In-flight Calibration of Satellite Ocean-Colour Sensors

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In-flight Calibration of Satellite Ocean-Colour Sensors

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To the Memory of Andreas Neumann,
Esteemed Colleague and Friend

Andreas Neumann (1957-2012)
In-Flight Calibration of Satellite Ocean-Colour Sensors

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Introduction

Robert Frouin, Andreas Neumann

Radiometric calibration of an optical sensor is the process that establishes the link between sensor output signal (voltage, digital number) and absolute physical values of the sensor input signal (radiant energy), i.e., the overall transfer function of the sensor. It is part of the sensor characterization, with respect to spectral and radiometric parameters. The parameters to be determined during the calibration process depend on sensor principle, detector type, and application.

Accurate radiometric calibration of space borne ocean-color sensors is essential to retrieving geophysical variables quantitatively in terms of absolute values (concentrations of water constituents, inherent optical properties, aerosol content in the atmosphere, etc.). The retrieval algorithms use values of spectral radiance (or derived reflectance) in the inversion procedures, and the accuracy of the derived product strongly depends on the accuracy of the radiance measurement. Furthermore, the evaluation of the remotely sensed quantities, including models and algorithms, requires a link between the data acquired in orbit and surface-based measurements.

The accuracy requirements for absolute calibration are especially demanding in ocean-color remote sensing, because the signal to extract is relatively small compared with the measured signal, dominated by atmospheric scattering. More than 90% of the measured radiance in the blue and green may originate from the atmosphere and surface, i.e., may not contain any information about the water body. Atmospheric correction subtracts the atmospheric scattering and surface signal, but amplifies the errors on the retrieved ocean parameters due to imperfect radiometric calibration. Consequently, retrieving marine reflectance to within ±5% in the blue in clear waters, the objectives of major satellite ocean-color missions, requires knowing the top-of-atmosphere reflectance to within a fraction of one percent. The situation is further complicated by the existence of several satellite missions that employ independently a variety --but not the same-- calibration techniques to achieve good performance. Consequently, the ocean-color products from different instruments may be biased, making it difficult to merge the data correctly and generate consistent long-term time series.

Radiometric calibration is generally performed in the laboratory before launch, but accuracy is not perfect and sometimes insufficient. In fact, this engineering calibration refers to standards while science applications require a calibration with respect to solar irradiance. The calibration standards provide reference light sources with known spectral distribution, but due to lower temperature they generally do not correspond to the spectrum of the Sun, with signals too low in the blue and too high in the red. The pre-launch calibration covers all measurements by laboratory means before instrument delivery that describe spectral and radiometric sensor performance. The objective is to provide an initial set of parameters that serves as reference for monitoring in-orbit performance and/or in-orbit calibration as well as initial functions to be used for data
processing to basic physical values. The procedures involve extensive laboratory set-ups and careful and time-consuming measurements.

Pre-launch calibration needs to be checked in orbit, because instruments are subject to degradation after launch. The reasons include out-gassing when the satellite leaves the atmosphere, aging of the optics, contamination of optical parts in orbit, and exposure of optical parts, detectors, and electronics to sun light and/or radiation (ultraviolet, particles). In-orbit calibration is therefore essential to ensure valuable data during the lifetime of the instrument through monitoring of sensor stability. The process covers all measurements made in orbit to either re-calibrate the sensor or to monitor and quantify changes in instrument parameters. This gives the basis to account for possible sensor changes in the data processing and make sure that the observed changes exist in reality, i.e., are the manifestation of geophysical phenomena. To address sensor degradation, satellite platforms are often equipped with onboard calibration devices. Indirect, so-called “vicarious”, methods are also used, either alternatively (in the absence of onboard calibrators) or to check the onboard device.

Absolute calibration in orbit of ocean-color sensors is usually performed using the Sun as calibration source. An onboard diffuser is required to convert the Sun irradiance into radiance. The advantages are that the Sun is the most stable light source, the complete sensor performance from entrance optics to detector is accounted for, and the nadir measurement can be referred to the natural illumination source. A problem is the degradation of the diffuser and the use of moving parts to position the diffuser in front of the entrance optics. Vicarious techniques based on earth target observations can be used alternatively and complementarily. They include the Rayleigh scattering technique for blue spectral bands, which exploits the fact that molecular scattering can be computed accurately and may dominate the top-of-atmosphere radiance in some situations. The absolute calibration in the blue bands can then be transferred to longer wavelengths using the specular reflection of the sun over the ocean. The top-of-atmosphere radiance can also be computed from measurements of marine reflectance and atmospheric parameters using an accurate radiation transfer code. Since atmospheric correction is necessary to retrieve water-leaving radiance (the variable of interest), a “system” vicarious calibration, in which retrieved and measured water-leaving radiance are forced into agreement, may ultimately allow sufficient accuracy, within the ±5% requirement on marine reflectance, for science applications.

For relative calibration in orbit, i.e., monitoring and quantification of sensor parameters with respect to a reference status (pre-launch calibration or initial post-launch status), one may use built-in light sources like lamps or diodes and extra-terrestrial sources like the moon. Lamps do not necessarily cover the entire optical path, depending on construction, but they allow linearity checks and other features (spectral properties). The problems are long-term stability and spectral irradiance distribution. The moon, on the other hand, cover the entire path from entrance optics to detector, but it does not fill the total field of view for push-broom instruments, and may cause problems due to spatial heterogeneity. Inter-band and multi-temporal calibration can also be achieved by viewing high and dense clouds. Such clouds are white spectrally, isotropic, and minimally influenced by
the surface and atmosphere below and above. Other suitable targets are desert sites, provided that they are homogeneous spatially and stable with time.

Since the Coastal Zone Color Scanner (CZCS) onboard NIMBUS-7, ocean-color sensors have matured, capabilities have improved, systems are no longer experimental but operational, and several satellites carrying different sensors are presently providing ocean-color data on a regular basis over long time periods. These sensors may acquire data of the same phenomena at distinct overpass times with specific viewing geometry and spectral and spatial resolution. The separate and independent measurements may complement each other (e.g., to improve spatial coverage of ocean-color products) and allow new science through synergistic investigations. Therefore a common, absolute scale is necessary for all sensors. This is especially important for generating consistent long-term records from multiple satellites. Since all sensors are calibrated before launch to a laboratory standard, the individual calibrations can be linked together using transfer radiometers. Once in orbit, however, the situation is more complicated, but inter-calibration of the sensors can be achieved by common measurements of dedicated targets or sources like the Sun, the Moon, and selected Earth sites.

This report provides a review of techniques developed and employed for the radiometric calibration of satellite ocean-color sensors while they operate in orbit. In Chapter 1, basic definitions and concepts are given, as well as accuracy requirements to generate ocean-color products of sufficient quality for science applications. In Chapter 2, the techniques that utilize onboard calibration devices, including lamps and diffusers, require a specific spacecraft maneuver, and/or use Space targets (Sun and Moon) are described. In Chapter 3, the focus is on vicarious calibration, absolute and relative, using natural Earth targets, including “system” vicarious calibration. The Earth targets may be located at the surface or in the atmosphere, over the ocean or land, and they may exploit specific physical processes, such as molecular scattering and Fresnel reflection, and viewing conditions. All the techniques, whether using onboard artificial light sources or Space and Earth targets, are presented with their accuracy, advantages, and limitations. Application examples are given. Finally, in view of the available techniques and their characteristics, recommendations are given on how to proceed with the radiometric calibration of ocean-color sensors during operational phase, in order to generate and maintain quality retrievals of water-leaving radiance during mission lifetime, including selection of calibration sites, requirements for in situ measurements, and sensor inter-calibration.
Chapter 1. Definitions and Requirements

Howard R. Gordon

1.1 Scope of the Review

The goal of this introductory review is to provide (1) the basic definitions of the quantities involved in the radiometric calibration of ocean color sensors, (2) the principle ideas and methodology of radiance and reflectance-based calibration, (3) some of the issues relating to non-ideal sensors (sensor characterization), (4) the calibration accuracy that is required to generate ocean color products with the desired accuracy, and (5) vicarious calibration methods for achieving this accuracy.

1.2 Definitions and Concepts

All ocean color sensors measure radiance. Figure 1.1 provides the operational definition of radiance. A detector of area $A_d$ (sensitive only to radiation in a small band of wavelengths $\lambda \pm \Delta \lambda/2$ around a central wavelength $\lambda$) is allowed to view a scene with a field of view that is restricted to the solid angle $\Omega$. If the radiant power measured by the detector is $P$, then the detector is said to measure a radiance $L$ given by

$$L(\lambda) = \frac{P}{A_d \Omega \Delta \lambda}.$$ 

The SI units of radiance are W/(m$^2$-Steradian-nanometers), but an equally popular unit is mW/(cm$^2$-Steradian-µm). Note that in this equation $P$ is proportional to $\Delta \lambda$ so as $\Delta \lambda \to 0$, $L$ approaches a well-defined limit. The radiance measured in this way is sometimes referred to as the field radiance as it is not always associated with a physical surface (e.g., the radiance of the sky). The device shown — the detector plus some form of solid angle restrictor — is called a radiometer. If the radiometer is pointed toward a physical surface, and if there are no losses (by scattering or absorption) or gains (by light sources or emitting gases) between the surface and the radiometer, e.g., if the surface and the radiometer are separated by a short distance in vacuum (or practically, in the visible spectrum, by a short distance in air), then the radiance measured by the radiometer is also the radiance leaving the surface: in the absence of losses, the radiance is conserved in propagating from the surface to the radiometer.

The ocean color sensors of interest here are located at the top of the atmosphere (TOA) aimed toward the Earth in such a manner as to measure the radiance escaping from the TOA. They measure the radiance $L_t$ that is the result of sunlight being reflected from the ocean-atmosphere system. The associated reflectance $\rho_t$ is defined by

$$\rho_t = \frac{\pi L_t}{F_0 \cos \theta_0},$$
where $F_0$ is the instantaneous solar irradiance (the radiant power of the solar beam per unit area, perpendicular to the Sun's rays, measured at the top of the atmosphere) and $\theta_0$ is the solar zenith angle. In fact, for the radiance measured anywhere within the ocean-atmosphere system the associated reflectance is defined in the same manner as above.

We shall use the term *diffuse source* to represent a (plane) source of radiance for which the measured radiance is independent of the angle (with respect to the normal to the plane) with which it is viewed in the measurement of the radiance. A sheet of white paper (non-glossy) illuminated by a small distant source of light and viewed in reflection is a good approximation to a diffuse source (and is referred to as a *Lambertian reflector*). Near-Lambertian reflectors with known (and usually near 100% reflecting) are usually referred to as calibration *plaques or reflectance plaques*. Another example is a spherical shell painted on the inside with flat white paint, illuminated by sources that are inside, and having a circular hole to allow light to escape. The hole itself then approximates a diffuse source in that the radiance exiting the plane of the hole is nearly independent of direction. Devices such as this are commercially available and are referred to as a *calibration spheres*.

### 1.3 Radiance- and Reflectance-Based Calibration of Ideal Sensors

The detector in Figure 1.1 is a device that produces an electrical output dependent on the radiant power falling on its surface. Calibration is the act of determining the relationship between the electrical response and the magnitude of the radiance inducing the electrical response. There are two methods of calibration that are useful for ocean color remote sensing. These are *radiance-based*, where the radiometer is aimed toward a source of known radiance, and *reflectance-based*, where the radiometer is aimed toward an illuminated target of known reflectance. These methods are described in this section.

**Radiance Based Calibration:**

Consider an ideal sensor (assumed to have an electrical response that is a linear function of the radiant power incident on it) that responds only to radiation in a small band of wavelengths $\lambda \pm \Delta \lambda/2$ around a central wavelength $\lambda$. Then viewing a diffuse source (calibration source) of known radiance $L_c(\lambda)$, e.g., a calibration sphere or a plaque illuminated by a known power per unit area, the sensor's response $V_c$ (voltage, current, etc.) will be

$$V_c(\lambda) = k_t(\lambda) L_c(\lambda).$$

Then if the same sensor views a scene of radiance $L(\lambda)$, the sensor's response will be

$$V(\lambda) = k_t(\lambda) L(\lambda) = \left[ V_c(\lambda)/L_c(\lambda) \right] \times L(\lambda),$$
so the measurement of \( V(\lambda) \) the provides measurement of the radiance of the scene. The MODIS sensor has an on-board calibration sphere that enables the *calibration constant* \( k_L(\lambda) \) to be monitored with time.

**Reflectance-based calibration:**

Let the same sensor view a Lambertian reflectance plaque of reflectance \( R_p \), defined to be the power per unit area reflected (reflected *irradiance*) from the plaque divided by the power per unit area illuminating the plaque (incident *irradiance*). If the plaque is illuminated by irradiance \( E_p \) the reflected radiance observed by the sensor will be \( R_p E_p / \pi \), and the sensor responds with an electrical signal

\[
V_p(\lambda) = k_L(\lambda) R_p(\lambda) E_p(\lambda) / \pi.
\]

Now, if the sensor views a scene that is illuminated by an irradiance \( E \), its response will be

\[
V(\lambda) = k_L(\lambda) \rho(\lambda) E(\lambda) / \pi,
\]

so

\[
V(\lambda) / V_p(\lambda) = \rho(\lambda) E(\lambda) / R_p(\lambda) E_p(\lambda).
\]

If \( E(\lambda) \) and \( E_p(\lambda) \) are the same (as would be the case if the reflectance plaque was carried along with the sensor in orbit and illuminated by the sun as in Figure 1.2), then

\[
V(\lambda) / V_p(\lambda) = \rho(\lambda) / R_p(\lambda),
\]

and measurement of \( V(\lambda) \) provides \( \rho(\lambda) \). Reflectance plaques are in fact attached to the sensors on SeaWiFS and MODIS to monitor the calibration in orbit as discussed next.

Consider the situation displayed in Figure 1.2. The sensor first views the Earth and measures a voltage or current \( V_t = k_r L_t = k_r F_0 \rho_t \cos(\theta_0) / (\pi a^2) \), where \( a \) is the Earth-Sun distance in A.U. Then the sensor views the in-orbit reflectance plaque and measures a voltage or current \( V_p = k_r L_p = k_r F_0 R_p \cos(\theta_p) / (\pi a^2) = K_r R_p \cos(\theta_p) \). Note that \( R_p \) is a known function (measured in the laboratory prior to launch) of the viewing angles \( \theta_0 \) and \( \theta_p \). Therefore,

\[
\rho_t \cos(\theta_0) = \frac{V_t}{V_p} R_p \cos(\theta_p),
\]

The reader should note that \( F_0 \) is not needed to find \( \rho_t \). This is important because error in measurements of \( F_0 \) would cause a similar error in computing the reflectance associated with a radiance-based measurement of \( L_t \).
It has been the experience that the reflectance of solar diffuser plaques in orbit will degrade with time. If account is not taken of this degradation; the estimated $\rho_t$ will be too large. This is remedied by monitoring the stability of $R_P$ (SeaWiFS uses the moon, and MODIS uses an onboard monitoring device).

1.4 Characterization of Non-Ideal Sensors

Assuming the calibration procedures described above are exact, i.e., the radiance of the calibration sources or the reflectance of the calibration plaques are precisely known, all sensors still have non-ideal performance that must be understood to properly utilize them. These need to be characterized. Among these are

- **Out-of-band response**: the detector responds not only to radiant power in a small band of wavelengths $\lambda \pm \Delta \lambda/2$ around a central wavelength $\lambda$, but has some response to radiant power outside this interval.
- **Polarization sensitivity**: the sensor's response is dependent on the polarization of the radiance it is measuring.
- **Bright target response**: a given pixel may respond not only to radiant power within its field of view, but to power outside its field of view as well (this is particularly serious for array detectors).
- **Non-linearity**: the relationship between the electrical response and the radiant power is non-linear.

We will discuss the first three of these in some detail.

**Out-of-Band Response:**

Sensors do not view the earth with narrow spectral bands as we have been assuming (Gordon, 1995). Figure 1.3 shows the pre-launch measured spectral response of SeaWiFS Band 8 (nominally 865 nm). The quantity provided $S_8(\lambda)$ is the electrical output of SeaWiFS from a nearly monochromatic input of radiance $1 \text{ mW/(cm}^2\text{-Steradian-\mu m)}$ at $\lambda$. Clearly, the notion that the sensor views only a narrow band of wavelengths is an oversimplification.

For a broad spectral source, e.g., the ocean-atmosphere system, the output of the sensor is proportional to

$$\langle L(\lambda) \rangle_S = \frac{\int L(\lambda) S_i(\lambda) d\lambda}{\int S_i(\lambda) d\lambda}$$
For SeaWiFS 865 band, approximately 9% of the Rayleigh component \( \langle L_r(\lambda) \rangle_{S_a} \) of the radiance at the TOA (\( \propto \lambda^{-4} \)) is backscattered from wavelengths below 600 nm! Thus, the influence of even an apparently small amount of out-of-band sensitivity can be significant, especially when the radiance is a strong function of wavelength. With out-of-band response, the “measured” radiance is dependent on the spectral distribution of the calibration source, which could be the moon, a calibration lamp, solar diffuser, or in the case of vicarious calibration, the ocean (Figure 1.4). Even if the radiances at \( \lambda_0 \) from the various sources, in the somewhat pathological example, for the \( S(\lambda) \) shown in Figure 1.4 are all the same at \( \lambda_0 \), the “measured” radiances will all be different. This suggests vicarious calibration, i.e., using the radiance reflected from the ocean-atmosphere system, will be best because the spectral distribution of the calibration source (the ocean-atmosphere system) will similar to that of the radiance the sensor will actually be measuring in operation; however, characterization of the out-of-band response is still essential.

Polarization Sensitivity

The polarization sensitivity of a radiometer can be understood in the following manner (Gordon et al., 1997). Shine linearly polarized radiances from a source of radiances \( L_{\text{Source}} \) into the instrument. Let the polarization (direction of \( E \) field) be specified by the angle \( \chi \), in a plane normal to the direction of propagation, with respect to some direction fixed in that plane with respect to the radiometer.

\[ L_m(\chi) = M_{11} L_{\text{Source}} \left[ 1 + a \cos^2(\chi - \delta) \right] \]

where \( M_{11} \) is a calibration constant (\( M_{11} = 1 \) if the radiometer is perfectly calibrated). If the incident light is partially polarized rather than fully polarized, i.e., has a degree of polarization \( P \) (\( 0 \leq P \leq 1 \)), then

\[ L_m(\chi) = M_{11} L_{\text{Source}} \left[ 1 + aP \cos 2(\chi - \delta) \right] \]

To calibrate the instrument, we use an unpolarized source (\( UP \)) of known radiance, so
\[ L_{m}^{UP}(\chi) = M_{11} L_{\text{Source}}^{UP}, \]

provides \( M_{11} \). Note that this would be the measured radiance for \( \alpha = 0 \), i.e., an instrument with no polarization sensitivity. Call this \( L_{\text{True}} \). Then

\[ L_{m}(\chi) = L_{\text{True}} \left[ 1 + \alpha P \cos 2(\chi - \delta) \right], \]

and if the polarization sensitivity is not addressed, the error in the associated radiance could be as much as \( \pm \alpha P \).

Given \( \alpha \) and \( \delta \) (determined through pre-launch characterization) along with \( P \) and \( \chi \) (characteristic of the radiance exiting the atmosphere), we can find \( L_{\text{True}} \) from \( L_{m} \). It should be noted, as we shall see later, that a radiance error of 1\% at 412 nm results in a water-leaving radiance error of \( \sim 10\% \) in low-chlorophyll Case 1 waters.

Potentially, how large can the error due to polarization sensitivity be for ocean color sensors? Consider a specific example. Figure 1.5 shows the amplitude \( (\alpha) \) of the polarization sensitivity as a function of angle of incidence (AOI) on the scan mirror of MODIS on Terra. (Note that AOI's of 15 and 60 degrees are at the edges of the MODIS scan, west and east, respectively, while 38 deg is at the center of the scan.) The blue curves are for 412 nm (Band 8) and the red curves for 869 nm (Band 16). For each spectral band, the individual curves refer to a specific side of the two-sided scan mirror. Thus, the polarization sensitivity can be several percent in the blue.

To understand the magnitude of the error the polarization sensitivity in Figure 1.5 could induce we need to know the degree of polarization of the radiance. In the blue, approximately 80\% of the total radiance is due to Rayleigh scattering in the atmosphere. Figure 1.6 provides the degree of polarization of the Rayleigh component of the total radiance as a function of position for two successive orbital passes of Terra in December. Notice that there are significant regions of the orbit where the polarization of the Rayleigh component is above 60\%. Combining this with the polarization sensitivity amplitude suggests that the induced radiance error at 412 nm could be as much as 3.5\% of the total radiance, which as we will see later is much too large (it could lead to a normalized water-leaving error of \( \sim 35\% \)). Thus, polarization sensitivity is a significant issue with MODIS, and may be in future sensors as well. It must be carefully characterized in future sensors if they are to fulfill their promise.

**Bright target/internally scattered light.**

Modern sensors have large focal planes containing linear or rectangular arrays of detectors. A cloud on one part of the focal plane can influence the signal on another part focal plane through internal reflections. This is shown schematically in Figure 1.7. The green circle represents a cloud superimposed over the four focal planes of MODIS. The vertical strips are the individual detector arrays with each strip corresponding to a different spectral band. Each element in an array corresponds to a single pixel. In the blue, the reflectance of a cloud is 4-5 times that of the ocean-atmosphere system, while in
the NIR the associated factor is 30-40 times. Radiance from the cloud can reflect off a focal plane and be scattered within the focal chamber to another part of the focal plane and thus, even though the cloud might be several pixels from a particular detector, it could provide a significant contribution to the measured radiance, especially in the NIR. This effect must be included in pre-launch characterizations.

1.5 Calibration requirements for Ocean Color Sensors

Figure 1.8 is a schematic of the remote sensing problem. Solar irradiance $F_0$ is incident at the top of the atmosphere (TOA) at a solar zenith angle $\theta_0$. This results in an upwelling radiance $L_u(z_1, \theta_w, \phi_w)$, just beneath the sea surface, a water-leaving radiance $L_w(z_1, \theta, \phi)$, just above the sea surface, and a radiance $L_t(0, \theta, \phi)$ exiting the TOA. The goal of remote sensing is, given $L_t$, find $L_w$. Actually, we want $[L_w]_N = L_w/t_s\cos\theta_0$ (Gordon and Clark, 1981), where $t_s$ is the transmittance of $F_0$ from the TOA to the sea surface. $t_s$ is called the diffuse transmittance because it is a transmittance of irradiance, as opposed to the direct transmittance which is the transmittance of a beam of collimated radiation.

