OPTICAL SENSOR CALIBRATION

M. Dinguirard
ONERA/DOTA, 2 avenue E. Belin - 31055 Toulouse CEDEX 4 - FRANCE
P.N. Slater
Optical Sciences Center, University of Arizona, Tucson AZ 85721, USA

ABSTRACT

This paper is a review of the various methods in use, or under development, to calibrate space-multispectral imaging systems in the solar-reflective range. We introduce the subject by distinguishing between absolute and relative calibration, briefly discussing the use of scene and sensor models, and describing five calibration desiderata. We then briefly describe the different types of existing methods, highlighting their advantages and disavantages, making the distinction between: preflight, on-board, and vicarious calibration. The different types of radiometric calibration: absolute, multi-temporal, inter-band, inter-sensor are mentioned with their related constraints. Finally, recommendations are made on how to improve these methods so that the scientific community may obtain remote sensing data of the highest quality.

1 INTRODUCTION

We start this review with brief definitions of absolute and relative radiometric calibrations, and a statement of their accuracy and uses. From there we introduce the need for scene and sensor models to allow calibrations to be applied as accurately and reliably as possible. The introduction is concluded with the identification of five general guidelines for calibration.

Absolute radiometric calibration is performed by ratioing the digital counts (DCs) output from a sensor, with the value of an accurately known, uniform-radiance field at its entrance pupil. At best, in the solar reflective range, uncertainties are 3-5% (one sigma), generally being highest at the extremes of the range.

For CCD linear- or area-array sensors equalization, sometimes called relative calibration, is determined by normalizing the outputs of the detectors to a given, often average, output from all the detectors in the band. The result of the normalization is that all the detectors give the same output when the entrance pupil of the sensor is irradiated with a uniform-radiance field. For this relative calibration, the absolute value of the radiance field needs to be known. Typically the RMS variation in the adjusted normalized outputs of the detectors is in the 0.1 to 0.5% range, depending on the signal-to-noise ratio of the digitized output signal from the sensor.

Relative comparison can also describe the ratio of the average outputs from two, or more, different bands of a sensor; it is then called inter-band calibration. A change in the ratio is indicative of a temporal change in response of one, or more, spectral bands.

Another relative calibration, refered to multi-temporal calibration, represents the ratio of the average outputs over the same stable scene for two different dates.

The first applications of remote sensing sensors in space mainly concerned geometrical and temporal measurements and scene classification. In the case of geometrical measurements, for example mapping, equalization corrects the image for striping and similar cosmetic defects.

Temporal studies require a knowledge of changes in the average values of the sensor's response in each band. If this is not known, then changes in the sensor's response are likely to be incorrectly attributed to changes in the observed scene. The results of in-flight calibration can be used to monitor sensor temporal changes. Usually, absolute calibration is used, in combination with multi-temporal calibration (Gellman, 1993), for better accuracy.

Scene classification concerns the statistical analysis of the DCs in a scene (Swain, 1978). In this case, relative calibration to remove striping etc, is highly important, absolute calibration is generally not.

Some applications, such as agriculture and monitoring natural disasters, benefit from the increasing number of remote sensors in operation (Kramer, 1994). To compare data from several sensors having different spatial resolutions and spectral bands, it is desirable, for some applications, and essential for others, to know how the responses of the sensors compare. Such comparisons can be made relatively, but are more dependable if referenced to an absolute scale. These applications also require a good knowledge of the scene physics, e.g. directional reflectance and atmospheric effects, as well as the pixel-level response of the sensor, e.g. stray light and MTF.

A model linking the digital output to the desired physical quantity has to be set up in order to take into account the different instrument parameters that have to be regularly checked in flight. Atmospheric radiative transfer models have to be used to account for the effect of the atmosphere on the measurement:

absorption, scattering, MTF, adjacency, directional effects, etc... This type of model allows remote-sensing-data users to know when changes in the observed scene are due to natural changes, such as water stress for vegetation, and not to changes in the observation conditions, BRDF, pixel size etc..

The usual approach to sensor calibration starts with the formulation of a calibration model. The simplest form of this model is a linear law linking the digital output X to the radiance L at the entrance pupil of the instrument (X = A L). The coefficient A is the absolute calibration coefficient to be determined. This is done, preflight by accurate measurements and then monitored on orbit by on-board calibration devices using secondary or tertiary standard light sources (lamps or the sun) and vicarious methods, using images of specific well known ground targets or the moon.

