comparisons with measurements from other instruments, acquired during ACE-Asia in the Northwest Pacific Ocean and Japan Sea (March-April 2001), AOPEX in the Mediterranean Sea (July-August 2004). The SIMBADA values agree with those of the other instruments, to within ±0.02 for aerosol optical thickness and ±10% for marine reflectance. No systematic bias is detected. Larger differences in marine reflectance are partly or principally explained by differences in solar irradiance (calculated, not measured for the SIMBADA radiometer). The measurements of marine reflectance made by underwater radiometers exhibit differences as large as those with the SIMBADA values. The Q factor correction makes the marine reflectance from SIMBADA closer to the marine reflectance from the other instruments. Additional comparison experiments, however, are necessary to definitely assess the accuracy of the SIMBADA measurements.

To improve the accuracy of the SIMBADA marine reflectance and extend measurements to highly turbid waters and cloudy skies, the following modifications to the instrument and processing algorithm are envisioned:

- First, the aerosol model, via the Angström exponent, will be taken into account in the calculation of the downward solar irradiance. A simple relation between Angström exponent and anisotropic factor of the aerosol phase function, the model parameter of interest, will be used. Alternatively, downward solar irradiance, instead of being calculated, will be measured by an external irradiance sensor, with the data acquired by the SIMBADA radiometer via radio waves, allowing measurements of marine reflectance under cloudy skies.

- Second, the correction of polarization effects by the water body will consider not only molecules, but also hydrosols. Simulations performed using the Monte Carlo method for a few cases (Deschamps et al., 2004) will be extended to include various combinations of detritus/mineral and phytoplankton particles, following Chowdhary et al. (2006).

- Third, marine reflectance will not be considered equal to zero at 870 nm, but estimated by approximating the spectral dependence of the marine reflectance in the red and near infrared (depends essentially on water absorption). This will allow extension of the SIMBADA data processing to highly turbid waters.

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5. REFERENCES