We will use reflectance $\rho$ rather than radiance $L$ to describe the processes. As described earlier, they are related by

$$\rho = \frac{\pi L}{F_0 \cos \theta_0}$$

The TOA reflectance is (Gordon and Wang, 1994)

$$\rho(\lambda) = \rho_r(\lambda) + \rho_a(\lambda) + t_v(\lambda)t_s(\lambda)[\rho_w(\lambda)]_N,$$

where $\rho_r(\lambda) = \rho_r(\lambda) + \rho_ra(\lambda)$, $\rho_r(\lambda)$ is the Rayleigh reflectance in the absence of aerosols, $\rho_a(\lambda)$ is the aerosol reflectance in the absence of Rayleigh Scattering, $\rho_ra(\lambda)$ is the reflectance component for photons that have been both Rayleigh and aerosol scattered, $t_v$ is the diffuse transmittance from the sea surface to the sensor, and $[\rho_w(\lambda)]_N$ is the normalized water-leaving reflectance corresponding to $[L_w]_N$, the normalized water-leaving radiance: $[\rho_w(\lambda)]_N = \pi [L_w]_N/F_0$. Typical values for the terms in the above equation for the waters off Hawaii obtained from SeaWiFS are shown in Figures 1.9-1.12 (Courtesy SeaWiFS Project and Dennis Clark). Of particular interest for calibration purposes is the observation that for these waters, $\rho_w/\rho_r$ ranges from 12% at 412 nm to 5% at 555 nm. Note that the increase in $\rho_w$ from 765 to 865 nm is a measurement artifact (the reflectance actually continues to decrease).

Figure 1.13 shows the variation of $[\rho_w(\lambda)]_N$ with pigment concentration (the pigment concentration is the sum of the concentrations of Chlorophyll $a$ plus Phaeophytin $a$) at four wavelengths ($\lambda = 443$, 520, 550, and 670 nm) for Case 1 Waters (Gordon 1997). The red line on each panel indicates 0.001 on the scale. Generally see that the reflectance at 443 nm rapidly decreases with pigment concentration, and is only a weak function of the concentration in the green. These data are not corrected for instrumental self-shading,
which is strongly dependent on absorption, so the reflectance at 670 nm is too low by roughly a factor of 1.5-2.

After considerable experience with the CZCS proof-of-concept mission, the originally announced goal for future ocean color sensors (SeaWiFS, MODIS, etc.) was that:

*The uncertainty in the (normalized) water-leaving radiance retrieved from the sensor in oligotrophic waters at 443 nm should not exceed 5%, and uncertainty in Chlorophyll should be $\leq 30\%$.*

For such waters, $\rho_w(443)N$ is approximately 0.04 (Figure 1.13), meaning that the maximum error allowed is 0.002. The atmospheric correction algorithm was specifically designed to meet this goal. If we take the error in atmospheric correction to typically be of the order of 0.001 in reflectance at 443 nm, then since the TOA reflectance is $\sim 0.20$ under these conditions (Figure 1.9), meeting this goal would require the sensor have a calibration uncertainty no more than about 0.001/0.20 or $\sim 0.5\%$ at 443 nm. This is difficult to meet even under pre-launch conditions. (This implies that an in-orbit calibration or calibration adjustment is required: *vicarious calibration*).

However, we can try to look at the radiometric calibration requirements in another way, i.e., using the *Chlorophyll a* requirement of 30% uncertainty. Figures 1.14 and 1.15 provide spectra of $\rho_w(\lambda)N$ computed using the Garver-Siegel reflectance model (Garver and Siegel, 1997; Maritorena, Siegel, and Peterson, 2002). They show that only in the low to moderate-$C$ waters is an accuracy of $\pm 0.002$ sufficient in the blue, and that the shape of the spectra is as, or more, important than the absolute reflectance. This is manifest in the “ratio algorithms” traditionally used in ocean color (Clark, 1981; Gordon and Morel, 1983). Figure 1.16 (Gordon, 1997) provides measurements of the ratio $\rho_w(443)N / \rho_w(550)N$ taken from Figure 1.13. It shows a clear relationship between the reflectance ratio and the pigment concentration. For these data,

$$C \equiv \left( \frac{\rho_w(550)N}{\rho_w(443)N} \right)^{1.7}$$

so the relative error in $C$ is (after dropping the cumbersome square bracket notation of normalized water-leaving reflectance)

$$\frac{\delta C}{C} \equiv 1.7 \times \left( \frac{\delta \rho_w(550) / \rho_w(550) - \delta \rho_w(443) / \rho_w(443)}{\rho_w(550)} \right)$$

and if the $\delta \rho_w$'s are the direct result of calibration errors, we see again that the impact on $C$ is minimized if the calibration error in the two bands is of the same sign! Similarly, for high $C$, Gordon *et al.* (1983) used
\[ C \equiv A \left( \frac{\rho_w(550)}{\rho_w(520)} \right)^{2.5} \]

yielding

\[ \frac{\delta C}{C} \equiv 2.5 \times \left( \frac{\delta \rho_w(550)}{\rho_w(550)} - \frac{\delta \rho_w(520)}{\rho_w(520)} \right) \]

In the worst-case scenario, the errors at the two wavelengths are of opposite signs, and assuming the magnitude of the relative errors at the two wavelengths is identical, a 30% error in \( C \) requires

\[ \frac{\delta \rho_w(443)}{\rho_w(443)} \equiv 0.09 \]

for the low-\( C \) algorithm. But

\[ \frac{\rho_w(443)}{\rho_w(443)} \sim 0.12 \Rightarrow \frac{\delta \rho_w(443)}{\rho_w(443)} \sim 0.09 \times 0.12 \sim 0.011 \]

\[ \frac{\rho_w(550)}{\rho_w(550)} \sim 0.05 \Rightarrow \frac{\delta \rho_w(550)}{\rho_w(550)} \sim 0.09 \times 0.05 \sim 0.0045. \]

Again, these calibration errors (~ 1% at 443 nm and 0.5% at 550 nm) are difficult to obtain even in a laboratory environment. In addition, note that for high \( C \) (~ 5 mg/m\(^3\)), where \( \rho_w(443) \) is approximately 0.002 to 0.004, we find that \( \rho_w(443)/\rho_w(443) \sim 0.012-0.024 \) or \( \delta \rho(443)/\rho(443) \sim 0.12-0.24\% \). Calibration to this accuracy is not possible at the present time.

The similar worst-case scenario using the 550 nm to 520 nm ratio algorithm for high \( C \) yields

\[ \frac{\rho_w(520)}{\rho_w(520)} \sim 0.10 \Rightarrow \frac{\delta \rho_w(520)}{\rho_w(520)} \sim 0.06 \times 0.10 \sim 0.006 \]

\[ \frac{\rho_w(550)}{\rho_w(550)} \sim 0.05 \Rightarrow \frac{\delta \rho_w(550)}{\rho_w(550)} \sim 0.06 \times 0.05 \sim 0.003. \]

In the best-case scenario, the errors in the individual bands have the same magnitude and the same sign. Then
\[
\frac{\delta C}{C} = 1.7 \times \left( \frac{\delta \rho_w(550)}{\rho_w(550)} - \frac{\delta \rho_w(443)}{\rho_w(443)} \right) \approx 0
\]

This can likely happen at low \( C \), but for high \( C \), \( \rho_w \)’s are small in the blue (\( \sim 0.001 \) to \( 0.002 \)), so the \( \delta \rho_w \)’s must be correspondingly smaller. Reality is somewhere between the best and worst cases.

We have seen that the calibration accuracy requirements are extremely severe if there is no correlation between the \( \rho_w \) error in one band and the \( \rho_w \) error in other bands. The principal error in \( \rho_w \) results from atmospheric correction. The atmospheric correction algorithm has the property that under most conditions it will yield the desirable situation in which the error in \( \rho_w \) will be of similar sign in each spectral band when the exact TOA reflectances are provided. What if the input TOA reflectances contain error, i.e., calibration error? To investigate this, we assume that the estimated reflectance in a given band has a relative error \( \alpha \), i.e.,

\[
\rho(\lambda)_{\text{Est}} = \rho(\lambda)_{\text{True}} [1 + \alpha(\lambda)].
\]

and operate the algorithm to find the error in atmospheric correction in the blue induced by various values of \( \alpha \), in the blue and near infrared (NIR). The resulting error in

\[
t_v(443) \rho_w(443)
\]

is provided in Figure 1.17 (Gordon 1997). These show that in the NIR, small calibration errors of opposite sign are as important as large errors with the same sign, and when calibration errors are of the same sign in all bands their effect is significantly reduced. In addition, Figure 1.17 shows that calibration error can void the tendency for the algorithm to cause errors of similar sign in all bands.

The following conclusions can be made regarding acceptable calibration errors:

- The 30% uncertainty in \( C \) can be met with this error as long as the error in the water-leaving radiances have the same sign in all spectral bands, but even then there will be difficulties at high \( C \) where \( \rho_w(443) \sim 0.002 \) – \( 0.004 \).
- To meet 5% uncertainty in \( \rho_w(443) \) in oligotrophic waters, \( \delta \rho(443) \rho(443) \sim 0.5\% \). (The relative error in \( L_w \) in these waters in the blue is approximately 10 times the relative error in \( L_v \).)
- The effect of calibration error on the error in atmospheric correction is also minimized when the calibration errors in all bands have the same sign.

It would seem that the calibration requirements of ocean color sensors are too stringent to be met by standard calibration techniques. However, they can be met to a certain extent by vicarious calibration techniques (Gordon 1987, Gordon 1998, Zhang and Gordon, 1997). We shall review these now.
1.6 Vicarious Calibration Concepts

The term *vicarious calibration* means an adjustment of the sensor's radiometric calibration coefficients, $k_L(\lambda)$ or $K_r(\lambda)$, based on radiometric (and possibly other) measurements made at the surface. There are two basic kinds of vicarious calibration: *radiometric* and *system*.

**Radiometric Vicarious Calibration**

In radiometric vicarious calibration, each term in the equation

$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_A(\lambda) + t_v(\lambda) + t_s(\lambda)[\rho_w(\lambda)]_N$$

for the TOA reflectance (Gordon and Wang, 1994) is estimated based on measurements made at the surface. This is accomplished as follows:

- $\rho_r(\lambda)$ is computed using the atmospheric pressure measured at the surface;
- $\rho_A(\lambda)$, $t_v(\lambda)$, and $t_s(\lambda)$ are estimated using sun photometer and sky radiance measurements (to retrieve aerosol properties) made simultaneously with the sensor estimate of $\rho_t(\lambda)$; and
- $[\rho_w(\lambda)]_N$ is determined by in-situ measurements of the upwelling water-leaving radiance.

Given the estimate of $\rho_t(\lambda)$ based on these measurements, the calibration of the sensor is then adjusted so the sensor-estimated and the surface-estimated values of $\rho_t(\lambda)$ agree. The accuracy of such a calibration is limited by the accuracy of the surface measurements (Zhang and Gordon, 1997).

**System Vicarious Calibration**

By “system” we mean calibration of the combined sensor and the atmospheric correction algorithm. This is accomplished in the following manner (Gordon 1998):

- Assume the calibration in longest NIR band, i.e., 865 nm for SeaWiFS, is correct (e.g., for SeaWiFS, assume there is no calibration error at 865 nm).
- Adjust the calibration in second longest NIR band (765 nm for SeaWiFS) so that the spectral variation of $\rho_t$ is consistent with the aerosol type actually measured at the calibration site, or typical of the calibration site.
- Apply atmospheric correction algorithm to $\rho_t$ and adjust the calibration to force agreement with the measured values of $[\rho_w(\lambda)]_N$. (Note that the various ancillary data, e.g., Ozone absorption, etc., are also measured at calibration site.)
- The first bullet can be avoided by applying radiometric vicarious calibration methods to longest NIR band.

System vicarious calibration has several advantages over radiometric vicarious calibration (Gordon, 1998):
• The residual calibration errors will all be of the same sign.
• The residual calibration errors will decrease from the NIR to the blue.
• The NIR error can be reduced/quantified by radiometric vicarious calibration. Reducing this error will concomitantly reduce the residual error in all shorter wave bands.
• Pragmatically, the sensor is being forced to do the job for which it was designed.

1.7 Concluding Remarks

We have tried to provide a brief introduction to the calibration of ocean color sensors. It is interesting to point out that, with a cursory glance at the requirements outlined in Section 5, one would naturally be led to conclude that the requirements for sensor calibration are so severe (beyond what is presently possible even in the laboratory) it would be impossible to derive useful information from ocean color observations beyond the "pretty pictures" that show patterns produced by currents, surface slicks, etc. Fortunately, because of the nature of the atmospheric correction algorithm, the in-water chlorophyll algorithms, and the concept of vicarious calibration, this conclusion is absolutely incorrect.

1.8 References


Figure 1.1 Schematic of a radiometer. A detector of area $A_d$ (sensitive only to radiation in a small band of wavelengths $\lambda \pm \Delta\lambda/2$ around a central wavelength $\lambda$) is allowed to view a scene with a field of view that is restricted to the solid angle $\Omega$. The tube restricting the field of view of the detector in the schematic is usually referred to as a *Gershun* tube.

On-Orbit Reflectance Calibration

SeaWiFS and MODIS

Figure 1.2 Schematic describing the use of a reflectance plaque to effect on-orbit calibration. The radiometer first views the ocean-atmosphere system and records a radiance $L_r$. It the views a reflectance plaque having a known bi-directional reflectance distribution function (BRDF) and measures a radiance $L_p$. 

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Figure 1.3 The spectral response of SeaWiFS band 8 (nominally 845-885 nm). (From Gordon, 1995.)

Figure 1.4 Schematic showing how various sources all having the same radiance at $\lambda_0$ but different spectral distributions would produce considerably different measured radiance $<L>_S$. 
Figure 1.5 Measured polarization sensitivity amplitude of MODIS (on Terra) in the blue and in the near infrared.

Rayleigh Component Polarization (%)

Figure 1.6 Degree of polarization $P$ (in %) of the Rayleigh scattering component of the top-of-atmosphere radiance at 412 nm for an orbital pass in December.
**Figure 1.7** Schematic showing a bright cloud (green circle) moving across the four MODIS focal planes (as the instrument scans the scene).

**Figure 1.8** Schematic of the remote sensing geometry showing the various radiances discussed in the text.
Figure 1.9 Several examples of the top-of-atmosphere reflectance $\rho_t$ off Hawaii measured by SeaWiFS.

Figure 1.10 Same as Figure 1.9, but for $\rho_t - \rho_r$. 
Figure 1.11 Same as Figure 1.9, but for $\rho_A$.

Figure 1.12 Same as Figure 1.9, but for $\rho_w$. 
Figure 1.13 Dependence of $[\rho_w]_N$ on the pigment concentration for 443, 520, 555, and 670 nm. The red bar corresponds to a reflectance of 0.001. (From Gordon, 1997.)

Figure 1.14 Examples of computed $[\rho_w]_N$ spectra for various chlorophyll concentrations for Case 1 and Case 2 waters.
Figure 1.15 Examples of computed $[\rho_w]_N$ spectra for various chlorophyll concentrations. The red lines correspond to a ±30% change in $C$ for Case 1 waters.

Figure 1.16 The reflectance ratio $[\rho_w(443)]_N / [\rho_w(550)]_N$ as a function of the pigment concentration from the data in Slide 31. (From Gordon, 1997.)
Figure 1.17 The error in the retrieved $t_v(443)\rho_w(443)$ for various calibration errors. (From Gordon, 1997.)
2.1 Introduction

The quantitative relation between the responses (i.e., voltage, digital number) of the ocean-color instrument to the input radiance it is intended to measure are affected by the space environment (e.g., exposure to ultraviolet light and particles) and the normal aging process of optical parts, detectors, and electronics. The variables of prime consideration in the check-of-calibration process are the radiant amplitude and the spectral location. The spatial response, affected by scattering and crosstalk, should also be considered, but will not be discussed in this chapter.

To monitor in space the radiometric gain or sensitivity, i.e., the slope of the relation between input and output signal, and the spectral response, several light sources are generally used. They are either internal, such as Tungsten lamps, or external, such as the Sun or the Moon. Zero radiation energy, used to determine the dark signal, is generally achieved by activating a shutter that blocks the Sun and Earth optical paths. Using space targets, unlike Earth targets, avoids atmospheric interference, which causes variation in the reflected energy observed from space. The Sun, a stable light source of well-known spectral irradiance, is the ultimate calibration standard. In the following the techniques and systems used for on-orbit calibration of ocean-color sensors are described.

2.2 Lamp Calibration

Tungsten lamps are commonly used as internal light sources. They have low energy requirements, and their emission spectra are precise. In essence, the laboratory standard calibration is monitored for change by reference to the internal lamp. The lamp output generally decreases with time, i.e., only changes in the sensitivity of the instrument can be observed. In other words, the internal lamp calibration is relative in nature. Traceability and repeatability with time are checked, but not traceability to a known source.

The lamp source radiation is typically collected and imaged at the entrance aperture by a transfer system, often after reflection by of transmission through a diffuser. Variable density filters, with transmission continuously varying from one end to the other (e.g., from 100% to a few %), can be swept across the optical path to change the input radiance at the entrance aperture. Superposing lamps also allows for different radiance levels. In general redundant lamps are used, and some are activated less frequently. In some systems, the radiance from the source is monitored by photodiodes, which may be placed at different locations along the optical path. This allows a check-of-stability of the source. Comparing the signals from the monitoring photodiodes and from the instrument detectors provides information about changes in the transmission of the calibration optics.
Calibration subsystems with internal lamps of light-emitting diodes for relative check have been incorporated in several ocean-color instruments, especially early ones, for example CZCS, MOS, OCTS, GLI, and OCM. The principle of internal calibration is illustrated in Figure 2.2-1, which depicts schematically the assembly contained in MOS.

Two small filament lamps, mounted besides the entrance slit, illuminate the collimator optics via auxiliary slits. By powering the lamps to 4 highly stabilized current levels, 16 different illumination intensities are generated for each spectral band of the instrument. Using this calibration assembly, significant changes in the sensitivity of MOS-B onboard IRS-P3 were detected during April to December 1996, i.e., during the first months after launch (Neumann, 2001). They reached about 3% in bands 2 (444 nm) and 10 (869 nm) (Figure 2.2-2). The gain for band 2 became fairly stable after that period, but for band 2 it continued to increase, reaching 6% in June 1999 (Figure 2.2). To give another example, the results obtained by Yoshida et al. (2004) for GLI onboard ADEOS-2 are displayed in Figure 2.2-3, including the relative output of the monitoring photodiode. They show a degradation of the instrument responsiveness (inverse of gain) with time in all the spectral bands in the ultraviolet, visible, and near infrared, reaching 3% at the end of the sensor life in November 2003. The diode output also decreased with time, to about 2% in November 2003.

Internal calibrators thus allow monitoring and, to some extent, quantification of the sensor parameters with respect to a reference, for example pre-launch calibration or initial post-launch calibration. They allow a check of linearity in sensor response, and they may be selected for specific spectral characteristics. However, they do not necessarily cover the entire field of view, depending on construction. Long-term stability is a major problem. Furthermore, their spectral distribution may differ substantially from the solar spectrum, which may introduce uncertainties when out-of-band response is significant. Relying solely on internal light sources to calibrate ocean-color sensors operating in orbit, which was the case for CZCS, is definitely insufficient. Lunar calibration, by orienting the spacecraft for moon viewing, provides an effective way to monitor sensor degradation after launch (Section 2.3). Complementary onboard techniques, such as solar calibration (Section 2.4), are necessary to know the absolute magnitude of the measured radiance in fundamental units.

2.3 Lunar Calibration

2.3.1 Method Description

All historic and current space-borne ocean-color sensors have experienced change (degradation) over time, e.g., by about 50% for the MODIS 412nm bands on both the Terra and Aqua spacecrafts (Franz et al., 2008). Degradation trending of radiometric sensitivity, therefore, is a major aspect of on-orbit sensor calibration and characterization activities. Instead of using internal lamps (Section 2.1), radiometric sensor degradation can be determined by measuring the sunlight reflected off the moon throughout the mission in regular intervals, e.g., monthly. The ocean color community recognizes that
lunar measurements have a superior track record (e.g., IOCCG, 2012). The main advantages of using the moon for calibration are that lunar observations are made without any atmospheric contamination and the lunar reflectance is constant over geological time scales (Kieffer, 1997), surpassing any reasonable radiometric precision requirements.

Although the lunar reflectance is constant, the lunar irradiance as seen from Earth or a Earth-orbiting spacecraft varies considerably, even for a constant lunar phase angle (a lunar phase angle of 0° corresponds to full moon, 90° to new moon; note that the irradiance from a new moon is essentially 0). This is illustrated in Figure 2.3-1, which displays the moon irradiance measured by SeaWiFS, in terms of normalized radiance, during the first 10 years of the mission. The variations are predictable and depend mainly on the moon-sun and earth-moon distances, and on libration (slight variations of the orientation of the moon relative to the Earth). The ROLO (Robotic Lunar Observatory, U.S. Geological Survey) model predicts these variations. The ROLO model has been derived from a multiyear measurement campaign of lunar irradiance using an Earth-based radiometer (Kieffer and Stone, 2005).

Each detector in the radiometer must acquire an image of the entire moon to enable tying the radiance measurements to the ROLO spectral irradiance model (the ROLO model only provides the irradiance for the entire moon). This prevents certain radiometer types (e.g., a push-broom scanner like MERIS) from using the moon as a calibration source. Over-sampling, however, may occur. SeaWiFS, for example, over-sampled the moon in track direction, i.e., the moon appeared elongated in track direction relative to scan direction (see Figure 2.3-2), leading to an increase in apparent irradiance. This effect can be corrected (Barnes et al., 2004), as opposed to under-sampling, where information is lost.