The following are five general guidelines for calibration:

1. To the extent possible, the same geometry and spectral radiance distribution and levels should be used in the calibration as occur in the operational image-acquisition mode of the sensor. This minimizes differences between measurement and use due to stray light, detector non-linearity, out-of-band rejection, etc... To meet this condition, the calibration should be full aperture, full field, full dynamic range and should use an appropriate source spectral distribution.

2. Several different and independant techniques should be used preflight and in flight to determine if systematic errors exist in one or more techniques and, to the extent possible, identify, remove or account for them in the calibration results.

3. The characterization of the sensor should be as detailed as possible. This requires measuring such parameters as MTF, stray light and ghosting, out-of-band spectral rejection, linearity, polarization, etc... Most of these measurements can be made more precisely in the laboratory than in flight. In some cases their precise determination can allow corrective algorithms to be written and applied to improve the radiometric accuracy of measurements in the vicinity, for example of cloud edges.

4. Related to the last point, the user needs to be informed about the limits of applicability of absolute calibration values associated with the scene data. Pixels near a cloud edge or pixels in a complex scene are unlikely to correctly represent the actual surface radiance for the reasons mentioned in 3 above. Calibration data are the result of measurements made with an extended spatially uniform source such as an integrating-sphere source or a solar diffuser which fill the entrance pupil of the sensor. The result of calibrations under these conditions, where there is no target detail in the scene, will not apply accurately, without correction, to pixels in the image of a complex scene.

5. The user also needs to know uncertainties in the published calibration data in detail. Typically, calibration data are presented as a single, one-sigma value for a sensor over a wide spectral range, for example, all the sensor's bands in the visible and near infrared, from 400 to 1000 nm. If the calibration was done with a standard lamp, a single value is inappropriate because the lamp itself varies in uncertainty of calibration over this range. There are other quantities, for example the signal-to-noise ratio, which also vary spectrally, so band-by-band calibration uncertainties should be published.

With these definitions, concepts and guidelines in mind, we will proceed to discuss instrument models and preflight and in-flight calibration. The latter includes on-board and vicarious calibration which is discussed in terms of land, cloud, ocean and also lunar observations.

2 INSTRUMENT MODEL

The first problem to be solved, when speaking of calibration or inter calibration, is the definition of a universal way to model the physical entities involved. Satellite optical sensors are instruments that measure the radiance due to the reflection and scattering of input solar irradiance from the ground and atmosphere. As they have given spectral bands we generally refer to the "effective" or "equivalent" radiance which is the weighted average of $L(\lambda)$ across the given spectral band of spectral sensitivity $s(\lambda)$:

$$L = \frac{\int_0^\infty L(\lambda)\, s(\lambda)\, d\lambda}{\int_0^\infty s(\lambda)\, d\lambda} \quad (W.m^{-2}.sr^{-1}.\mu m^{-1})$$

Note that if $L(\lambda)$ equals L_o (a radiance independent of λ) then $L = L_o$.

As this radiance is the solar flux reflected by the scene (ground + atmosphere) one can also express L by :

$$L = \frac{\rho^*}{\pi} \cdot E_s \cdot \cos\theta_s \cdot u(t)$$

where the earth-atmosphere system is assumed lambertian :

ρ^* is the top of atmosphere (TOA) equivalent reflectance of the scene,

E_s the equivalent exo-atmospheric solar-spectral irradiance $(W.m^{-2}.\mu m^{-1})$,

θ_s the solar zenith angle and u(t) the term taking into account the temporal variation of the earth-sun distance.

With the normalisation :

$$E_S = \frac{\int_0^\infty E_S(\lambda)\, s(\lambda)\, d\lambda}{\int_0^\infty s(\lambda)\, d\lambda}\ ;$$

$$\rho^* = \frac{\int_0^\infty \rho^*(\lambda)\, E_S(\lambda)\, s(\lambda)\, d\lambda}{\int_0^\infty E_S(\lambda)\, s(\lambda)\, d\lambda}$$

$E_s(\lambda)$ is provided by tables (Neckel, 1984 and Iqbal, 1983).

So the physical quantities related to the output signal are either L or ρ^*.

Note that the applications that need only a good knowledge of ρ^* have a better accuracy (if sun referenced) as the error in the knowledge of $E_s(\lambda)$ and $s(\lambda)$ is reduced by the definition of ρ^*.