For any ocean-color sensor viewing the moon, the lunar calibration time series takes the form (Eplee et al., 2004):

\[
A(t, \lambda) = [L_{\text{obs}}(t, \lambda, \alpha, \gamma, l_{\text{sc}}, b_{\text{sc}}, l_{\text{sun}}, b_{\text{sun}})/L_{\text{obs}}(t_0, \lambda, \alpha, \gamma, l_{\text{sc}}, b_{\text{sc}}, l_{\text{sun}}, b_{\text{sun}})] \cdot f_1(t) f_2(t, \alpha, \gamma) f_3(l_{\text{sc}}, b_{\text{sc}}, l_{\text{sun}}, b_{\text{sun}}) f_5(t, \lambda)
\]  

(2.3-1)

where \( A \) is the relative calibration coefficient (time and spectral band dependent), \( L_{\text{obs}} \) is the integrated radiance observed at time \( t \), \( f_1, f_2, f_3, f_4, \) and \( f_5 \) are correction factors for distance, over-sampling, phase angle, libration, and noise, respectively, and \( t_0 \) is the reference time to anchor the relative calibration (e.g., the time of the first lunar calibration). These factors depend on \( t \), \( f_1, f_2, f_3, f_4, \) and \( f_5 \), the phase angle, \( \alpha \) (\( f_2 \) and \( f_3 \)), the track angle \( \gamma \) (\( f_2 \)), and the latitude and longitude of the sub-spacecraft point, \( l_{\text{sc}} \) and \( b_{\text{sc}} \), and the latitude and longitude of the sub-solar point, \( l_{\text{sun}} \) and \( b_{\text{sun}} \). (\( f_4 \)).

Compared to lamp calibrations (Section 2.2) and solar diffuser calibrations (section 2.3), the main advantages of lunar calibrations are: 1) long term stability of the source (no degradation of lamp or diffuser), 2) instruments on different spacecrafts can view the moon (without simultaneity requirement), allowing cross-calibration even without temporal overlap of the missions (Eplee et al., 2011) no requirement for pre-launch
characterization (lamps and solar diffuser BRDF need to be characterized before launch, 4) no additional cost during instrument built, and 5) no on-orbit mechanism (on MODIS Terra, the solar diffuser door failed, see Franz et al., 2008). The main disadvantages are: 1) a spacecraft maneuver is generally required, 2) typically only 1-2 opportunities exist per month (up to one opportunity per orbit for solar diffuser calibrations, more for lamp calibrations), 3) a photometric model of the moon (e.g., ROLO) is required, and 4) the lunar image is typically acquired only at one scan angle (some (but not all) solar diffuser or lamp calibration approaches cover all scan angles).

2.3.2 Challenges

Using the moon as a calibration source requires addressing satisfactorily a number of challenging issues. These include taking into account lunar intensity variations, selecting optimum phase angle and calibration frequency, and performing spacecraft maneuvers.

1) Lunar irradiance variations: Lunar irradiance measured from an earth orbiting sensor depends strongly on several factors, such as the instrument-moon distance, the moon-sun distance, libration, and lunar phase angle, see Figure 2.3-1. The ROLO model captures these variations. Therefore, lunar irradiance variations are a manageable issue. However, it should be noted that the availability of the ROLO model to non-US missions should not be taken for granted due to export control restrictions imposed on US agencies. For example, in the case of the OCM-2 sensor on Oceansat 2 (ISRO), a significant administrative effort was required for the delivery to ISRO of lunar irradiances calculated with ROLO.

2) Spatial reflectance variations: Lunar reflectance has strong spatial variation, as evidenced by the dark marias and bright highlands that are readily visible to human observers. For a typical Earth-observing sensor with 1km resolution, these brightness variations are resolved in the acquired image, as shown in Figures 2.3-2 and 2.3-3. The ROLO model provides only the disk-integrated lunar irradiance (i.e., the sum of radiances over all lunar pixels); it cannot provide the radiance for individual pixels. Although a lunar radiance model for individual pixels is under development, the expected precision is at best about 5.0% for individual measurements and 0.5% for long-term precision (T. Stone, private communication). This is an issue for sensors like MODIS, because these sensors measure the lunar image with multiple detectors. MODIS uses up to 10 detectors for its 1km resolution bands. Only one calibration factor per band and mirror side is derived for the operational MODIS calibration. Note that a) MODIS uses lunar measurements only as a detector-independent adjustment to the scan angle dependence of the radiometric sensitivity (Sun et al., 2007), and b) it is possible to derive one calibration factor per detector for the MODIS 1km bands, but the uncertainties are much larger (Sun et al., 2007). To summarize, the spatial reflectance variations of the lunar surface severely complicate the calibration effort, unless each sensor element (e.g. each detector) that needs to be calibrated acquires a complete image of the lunar disk to allow a comparison with the irradiance provided by the ROLO model. SeaWiFS fulfilled this condition.
3) **Calibration frequency:** Lunar irradiance varies strongly with phase angle. To optimize the long-term trending precision, phase angle should be kept constant, which means that lunar calibration measurements could be performed only once every lunar month (29.5 days). If measurements are scheduled at the same absolute value of phase angle before and after full moon, two lunar calibrations per month are possible, leading to a potential increase in precision. This would be especially helpful at the beginning of the mission (trending precision is usually worst at the beginning and end of a time series). Although the interval of once or twice a month is sufficient for long-term trending, a separate calibration mechanism (e.g., a solar diffuser) is needed to resolve short-term variations of radiometric sensitivity of the sensor.

4) **Optimum phase angle:** The choice of phase angle involves at least two considerations. The first consideration is that the larger the phase angle, the fewer the useful (sunlit) lunar pixels are available for the irradiance calculation. Therefore, a larger phase angle is expected to decrease the precision of the irradiance measured by the sensor, although this has not been quantified. The second consideration is that at very small phase angles, lunar backscatter decreases the accuracy of the ROLO model (the opposition effect, Stone et al., 2004). For SeaWiFS, a phase angle of 7° was chosen, leading to excellent results (note that SeaWiFS was used to validate the ROLO model, see Barnes et al., 2004). The ROLO model uncertainty of 1% for each measurement is valid for phase angles larger than 7°, but the ROLO model uncertainty for long-term measurements of 0.1% has only been demonstrated for the SeaWiFS phase angle. Preferably, the phase angle should be always at either waxing or waning moon (no preference for either one) to avoid switching phase angle between calibrations. For different target phase angles, long-term precision implications must be analyzed. Note that lunar phase increases by about 0.85° per orbit, so in any lunar month, an Earth-orbiting sensor may miss the optimal phase angle by up to 0.85°/2. Limiting the range of phase angles to 6.5° to 7.5°, for example, will allow one measurement in this range per lunar month (or two for both waxing and waning moon).

**Lunar calibration maneuvers:** The type of spacecraft maneuver that will be performed has implications for the optimum lunar phase angle. Low phase angles, such as were observed by SeaWiFS, require a back flip of the satellite so that the instrument observes the Moon near nadir. Intermediate phase angles (50° to 58°) can be observed by a roll of the spacecraft, as is done by MODIS on the Terra and Aqua spacecrafts and by VIIRS on Suomi NPP. For either type of maneuver the timing of the calibration can be optimized within the spacecraft operational constraints to maintain the phase angle of the lunar observations to within a degree over the mission.

### 2.3.3 Uncertainty

The uncertainty related to phase angle dominates the relative uncertainty of the ROLO model. By acquiring lunar measurements over a small range of phase angles, the uncertainty related to phase angle can be effectively eliminated, and a long-term trending precision of 0.1% can be achieved (Stone and Kieffer, 2004).
Increasing the frequency of lunar measurements is expected to increase the precision of the trending of radiometric degradation of the sensor (but not necessarily the accuracy). The amount of this increase is speculative at the moment. The SeaWiFS precision was achieved with only one measurement per month. Possible advantages of additional phase angles have to be weighed against the increased resources needed to obtain the additional measurements (e.g. the power needed to maneuver the instrument into a position where it can see the moon). An obvious choice for increasing the number of lunar measurements beyond a single measurement would be to calibrate at both 7° before and after full moon, as discussed above.

Note that lunar irradiances provided by the ROLO model are known to contain a relatively large bias (about 5-10%, see Stone and Kieffer, 2004). Nevertheless, the precision of the lunar irradiance provided by the ROLO model is excellent. Therefore, lunar measurements are ideal (depending on instrument type, see above) for relative temporal gain trending, but not the first choice for absolute calibration accuracy. At the time of this writing, efforts are in the early planning stages at NIST (National Institute of Standards and Technology, Gaithersburg, USA) to develop a lunar measurement campaign that may allow significant improvement in the absolute accuracy of the ROLO model.

2.3.4 Application example

Lunar calibration was the primary calibration approach for SeaWiFS. The radiometric gain trends after all corrections (but before fitting to an analytical function in time) are shown in Figure 2.3-4. The long-term stability that has been achieved with this methodology for the SeaWiFS mission lifetime is on the order of 0.1% (Eplee et al., 2011). The MODIS sensors on the Terra and Aqua spacecrafts have used lunar calibrations as secondary calibration approaches (to monitor the scan angle dependence of the radiometric degradation; a solar diffuser acts as the primary calibration source, see Sun et al., 2007). For the recently launched VIIRS sensor on Suomi NPP, the current operational calibration uses the solar diffuser measurements only. It is expected that in the near future, lunar calibration will be used as the primary calibration approach for VIIRS ocean-color products produced by NASA (Eplee et al., 2012).

2.4 Solar Calibration

2.4.1 Method Description

It is generally accepted that reflectance-based radiometric calibration of optical sensors in the visible and near infrared spectral domain using the Sun as light source provides the best absolute radiometric accuracy for space-borne radiometers (Slater et al., 1995; see also Section 1.3). The extra terrestrial solar irradiance illuminating the calibration plaques is very well known and very stable in the visible and near infrared, and the solar diffuser plaque can be considered as an embarked secondary reflectance standard, traceable to standard laboratories, such as NIST (USA), NPL (UK) or PTB (D). Solar diffusers have been used in the majority of the heritage ocean color missions, such as SeaWiFS, MOS,
GLI, OCM, MODIS, and MERIS as well as in recent and future missions such as GOCI, VIIRS, and OLCI.

Carefully designed solar diffuser based calibration hardware (Figure 2.4-1) can allow for full pupil and full optical path radiometric calibration for scanning radiometers such as SeaWiFS and MODIS, and for full pupil, full optical path, and full field of view radiometric calibration for push-broom instruments such as MERIS. It can be used over the complete solar reflective spectral domain ranging from the ultra violet to the short wave infrared.

During radiometric calibration, the solar diffuser is illuminated by a solar flux proportional to the square of the distance between the sun and the earth leading to a yearly variation of ±1% in irradiance. The resulting calibration radiance field, after correction of the sun-earth distance, will vary spectrally and spatially according to the Bidirectional Reflectance Distribution Function (BRDF) behavior of the diffuser plaque (e.g., Nicodemus et al., 1977). We have:

\[ L = F_0 \, r_p \cos(\theta_0)/(\pi a^2) \]  

(2.4-1)

where \( L \) is the input radiance, \( F_0 \) is the Sun irradiance, \( r_p \) the bidirectional reflectance of the plaque, \( q_0 \) is the Sun zenith angle, and \( a \) is the Earth-Sun distance. During the calibration process, the above terms need to be applied to compute the radiance \( L \), and the instrument radiometric equation must include all instrument specific corrections such as: non-linearity, time delay integration, smearing, polarization, stray light, scan mirror position etc., before determining the end to end instrument “gains” -- counts to radiance conversion factors-- per pixel and per band, from which the instrument’s degradation model - also known as radiometric trending - can be derived. For MERIS, the radiometric model that relates measured radiance to digital count can be written (e.g., MERIS Team, 2011):

\[ X_{b,k,m,t} = NL_{b,m} \left\{ g(T_{i}^{TVU}) \left[ A_{b,k,m} (L_{b,k,m,t} + G_{b,k,m}(L_{*,*,*,*}) + Sm_{b,k,m,t}(L_{b,k,m,*})) \right] + g_c(T_{i}^{CCD}) C_0^{b,k,m} \right\} \]  

(2.4-2)

where subscripts, \( b, k, m, \) and \( t \) denote the spectral band, the spatial pixel, the camera, and the acquisition time, respectively, subscript * stands for multiple values up to the entire range of the subscript it replaces, \( X_{b,k,m,t} \) is the MERIS raw sample (numerical count), NL is a non-linear function, \( T \) is the temperature of the amplifiers, and \( T^{CCD} \) is temperature of the detectors, \( g \) and \( g_c \) are (dimensionless temperature correction functions, \( G \) is a linear operator representing the stray light contribution to the signal, \( A \) is the “absolute radiometric gain”, \( S \) is the smear signal, due to continuous sensing of light, and \( C_0 \) is the calibrated dark signal (depends on band and gain settings).

The uncertainty associated with the sun-earth distance is minimal as it is known with great accuracy, the solar flux in the visible, near infrared and shortwave infrared domain has been demonstrated to be very stable and its spectral irradiance level well known (Thuillier et al., 2003), the space-craft’s orbit and attitude are generally very well known.
allowing for precise computation of the calibration geometry, leaving the lion’s share of
the uncertainty of reflectance based calibration to the knowledge of the BRDF of the
calibration plaque, and the spectral response function of the detectors (see Section 2.4.5).

During the yearly orbital cycle of helio-synchronous orbits, the solar illumination angle
on the plaque during calibration can be timed in such a way as to occur at a fixed solar
elevation angles on the plaque. However, the illumination azimuth angle will vary by up
to 15 degrees if no dedicated yaw maneuvers are performed to correct for the variation.
This change in illumination geometry on real diffusers, which are not perfect Lambertian
scatterers, can have a significant impact on the calibration radiance level (up to ± 3%), in
particular for low solar elevation geometries as used i.e. in MERIS (Delwart and Bourg,
2009). In the case of MODIS, the seasonal change in illumination geometry leads to a
variation (after correction using characterization results from a yaw maneuver) of the
measured gain factors of about +/-0.5% (Meister et al., 2008). An improved angular
dependence of the transmission of the solar diffuser screen has recently been derived
(Wang et al., 2011), but has not yet been implemented into the operational processing.

An in-depth analysis of the diffusion characteristics of a volume scattering diffuser such
as Spectralon, has shown (Bruegge et al., 2001) that in order to provide well behaved
“Lambertian” BRDF characteristics, it was necessary to keep the solar illumination of the
plaque at elevation angles > 45 degrees (the closer the illumination is to grazing
incidences, the more pronounced the asymmetry in the scattering lobe is in both view
azimuth and elevation). Nevertheless, in order to have a calibration signal level close to
what is commonly found in ocean-colour missions, the design choice is frequently to
select a white diffuser and a low solar illumination angle, i.e., MERIS, or include a sieve
attenuator, e.g., MODIS (Waluschka et al., 2004) or VIIRS, which will introduce
azimuthally dependent calibration signal levels. A grey diffuser (see Section 2.4. about
diffuser types for more details), when one will be qualified for space use, will allow for
higher illumination angles which should provide a BRDF much less sensitive to sun’s
azimuth annual cycle, at optimum radiance levels, and hence could ensure a more
consistent absolute radiometric accuracy across the field of view of large swath push-
broom instrument such as MERIS and OLCI.

It should be noted, that vicarious calibration can only bring a single scaling factor per
band --for the complete field-of-view-- approximately every year, due to the difficulty of
gathering sufficient amounts of high quality in-situ data to determine this system level
correction, and that for both push-broom and scanning instruments, the final system level
accuracy of the absolute radiometric calibration across the instrument’s field of view will
always include the systematic errors of the BRDF model used during calibration for
MERIS (Delwart and Bourg, 2009), and the response versus scan (Chen et al, 2011) and
polarization corrections errors for MODIS.

Diffusers, at least the most commonly used material - Spectralon™, have been shown to
age (browning) after exposure to solar radiation, mainly ultraviolet (Siegman et al., 1993;
Petrov et al., 1994; Leland and Arrechi, 1995; Chommeloux et al., 1998), and a strategy
to correct for this aging is required in order to achieve the radiometric accuracy required
by ocean-colour missions over its lifetime. Different methods have been employed historically, i.e. MODIS and GOCI use a solar diffuser stability monitor (Chen and Xiong, 2009; Kang et al., 2010), while MERIS uses a second --less frequently exposed--diffuser plaque to measure the relative aging of the regularly used plaque (Rast et al., 1999). Calibration methodology using the moon as a reflectance standard (Kieffer et al., 2005) have also been used for radiometric trending and the evaluation of the aging of the diffusers for both SeaWiFS and MODIS --this is discussed in Section 2.3.

After accounting properly for the above, i.e., the sun-earth distance --solar elevation being identical and the plaque’s BRDF and the diffuser aging, the end-to-end instrument detector gain degradation with time can be determined, trended, and included in the level 1 processing (Xiong et al., 2007; Delwart and Bourg, 2011). Note that due to an inability to independently monitor the solar diffuser reflectance change on-orbit, the SeaWiFS solar diffuser was used to verify short-term stability but was ultimately not used to calculate the on-orbit gains (Eplee et al., 2007).

Instruments with a rotating telescope (e.g., SeaWiFS, MODIS, and VIIRS) typically acquire the solar diffuser signal only for a very limited range of angles. In the case of MODIS, the scan-angle mirror reflectance degradation has an angular dependency (Xiong et al., 2007). Therefore, the solar diffuser calibration is not sufficient for a determination of the gain at all scan angles. Initially, lunar calibrations were used to support the on-orbit gain determination. However, especially for the shorter wavelengths (400nm-500nm), additional, scan-angle dependent corrections (not derived from the solar diffuser measurements) are required to produce ocean-colour products (Kwiatkowska et al., 2008; Meister et al., 2012). In the case of SeaWiFS, it was determined that the scan angle dependency of the gains did not change on-orbit, and therefore a calibration source at a single scan angle (e.g., using a solar diffuser) would be adequate (but was ultimately not used, see above).

2.4.2 Characterizing diffuser plaques on the ground

The scattering characteristics of a diffuser plaque can be very well measured in the laboratory. However, great care is needed in the acceptance of the characterization bench before starting a characterization campaign, as these are very costly and lengthy efforts (Datla et al., 2009). The characterization method to be used, has to be tailored to the application, i.e., large plaques, position of entrance pupil on the plaque, large viewing angle range, spectral domain, etc., to restrict the measurements to the lowest number of degrees of freedom possible, while being as close as possible to the optical conditions expected during calibration on-orbit.

A number of facilities exist today where such measurement are performed (Figure 2.4-2), and the techniques have been continuously improving. For more details on the method used, see Feng et al. (1993), Shiff et al. (1993), Proctor and Barnes (1996), Barnes et al. (1998), Smorenburg et al. (1995), and Yoon et al. (2009). Round Robin activities have been performed across laboratories, and have shown that in general an agreement to
better than 1% can be achieved over a large spectral and geometrical domain (Early et al., 2000; Butler et al., 2003).

2.4.3 Modeling the BRDF of diffuser plaques

In order to exploit the BRDF characterization data, one needs to fit a BRDF model before applying it during calibration. This is necessary, in order to cover the complete spectral and geometrical domain of interest, in a consistent way. A simple model can be used when the geometrical domain is small as i.e. for scanning instruments, however, it becomes critical when used for the calibration of large field of view push-broom instruments.

Attempts have been made i.e., for MISR (Flasse et al., 1993; Bruegge et al., 2001), see Figure 2.4-3, and for MERIS (Delwart and Bourg, 2009; Courreges-Lacoste et al., 2003). These models, however, have their limitations, and the residual error introduced by the model cannot be corrected for by the system level vicarious calibration, even if this system-level correction will compensate on average for its shortcomings.

2.4.4 Characterizing the instrument on the ground

The instrument radiometric response can be measured on the ground with an integrating sphere (IS) to accuracy sufficient to determine the instrument’s saturation level ± 5% (or better). Such measurements establish a radiometric baseline for a “transfer to orbit” experiment - a comparison of the instrument’s gains as measured with on-ground and on-board methods, i.e., IS versus Sun illuminated diffuser plaque, as performed for example by SeaWiFS (Barnes and Zalewski, 2003a,b). Attempts have been made to illuminate the diffuser plaque on-ground with a solar simulator (i.e., for MERIS. However, due to relatively small size and non-uniformity of the solar simulator illuminating spot --not covering the diffuser plaque uniformly-- the analysis of these results was limited to a relative verification of the diffusers BRDF characteristics and associated BRDF model.

The transfer to orbit exercise will have limitations due to the difference in the illumination signal on the plaque on-orbit with the sun at approximately 6000-K, while sources commonly used on-ground, whether in the IS or in a solar simulator, will only have a brightness temperature of approximately 3000-K. This will lead to significantly different signal levels across the spectral domain (colour), resulting in different sensor responses even if only a small amount of integrated out-of-band response is present. Further, the Fraunhofer absorption lines present in the solar spectrum are not present in the output of a tungsten lamp, and for sensors with band-passes of 10 nm, this can affect the response by up to a few percent.

SeaWiFS was taken out of the laboratory, and the solar diffuser illuminated directly by the sun (Barnes and Zalewski, 2003). This provided a uniform illumination with the appropriate spectrum, and although this method allows a substantial reduction of the difference in the illumination signal between on-ground and on-orbit, it is still significantly affected by atmospheric scattering (Rayleigh and Mie) and atmospheric
absorption (by water vapor, ozone, and oxygen), which needs to be carefully corrected for before determining the instrument’s absolute radiometric response. In the end, the uncertainties associated with such method can reach levels similar to those available in laboratories --while being extremely risky from a contamination point of view-- reducing the main usefulness of such experiment only to verifying the impact of the out-of-band response of filter-based scanning radiometers such as MODIS and SeaWiFS.

2.4.5 Diffusers Types

A number of diffuser types have been used historically as on-orbit reflectance secondary standard, such as white thermal control paint YB71 panels (SeaWIFS), de-polished aluminium (OMI, SCIAMACHY, GOME), de-polished quartz quasi volume diffusers (OMI, GOMES-2), and Russian Opal tiles (Clarke, 1998) (ATSR series). Space grade Spectralon® by Labsphere, Inc., however, is by far the most commonly used reflectance standard in space applications to date (Brueggge et al., 1993), i.e., for MODIS, MERIS, VIIRS, etc.

Spectralon, is made from sintered polytetrafluoroethylene (PTFE - or Teflon) pellets according to a proprietary method developed by Labsphere, Inc. (see http://www.labsphere.com/uploads/datasheets/space-grade-spectralon-product-sheet.pdf and Chang et al., 2007 for high power applications). Labsphere also produces “doped” diffusers, which can include rare Earth elements (i.e. Erbium), and provide spectral features used in spectral calibration (see Section 2.5), and black pigments (proprietary) used in grey scale diffuser (Figure 2.4-4). Grey scale diffusers (Georgiev and Butler, 2008) have not flown on space missions to date, but hopefully they will in the future with the advantages mentioned above. For more on Spectralon, see http://www.labsphere.com/uploads/technical-guides/a-guide-to-reflectance-materials-and-coatings.pdf. Note that other companies also make sintered space grade PTFE diffusers such as SphereOptics, which will be used for the MERIS follow-on OLCI, and Fluorion diffusers from Altran technologies with no past or planned space experience.

The mechanical characteristics of Spectralon are suitable (Tsai et al., 2008), i.e., the material is sufficiently stiff to keep the stringent flatness requirements and sufficiently supple to sustain the vibration loads of a launch into orbit. As PTFE is a dielectric, it is important to provide an adequate grounding within the calibration mechanism in order for charges not to accumulate and produce arching. Great care must be taken in the manufacturing of space-grade Spectralon due to contamination, from the selection of the original PTFE pellets up to the milling and shaving post-manufacturing process. Contaminants, mainly organics, are known to produce both photoluminescence, and degradation of the plaque reflective properties in the ultraviolet to blue-green regions when exposed to solar radiation (Petroy et al., 1994; Leland and Arrechi, 1995). In order to mitigate these effects, a post-manufacturing cleaning process must be applied (Chommeloux et al., 1998) in order to minimize the level of contaminants remaining.

It must be noted, that in order to keep the plaque’s reflectance as stable as was achieved on MERIS, <2% at 412nm and <1% above 490nm after ten year on-orbit (Delwart and
Bourg, 2011), great care must be taken for what concerns cleanliness. The diffusers need to be kept at Class 100 standards cleanliness throughout the diffuser characterization campaign, shipping, integration, and testing phase of the instrument, up to on-orbit. The plaques have to be followed by cleanliness witnesses until they are integrated on the instrument, and then kept in a positive pressure of clean dry Nitrogen --requiring that a purge be continuously applied until the launcher fairings are closed, and the count down begins. Note that such periods can last many years! Finally, on-orbit the calibration mechanism should be such as to protect the diffuser from solar radiation while the diffuser is not deployed for calibration. For the MERIS diffuser (deployed every 200 orbits), the accumulated duration of solar illumination --at 30-degree elevation-- was less than 7 hours after ten years (50000 orbits) of operations. The aging of Spectralon at these levels of illumination behaves in a very linear manner (Figure 2.4-5), allowing a determination of the foreseen aging of the Spectralon plaque for different instrument designs.

2.4.6 Speckle in diffuser-based calibration

Speckle is an optical interference pattern created when partially coherent radiation is scattered from a large number of “secondary emitters” as found on rough surfaces (Dainty, 1975). Solar diffusers are chosen for their good scattering characteristics and hence will introduce speckling in the calibration radiation field, the amplitude of which will increase with increasing wavelength, i.e., coherence for a fixed bandwidth. Such effects have been measured on MERIS (see Figures 2.4-6 and 2.4-7), and can reach up to a few tenths of a percent in the near infrared for a 10 nm bandwidth.

Note that although this effect is quite small, it will anyway introduce observable across-track striping in the data products of push-broom instruments if not corrected for, e.g., using image equalization methods. Speckling is only a minor problem for scanning telescope radiometers like MODIS or SeaWiFS, because the solar diffuser signal for these instruments is acquired and averaged over a certain angular range (forty 1km frames in the case of MODIS), which smoothes out the speckling effect.

Speckle in diffuser based calibration of spectrometers, has been investigated in depth (van Brug and Courreges-Lacoste, 2007), and has shown to be much more pronounced in surface rather than in volume scattering materials, and that speckle also affect atmospheric chemistry profiling spectrometers in the spectral dimension (i.e., spectral features), while push-broom radiometers will primarily be affected by spatial speckle, creating across-track stripping. Care for what concerns speckle also needs to be taken during the definition of the BRDF characterization bench (Georgiev and Butler, 2005), in particular when using coherent illumination such as tunable lasers or diodes, in order to minimize the errors associated with speckle during the characterization campaign.

2.4.7 Polarization characteristics of diffusers

At the interface between any two materials, an electromagnetic field will be transmitted and reflected differently according to the polarization of the incident ray and the
geometry. This will polarize the light reflected or transmitted from this interface, e.g., as for a Brewster polarization plate. Hence, one expects that solar diffuser also polarizes the un-polarized radiation coming from the sun illuminating it and will introduce errors in the calibration method, in particular for instruments with intrinsic polarizing characteristics i.e. not including a polarization scrambler, if not properly accounted for.

Figure 2.4-8 displays the ratio of the BRDF in s- and p-polarization, in the MERIS calibration geometry, which can reach 6% and vary across the field of view of the instrument by up to 3%. The use of polarization scramblers as in SeaWIFS and MERIS reduces the instruments sensitivity to polarization during calibration and observation to roughly the level of the radiometric noise, and no polarization correction needs to be applied for such designs.

It is interesting to note that the s-polarization for a 30 degree elevation illumination angle, scatters more than the p-polarization in the MERIS view geometries, suggesting a stronger volume scattering for s-polarization than p, with a marked increases in the scattering lobe as one gets closer to the specular direction. This can be explained by recalling that classically the p-polarized incident light is preferentially transmitted into the material, with less light reflected in the forward direction. Therefore the p-polarized irradiance will contribute most efficiently to the multiple scattering, which is depolarizing (Haner et al., 1999). This behavior further reinforces the need to illuminate the Spectralon solar diffuser at high elevation angle, not only to have a better behaved and more Lambertian scattering lobe, but also for the calibration signal to be as un-polarized as possible, in particular for instruments designs with intrinsic polarizing characteristics.

2.4.8 Application example: MERIS on-orbit calibration

For MERIS, the absolute calibration coefficients (inverse gain) $A_{b,k,m}$ (see Equation 2.4-2) are computed as follows:

$$A_{b,k,m,t} = \frac{L_{b,k,m,t}}{X'_{b,k,m,t}} \tag{2.4-3}$$

where $X'_{b,k,m,t} = NL^{-1}(X_{b,k,m,t}) - C^0_{b,k,m} - Sm_{b,k,m,t}$ is the calibration count corrected for non-linearity, dark offset, and smear. The stray light contribution is computed and added to the calibration radiance before use. This process includes an iterative loop: As the stray light contribution is estimated from the corrupted signal, the corrected signal allows deriving a better estimate of the stray light contribution that in turn allows computing a better corrected signal. Iterations are stopped when improvement stops being significant.

Exposure of the instrument to the space environment implies aging of its components, including diffuser plates and optics. If degradation of the sensor itself is inherently part of the instrument response, and as such must be accounted for in the $A_{b,k,m,t}$ computation, aging of the diffuser plate impacts the estimation of the radiance at instrument entrance. It is thus necessary to monitor and quantify this aging independently, and this was accomplished for MERIS using a second diffuser plate deployed much less frequently.
Two approaches are possible to handle the variation of the instrument response with time. The first one is to frequently update the calibration coefficients, and the second one is to model their evolution in time. The second option (trending was selected for MERIS.

**Dark offset**

In nominal operations, dark offset is measured during every radiometric calibration. 1000 frames are acquired and averaged on-board is transmitted to ground along with the radiometric measurements, allowing to derive offset correction coefficients as well as to monitor its long-term stability.

OCL-ON ark offsets, i.e., dark offsets obtained with the offset control loop enabled, proved to be extremely stable over the mission as shown on Figure 2.4-9 for band 1 and the smear band (all observation bands behave similarly to band 1). Long-term stability is better than 0.04 counts at ADC output for all observation bands and lower than 0.16 counts for the smear band.

Analysis of the OCL-ON temporal behavior of Dark Offset shows that there is no trend. Figure 2.4-10, which displays the per camera spatial averages as a function of orbit for band 1 and the smear band, clearly demonstrates OCL-ON dark offset temporal stability. Such behavior justifies that a temporal average can be used to build the Dark Offset correction coefficient table per pixel. In conclusion, in OCL-ON mode, the MERIS dark offset is extremely stable to better than a tenth of a bit of a twelve bit word.

**Radiometric gain**

In nominal operations, the radiometric gain is measured during every radiometric calibration, i.e., every two weeks. 500 frames are acquired during solar illumination and averaged on-board before transmission to ground where the radiometric gains are derived and its long-term stability monitored.

The gain measurements, displayed in Figure 2.4-11 Left column, show an instrument degradation of 5% max (B1, Cam5) for the whole duration of the mission, and cameras 1, 3 and 4 show seasonal variations in their gains, due to the limitation of the diffuser’s BRDF model in azimuth. Different strategies have been employed to mitigate these BRDF model limitations (Delwart and Bourg, 2011), normalizing to the near infrared band gains assumed constant during the early years of the mission, and using all measured gains once the data availability is such that the degradation trend results are not biased by azimuth effects.

**Optics degradation model**

Optics is known to degrade exponentially when exposed to a space environment (Barnes et al. (2001). These authors developed a degradation model for SeaWiFS that was also selected for MERIS (see Equation 2.4-4). Starting from a reference value \( G(t_0)G(t_e) \), the gain evolution with time is given by
\[ G(t) = G(t_0) \left[ 1 - b \left( 1 - g e^{-d t} \right) \right] \]  

(2.4-4)

where \( t \) is time, \( t_0 \) a time of reference, \( b \) can be considered as the maximum degradation, \( d \) as the time scale of the exponential, and \( g \) as a time offset. These parameters are plotted for all MERIS pixels of Band 1 in Figure 2-4-12.

The degradation model fit is estimated to be better than 0.1% RMS. The same estimator applied to the diffuser-2 validation data set restricted to the same time period is even better. It is assumed that this improvement is due to better quality of the BRDF model for diffuser-2. These results are shown on 2.4-13 (top: diffuser-1, bottom: diffuser-2).

The degradation model derived using the complete calibration data set, was compared to the gains measured within a limited azimuth range (0.2 degrees centered around 27.3 degrees). This methodology of comparing the modeled degradation with raw degradation measurements at close to constant Sun azimuth angles is used to estimate the performance of the model. Figure 2.4-14 displays the performance of the model for all pixels of bands 1 and 15 (412 and 900 nm respectively) for all the calibration orbits satisfying the Sun azimuth constraint over the time period used for the fit. The ratios remain within 1 ± 0.001 for both bands.

Figure 2.4-15, left, shows the trending model performance for orbit 39639 (09/30/2009) for all MERIS bands based on diffuser-1 data. This date corresponds to one year after the modeling data set upper limit and to the latest occurrence of a diffuser-2 orbit within the Sun azimuth monitoring range (27.3 ± 0.1 degrees). A very small drift may be seen for band 1, of about 0.3%. Figure 2.4-15, right, shows the same performance estimation, but based on diffuser-2 data. The results are very similar.

Figure 2.4-16 displays the camera averaged model performance against data of diffuser-1 (left) and diffuser-2 (right) for band 1. It can be seen that in both case a slight deviation from 1.0 occurs in the central region, showing that the model curvatures does not exactly follow that of the data. Despite the small number of orbits available for diffuser-2, the two estimations behave very similarly, with camera 1 slightly below the unit ratio and all others slightly above. The maximum deviation does not exceed 0.2% for diffuser-1 and 0.25% for diffuser-2.

In summary, the instrument’s throughput has only suffered a limited level of degradation (max 5% at 412nm in only one camera, after 9 years on-orbit), and this degradation was very well captured by regular radiometric calibrations measurements combined with a trending model including both the diffuser aging and the instrument sensitivity degradation. Note also that The MERIS radiometric scale based on the on-board calibration diffuser plates has been validated against a number of vicarious calibration methods and shown to be well within the estimated performance of <4%.

2.4.9 Uncertainty
The error budget of the solar calibration, leaving aside the uncertainty on the solar irradiance, is mainly driven by the accuracy of the characterization of the diffuser plates and its modeling, the instrument spectral model, and to a lesser degree by the modeling errors of the diffuser aging, and by instrument degradation. Using well-protected and therefore very stable onboard diffuser plates as secondary standards and monitoring the aging of the dedicated calibration plate by a second, less frequently exposed “identical” plate (case of MERIS), allows for the correction of the diffuser aging, during the radiometric gain trending, to an accuracy of better than 0.2%. This makes it possible to reach an overall model error budget of <2%, as established for MERIS.

Uncertainty associated with knowledge of the solar irradiance contributes to the final error budget for the absolute calibration coefficients. Various solar observations have been merged and determined to have an error of ±1% (Neckel and Labs, 1984; Thuillier et al., 2003). Taking into account this error, the absolute radiometric calibration, radiance-based, can be performed with an overall uncertainty as low as ±3% (see also Krause et al., 2002).

It is important to emphasize, however, that ocean-color remote sensing deals with normalized radiance or reflectance, i.e., the magnitude of the solar irradiance is not needed, even though the basic ocean-color product generated by satellite ocean-color projects is water-leaving radiance. Bio-optical algorithms and inversion schemes to retrieve marine properties generally use remote-sensing reflectance (e.g., IOCCG, 2006). A reflectance-based calibration, however, requires that the solar flux should be constant between the time of the onboard calibration and the time of the ocean measurements. This is the case --the solar constant changes by only 0.2% over a 22-year solar cycle (see Barnes and Zalewski, 2003a). In view of the above, onboard reflectance calibration using the Sun and diffusers should be achievable with an overall uncertainty of ±2%, and this should be considered as the goal for the on-orbit, purely radiometric, absolute reflectance calibration of ocean-color sensors.

2.5 Spectral Calibration

2.5.1 Introduction

Knowledge of an optical instrument’s spectral characteristics is essential for determining radiometric response. The spectral radiance of the illumination source needs to be integrated over the instrument’s line-shape response to quantify the amount of energy measured, noting that it will be different in calibration (e.g., solar spectrum) than in observation, which will be dominated by Rayleigh scattering in the atmosphere, especially at the ocean-color wavelengths. Denoting by \( S_i \) the instrument’s spectral response, the measured radiance is given by (see Section 1.4):

\[
\langle L(\lambda) \rangle_S = \frac{\int L(\lambda) S_i(\lambda) \, d\lambda}{\int S_i(\lambda) \, d\lambda}.
\]  

(2.5-1)
To convert the measured radiance to reflectance, both during observation and reflectance-based calibration, the in-band solar irradiance can be computed by replacing $L(\lambda)$ in the above equation by irradiance $F_0(\lambda)$ (remembering to account for the varying Earth-Sun distance).

Instruments using multi-layer spectral filters need to have the “optical system” (filter, dichroic mirrors, etc.) response function measured precisely on the ground, over a large spectral domain covering not only to determine the filter’s “in-band” response, but also to quantify the amount of “out-of-band” signal the design allows through. The instrument’s overall spectral response will be the product of the spectral characteristics of all optical elements involved in the optical path of each band, which may be different for each band, such as in scanning radiometers like MODIS (see Figure 2.5-1).

A good estimate of the instrument’s spectral response can be achieved by combining the spectral characteristics of all optical elements measured at component level. However, it is crucial to measure the instrument end-to-end spectral response on the ground, with the instrument fully integrated, (1) to verify that the effective instrument spectral response is actually the product of all the elements’ individual spectral responses, and (2) to quantify the amount of stray signal, i.e., stray light and out-of-band spectral response the instrument has, in order to “accept” the instrument (i.e., to figure out whether it performs within the required/specified levels) and, as a minimum, to account for the stray signals in the processing, either as a correction term, or as an uncertainty.

Historically, multi-layer filters have not been very stable in the in space environment, mainly due to water vapor absorbed in the coating while on the ground. This water vapor will evaporate in orbit, changing the physical dimensions of the coating layers, and therefore introducing a spectral shift in the filter response. Modern filters on the other hand, have shown negligible degradation over time, as revealed on orbit for MODIS from its spectral calibration device (Guenther et al., 1996), see Section 2.5.2.

For imaging spectrometers such as MERIS, on the other hand, one needs to develop spectral models of the spectrometers (cameras) making up the instrument’s field of view. A band generally consists of a number of spectral samples, i.e., charge-coupled device (CCD) “lines” (see Figure 2.5-2 for MERIS), and the band’s overall spectral response is the sum of the spectral response of each “spectral-pixel = line” making up that band. The models should provide the spectral response of all CCD detector elements or, as a minimum, those involved in the operational band settings, to allow for computation of the spectral response for each pixel across the instrument field-of-view (MERIS=3700 pixels) and for all bands (MERIS=15). For more details, see Section 2.5.6.

### 2.5.2 Monochromators

Spectral calibration may be accomplished using onboard monochromators. These optical devices take a broadband light source and single out a specific narrow-band region of the electromagnetic spectrum. They have been used operationally for tracking on-orbit variations in MODIS spectral characteristics.
The MODIS onboard Spectro-Radiometric Calibration Assembly (SRCA) is an instrument by itself. It is capable of performing multiple functions. By slightly changing its configuration, the SRCA can be operated in three modes: radiometric, spatial, and spectral (Montgomery et al., 2000). When the SRCA is operated in spectral mode, it is configured as a monochromator with light sources and a collimator, as shown in Figure 2.5-3. When it is in radiometric or spatial mode, a plain mirror replaces the grating and the monochromator becomes an optical relay. The SRCA is also capable of performing wavelength self-calibration using a stable and well-calibrated spectral peaks of the didymium filter and a pair of reference detectors.

On the ground, the SRCA was characterized in a thermal vacuum (TV) chamber at both sensor and spacecraft levels before launch. The SRCA was operated on-orbit before the MODIS nadir door was opened. Two months after the MODIS-Terra nadir door was opened, the SRCA commenced normal spectral mode operations. A similar approach was used for MODIS-Aqua. The SRCA is routinely operated in the spectral mode every three months. The SRCA on-orbit performance is very stable.

The transfer to orbit of the spectral characterization was achieved by running on the ground the onboard SRCA in the spectral mode at nearly the same time as measuring the spectral characteristics and comparing the results (Xiong et al., 2006). It can be reasonably assumed that any bias is unchanged from pre-launch to on orbit. With its internal wavelength self-calibration capability, the SRCA can be used to track the MODIS spectral performance from pre-launch to on-orbit and throughout its life.

Pre-launch tests demonstrated that use of ion-assisted deposition (IAD) filters greatly reduced band response shifts from the ambient to TV environments for the bands in the visible and near infrared. However, the on-orbit instrument temperature could still induce wavelengths shifts. The averaged temperature coefficient was measured to be 0.011 nm/K pre-launch and 0.008 nm/K on-orbit, see Figure 2.5-4. Although these temperature coefficients measured pre-launch and on orbit are both very small, the on-orbit results showed more variation. These thermal variations appear to be related to the bandwidth, however. In comparison with the temporal changes, the impact of instrument temperature change is minor.

It has been observed that the recovered relative spectral response (RSR) profiles are fairly stable. Small changes have been detected for some bands, particularly in band 8 (0.412 µm) at its shorter wavelength sub-peak (Figure 2.5-5). Considering all the difficulties and challenges involved in the spectral characterization, such as wavelength calibration, reference transfer, changes in the on-orbit operational environment, and temperature and electronics configuration, the MODIS SRCA has been functioning well, providing useful information on the sensor’s spectral performance (see Figure 2.5-6 below for MODIS Terra).

The MODIS-Terra central wavelengths have shifted slightly since the pre-launch characterization, slightly toward shorter wavelengths during the first 1.5 years of on-orbit
operation, for most of the bands, and have remained relatively stable since Xiong et al., 2006). With the exception of band 8, the central wavelength shifts for all the Terra MODIS bands in the visible and near infrared are less than 0.5 nm. If the initial changes from pre-launch to shortly after launch are ignored, the on-orbit shifts over the last five years have been within 0.2 nm on average. It seems that using IAD technology stabilizes the band central wavelengths. For MODIS-Aqua, the shifts in central wavelength are also less than 0.5 nm, but for all bands, and the changes in bandwidth are also less than 0.5 nm, except for band 8 (-0.8 nm), (Xiong et al. (2012).

2.5.3 Erbium-doped diffuser

The MERIS on-board calibration mechanism includes an Erbium doped Spectralon™ diffuser plate dedicated to spectral characterization, which offers a number of spectral absorption features (Figure 2.5-7) in the visible/near infrared spectral range. The absorption peaks selected for MERIS are those centred at 408 nm (Peak 1) and 522 nm (Peak 3).

Spectral calibration, using an Erbium doped solar diffuser plate, is performed in two steps. On the first orbit, the instrument is configured to have 15 adjacent bands at the highest spectral sampling interval (1.25nm in MERIS) centered on a spectral feature (Peak 1 or 3) and a radiometric calibration sequence is performed by deploying the frequently used "white" diffuser. On the following orbit, keeping the same spectral calibration band settings, the “pink” Erbium doped diffuser is deployed during the calibration sequence. On the ground, the “spectral calibration pixels” are radiometrically calibrated using the “white” diffuser calibration signal, and when this calibration is applied to the measurement of the “pink” diffuser, it will show the Erbium spectral feature. To determines the position on the detector element of the CCD array of the peak of the Erbium absorption feature, a shape-matching algorithm is employed, comparing the Erbium measurements, to a high resolution spectrum of Erbium (Figure 2.5-7), convolved with the spectral line shape of the pixels (2 nm).

Although these measurements have shown to be very useful to monitor the health of the instrument and determine the spectral stability of the instrument through regular measurements (every three months), the accuracy of the absolute wavelength derived from this method (estimated to be ± 0.3 nm) is not as good as those from the other methods. This is probably due to the width and shape (Peak 3 is a doublet) of the absorption feature, and clearly not due to the weakness of the spectral signal.

2.5.4 Oxygen A-band

The absorption feature of atmospheric oxygen A-band (Figure 2.5-8) can be used for spectral calibration of spectrally programmable imaging spectrometers such as MERIS. This requires using complex algorithms, such as pressure minimization technique (Dubuisson et al., 2003 --LISE method), or neural network (Delwart et al., 2007 --FUB method), both based on radiative transfer computations, in order to localize the spectral
feature on the CCD array. The results are remarkably reproducible from one orbit to the other, and both methods yield very similar results, see Figure 2.5-9.

Figure 2.5-10 displays the median values of the along-orbit results for orbits 7766-7 for both the pressure minimization and neural network methods. A residual along-orbit variation can be seen, which appears to be highly correlated with the underlying surface type, in this case mostly cloud or water. For spectral calibration, bright desert targets have been selected for MERIS. The method accuracy was estimated to be better than 0.2nm (Delwart et al., 2007).

2.5.5 Fraunhofer lines

The solar Fraunhofer absorption lines in the solar spectrum can also be used for spectral calibration of spectrally programmable imaging spectrometers, using the solar diffuser (Delwart et al., 2004). The processing is performed using raw data, as radiometric calibration would remove the spectral signature inherent to the solar illumination. Figure 2.5-11 details the spectral band settings used in MERIS, requiring three orbits with each two different band settings (i.e. Lines 1 and 4, 2 and 5, 3 and 6) in order to acquire the six selected Fraunhofer absorption features.