Usually, the sensor is linear and, after dark signal subtraction, the digital output X is proportional to the radiance :

$$X = A\,L.$$

But, in order to take into account a possible non linearity of the sensor at very low signal, a quadratic law can be adopted :

$$X = AL + BL^2.$$

The calibration methods provide the absolute calibration coefficient A and, if necessary, B.

Some sensors adopt a different way of modelization and refer the signal output to the radiance (or reflectance) integrated in the band :

$L = \int L(\lambda)\, s(\lambda)\, d\lambda$ in $W.m^{-2}.sr^{-1}$ which makes the measurement error more sensitive to the knowledge of the instrument spectral response, which may be incorrect due to uncertainties in preflight measurements or on orbit degradation.

In CCD cameras, in order to take into account the sensitivity difference between pixels, the instrument model has to be a little more complex. According to the type of CCD sensor (linear or area), the model tries to describe the instrument behaviour as completely as possible. For SPOT for example, the complete model is :

$$x_{jmk} = A_k\, G_m\, g_j\, L_{jk} + C_{jk} \text{ with } g_j = g_{bn}\, \gamma_b$$

and the normalization :

$$\frac{1}{N}\sum_{n=1}^{N} g_{bn} = 1 \ ; \ \frac{1}{4}\sum_{b=1}^{4} \gamma_b = 1$$

Where : k identifies the spectral band, m the onboard gain number ($G_m = (1,3)^{m-3}$), j identifies the pixel number along the spectral line, b identifies the CCD array (for SPOT, there are four different CCD linear arrays in each spectral line) and n the pixel number in the array (max N).

x_{jmk} is the raw digital output C_{jk} the dark signal, g_j the pixel relative sensitivity (equalization coefficient) .

The equalization process first determines the coefficients C_{bnk} and g_j, then computes the level 1A data :

$$X_{jmk} = \frac{x_{jmk} - C_{jk}}{g_j} = A_k\, G_m\, L_{jk}$$

In POLDER the model is more complex: it separates the high and low frequency variability of the equalization coefficients and also takes into account the polarization (Goloub, 1992).

If no model exist or if there are unexpected effects (e.g. non linearity), spatial digital filters are developed (Reinartz, 1997).

3 PRE-FLIGHT CALIBRATION

The measurements necessary preflight to fully characterise the instrument model are: the measurement of the instrument spectral response and the measurement of the radiometric model coefficients, i.e. the absolute calibration coefficient (A, or A and B if a quadratic model is used) and the equalization coefficients.

The spectral response has to be accurately characterized and the possible "out-of-band" response estimated (Bruegge, 1996).

For the absolute calibration coefficient, preflight calibrations usually refer to the use of light sources routinely checked against "official" standards provided by national standards laboratories.

AVHRR, SPOT, Landsat and the EOS instruments (ASTER, MISR, MODIS for example) were checked against large integrating spheres or hemisphere sources (Guenther, 1990; Meygret, 1994; Ono, 1996; Bruegge, 1996 and Guenther, 1996). As are (or have been) the Vegetation and POLDER instruments. This type of integrating sphere is also used to determine the preflight relative calibration coefficients, as the source is spatially uniform and covers the whole field of view.

Some instruments use collimated tungsten sources whose radiance is determined by a calibrated spectroradiance-meter. This kind of source is more appropriate for the characterization of the on-board calibrators such as the MERIS solar diffuser and the SPOT fibre-optics system.

To increase their accuracy and avoid sytematic errors, these sources are usually inter-calibrated by the sensor itself (Leroy, 1990) or by a transfer radiometer (Biggar, 1993a and 93c; Guenther, 1990 and Sakuma, 1994).

Integrating spheres or collimators have the advantage that their calibration can be traced to standard sources in national standards laboratories. On the other hand, they do not calibrate the instrument with radiation of the spectral distribution with which it will be used. Actually it is extremely difficult to establish such a method because it means that the calibration coefficients have to be adjusted for every spectral reflectance they record. However, it is generally conceded that it is better to use a source distribution similar to that of the sun, an approximately 6000K blackbody source, than an approximately 3000K blackbody lamp. For SeaWiFS and ScaRaB the pre-flight measurements were also performed using the sun as source (Biggar, 1993b and 1997, Mueller, 1996, Dinguirard, 1997), so called solar-radiation-based calibration (SRBC). This significantly reduces the problem of dissimilar spectral distributions and mitigates it completely in the comparison of results between preflight SRBC and on-orbit reference to a solar diffuser.