Figure 2.5-12 shows, for selected Fraunhofer lines 1 and 2, a high spectral resolution plot (top right) with examples of the 3 MERIS band-pass (individual spectral pixels) overlaid, as well as the raw measurement signal [DN] for three pixels (center and edge of FOV) of each of the five MERIS cameras.

The results displayed in Figure 2.5-13 show that for the 396 nm absorption line, the spectral calibration results are well defined, mainly due the strength of the absorption feature. On the other hand, the results for the 854 nm absorption lines, are much noisy, yet still reflect the spectral signature of the instrument rather well. This Fraunhofer line is kept in the processing due to its spectral position near the near infrared end of the spectral range.

However, the quality of the method for the 588 nm and 866 nm lines was considered inadequate, and these results obtained using those lines were not used. Selection of the Fraunhofer lines for the instrument model (see Section 2.5-6 about spectral model) was made based on their coherence with each other. Figure 2.5-14 confirms that, for Fraunhofer line 3 (588nm, row153), the method returns results that are not consistent with the others with regards to dispersion, and that line 6 (867nm, row382) shows unphysical smile behavior.

2.5.7 Spectral model for imaging spectrometers

Imaging spectrometers need an instrument spectral model (dispersion law) in order to compute the in-band solar irradiance illuminating the calibration plaque during calibration or the earth during observation (Figure 2.5-15 for MERIS). As expected from the MERIS optical design, the measurements confirmed a very linear dispersion across
the spectrum (Figure 2.5-16, top), with a residual deviation $\pm 0.3$nm with regards to a linear best fit (Figure 2.5-16, bottom).

From these measurements, a relatively simple and robust model could be derived for each MERIS camera, considering separately a mean dispersion law and an across-track deviation term.

$$\lambda(k,l) = <\lambda>(l) + \Delta\lambda(k)$$ (2.5-2)

Where $k$ and $l$ stand for the spatial and spectral co-ordinates of a given detector, respectively, $<\lambda>(l)$, the mean dispersion law (mainly linear), is a polynomial of order 3 (best fit), and $\Delta\lambda(k)$, the across-track variation term, is a linear fit of the data at 395, 656 and 762 nm expressed relative to its mean value.

This simple equation defines the wavelength $<\lambda>(l)$ for the central pixel (370) of the CCD array, and the smile $\Delta\lambda(k)$ is accounted for with a linear spectral offset as a function of position in the field of view. The residual error from the spectral calibration with respect to the spectral model shows a RMS accuracy of the order of $\pm 0.1$ nm (Figure 2.5-17), which could be improved with a more stringent selection of the calibration data, and a more elaborate model, in particular at the edge of each camera’s field-of-view, where distortion is known to be more significant.

Finally, the instrument line-shape response for all pixels and bands is computed from the on-ground measurements, by introducing a variable bandwidth, to the Gaussian response function of the pixels, as a function of line number or wavelength. Figure 2.5-18 presents the variation of the pixel (line) spectral bandwidth as a function of line number (wavelength) for all five MERIS cameras. The spectral dependence of the bandwidth was fitted, per camera, with a fourth order polynomial in order to account for its spectral evolution. The root mean square of the bandwidth is included in the plot as the error bar, showing that bandwidth does vary from pixel to pixel, within each camera, due to slight response non-uniformity (< 5%) within the 22.5$\mu$m pixels.

Although on-orbit calibration can provide an adequate spectral model, it is mandatory that a complete spectral characterization of imaging spectrometers be made on the ground, in order to i) verify the proper integration of the optics, and ii) provide the CCD pixel’s line-shape response, and camera dispersion law iii) provide a pre-flight reference from which the spectral stability of the instrument can be derived. It must be noted that it is important to take proper care of the wavelength shifts from air to vacuum environments, as these can be significant (0.2nm) in the near infrared.

### 2.5.8 Spectral stability of MERIS

The spectral stability of the instrument has been monitored regularly by the onboard (Erbium) spectral calibrations and the bi-yearly spectral campaigns (Fraunhofer and oxygen A-band measurements). The results indicated that the spectral stability of the instrument is to within the measurement accuracy, i.e., ±0.1 nm. However, as can be seen
in Figure 2.5-19, cameras 2 and 4 have suffered a shift of their spectral response during the first year on orbit, of approximately 0.15 nm, which later stabilized to within 0.05nm for Camera 2 and 0.07nm for Camera 4, while Cameras 1,3,5 have barely drifted < 0.05 over the complete mission lifetime. This spectral shift is wavelength independent as can be seen in 2.5-20,i.e., not affecting the spectrometer’s dispersion law, but only causing a uniform spectral offset per camera for all bands.

The calibration data used to derive the instrument spectral model is from fall 2003 measurements (Delwart et al., 2004), and the regular spectral calibrations of MERIS have shown the instrument to be stable to within ±0.05nm since then. Such small amount of spectral shift has a very low impact on the absolute radiometric accuracy, e.g., ±0.05 % at 442nm, and did not justify specific spectral trending.

2.6 References


Figure 2.2-1 Principle of the Modular Optoelectronic Scanner (MOS) internal calibration. (After Zimmermann and Neumann, 2000.)

Figure 2.2-2 Change in the gain of the Modular Optoelectronic Scanner (MOS) in spectral bands 2 and 10 during the period from April 1996 to December 2000, as determined by internal lamp calibration. (After Neumann, 2001.)
Figure 2.2-3 Change in the responsivity (inverse of gain) of the global Imager (GLI) spectral bands in the ultraviolet, visible, and near infrared, scan mirror B, from January to November 2003, as determined by internal lamp calibration. (After Yoshida et al., 2004.)
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Figure 2.3-2 The moon (at 7° phase angle) as seen in several scan lines by SeaWiFS. The track direction (vertical) is elongated because of over-sampling.
Figure 2.3-3 The moon (at 55° phase angle) as seen in one scan line by the MODIS Aqua 412nm band (1km nominal spatial resolution). In this case, 7 detectors scanned across the moon horizontally.

Figure 2.3-4 Same data as in Figure 2.4 after correcting for the true variability of the lunar irradiance as calculated by the ROLO model (and after correction for over-sampling, an effect on the order of about 1% for SeaWiFS).
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Figure 2.4-6 Speckle effects in MERIS diffuser calibration. (Top) Yearly solar illumination azimuth angle, (Bottom) Solar illumination angles for the geometries used in Figure 2.4-7.
Figure 2.4-7 Speckle effects in MERIS diffuser calibration. Relative difference of the instrument gains computed from three calibrations orbits, i.e., 3175 (black), 2899 (Red), 2697 (Blue), compared to a reference one (3068) across the filed of view of MERIS (925 pixels in reduced resolution), for Top: 510nm, Center: 709nm and Bottom: 900nm. All bands have a 10nm band-pass.
Figure 2.4-8 Polarization ratio for s and p polarized illumination in the MERIS geometry.

Figure 2.8-9 Dark Calibration measurements as a function of spatial pixel for all orbits in OCL-ON setting for band 1 (left) and smear band (right), scaled to micro-band level. 215 orbits are plotted on top of each other.
Figure 2.4-10 Temporal evolution of per camera averaged Dark Offsets for all OCL On orbits, for band 1 (top) and the smear band (bottom). No temporal trend appears.
Figure 2.4-11 Left column: Mean radiometric gain degradation per camera for all bands since launch, Middle column: Band 1 Radiometric Gain for all pixel and fitted degradation trend in blue, Right column: residual error between measurement and instrument degradation trend. Results for cameras 1 to 5 are displayed from top to bottom.
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Figure 2.4-13 Model quality estimated through modeling RMS error. Top: diffuser-1 (model derivation data set); Bottom: diffuser-2 data for the same time period.
Figure 2.4-14 Trending model performance (raw degradation over model) for all pixels of bands 1 (412nm, top) and 15 (900nm, bottom) and for all orbits acquired at Sun azimuth within [27.2, 27.4] degrees enclosed in the period modeling data time range.
**Figure 2.4-15** Performance of the 2009 trending model in November 2011: camera average model drift as a function of MERIS band.
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Figure 2.5-4 Center wavelength (CW) temperature coefficients measured pre-launch and on-orbit with standard deviations.
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**Figure 2.5-6** Terra MODIS CW shift trending for band 13 (all detectors).
Figure 2.5-7 Erbium doped Spectralon™ Diffuser reflection spectrum and instrument spectral band configuration.
Figure 2.5-8 Oxygen A-band absorption spectrum and instrument spectral band configuration for spectral calibration.
Figure 2.5-9 MERIS oxygen A-band spectral calibration results (pix-297) for the FUB method and the LISE method.

Figure 2.5-10 Along-orbit variation [nm] of oxygen A-band results (FUB method, curves at top) for central pixels of each MERIS camera and corresponding top-of-atmosphere radiance at 865 nm (distorted spatial scale, bottom image, with approximate location of the camera central pixels overlaid using same color codes than for variation curves).
Figure 2.5-11 Instrument band configuration for Fraunhofer spectral calibration of MERIS.

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<td>593.125</td>
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</table>

Figure 2.5-12 Instrument response of each (5) MERIS camera, and a high spectral resolution plot of the Line 1 and Line 2 Fraunhofer absorption features used.
**Figure 2.5-13** Fraunhofer spectral calibration results from the fall 2003 campaign using diffuser data.

**Figure 2.5-14** Fraunhofer calibration results w.r.t. instrument model – Deviation from the linear fit [nm].
Figure 2.5-15 Reference solar irradiance around 440 nm and the extreme spectral response functions of MERIS band 2 (for pixel 740 of camera 1 and pixel 1 of camera 2 as “bluest” and “reddest”, respectively).
**Figure 2.5-16** Characterized central wavelength for Camera 4. Top: Wavelength (nm) as a function of CCD line number. Bottom: Deviation from linear trend [nm] as a function of line number (Line 1 = 390nm, Line 520 = 1040 nm) for seven points in the field of view.
Figure 2.5-17 Residual modeling error for selected data (data - model). The legend mentions the CCD row index and can be translated (from top/blue to bottom/red) into 395, 486, 656, 762, 854, and 866nm.

Figure 2.5-18 Pixel bandwidth deviation [nm] from linear trend as a function of line number (Line 1 = 390 nm, Line 520 = 1040 nm).
Figure 2.5-19 Spectral shift since first spectral calibration (orbit 652, 04/15/2002).

Figure 2.5-20 Spectral stability from orbits 652 (04/15/2002) to 3592403/11/2012) as monitored using all spectral calibration measurements, for each camera. The legend of each curve recalls the wavelength of the measurement.
Chapter 3. Calibration Using Natural Earth Targets

Bertrand Fougnie, Robert Frouin

3.1 Introduction

To cope with degradation after launch, most ocean-color sensors are equipped with onboard calibration devices. These devices include internal lamps, solar diffusers, and monochromators, as discussed in Chapter 2, and the spacecraft may be positioned to view the Moon as a calibration target. The accuracy provided by onboard techniques, however, may not be sufficient for ocean-color applications, and vicarious techniques are needed to verify the onboard device and achieve the required accuracy.

Some ocean-color sensors, in particular the POLDER instrument, do not have onboard calibration capability at all, or very limited capability. They rely on vicarious techniques using natural Earth targets for calibration, absolute and relative (i.e., multi-temporal and inter-band). The choice was deliberate for the POLDER instrument: it was too expensive to implement a calibration system in the compact POLDER design, and it was difficult to build a device that covered the entire bidirectional field-of-view.

A variety of vicarious techniques using natural Earth targets have been developed and applied successfully to check the calibration of ocean-color sensors. They use Rayleigh scattering over ocean for absolute calibration, high-altitude reflective clouds, desert sites, or ocean Sun glint for relative calibration, and they include “system” vicarious calibration, in which instrument and algorithm are intimately linked. These techniques are reviewed in the following, with uncertainties and application examples.

3.2 Absolute Calibration Using Rayleigh Scattering

3.2.1 Introduction

The top-of-atmosphere (TOA) signal measured by a satellite sensor observing oceanic targets is in large proportion due to scattering of the incident solar irradiance by atmospheric components, especially in the visible. In this spectral range, the molecular scattering, so-called Rayleigh scattering, is the main process contributing to the TOA signal and this contribution can be accurately predicted and computed using surface pressure, knowing the spectral response of the instrument.

Other processes contributing to the TOA signal are aerosol scattering, back scattering by the water body, diffuse reflection by whitecaps, specular (or Fresnel) reflection by the surface, and gaseous absorption. Satellite acquisitions over such oceanic targets can be selected so that the contribution of these secondary processes is minimized. For these acquisitions, the molecular scattering signal may constitute as much as 90% of the TOA signal, for spectral bands from blue to red bands (typically 443 to 670nm). This forms the basis of the calibration method using Rayleigh scattering.
This method, derived from Vermote et al. (1992), was previously explained in Hagolle et al. (1999). The approach is statistical, in the sense that climatology is used for marine reflectance, and that cases too contaminated by aerosols are rejected, i.e., the effect of aerosols require a very small correction. This contrasts with the vicarious radiometric calibration using in-situ measurements, in which the TOA signal is accurately computed using measurements of aerosol optical properties and water-leaving radiance. The advantage of the method using Rayleigh scattering is that the calibration is neither geographically or geo-physically limited, but it is derived from a large set of oceanic sites, from both hemispheres and for a large set of conditions.

3.2.2 Selection of Observations

Geographical selection. The marine contribution represents 10 to 15% of the TOA signal for the blue bands and is consequently an important source of error in attempting to met the 1 or 2% accuracy on the TOA signal. A climatological study, based on analyzing one year of SeaWiFS data, was performed by Fougnie et al. (2002) to select adequate oceanic sites for which spatial homogeneity is guaranteed and for which moderate seasonal effects exist. Using such pre-defined oceanic sites the dispersion of the results inside a given site is reduced significantly, as well as biases between results obtained over the different sites. In practice, six major oceanic sites were recommended in Fougnie et al. (2002), the North and South Pacific, the North and South Atlantic, and in the Indian oceans (see Table 3.1 and Figure 3.1).

Table 3.1 Major oceanic sites recommended for the statistical calibration method using Rayleigh scattering. (After Fougnie et al., 2002.)

<table>
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<th>n°</th>
<th>Name</th>
<th>Location</th>
<th>Latitude (deg)</th>
<th>Longitude (deg)</th>
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<td>6</td>
<td>IndS</td>
<td>South of Indian</td>
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<td>89.5</td>
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</table>

Clear-pixel selection. It is obvious that a cloud mask is applied on data, but in addition, only pixels distant by about 10 pixels from a cloud are kept. Furthermore, a strict threshold is applied to the TOA reflectance (in fact the product of reflectance and $\cos(\theta_v) \cdot \cos(\theta_s)$) in order to reject data with sensible aerosol loading and sub-pixel clouds. A threshold is also applied to the surface wind speed extracted from meteorological data to avoid possible contamination by surface whitecaps: only situations with a wind speed smaller than 5m/s are selected. Importantly, we can be very restrictive about these thresholds (i.e., only very clear pixels are retained), yet obtain statistically significant results.
Geometrical selection. Pixels potentially contaminated by sun glint are rejected, i.e., observations with viewing direction inside a cone of ±60° around the specular direction are discarded. Also, acquisitions corresponding to extreme geometries, such as solar or viewing zenith angle greater than 60°, are rejected.

Ancillary Data. Some exogenous data are necessary to accurately compute the TOA signal, such as the surface pressure, the surface wind speed, or the total ozone amount. Naturally, only pixel for which these ancillary data are available are selected.

3.2.3 Computation of the TOA signal

The following general formulation is used to compute the TOA signal (reflectance):

\[ \rho_{\text{TOA}}(\theta_s, \theta_v, \phi) = t_g(\theta_s, \theta_v)\{\rho_A(\theta_s, \theta_v, \phi) + \rho_w(\theta_s, \theta_v, \phi)T(\theta_s, \theta_v)/[1-S_A\rho_w(\theta_s, \theta_v, \phi)]\} \]  

(3.2-1)

where \( \theta_s, \theta_v, \) and \( \phi \) are the solar and viewing zenith angles and relative azimuth angle, respectively, \( t_g \) is the total gaseous transmittance, \( \rho_A \) is the molecular and aerosol contribution including coupling terms and specular reflection by the wavy surface, \( \rho_w \) is the marine reflectance, \( T \) is the total atmospheric transmission for aerosols and molecules, and \( S_A \) is the atmospheric albedo. Note that \( t_g \) depends on the amount of absorbers (essentially ozone), \( \rho_A \) on aerosol optical thickness, surface pressure, and wind speed, \( T \) on surface pressure and wind speed, and \( S_A \) on aerosol optical thickness. These different terms are evaluated as described below.

Aerosol and molecular scattering contribution. The atmospheric functions \( \rho_A, T, \) and \( S_A \) are computed using an accurate radiative transfer model, such as the successive order of scattering code of Deuzé et al. (1989). This code includes polarization and specular reflection by the wavy surface. The molecular scattering contribution is accurately computed knowing the surface pressure and the molecular optical thickness corresponding to the considered spectral band. For this, the Rayleigh equivalent optical thickness is calculated for a given spectral band by weighting the spectral optical thickness computed according to Gordon et al. (1988) by the spectral solar irradiance and the spectral response within the band. The background aerosol contribution is computed knowing its optical thickness estimated at 865nm (or another reference band) and extrapolated for the considered spectral band using a Maritime 98 aerosol model (Gordon and Wang, 1994). In practice, the restrictive thresholds used for the clear pixel selection lead to a residual aerosol optical thickness lower than 0.05 at 865nm, and usually about 0.02-0.035.

Marine contribution. This contribution, representing about 10% of the TOA signal, is estimated over the pre-defined oceanic sites through a climatological study (Fougnie et al., 2002). The typical marine reflectance for these sites is 0.033 at 443nm, 0.020 at 490nm, 0.0049 at 555nm, and 0.0007 at 670nm, and is close to values derived through a bio-optical model using a surface pigment concentration of 0.07 m/m³. A spectral interpolation can be performed when the spectral band of interest is not exactly the same
as one of the SeaWiFS spectral bands for which the climatological values are available. In addition, a bi-directional correction is added as an option in order to take into account sensible differences in the viewing and solar geometries of the pixel to calibrate and the angular conditions of the climatological values derived from SeaWiFS (e.g., due local time of overpass or case of multi-directional viewing sensors). This correction is made according to Morel and Gentili (1993).

Gaseous contribution. A gaseous absorption is performed for each spectral band. The main contributors are water vapor (mainly around 565 and 865nm), ozone (mainly around 490, 565, and 670 nm), oxygen (around 765 nm), nitrogen dioxide (mainly around 443 and 490 nm). The correction is made according to the SMAC model (Rahman and Dedieu, 1994) using exponential variation with air mass and gaseous amount.

3.2.4 Error budget

Table 3.2 summarizes the error budget of the method. For this budget, we have estimated the impact on calibration results of typical uncertainties on the input parameters. We have considered errors made on the surface pressure and surface wind speed (impacting the Rayleigh contribution), on the calibration of the 865nm band and on the expected aerosol model (impacting the aerosol contribution), on the gaseous absorption, and on the marine reflectance. In this error budget evaluation, using the root-mean-squared (RMS) error as a measure of performance is appropriate and realistic, because of the large amount of data considered in the synthesis, i.e., several geometric, geographic, and geophysical conditions.

In general, the error budget, in terms of RMS, is less than 3.5%. For shorter wavelengths, 443, 490, and 510 nm, the performance is determined by the accuracy on the marine reflectance. This confirms the interest of and justifies using in some cases the complementary vicarious approach based on in-situ measurements to improve the accuracy of the statistical results. For wavelengths near 565nm, the performance depends quite equally on the errors of all the parameters. In the red, i.e., 670nm, error in the calibration in the near infrared (865 nm) becomes the limiting factor to accuracy.

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<td>3,00</td>
<td>2,43</td>
<td>2,11</td>
</tr>
<tr>
<td>MAX</td>
<td>6,06</td>
<td>5,73</td>
<td>5,70</td>
<td>5,55</td>
<td>4,64</td>
</tr>
</tbody>
</table>
3.2.5 Calibration algorithm and analysis

The evaluation consists in comparing the TOA normalized radiance computed with the radiative transfer model (CI) with the normalized radiance derived from the sensor measurements (MI), assuming a given calibration (the one we want to evaluate). Consequently, the ratio $\Delta A_k$, defined as MI / CI, provides a measure of the difference in calibration coefficients with respect to reference values. This comparison is made for each selected pixel and/or viewing direction.

It was evidenced that a site-by-site analysis is sometimes useful. In fact, residual biases still exist on the knowledge of marine reflectance and these biases differ for each oceanic site. If we limit the analysis to one given site, the bias will be the same for each pixel of the data set, and some particular relative effects (of course not absolute), such as a small temporal decrease or multi-angular calibration errors, become easier to detect.

The analysis with other various parameters, can help with understanding potential problems. For example, the variation with viewing geometry (zenith viewing angle for instance) may indicate some problem in the multi-angular calibration, called sometimes the smile effect. The variation with aerosol content may reveal a problem in the calibration of the 865nm spectral band (or the spectral band used to estimate the aerosol amount), or on the supposed aerosol model (Maritime 98). The variation with the Rayleigh contribution or with geometry may point to some residual problem with the polarization sensitivity of the instrument.

3.2.6 Application examples

Figures 3.2 and 3.3 display $\Delta A_k$ obtained for POLDER-2 at 443, 490, and 670 nm during the period from January to June 2003 and MERIS at 490 and 620 nm during the period from January to September 2003. The estimated $\Delta A_k$ calibration coefficients for POLDER-2, with respect to pre-launch values, do not depend on aerosol optical thickness, viewing zenith angle, and geographic location for POLDER-2. A small dependence with reflectance is apparent for MERIS, especially at 490 nm, and a small change with time. The dependence with reflectance may be a manifestation of non-linearity in the instrument response. The values (± one standard deviation) are 0.995 (±0.019), 0.976 (±0.014), and (0.902±0.017) for POLDER-2, and 1.008 (±0.012) and 0.994 (±0.012) for MERIS. The standard deviations represent less than 2% of the $\Delta A_k$ values, attesting of the good accuracy of the method. The temporal evolution of the radiometric calibration may be monitored by systematically and operationally examining suitable sites, allowing not only detection of long-term trends, but also of high frequency changes that may occur as a result of changes in the data processing or due to onboard calibration adjustments, as evidenced in Figure 3.4 for MERIS.

As the examples illustrate, the Rayleigh scattering method is efficient for the absolute calibration of ocean-color sensors. The method provides calibration coefficients with an inaccuracy of 3-4% (better statistically), for spectral bands in the visible and red. The method is not applicable to the near infrared, where molecular scattering is ineffective. A
more accurate specification of the marine reflectance in the blue would reduce uncertainties in this spectral range. Using oligotrophic waters is not ideal in the blue because the marine reflectance is high, but it is difficult to find oceanic areas away from the coast with high and stable chlorophyll concentrations.

3.3 Inter-Band Calibration Using Sun Glint

3.3.1 Introduction

The sun glint reflectance from the ocean surface is high and spectrally flat over the spectral range of interest, visible to near infrared. Consequently, it provides an opportunity to inter-calibrate spectral bands. After a proper selection of data is made (see below), the processes contributing to the TOA signal are molecular scattering, a background aerosol scattering, back scattering by the water body, gaseous absorption, and of course, specular reflection (glitter), which contributes to 60 to 90% of the total signal depending of wavelength and wind speed.

The sun glint reflectance depends essentially on the geometrical conditions and on surface roughness. It is predicable using models based on observations (Cox and Munk, 1955), but a difficult task is determining accurately the surface wind speed (for which it is difficult to claim a RMS accuracy better than 1-2 m/s), leaving aside the potential limitations of the model. This explains why the sun glint approach is not a good candidate for absolute calibration. However, it is adequate for inter-band calibration, in which the problem is avoided using a reference band, in practice a band in the red (670nm), used to fully characterize the glitter signal, whatever the wind speed and direction, or more precisely, the surface roughness.

3.3.2 Selection of Observations

Geographical selection. The sun glint areas are indeed bright, but pre-selected oceanic sites are used to reduce the uncertainties on marine reflectance. Oceanic sites are the same than those presented in Section 1 for the calibration using Rayleigh scattering (Fougnie et al., 2002).

Clear-pixel selection. For multi-directional sensors such as POLDER or MISR, a threshold is applied on the signal measured in the near infrared in a direction for which the glitter contamination becomes null (the case of POLDER is described in detail in Hagolle et al., 1999). If the sensor is not multi-directional, exogenous data can be used to estimate the aerosol amount and reject targets potentially contaminated by aerosol (as shown by Hagolle et al., 2004), otherwise the accuracy of the method is degraded.

Geometrical selection. The brightest conditions are selected using a threshold on the wave angle \( \theta \), defined by

\[
\theta_n = \arccos\left\{\frac{\cos(\theta_v) + \cos(\theta_s)}{2 \cos(\theta_v/2)}\right\}
\]  

(3.3-1)
with

\[
\theta_p = \arccos\left\{\cos(\theta_s)\cos(\theta_v) + \sin(\theta_s)\sin(\theta_v)\cos(\phi)\right\}
\]  

(3.3-2)

where \(\theta_s\) and \(\theta_v\) are the solar and viewing zenith angles, \(\phi\) is the relative azimuth angle, and \(\theta_p\) is the angle between the solar and viewing directions. Only the pixels corresponding to a wave angle below 4° are retained.

Ancillary data. Some exogenous data are necessary to compute accurately the TOA signal, namely the surface pressure, the surface wind speed, and the total ozone amount, and only the pixels for which these ancillary data are available are selected. A restrictive threshold is applied to the surface wind speed: observations with wind speed greater than 5m/s are discarded in order to avoid possible contamination by surface whitecaps.

3.3.3 Computation of the TOA signal

The following general formulation is used to compute the TOA signal (reflectance):

\[
\rho_{TOA}(\theta_s, \theta_v, \phi) = t_g(\theta_s, \theta_v)\rho_A(\theta_s, \theta_v, \phi) + \rho_g(\theta_s, \theta_v, \phi) T_{dir}(\theta_s, \theta_v) + \rho_m(\theta_s, \theta_v, \phi) T(\theta_s, \theta_v) \sigma A_{\rho_m(\theta_s, \theta_v, \phi)}^{-1}
\]  

(3.3-3)

where \(t_g\) is the total gaseous transmittance, \(\rho_A\) is the molecular and aerosol contribution including coupling terms, \(\rho_g\) is the sun glint reflectance, \(T\) is the total atmospheric transmission for aerosols and molecules, \(T_{dir}\) is the direct atmospheric transmission for aerosols and molecules, and \(S_A\) is the atmospheric albedo. Compared with Eq. (3.3-1) of Section 1, Eq. (3.3-3) includes explicitly the sun glint contribution. The different terms of Eq. (3.3-3) are evaluated as described below.

Glitter reflectance. The reference band in the red (e.g., 670nm) is used to estimate the sun glint reflectance, after correcting the contributions due to Rayleigh and aerosol scattering and gaseous absorption, and the marine reflectance.

Aerosol and molecular scattering contribution. Like in the Rayleigh scattering method, \(\rho_A, T\), are computed using an accurate radiative transfer model, such as the successive order of scattering code of Deuzé et al., (1989), which includes polarization and specular reflection on the wavy surface. The molecular scattering contribution is computed knowing the surface pressure and the molecular optical thickness corresponding to the spectral band considered. The background aerosol contribution is computed using the aerosol characterization made in a viewing direction outside the glitter influence when the sensor is multi-directional (e.g., POLDER, MISR), or using arbitrary assumptions (e.g., climatological values) when this is not the case (e.g., SeaWiFS, MERIS, MODIS).

Marine contribution. The term involving the marine reflectance, represents about 5% of the TOA signal for the shorter wavelengths in the sun glint viewing conditions, and much less in the reference band in the red. The marine reflectance is specified from the
statistical study of Fougnie et al. (2002). Typical values at the pre-selected oceanic sites are given in Section 3.2.3.

Gaseous contribution. Gaseous absorption, due essentially to water vapor (mainly 565 and 865), ozone (mainly 490, 565 and 670), oxygen (765), and nitrogen dioxide (mainly 443 and 490 nm) is corrected in each spectral band using a transmittance model, for example the SMAC model (Rahman and Dedieu, 1994) as in Section 3.2.3.

3.3.4 Error budget

To estimate the error budget of the sun glint calibration method, the major errors are considered. These include the error on the refractive index of water (limitation above 1 micrometer, small variations with temperature and salinity). The inter-band method is not extended to spectral bands centered at 1.0 or 1.6\(\mu\)m, but uncertainties on the refractive index in the near infrared becomes predominant in the error budget. Other errors taken into account are those on the marine reflectance (20%), on the gaseous correction considering a 20% error on the amount, on the aerosol correction considering a wrong aerosol model and a biased optical thickness of 0.03, and on wind speed. Note that the error due to the wind speed is negligible because the glitter signal is not computed using the wind speed, but is measured through the reference red band.

The sun glint signal is a very polarized target especially for the particular geometric configuration of observing near the Brewster angle (see Hagolle et al., 2004). Consequently, errors due to polarization sensitivity of the sensor may be significant: for ocean color sensors, the residual difference error between spectral bands is estimated at 0.5%.

<table>
<thead>
<tr>
<th></th>
<th>443</th>
<th>490</th>
<th>510</th>
<th>565</th>
<th>865</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface pressure (Rayleigh) 15hPa</td>
<td>0.34</td>
<td>0.25</td>
<td>0.22</td>
<td>0.16</td>
<td>0.03</td>
</tr>
<tr>
<td>Seawater refraction index</td>
<td>0.30</td>
<td>0.24</td>
<td>0.21</td>
<td>0.14</td>
<td>0.60</td>
</tr>
<tr>
<td>Aerosol error (model and amount)</td>
<td>1.01</td>
<td>0.78</td>
<td>0.69</td>
<td>0.43</td>
<td>0.53</td>
</tr>
<tr>
<td>Gas amount error of 20%</td>
<td>0.75</td>
<td>0.83</td>
<td>1.03</td>
<td>1.78</td>
<td>0.77</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Marine reflectance</td>
<td>1.50</td>
<td>1.10</td>
<td>0.94</td>
<td>0.33</td>
<td>0.00</td>
</tr>
<tr>
<td>Polarization sensitivity</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>RMS</td>
<td>2.07</td>
<td>1.70</td>
<td>1.66</td>
<td>1.94</td>
<td>1.21</td>
</tr>
<tr>
<td>MAX</td>
<td>4.40</td>
<td>3.71</td>
<td>3.58</td>
<td>3.34</td>
<td>2.43</td>
</tr>
</tbody>
</table>

Table 3.3 gives the error budget for the inter-band calibration between the reference band (here 670nm) and the other bands. Of course, when considering absolute aspects, i.e., to propagate the absolute calibration to the other bands, the calibration error of the reference band should be considered. In the Table, MAX is the maximum error than we can expect.
Consequently, when a large number of data are used to perform the inter-band calibration, which is generally possible, this maximum error corresponds approximately to the 3-sigma error on results obtained for very different geometrical, geographic and geophysical conditions. The root-mean-squared of the individual errors, RMS, is a good indicator of the actual accuracy of the method. It is generally less than 2%, the maximum value being obtained at 443 nm due to the uncertainty on the marine reflectance. At 565 nm, RMS is almost 2% due to possible uncertainty in the ozone amount (the largest uncertainty), hence the gaseous transmittance.

3.3.5 Calibration algorithm and analysis

The calibration method compares the measurements provided by the satellite sensor in the presence of sun glint (MI) with an estimation of the TOA reflectance (CI). The ratio \( \Delta A_k \), defined as MI / CI, gives the absolute calibration coefficient in the spectral band considered. This comparison is made for each selected pixel and/or viewing direction. In the process, the intrinsic sun glint reflectance \( \rho_g \) is derived from the reflectance measured by the instrument in the reference spectral band. It is then used to predict the reflectance in the other spectral bands, i.e., to obtain CI. The choice of the reference band is crucial for the global accuracy of the method. In order to obtain a good accuracy, the reference band must be well calibrated, since any calibration error in the reference band is transmitted to the band to be calibrated. Since for many ocean color sensors, confidence on the pre-flight calibration is lower than for the Rayleigh scattering calibration, the reference band may be chosen among the spectral bands that are calibrated with the latter.

The algorithm first searches for the reference band the wind speed for which the simulated TOA reflectance equals the measured one. Then this wind speed estimate is used to compute the reflectance that should be measured in the other bands. The computations of the TOA reflectance require information on aerosol optical properties. It is necessary to obtain this information from another sensor that does not observe in the sun glint. The sensitivity study of Hagolle et al. (2004) indicates that accuracy is weakly affected by aerosol optical thickness for maritime aerosols (small spectral dependence of the aerosol reflectance), and that pixels for which the optical thickness is above 0.15 and the Ansgstrom coefficient is above 0.3 should be discarded.

3.3.6 Application examples

Figure 3.5 displays the \( A_k \) calibration coefficients obtained for POLDER-1 at 443, 565, 765, and 865 nm as a function of the TOA reflectance at 670 nm, the reference band. They show little dispersion, especially at 765 and 865 nm, near the reference band. The dispersion is larger at 443 nm, and increases with the reflectance at 670 nm. This can be attributed to uncertainty in the modeling of the interactions between surface reflection and molecular scattering and to uncertainty in the water reflectance. The transfer of the calibration in the red to the near infrared is accurate, and allows an absolute calibration in this spectral range, complementing the Rayleigh scattering method.
Figure 3.6 illustrates the potential of the method for monitoring temporal changes in the calibration. The $A_k$ calibration coefficient at 490 nm, transferred from 670 nm as described above, is displayed as a function of time during the operational periods of POLDER-1 and POLDER 2. No significant temporal trend is apparent for POLDER 1, but a significant decrease with time is detected for POLDER-2. This decrease has been confirmed using other calibration methods, including the Rayleigh scattering method.

The sun glint calibration method is an efficient way to transport the calibration of spectral bands in the visible to infrared bands up to 1,650 nm with a good accuracy. If the uncertainty of the calibration coefficient of the reference band at 670 nm is 2% RMS (see Section 1), the calibration of a band at 865 nm can be obtained with an uncertainty of about 3.3%. It is important to note, however, that many ocean color sensors saturate over sun glint, limiting the application of the method. Furthermore, issues of non-linearity in the sensor response need to be carefully addressed for the method to be effective for ocean-color remote sensing.

### 3.4 Inter-Band Calibration Over Bright Clouds

#### 3.4.1 Introduction

From the point of view of satellite sensor calibration, high and dense scattering clouds are diffusers comparable to the moon, i.e., they exhibit a white spectral signature and very limited perturbing contributors, which strongly simplifies the modeling. Such clouds are excellent candidates for inter-band calibration purposes or multi-temporal monitoring, as discussed in Vermote and Kaufman (1995), Hagolle et al. (1999), Lafrance et al. (2002), and Fougnie et al. (2007).

Selecting high convective clouds guarantees negligible or very small surface effect, aerosol and Rayleigh scattering contributions, and a small impact of cloud microphysics, i.e., of the particle types composing the cloud. The modeling of such an intensively scattering system becomes greatly simplified, indeed.

A first approximation of a perfectly white spectral behavior of the cloud, after correction of gaseous absorption, gives an inter-band calibration accuracy within a few percent by extrapolating the cloud reflectance measured at a given spectral band of reference. A refined modeling, described hereafter, uses the reference band to invert the cloud optical thickness assuming a type of cloud top particles, and computes for other bands the reflectance to be compared with the satellite sensor measurement through a radiative transfer look-up-table.

#### 3.4.2 Selection of Observations

The success of the calibration over clouds is made by a rigorous selection of adequate targets and viewing geometries (see details in Lafrance et al., 2002).
Geographical selection. The candidate targets are thick convective cumulonimbus clouds over oceans, i.e., a relatively dark surface. They are developed above subtropical warm oceans, in inter-tropical latitudes between 30°N and 30°S, regularly affected by atmospheric convective dynamics.

Cloud selection. The two most important characteristics to consider for selection are dense scattered convective cloud and very high altitude clouds. This can be guaranteed using the following criteria. A powerful criterion makes use of absorption bands near 763nm, when available, from which it is possible to derive the apparent oxygen pressure, yielding a good estimation of the cloud top altitude. A restriction to apparent pressure lower than 400hPa leads to cloud altitude higher than 8km. But the altitude is not sufficient: cirrus clouds are not good candidates, while cumulonimbus are adequate. The best criterion to guarantee the selection of a very dense convective cloud is the TOA reflectance that must be greater than 0.8 in the near infrared band (e.g., 865 nm). Another complementary spectral criteria may be carefully used considering the fact that the residual Rayleigh contribution above the cloud is about 2-3% in the blue band. To select clouds above the ocean, observations located at less than 30km from a coastline are discarded. Finally, a criterion is considered for characterizing the homogeneity of the cloud: the relative standard deviation of the TOA reflectance for NIR band in a 30x30km² must be less than 3%.

Geometrical selection. It is recommended to reject observations corresponding to viewing geometries near the specular reflection by selecting relative viewing azimuth angles between 30 and 150°. In order to avoid possible shadowing effects, measurements corresponding to solar zenith angle greater than 30° or viewing zenith angle greater than 40° are discarded. In addition, restricting the analysis to such “near-nadir” geometries limits the impact of cloud microphysics, actually unknown (Lafrance et al., 2002).

3.4.3 Computation of the TOA signal

The computation of the TOA signal is made using the formulation described below:

\[ \rho_{\text{TOA}}(\theta_s, \theta_v, \phi) = t_g(\theta_s, \theta_v) \cdot \rho(\theta_s, \theta_v, \phi) \left( \tau_{\text{cld}} + \tau_a + \tau_R \right)_{n=1 \text{ to } 16 \text{ layers}} \] (3.3-1)

where \( t_g \) is the total gaseous transmittance, \( \rho \) is the reflectance at the top of the cloud/atmosphere system, and for each layer \( n \), \( \tau_{\text{cld}} \) the cloud optical thickness, \( \tau_R \) and \( \tau_a \) the molecular and aerosol optical thicknesses. The reflectance at the top of the cloud/atmosphere system, \( \rho \), is computed using a Discrete Ordinates code computing method (Stamnes et al., 1988) and assuming a vertical description of the cloud and atmosphere divided into 16 layers, and for which cloud particle type, aerosol type, and optical thickness are defined according Lafrance et al. (2002).

Cloud optical thickness. The reference band in the red (e.g., 670nm) is used to estimate the cloud optical thickness by an inversion algorithm using look-up-tables computed with the Discrete Ordinates code. An accurate description of the cloud microphysics should require a multiphase and vertical profile description, which is usually unknown. In the
modeling, the convective cloud is divided into a lower layer from 1 to 6km high composed of liquid water droplets, covered by an upper layer from 6 to 15km high composed of ice particles. This approximation, discussed in Lafrance et al (2002), is in fact realistic. The liquid layer is homogeneous with a size distribution corresponding to cumulonimbus droplets as reported in Stephens (1978). The ices particles are hexagonal columns, plates or compact hexagonal crystals as observed by Chepfer et al. (1998). Each particle is characterized by its albedo, asymmetry factor, phase function, and scattering and extinction coefficients. In practice, the plate particle type is used as a good compromise, and variations with model particle have a small effect.

**Molecular scattering contribution.** The vertical molecular profile is computed for the 16 atmospheric layers by the product of the vertical pressure profile for a standard tropical profile (McClatchey et al., 1972) by the usual molecular optical thickness.

**Aerosol scattering contribution.** The aerosol contribution is taken representative to mid-latitude summer conditions, i.e. a WMO (1986) Maritime-I case including 3 homogeneous layers: an under layer of maritime aerosols from sea surface to 2km high with an optical thickness of 0.05 at 550nm, a layer of continental aerosols from 2km to 12km high with an optical thickness of 0.025 at 550nm, and an upper background layer of stratospheric aerosols up to 12km high with an optical thickness of 0.005 at 550nm. The global aerosol optical thickness is consequently 0.08 at 550nm.

**Surface contribution.** The ocean surface contribution is assumed lambertian marine reflectance corresponding to a typical surface chlorophyll concentration of 0.1 mg/m3. Sun glint is not considered because viewing geometries favoring sun glint are discarded.

**Gaseous contribution.** For the selected convective cloud conditions, water vapor and oxygen absorption can be neglected in the 443 to 865 bands, as shown in Lafrance et al. (2002). On the other hand, the ozone contribution, mainly affecting 490, 565, and 670 must be taken into account using a transmittance model, for example the SMAC model (Rahman and Dedieu, 1994), with as input the ozone content from TOMS data or climatology.

### 3.4.4 Error budget

To estimate the error budget of the calibration method over clouds, the major errors are considered. Using very dense and high convective clouds essentially limits the errors to the particle model for the top of the cloud, the cloud top altitude leading to an uncertainty of on the Rayleigh scattering contribution above the cloud (error of 3km), the gas content (error of 20% on ozone, and oxygen), and the background stratospheric aerosol content (100% error on the optical thickness). Uncertainties on the other contributors have a very small or negligible effect. The various errors are quantified and summarized in Table 3.4.
Table 3.4 Typical error budget for the inter-band calibration method over clouds.

<table>
<thead>
<tr>
<th>Error Type</th>
<th>443</th>
<th>490</th>
<th>565</th>
<th>765</th>
<th>865</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud particle model (microphysics)</td>
<td>2.19</td>
<td>1.01</td>
<td>0.73</td>
<td>0.47</td>
<td>2.33</td>
</tr>
<tr>
<td>Cloud top altitude (3km)</td>
<td>0.69</td>
<td>0.42</td>
<td>0.18</td>
<td>0.07</td>
<td>0.11</td>
</tr>
<tr>
<td>Aerosol (100% on stratospheric AOT)</td>
<td>0.14</td>
<td>0.09</td>
<td>0.05</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>Gas amount (20% for O$_3$/O$_2$)</td>
<td>0.39</td>
<td>0.19</td>
<td>0.81</td>
<td>0.95</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>RMS</strong></td>
<td>2.33</td>
<td>1.12</td>
<td>1.11</td>
<td>1.06</td>
<td>2.36</td>
</tr>
<tr>
<td><strong>MAX</strong></td>
<td>3.41</td>
<td>1.72</td>
<td>1.77</td>
<td>1.51</td>
<td>2.82</td>
</tr>
</tbody>
</table>

For the 490, 565 and 765nm spectral bands, close to the 670nm reference band, the error due to cloud microphysics is very small. For the 565 and 765nm bands, the method inaccuracy is mostly due to the uncertainty on gaseous transmission, which represents about 6% for both bands (ozone for 565 nm and oxygen for 765 nm). For the 443nm blue band, inaccuracy is dominated by errors on cloud top altitude, directly linked to the observed Rayleigh scattering contribution, and cloud microphysics. At the opposite part of the spectrum, i.e., 865 nm, cloud microphysics becomes the main uncertainty. The error budget is the most favorable at 490, 565, and 765nm, for which the RMS performance is about 1%.

3.4.5 Calibration algorithm and analysis

As described in section 3.2.5, the ratio of the measurements made by the satellite sensor to the TOA reflectance estimate gives the absolute calibration coefficient, $\Delta A_k$, for the considered spectral band. In the process, the intrinsic cloud optical thickness $\tau_{cld}$, derived from the reflectance measured by the instrument in the reference spectral band, is used to predict the reflectance in other spectral bands. As for inter-band calibration over sun glint, the choice of the reference band is crucial for the global accuracy of the method. In order to obtain a good accuracy, the reference band must be well calibrated, since any calibration error in the reference band is transmitted to the band to be calibrated. A spectral band that was previously calibrated over Rayleigh scattering is usually selected and the best compromise was found to be 670nm (red band).

Assuming a cloud particle type (hexagonal, plate, or column) for the upper layer of the cloud, the inter-band calibration over clouds method is an efficient way to transport the calibration of a reference band in the visible to other bands in the visible and to near-infrared bands, from 490 to 865nm. For greater wavelengths, assumptions made on cloud microphysics, and especially the absorption process inside the clouds, becomes a limiting factor. For example, it was impossible to calibrate in absolute the 1020nm spectral band of the POLDER-3 instrument aboard PARASOL using the cloud inter-band methods to propagate absolute calibration in the red, but nevertheless pertinent results were obtained for multi-temporal calibration. For sensors designed for ocean color observations, non-linearity issues of the instrumental response must be carefully addressed for unbiased interpretation of the results. However, the main limitation is saturation occurrences, since
such sensors have acquisition dynamic ranges that are often dimensioned for clear atmosphere observations.

3.4.6 Application examples

Figure 3.7 displays the $A_k$ calibration coefficients obtained for POLDER-2 at 443, 490, 765, and 865 nm as a function of the TOA reflectance at 670 nm, the reference band. As for the inter-band method over sun glint, they show little dispersion, especially at 765 and 865 nm, near the reference band. The dispersion is larger at 443 nm, and increases with the reflectance at 670 nm. This can be attributed to uncertainty on the cloud altitude, and consequently on the molecular scattering contribution above the cloud. The transfer of the calibration in the red to the near infrared is accurate, and allows an absolute calibration in this spectral range, complementing other calibration methods (Rayleigh, sun glint).

Figure 3.8 illustrates the potential of the method for monitoring temporal changes in the calibration coefficients. The $A_k$ calibration coefficient for 490nm to 1020nm, transferred from 670nm as described above, is displayed as a function of time during the first 18 months of POLDER-3 aboard PARASOL. Assuming 765nm as a temporal stable reference (hypothesis corroborated by other results), a significant decrease with time was detected, monitored, and modeled for all spectral bands. This decrease has been confirmed using other calibration methods, including the Rayleigh scattering method, the inter-band calibration over sun glint and cross-calibration over desert sites (Fougnie et al., 2007).

3.5 Cross-Calibration Over Desert Sites

3.5.1 Introduction

Measurements over natural targets of reference such as desert sites have been exploited for many years for cross-calibration and multi-temporal monitoring purposes in the solar spectral range. Accessibility in term of cloudiness and stability with time are the main advantages of such sites.

In the cross-calibration exercise of two sensors, simultaneous measurements of the sensor to calibrate and the reference sensor, hereafter called StC and RS, respectively, are usually required in order to minimize geometric effects strongly limiting the direct comparison of measurements. The use of stable and homogeneous desert sites allows a larger applicability of such comparisons through a bidirectional and spectral characterization of the surface reflectance of the site.

In this approach, 20 adequate desert sites have been selected, and observations by several space sensors, including ocean color sensors, have been collected for many years (Cabot et al., 1999). The size of the desert sites is 100x100 km$^2$ and for one given acquisition, the radiometric and geometric quantities are averaged over the site and saved into the archive. This archive offers the ability to select various reference sensors depending on
the objective. It allows, in particular, multi-sensor comparison as reported, for example, in Fougnie et al. (2002).

3.5.2 Selection of Observations

Geographical selection. Observations over 20 desert sites are privileged (Table 3.5). These reference sites have been identified through a systematic climatological study using METEOSAT-4 data (Cosnefroy et al., 1993). Selection criteria were i/ an excellent spatial homogeneity based on a 3% dispersion threshold on the TOA reflectance over the 100x100km² area, ii/ a temporal stability at seasonal scale better or equal to 15%, iii/ a low cloud cover with annual percentages of clear days greater or equal to 50%, and iv/ precipitation lower than 10mm per month to avoid surface reflectance anomalies (Cosnefroy et al., 1996).

Table 3.5 Name and location (latitude, and longitude) of the 20 desert sites according Cosnefroy et al. (1996).

<table>
<thead>
<tr>
<th>Site</th>
<th>Lat.</th>
<th>Lon.</th>
<th>Site</th>
<th>Lat.</th>
<th>Lon.</th>
<th>Site</th>
<th>Lat.</th>
<th>Lon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria 1</td>
<td>23.80</td>
<td>-0.40</td>
<td>Libya 1</td>
<td>24.42</td>
<td>13.35</td>
<td>Mauritania 1</td>
<td>19.40</td>
<td>-9.30</td>
</tr>
<tr>
<td>Algeria 2</td>
<td>26.09</td>
<td>-1.38</td>
<td>Libya 2</td>
<td>25.05</td>
<td>20.48</td>
<td>Mauritania 2</td>
<td>20.85</td>
<td>-8.78</td>
</tr>
<tr>
<td>Algeria 3</td>
<td>30.32</td>
<td>7.66</td>
<td>Libya 3</td>
<td>23.15</td>
<td>23.10</td>
<td>Niger 1</td>
<td>19.67</td>
<td>9.81</td>
</tr>
<tr>
<td>Algeria 5</td>
<td>31.02</td>
<td>2.23</td>
<td>Arabia 1</td>
<td>18.88</td>
<td>46.76</td>
<td>Niger 3</td>
<td>21.57</td>
<td>7.96</td>
</tr>
<tr>
<td>Egypt 1</td>
<td>27.12</td>
<td>26.10</td>
<td>Arabia 2</td>
<td>20.13</td>
<td>50.96</td>
<td>Mali 1</td>
<td>19.12</td>
<td>-4.85</td>
</tr>
<tr>
<td>Sudan</td>
<td>21.74</td>
<td>28.22</td>
<td>Arabia 3</td>
<td>28.92</td>
<td>43.73</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cloud selection. The cloud mask is based on a threshold using a spectral criterion. Measurements for which \((\rho_{865} - \rho_{443})\) is less than \(0.2*(\rho_{865} + \rho_{443})\), where \(\rho_{865}\) and \(\rho_{443}\) are top-of-atmosphere reflectance at 865 and 443nm, respectively, are declared cloudy. The second powerful criterion is to use oxygen absorption bands when available, for example bands centered on 753 and 760nm for MERIS or 763 and 765nm for POLDER. Observations for which the difference between the surface pressure and the apparent pressure derived from the absorption bands is greater than 200hPa are flagged cloudy and discarded.

Geometrical selection. No particular restriction is required, but it was identified that calibration results derived from acquisitions near the backscattering direction or for very large viewing zenith angles become inaccurate because of bidirectional effects of the ground surface and/or limitation in the atmospheric correction.
3.5.3 Computation of the TOA signal

The following general formulation is used to compute the TOA signal (reflectance) for a given spectral band \( \lambda \):

\[
\rho_{\text{TOA}}(\lambda, \theta_s, \theta_v, \phi) = t_g(\lambda, \theta_s, \theta_v) \cdot \{ \rho_A(\lambda, \theta_s, \theta_v, \phi) + \rho_{\text{surface}}(\lambda, \theta_s, \theta_v) \cdot T(\lambda, \theta_s, \theta_v) / [1 - S_A(\lambda) \cdot \rho_{\text{surface}}(\lambda, \theta_s, \theta_v)] \} \tag{3.5-1}
\]

where \( \theta_s, \theta_v, \) and \( \phi \) are the solar and viewing zenith angles and relative azimuth angle respectively, \( t_g \) is the gaseous transmittance, \( \rho_A \) is the molecular and aerosol contribution including coupling terms, \( T \) is the total atmospheric transmission for aerosols and molecules, \( \rho_{\text{surface}} \) is the desert surface reflectance, and \( S_A \) is the atmospheric albedo.

**Surface reflectance.** The surface reflectance \( \rho_{\text{surface}} \) considered in Eq. 3.5-1 to compute the TOA reflectance for the StC is derived according to the following approach. Starting with \( \rho_{\text{RS}} \), the TOA reflectance measured by the RS, the reference surface reflectance \( \rho_{\text{RS, surface}} \) is computed using

\[
\rho_{\text{RS, surface}} = [\rho_{\text{RS}} - \rho_A \cdot t_g] / [T \cdot t_g - S_A \cdot \rho_A \cdot t_g + S_A \cdot \rho_{\text{RS}}] \tag{3.5-2}
\]

where \( t_g, S_A, \rho_A, \) and \( T \) are defined as previously, and where \( \theta_s, \theta_v, \phi, \) and \( \lambda \) are omitted for clarity. Different options are possible to estimate the surface reflectance for the StC, \( \rho_{\text{surface}} \). A band-by-band approach, directly assuming for a given spectral band \( \lambda \) that \( \rho_{\text{surface}} = \rho_{\text{RS, surface}} \), may be used when spectral bands of StC and RS are nearly identical as for example when cross-calibrating all POLDER-1 spectral bands with POLDER-2, MODIS/Aqua with MODIS/Terra, or when cross-calibrating the MERIS 490nm band with the SeaWiFS 490nm band. More generally, the surface reflectance \( \rho_{\text{surface}} \) can be assessed by a combination of the transmission of the spectral band \( \lambda_{\text{StC}} \) and a surface reflectance spectrum, \( \rho_{\text{spectral}} \), according to

\[
\rho_{\text{surface}}(\lambda_{\text{StC}}) = \int_{\lambda_{\text{StC}}} \rho_{\text{spectral}}(\lambda) \cdot t(\lambda) \cdot d\lambda. \tag{3.5-3}
\]

where the surface spectrum is obtained through spectral interpolation of \( \rho_{\text{RS, surface}} \) using a spline function (Tinel et al., 2006) or a specific mathematical model (Cabot et al., 1999; Miesch et al., 2003)

**Atmospheric scattering contribution.** The atmospheric TOA reflectance, including molecules, aerosol, and coupling terms, is computed using the 6S radiative transfer code (Vermote et al., 1997), assuming a constant desert aerosol model with an optical thickness of 0.2. The assumptions about aerosols are expected to be representative of the average conditions, except for marginal large aerosol events (Cabot et al., 1999).

**Gaseous contribution.** Ozone content, water vapor, and surface pressure are taken from meteorological data. Gaseous transmittance is computed for atmospheric corrections using the SMAC transmittance model (Rahman and Dedieu, 1994).
3.5.4 Error budget

Table 3.6 summarizes the error budget of the cross-calibration method, which is limited to the main uncertainties on the input parameters, approximation on the modeling, and assumptions on the description of the atmosphere-surface system. The errors considered are those made on the surface reflectance model (estimated in Miesch et al., 2003 but unfortunately depend on the interpolation method), on the selection of the reference measurements (including the selection of the reference geometry using the sensitivity study of Cabot et al. (1998, 1999), on the gaseous absorption, on the atmospheric correction (including aerosol contribution and surface pressure uncertainty), and on the reference sensor reflectance (including an inter-band calibration error). Like for the other calibration methods, the root-mean-squared (RMS) error is considered as an appropriate and realistic measure of performance.

Table 3.6 Typical error budget for the desert sites calibration method.

<table>
<thead>
<tr>
<th>Error Type</th>
<th>443</th>
<th>490</th>
<th>510</th>
<th>565</th>
<th>670</th>
<th>765</th>
<th>865</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface reflectance model: 2%</td>
<td>1.23</td>
<td>1.53</td>
<td>1.73</td>
<td>2.08</td>
<td>2.10</td>
<td>2.28</td>
<td>2.06</td>
</tr>
<tr>
<td>Geometry</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Surface pressure: 10hPa</td>
<td>0.49</td>
<td>0.34</td>
<td>0.26</td>
<td>0.14</td>
<td>0.05</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Gas amount: 20%</td>
<td>0.04</td>
<td>0.32</td>
<td>0.61</td>
<td>1.51</td>
<td>0.56</td>
<td>2.08</td>
<td>0.12</td>
</tr>
<tr>
<td>Aerosol content: 30% on $\tau_a$</td>
<td>2.57</td>
<td>2.60</td>
<td>2.32</td>
<td>1.72</td>
<td>1.14</td>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>Aerosol model</td>
<td>2.87</td>
<td>1.60</td>
<td>1.01</td>
<td>0.05</td>
<td>0.60</td>
<td>0.86</td>
<td>1.01</td>
</tr>
<tr>
<td>Reference inter-band calibration</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>RMS</td>
<td>4.23</td>
<td>3.63</td>
<td>3.33</td>
<td>3.29</td>
<td>2.76</td>
<td>3.53</td>
<td>2.71</td>
</tr>
<tr>
<td>MAX</td>
<td>8.70</td>
<td>7.90</td>
<td>7.45</td>
<td>6.99</td>
<td>5.94</td>
<td>7.75</td>
<td>5.61</td>
</tr>
</tbody>
</table>

In general, the error budget, in terms of RMS, is about 3-4%. For longer wavelengths, the major source of error originates from the surface reflectance estimation because of limitations on the interpolation model or inter-band calibration error of the reference sensor. For shorter wavelengths, the error on the atmospheric contribution becomes the dominant factor.

For multi-temporal calibration purposes, the error budget is significantly improved, since the impact of errors affecting the estimation of surface reflectance, i.e., inter-band calibration of the RS and surface reflectance model, are strongly reduced. The accuracy of the method for multi-temporal calibration is nearly twice better for the red/near infrared bands. The improvement is not so important for shorter wavelengths, because other processes, mainly atmospheric contribution errors, are major factors.

3.5.5 Calibration algorithm and analysis

For each acquisition of the StC, the algorithm searches all the measurements of the RS acquired for the same geometric conditions, i.e. same solar and viewing azimuth/zenith angles +/- a given tolerance (typically 2°). Reciprocal viewing conditions are also
considered (Cabot et al., 1999) and are useful to extend the dataset when cross-calibrating sensors with very different acquisition geometries, for example when comparing MODIS/AQUA acquisitions near 13:30UT with MODIS/TERRA acquisitions near 10:30UT. In addition, if the data archive of the RS covers many years, several reference acquisitions would be found, as the same geometric coincidence between StC and RS is usually found every year. Consequently, for one acquisition of the StC, several acquisitions of the RS are usually selected as reference.

For each couple of measurements identified, composed of a StC measurement and a RS measurement, the evaluation consists in comparing the normalized radiance measured by the StC (MI) with the TOA normalized radiance (CI) computed using Eq. 3.4.1 with as input the surface reflectance estimated using the RS measurement obtained from Eq. 3.4.3. The ratio $\Delta A_k$, defined by $\frac{\text{MI}}{\text{CI}}$, provides for each spectral band an estimation of the cross-calibration between the StC and the RS.

As it is the case for all calibration methods, an analysis of the sensitivity of results with input parameters can help with understanding potential problems. For example, strong variations with viewing zenith angles pronounced in the blue part of the spectrum may reveal atmospheric correction problems, i.e., an inaccurate representation of aerosol model and content. The multi-temporal analysis requires a regular temporal sampling over each site (or not to consider inadequate site). Since for ocean color sensors the dynamic range is often dimensioned for clear atmosphere normalized radiances, a strong deviation of $\Delta A_k$ may suggest nonlinearity problems of the instrumental response (Fougnie et al., 2001; Hagolle and Cabot, 2005).

### 3.5.6 Application examples

Figure 3.9 illustrates the cross-calibration method for the POLDER-2 and -3 instruments. The $\Delta A_k$ coefficients for the POLDER-3 acquisitions in 2005 were obtained using as reference the POLDER-2 measurements acquired in 2003. A very good consistency within 1-2% is found for 490, 670, and 865 nm and RMS errors are in accordance with the error budget detailed in Section 4.4.

Figure 3.10, from Fougnie et al. (2002), shows the SeaWiFS temporal trends as observed over desert sites for the 490, 670, and 865 nm bands. Results were averaged month by month and the RMS errors are still consistent with the error budget. The temporal drift for 670 and 865 bands evidenced by this method, about 0.7 and 2.5% per year respectively, confirmed the results reported in Barnes et al. (2001).

### 3.6 Absolute Calibration Using Sky Radiance and Solar Extinction

#### 3.6.1 Introduction

An absolute calibration method suitable for the red and infrared bands of ocean-color sensors was proposed in Gordon and Zhang (1996) (see also Gordon, 1997, 1998). It involves making surface measurements of solar extinction and sky radiance at the time of
satellite overpass. Using the algorithm developed by Wang and Gordon (1993) to estimate aerosol phase function and single scattering albedo, Gordon and Zhang (1996) showed that the top-of-atmosphere radiance can be predicted with an accuracy of 1-2% in the near infrared (if the surface radiometer is perfectly calibrated). They indicated “a reasonable calibration strategy in the near infrared is to place unattended sun photometer and sky radiometer units on small remote islands”. A variant of this method was proposed recently in Santer and Martiny (2003). Instead of iterating directly over phase function and single scattering albedo, the measured sky radiance is first corrected for multiple scattering effects. The “pseudo” phase function, i.e., the product of phase function and single scattering albedo, is then obtained immediately using the primary scattering formulation. The process is repeated once to improve the correction of multiple scattering and, therefore, the determination of the “pseudo” phase function. Both studies concluded that the most important source of error in the prediction of the top-of-atmosphere radiance is the accuracy of the sky radiance.

3.6.2 Predicting TOA radiance from CIMEL measurements

In the spectral range of interest, 700-900 nm, the diffuse reflectance of Case-I waters, i.e., waters whose optical properties are governed by their biogenic content, is practically null (Morel, 1988). When the surface winds are light (i.e., speed of less than 7 m/s), the ocean surface is generally free of whitecaps, and their eventual effect on surface reflectance is also negligible (Frouin et al., 1996). In these conditions, the only contribution from the surface to the top-of-atmosphere (TOA) radiance is due to Fresnel reflection. This contribution can be taken into account using the Cox and Munk (1954) model for isotropic wave-slope distribution, which depends on wind speed. Away from the direction of specular reflection, the satellite signal is mostly atmospheric in nature, i.e., essentially composed of photons that have not interacted with the surface and water body, with contributions due to scattering by molecules (Rayleigh scattering) and aerosols.

An accurate radiative transfer code, such as the successive-order-of-scattering computer code (Deuzé et al., 1989), may be used to solve the radiation-transfer equation and predict the TOA radiance, $L_{TOA}$. This code has been compared with a Monte Carlo code (Santer et al., 2004), and the study has shown that agreement between the output of the two codes is within 1% over land and 1.2% over ocean. A difficulty with successive-order-of-scattering computations resides in the selection of the number of Legendre polynomials that describe the aerosol phase function. Indeed, when the phase function presents a pronounced forward peak, a large number of polynomials are needed to recompose it properly. If the number of polynomials is too small, the recomposed phase function may exhibit oscillations in the forward and backward scattering regions. Increasing the number of polynomials, however, increases computation time. An optimum number of 80 polynomials are used for the computations. If oscillations still occur with 80 polynomials (rarely the case), then the phase function is truncated and the aerosol optical thickness modified accordingly. The input variables of the radiation-transfer code to compute $L_{TOA}$ are the aerosol optical thickness, the “pseudo” aerosol phase function, and the surface wind speed. The scattering properties of the aerosols may
be obtained using data from CIMEL radiometers of the Aerosol Robotic Network (AERONET) (Holben et al., 1998).

**Solar extinction measurements**

A basic description of the aerosols can be obtained from the solar extinction measurements. The solar irradiance \( E(\lambda) \) measured by the CIMEL instrument in spectral band centred on \( \lambda_i \) can be related to the total optical thickness of the atmosphere \( \tau_{\text{tot}} \) using the Langley-Bouguer law, that is

\[
E(\lambda) = E_0(\lambda) \left( \frac{d}{d_0} \right)^2 \exp\left[-m \tau_{\text{tot}}(\lambda)\right],
\]

where \( E_0 \) is the extra-terrestrial solar irradiance, \( d \) and \( d_0 \) the actual and mean Earth-Sun distance, respectively, and \( m \) the total air mass. Knowing the calibration coefficient \( E_0 \), the total optical thickness \( \tau_{\text{tot}} \) can be easily derived from Eq. (3.6-1). The aerosol optical thickness \( \tau_a \) can be deduced from \( \tau_{\text{tot}} \) by subtracting the ozone optical thickness \( \tau_{\text{o3}} \) and the Rayleigh optical thickness \( \tau_r \) (obtained from the ozone content and the surface pressure, respectively), using

\[
\tau_a(\lambda) = \tau_{\text{tot}}(\lambda) - \tau_{\text{o3}}(\lambda) - \tau_r(\lambda).
\]

A dynamic Angström coefficient \( \alpha(\lambda_1, \lambda_2) \) between wavelengths \( \lambda_1 \) and \( \lambda_2 \) can be computed from \( \tau_a(\lambda) \). It is defined as

\[
\alpha(\lambda_1, \lambda_2) = \ln[\tau_a(\lambda_1)/\tau_a(\lambda_2)]/\ln(\lambda_1/\lambda_2).
\]

This coefficient characterizes the spectral dependency of \( \tau_a \), an indicator of size distribution and, therefore, aerosol type. However, \( \alpha(\lambda_1, \lambda_2) \) is not sufficient to determine completely the aerosol type. Nevertheless, an aerosol model can be associated to \( \alpha(\lambda_1, \lambda_2) \). Following the SeaWiFS standard atmospheric correction algorithm (Gordon and Wang, 1994; Gordon, 1997), the aerosol model can be selected among twelve candidates based on Shettle and Fenn (1979) data, namely Maritime, Coastal, Tropospheric, and Urban types with a relative humidity of 70, 90, and 98%. Among these models, only the Urban type absorbs substantially. In the following, the candidate models will be referred to as for example M98 (Maritime model with a relative humidity of 98%) or T70 (Tropospheric model with a relative humidity of 70%).

Once the model is identified, its single scattering albedo and phase function are determined, and they can be used with the CIMEL-derived aerosol optical thickness as input variables to the radiation-transfer code to simulate the TOA radiance. This approach to calibration, however, depends critically on the set of aerosol models to choose from, and the set of models described above may not be realistic or appropriate to the problem, as documented in some studies (e.g., Gross et al., 2003 and Smirnov et al., 2003).
Sky radiance measurements

Another approach to simulate the TOA signal utilizes CIMEL sky radiance measurements. In this method, proposed by Santer and Martiny (2003), no assumption on the aerosol model is required to obtain the phase function. The inversion scheme can be summarized as follows.

As the CIMEL radiometer measures the total downward radiance, we first correct the measured radiance from multiple scattering effects. We call \( f \) the corrective factor defined as:

\[
f = \frac{[L^{(1)}]/L_{theo}}{[L^{(1)}]/L_{meas}},
\]

where \( L^{(1)} \) and \( L \) stand respectively for the primary and total radiance in the atmosphere. Simulated \( L^{(1)} \) and \( L \) are obtained using the successive-order-of-scattering radiation-transfer code. The aerosol parameters used as first input to the code are \( \tau_a \) and \( \alpha \) derived from the CIMEL extinction measurements and the associated Junge size distribution \( n(r) \) written as:

\[
n(r) = C r^{(\alpha-3)}.
\]

Once the measured PPL radiance is corrected for multiple scattering effects, we use the primary scattering approximation for a homogeneous atmosphere formalized as:

\[
P' = 4L^{(1)} \exp(\tau_{tot}/\mu_v) \{1 - \exp[-\tau_{tot}(1/\mu_s - 1/\mu_v)]\} \{\mu_v/(\mu_s - \mu_v)\}^{-1},
\]

where \( P' \) is the total “pseudo” phase function (molecules plus aerosols) and \( \mu_v \) and \( \mu_s \) are the cosine of the view and solar zenith angles, respectively. The total “pseudo” phase function \( P' \) is related to the “pseudo” phase function of the aerosols \( \omega_aP_a \) via the following equation:

\[
P' = (\omega_a\tau_aP_a + \tau_rP_r)/(\tau_a + \tau_r),
\]

where \( \omega_a \) and \( P_a \) are the single scattering albedo and phase function of the aerosols, respectively, and \( P_r \) is the phase function of the molecules. Knowing \( \tau_{tot} \) from the CIMEL extinction data and the geometrical conditions, \( \omega_aP_a \) is easy to deduce from the primary scattering radiance \( L^{(1)} \) previously derived from Equation (3.6-4).

The process is then iterated as follows. The parameter \( f \) is computed again using the radiation-transfer code, but with the \( \omega_aP_a \) derived from Equations (3.6-6) and (3.6-7) (step above) instead of the \( \omega_aP_a \) computed from a Junge size distribution and a real refractive index of 1.45 (order zero). Equations (3.6-6) and (3.6-7) are then applied to get a new value of \( \omega_aP_a \). The iterative process is stopped when \( f \) is stabilized to within less than 0.5%. Note that \( P' \) is required as input to the radiation-transfer code, not the individual terms on the right-hand side of Equation (3.6-7), but working with \( \omega_aP_a \) provides for easier quality control of the results.
Error budgets on $F$, $\omega_a P_a$, and $L_{TOA}$

The radiance-based method described above relies on an iterative process to retrieve the aerosol “pseudo” phase function $\omega_a P_a$. According to Equation (3.6-6), the basic errors associated with $\omega_a P_a$ are due to errors on the parameter $f$ and on the extrapolation of the phase function to 180°, and to uncertainties linked to the calibration of the CIMEL radiometer, both in radiance and irradiance.

Figure 3.11 displays the error budget on $\omega_a P_a$ derived for the M90 model (solid line), the T90 model (dashed line), and the U90 model (micro-dashed line). The visibility is 23 km, the solar zenith angle is 75 degrees, and the wind speed is 7ms$^{-1}$. Wavelength is 865 nm. The error increases with scattering angle in the backward scattering region, reaching 2.2% for the most absorbing model, U90, which is quite satisfactory. Note that the individual errors on $\omega_a P_a$ are positive or negative and therefore partly compensate.

In the error budget for $L_{TOA}$ (Figure 3.12), we have also to account separately for uncertainties on wind speed and aerosol optical thickness. Simulations of $L_{TOA}$ at 865 nm were performed for the same aerosol models as in Figure 3.11, a visibility of 23 km, two solar zenith angles ($\theta_s$ of 30° and 60°), and an azimuth difference $\Delta \phi$ of 90°. The results, reported in Figure 3.5.2, indicate that the maximum error on $L_{TOA}$ occurs in the case of a high solar elevation ($\theta_s=30°$) and low viewing zenith angles. Nevertheless, even in that case, the error on $L_{TOA}$ does not exceed 3.2% in the SeaWiFS geometry ($\theta_v$ from 20° to 70°). In an optimum case ($\theta_s=60°$), the uncertainty related to $L_{TOA}$ is on the order of 2% in the SeaWiFS geometry. In conclusion, the radiance-based method has a typical inaccuracy between 2 and 3% depending on solar zenith angle and sensor geometry.

Including typical errors due to atmospheric transmittance (0.6%), aerosol polarization (1%), and radiation-transfer model (1.2%), the error budget for $L_{TOA}$ at 865 nm becomes 2.6 to 3.4%, depending on angular geometry. This error budget, however, does not take into account environmental effects, i.e., interactions between photons and the land surface, which may be significant for some coastal sites (see Schwindling et al., 1998 for a discussion of these effects).

3.6.3 Application to SeaWiFS calibration in the near infrared

The calibration method has been applied to the calibration of SeaWiFS in the near infrared (band 8, centered at 865 nm) (Martiny et al., 2005). CIMEL data acquired at two locations were used, from a platform off Venice, Italy, and from a site on the west coast of Lanai, one of the Hawaiian Islands, near the MOBY buoy site. Environmental effects are not significant for the conditions selected for the study. Strict criteria have been used to select SeaWiFS and CIMEL data acquired during the years 1999 and 2000 at the Venice site and during about 50 pre-selected days of the years 1998, 1999, and 2001 at the Lanai site. The first criterion is that SeaWiFS data must have scattering angles lower than 150° in order to match CIMEL sky-radiance measurements. The second criterion deals with the atmospheric stability, in space for SeaWiFS imagery, and in time for
CIMEL data. This has resulted in 26 selected days for the calibration study: 19 for the Venice site and 7 for the Lanai site. For each day, the $L_{TOA}$ computations have been made at the equivalent wavelength of SeaWiFS band 8 and at the angular geometry of the SeaWiFS observations. Since one to six “pseudo” aerosol phase functions have been derived per day, one to six TOA L values have been obtained per day, from which the mean and the associated standard deviation have been calculated. At the end, values have been organised in two types of data points, based on the number of phase functions available per day.

Using for the analysis the days with at least two phase-function retrievals, i.e. 20 days out of 26 days, the TOA L computations have indicated that the SeaWiFS radiance in band 8, as provided by the SeaWiFS Project Office, is biased low by 7.0% ± 2.8% (Figure 3.13). No significant dependence on aerosol optical thickness and scattering angle is detected. These findings, instrument independent, are in agreement with results from recent calibration studies accomplished in the framework of the MERIS calibration-validation activities (Table 3.7). They suggest, in other respects, that the systematically too high SeaWiFS estimates of aerosol optical thickness at 865nm (Ainsworth et al., 2001) may be due to aerosol model phase functions that are not representative of actual conditions.

### Table 3.7 Summary of recent calibration studies for the SeaWiFS and MERIS sensors.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Method</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martiny et al., 2004</td>
<td>Simulations using CIMEL sky radiance measurements over ocean</td>
<td>MERIS: - 0.8%</td>
</tr>
<tr>
<td>Antoine and Chami, 2004</td>
<td>Simulations using CIMEL extinction measurements over ocean</td>
<td>MERIS: + 2.0%</td>
</tr>
<tr>
<td>Hagolle and Cabot, 2004</td>
<td>Sun Glint method</td>
<td>MERIS: + 1.6%</td>
</tr>
<tr>
<td></td>
<td>Sensors inter-calibration with POLDER as a reference over desert targets</td>
<td>SeaWiFS / MERIS: -8.0%</td>
</tr>
<tr>
<td>Govaerts and Clerici, 2004</td>
<td>Sensors inter-calibration with SEVIRI/MSG as a reference over desert targets</td>
<td>SeaWiFS / MERIS: -7.3%</td>
</tr>
<tr>
<td>Nieke et al., 2004</td>
<td>Simulations using CIMEL measurements over snow targets</td>
<td>SeaWiFS / MERIS: -2.9%</td>
</tr>
</tbody>
</table>

The methodology presented above can also be applied to bands in the red as well as shorter wavelength bands, if the diffuse marine reflectance is known or measured. It
provides an alternative, purely radiometric “vicarious” calibration to the “entire system” calibration (Evans et al., 1994) routinely performed by the SeaWiFS Project Office, which does not separate sensor from algorithms. A fairly automated radiometric calibration system based on the proposed methodology and exploiting the remote acquisition of CIMEL data from island and coastal sites around the globe, might be envisioned. It would allow one to check and monitor operationally, at relatively low cost, the absolute calibration of current and future satellite ocean-color sensors at least in the red and near infrared, where the ocean can be considered black, while they operate in orbit.

3.7 “System” absolute calibration

3.7.1 Introduction

The required accuracy on water-leaving radiance for ocean biogeochemistry studies, i.e., ±5% absolute in the open ocean (see Chapter 1), is extremely demanding in terms of radiometric calibration, because the radiance measured from space at ocean-color wavelengths may be 10 times larger than the water-leaving radiance (e.g., Gordon, 1987). Assuming perfect atmospheric correction, the absolute radiometric calibration of the satellite sensor must be accurate to a fraction of one percent. This is not achievable by the purely radiometric vicarious calibration methods described above, which are accurate to a few percent at best. An in-orbit calibration strategy for achieving the required accuracy, originally developed for the Coastal Zone Colour Scanner (CZCS) (Evans and Gordon, 1994), consists of comparing retrievals of water-leaving radiance with in situ measurements at the time of satellite overpass and adjusting the calibration coefficients to force agreement between retrieved and measured quantities (Gordon, 1998). This strategy, which aims at correcting for any error due to purely radiometric calibration techniques, after taking into account pre-launch instrument calibration/characterization, transfer to orbit, and temporal degradation, and for biases in the atmospheric correction algorithm, has been employed operationally for the processing of imagery from major satellite ocean-color missions.

3.7.2 Method description

In this “system” vicarious calibration, the instrument is not considered separately from the atmospheric correction scheme, but part of the same system, because both are necessary for the retrieval of water-leaving radiance. For most ocean-color sensors, two spectral bands in the near infrared are used to determine aerosol radiance and, therefore, perform atmospheric correction in the visible bands (Gordon, 1997). They are for example centered on 765 and 865 nm for SeaWiFS, 748 and 869 nm for MODIS, and 779 and 865 nm for MERIS. The “system” vicarious calibration method assumes that the water body at the calibration site is black (null water-leaving radiance) and that the longer near infrared band is perfectly calibrated. The radiometric calibration in the shorter infrared band is then adjusted such that the expected aerosol model at the calibration site (Eplee et al., 2000) is retrieved correctly by the atmospheric correction scheme. Since this calibration is independent of the calibration in the visible bands, it does not need to be
performed at the calibration site for the visible bands. Suitable locations should have known and stable aerosol type, low aerosol loading, and negligible water-leaving radiance in the near infrared. Two locations that fit the requirements are currently used by the NASA OBPG to calibrate the shorter infrared bands of SeaWiFS and MODIS: the South Pacific Gyre and the Southern Indian Ocean (Franz et al., 2007). The assumed aerosol model at those locations is the maritime model of Shettle and Fenn (1979) with 90% relative humidity. Once the calibration in the near infrared bands is accomplished, the atmospheric correction scheme is operated on satellite imagery acquired over the calibration site to retrieve water-leaving radiance in the shorter, ocean-color bands of the satellite sensor, and the retrievals are compared with in situ measurements. The calibration coefficients are finally adjusted to yield the expected water-leaving radiance.

The calibration site for the visible bands must ideally satisfy specific criteria (Gordon, 1998). First, the aerosols should be of mostly maritime origin (especially non absorbing) with optical thickness below 0.1 in the visible (i.e., very clear atmosphere). In such situations, molecular scattering is the dominant process affecting the top-of-atmosphere radiance in the visible, reducing the impact of inherent uncertainties associated with the atmospheric correction scheme. Second, the water-leaving radiance should be uniform over the scale of several pixels, and the spatial contrast should be minimum over a distance of about 10-20 km to minimize adjacency effects. Third, the water-leaving radiance should be as small as possible to reduce the effect of errors in the measured water-leaving radiance, i.e., the calibration site should be located in mesotrophic waters. Unfortunately, such waters often occur in coastal regions, where aerosols are likely to be absorbing and have an optical thickness above 0.1 in the visible.

In principle any available water-leaving radiance data set collected during cruises in the world oceans, dedicated or opportunistic, could be used for the “system” calibration if the above criteria are met. One difficulty is managing and quality controlling different data sets. It is desirable, however, to have long-term calibration sites, logistically attractive, where instrumentation can be properly maintained on a regular basis during the lifetime of a satellite mission. Such sites exist, where buoys with appropriate instrumentation have been deployed for many years, namely MOBY located off Lanai (Clark et al., 2003) and BOUSSOLE located in the northwestern Mediterranean Sea (Antoine et al., 2008). The optical mooring measurement program is complemented by regular cruises during which marine optical and biological properties are measured. Coastal CIMEL sun photometer stations provide information about aerosol properties. The sites only possess the first two desirable attributes, i.e., spatial homogeneity and relatively small aerosol influence. The clear waters make the accuracy requirement on water-leaving radiance challenging. The MOBY and BOUSSOLE sites have been operated systematically since 1997 and 2003, respectively, and the data have been adequate for “system” vicarious calibration of SeaWiFS, MODIS, and MERIS.

A basic assumption in the “system” vicarious calibration is that the pre-launch calibration of the longer near infrared band, after transfer to orbit, is correct. Wang and Gordon (1998) examined this assumption using simulated data and concluded that as long as the calibration error at 865 nm is less than 10% in magnitude, when aerosol optical thickness
is moderate (less than 0.2 at 865 nm), the calibration in the visible bands remains sufficiently accurate. Eplee et al. (2000) confirmed this theoretical result, by showing that for SeaWiFS changing the sensitivity by 5% at 865 nm would only require changing the sensitivity by 0.5% at 555 nm and 0.3% at 443 nm to restore agreement between satellite estimates of water-leaving radiance and measurements.

The “system” vicarious calibration is sensor independent (i.e., applicable to any ocean-color sensor), but intimately linked to the atmospheric correction scheme. Therefore, if the scheme is altered, e.g., to account for new aerosol models, new calibration coefficients must consequently be used to maintain consistency. Other atmospheric schemes may proceed in different ways, and their application to Level 1b imagery is not straightforward, i.e., a specific “system vicarious calibration is required beforehand. Furthermore the calibration adjustments, since atmospheric correction dependent, are not expected to offset algorithm deficiencies over the entire range of oceanic and atmospheric conditions, since performed over open-ocean sites with typical maritime aerosols, especially in coastal regions and inland waters. These limitations notwithstanding, the “system” vicarious calibration method is suitable --and essential-- to provide the required accuracy on water-leaving radiance for science applications in the vast majority of the world oceans.

3.7.3 Method accuracy

Uncertainties in the “system” vicarious calibration may be due to errors in the atmospheric correction algorithm, uncertainties in the near infrared calibration, uncertainties in the water-leaving radiance measurements, possible changes in the satellite sensor not captured during the transfer to orbit of the pre-launch calibration coefficients, and other factors, e.g., bidirectional effects in the water-leaving radiance, ignored or not properly taken into account. From various sensitivity studies, including global clear-water time series analysis, Eplee et al. (2000) concluded that the SeaWiFS gains obtained by the “system” calibration method applied at the MOBY site were accurate to 0.9% at 765 nm and 0.3% in the visible bands. Franz et al. (2007) performed a similar study with about 10 years of SeaWiFS data instead of a few years, showing that the vicariously adjusted gains were very stable during the first 10 years of the mission, with a standard deviation consistently or below 1% at all wavelengths and an accuracy of about 0.1% on the mean values. They also investigated the change in vicarious gain with respect to sample size. Stabilization to within 0.1% of the 10-year averaged value was achieved with about 30, 40, and 30 samples at 443, 555, and 765 nm, respectively, and it took 2-3 years to obtain the sufficient amount of samples at the MOBY site. This provides some indication about the number of satellite/surface match-ups and, therefore, the in situ measurement program required to reach adequate quality in remotely sensed water-leaving radiance via “system” vicarious calibration.

3.7.4 Application example

Figure 3.14, from Franz et al. (2007) illustrates the “system” vicarious calibration method. The results are for SeaWiFS, and they were obtained using screened
SeaWiFS/MOBY match-ups during September 1997 to March 2006. The screening process was extensive, with strict criteria for the presence of clouds and their shadows, stray light, and whitecaps, variations in illumination conditions during the MOBY measurement cycle, navigation problems and atmospheric correction failure, etc. within a 5x5 pixel box centered on the MOBY location. Consequently, only 10% or 150 of potential match-ups passed the screening process.

The vicarious calibration adjustments are relatively small, i.e., 3.8% at 412 nm, decreasing progressively to 2.8% at 765 nm, with a standard deviation of about 1% about the mean values, i.e., within the uncertainty derived from the calibration transfer-to-orbit experiment (Barnes et al., 2000). No significant trends with solar and viewing zenith angles are detected. The adjustments are also stable with time suggesting that temporal degradation is accounted for properly by the onboard lunar and calibrations (Barnes et al., 1999, 2001) and that the MOBY data are consistent over the 10-year time series.

3.8 References


Figure 3.1 Geographic location of the recommended sites for Rayleigh scattering calibration (After Fougnie et al., 2002.)

Figure 3.2 Absolute radiometric calibration of POLDER-2 at 443, 490, and 670 nm, right to left, respectively, during the period from January to June 2003. Calibration coefficients $\Delta A_k$ are displayed as a function of viewing zenith angle (top), aerosol optical thickness (middle), and longitude (bottom).
**Figure 3.3** Absolute radiometric calibration of MERIS at 490 nm (left) and 620 nm (right) during the period from January to September 2003. Calibration coefficients $\Delta A_k$ are displayed as a function of reflectance (top), aerosol optical thickness (middle), and date (bottom).

**Figure 3.4** Temporal change in the MERIS calibration coefficient $A_k$ at 490 nm.
Figure 3.5 Inter-band calibration ($A_k$ coefficient) of the POLDER-1 spectral bands at 443, 565, 765, and 865 nm using the sun glint method. The spectral band of reference is centered at 670 nm.

Figure 3.6 Temporal evolution of the $A_k$ coefficient at 490 nm obtained for POLDER-1 (top) and POLDER-2 (bottom) using the sun glint inter-band calibration method.
Figure 3.7 Inter-band calibration ($A_k$ coefficient) of the POLDER-2 spectral bands at 443, 490, 765, and 865 nm using the cloud method. The spectral band of reference is centered at 670 nm.

Figure 3.8 Temporal monitoring of the radiometric sensitivity obtained for PARASOL/POLDER3 spectral bands (except 443) using the inter-band calibration over cloud method and 765 as a temporal stable reference.
**Figure 3.9** Cross-calibration of POLDER-2 and -3 instruments in the 490 (top), 670 (middle), and 865 nm (bottom) spectral bands. Measurements are PARASOL acquisitions from March to September 2005 and reference data are POLDER-2 acquisitions from April to October 2003.

**Figure 3.10** Multi-temporal calibration of SeaWiFS using POLDER-1 as reference, for spectral bands at 490 (up), 670 (middle), and 865 (bottom).
Figure 3.11 Error budget on the $\omega_a P_a$ product derived for the M90 model (solid line), the T90 model (dashed line), and the U90 model (micro-dashed line). The visibility is 23km, the solar zenith angle 75°, and the wind speed 7m/s.

Figure 3.12 Error budget on $L_{TOA}$ computed for the M90 model (solid line), the T90 model (dashed line), and the U90 model (micro-dashed line). The visibility is 23km, the solar zenith angle 30° (upper plots) and 60° (lower plots), the relative azimuth angle 90°, and the wind speed 7m/s.
Figure 3.13 SeaWiFS radiometric calibration in the near infrared (band 8), for the 19 days selected for the Venice site and the 7 days selected for the Lanai site. (a) CIMEL-retrieved TOA radiance versus SeaWiFS TOA measurements. (b) Relative difference between SeaWiFS measurements and CIMEL retrievals. Labels on the top represent the number of principal plane sets used for the computation of the TOA radiance. (After Martiny et al., 2005.)
**Recommendations**

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A variety of techniques are available for checking the calibration of satellite ocean-color sensors after launch and maintaining the level of radiometric quality required for biogeochemistry applications during the entire operational phase of the missions. These techniques are diverse, based on different physical principles, and have different accuracies. They require onboard devices or spacecraft maneuvers, utilize artificial or natural light sources, or exploit observations of suitable targets under specific conditions. Each technique may address a particular aspect of the calibration problem, such as absolute calibration, relative inter-band calibration, relative multi-temporal calibration, and sensor inter-calibration. Some techniques are generally applicable to all sensors, and others are sensor specific. For example inter-band calibration using sun glint or reflective clouds is not appropriate when the sensors saturate over those targets. Since calibration accuracy requirements are very demanding, i.e., a small fraction of one percent absolute, they should be carefully considered in the design of ocean-color radiometers. *Any post-launch calibration strategy or plan should take into consideration all the techniques available to bring about beneficial information regarding instrument radiometric performance. Redundancy in the techniques is not a luxury, but necessary to make sure that instrument changes are well understood and corrected adequately, and accuracies well established.* Specific recommendations are given below.

1. To achieve the uncertainty requirements for scientific applications, e.g., ±5% absolute in the blue and ±1% relative (i.e., band to band), or 30% on chlorophyll concentration, radiometric calibration should be accurate to a fraction of 1%. This is not achievable by standard, purely radiometric techniques, but the target accuracy by those techniques should be ±2%.

2. Reflectance calibration has a number of advantages compared with radiance calibration. The solar constant does not need to be known, and it is much easier to do on-orbit reflectance calibration than radiance calibration. But the bi-directional reflectance of the reference target should be monitored for stability. Furthermore, in the atmospheric correction process the molecular reflectance is given in look-up tables, and transforming this reflectance into radiance may greatly increase the error in water-leaving radiance.

3. Sensors have non-ideal performance that must be understood. They should be fully characterized before launch for out-of-band response, polarization sensitivity, bright target/scattered light response, and non-linearity.

4. Vicarious calibration or calibration adjustment is needed to meet accuracy objectives. “Radiometric” vicarious calibration techniques should be applied first, even though they may not be sufficient in terms of accuracy. “System” vicarious calibration, i.e., calibration of the sensor and the atmospheric correction algorithm, should be applied to refine the coefficients obtained by the “radiometric” vicarious techniques.
5. Calibration sites should be selected so that the satellite signal can be computed with the best accuracy possible, i.e., sufficiently far from land, in spatially homogenous oceanic regions, where the contribution of the ocean is as small as possible, where aerosol optical thickness is generally low and aerosols are not absorbing, and where cloud cover is favorable. Coastal sites are generally not adequate for vicarious calibration, although they are necessary for algorithm validation. Measurements of not only water-leaving radiance, but also aerosol optical properties and ancillary variables should be made at the calibration sites. Sites like MOBY and BOUSSOLE have sufficient attributes to achieve the calibration accuracy required for ocean-color applications.

6. Measurements at any suitable location (not only a few sites), collected with diverse instrumentation, should be considered in the check-of-calibration activities to ensure proper accuracy, provided they meet the strict calibration criteria. This would facilitate the acquisition of a sufficient number of match-ups to achieve convergence on calibration coefficients early in the mission operational phase.

7. The data used by ocean-color project offices for sensor calibration, including satellite radiance, water-leaving radiance, aerosol measurements, and ancillary measurements should be made available to the ocean-color community at large. This would allow investigators to perform their own calibration, using their own radiation transfer codes and atmospheric correction algorithms.

8. Space agencies rely for calibration on schemes that differ, even when instruments are similar in concept and principle. Some resolution needs to occur. A common strategy should be devised and applied to all the sensors. Emphasis should be placed on sensor inter-calibration to improve the spatial coverage of ocean-color products and yield long-term consistent time series from multiple satellites for climate studies.