Besides the model parameters (spectral sensitivity and absolute calibration coefficient), the instrument response has to be carefully characterized preflight. It is, for example, essential to control: the sensitivity to polarization, the stray light effects, the sensor linearity and the MTF. Some of these parameters are difficult to check on board (except MTF and linearity) and are useful to improve image-correction algorithms.

4 ON BOARD CALIBRATION

On-board calibrators are used to obtain frequent checks of sensor calibration in flight. They use artificial (generally lamp) sources or natural sources (the sun). These sources are used directly or through optical systems. The ideal case is when these sources are viewed like earth scenes (the light goes through all the optics and fills the whole aperture). The equalization coefficients need to be determined in flight by looking at spatially uniform landscapes. The absolute coefficient is obtained by looking at sources of known radiance.

SeaWiFS (Barnes, 1993), MERIS (Baudin, 1996), MISR (Bruegge, 1993), MODIS (Guenther, 1996) and MOMS (Schroeder, 1997), for example, use diffuse solar panels, which act as calibrated secondary sources. These panels are, to a first order, spectrally flat (white) and lambertian in the solar domain (spectral characteristics as well as BRDF are measured in the laboratory). They are placed just in front of the sensor optics during calibration sequences and reflect the sun's irradiance. This method has the advantages of providing a high output in the blue part of the spectrum, in which lamps have very low output, and calibrating the entire optical system. But these devices, when exposed to the space environment and high energy solar radiation, are subject to radiation degradation.

SPOT HRVs (1 to 4) use fibre-optics systems that transfer the solar irradiance onto the focal-plane-CCD-array via the calibration unit (Begni, 1986), which also includes a lamp. The calibration beam goes through the whole optics but does not fill the whole aperture. Although protected by a shutter and exposed to the sun for only a few minutes each month, it proved to be sensitive to radiation (Meygret, 1994). The internal lamps were not calibrated in an absolute sense but appeared to be very stable (Henry, 1992) and are essential to monitor any temporal changes of the absolute calibration coefficient.

The Vegetation camera on board SPOT4 will also use lamps mounted in an external device which will illuminate, during special calibration sequences, the entrance pupil of the camera.

The TMs on Landsat 4 to 7 use an internal calibrator with lamps that only illuminate the filters and detectors at the end of each scan (Thome, 1997). In addition to this calibrator, the Enhanced Thematic Mapper Plus on Landsat 7 will have, like MISR and MODIS, a diffuser panel allowing solar calibration once per orbit. It will also include a partial aperture solar calibrator, similar to that used on the first Landsat Multispectral Scanner System (Lansing, 1986), that sends a narrow beam of sunlight through all elements of the sensor (Markham, 1996).

Unfortunately, for most of the sensors, it is very difficult to check the spectral response in flight. Exception are MERIS and MODIS. MERIS uses another Spectralon panel with specific spectral absorbing pigments added and expects a 2-nm uncertainty spectral calibration. The spectral mode for the MODIS on-board Spectroradiometer Calibration Assembly is expected to provide an uncertainty of 0.3 to 0.7 nm in the centroid of each filter from 0.4 to 1.0 μm respectively. For other sensors, the spectral response is assumed to be constant and equal to preflight measurements, the estimated changes being included in the error budget of the absolute calibration. Table 1 summarises the Advantages/Disavantages of these methods:

5 VICARIOUS CALIBRATION

As the on-board systems have to be checked to monitor their possible degradation, and as some instruments do not have on-board calibration facilities e.g., POLDER, SPOT5, AVHRR in the solar reflective range, vicarious methods using natural earth scenes have been developed. These methods depend on the accurate characterization (or identification) of reference scenes whose TOA radiance can be determined and thus used as "reference" or "standard" sources once the satellite is on orbit. These methods can also be used to validate the level 1 calibration algorithms and the level 2 data products such as ground reflectance and radiance.

Some of these methods, like those using test sites and molecular scattering (§5.1 and 5.2) are really "absolute" methods, i.e. they directly provide the TOA radiance or reflectance of the scene. Others are "relative": the use of stable deserts to check for temporal changes, and the use of clouds and glitter for the purpose of inter-band calibration.

5.1 *Test sites*

Certain test sites : White Sands, New Mexico; Rogers dry lake at Edward's AFB, California; Lunar Lake and Railroad Valley, Nevada; and La Crau, south France; are frequently used to perform the absolute calibration of remote sensing sensors. These sites are sufficiently large, homogenous and cloud free to allow good ground characterization and be used as radiance- or reflectance-reference targets. Ground reflectance and atmospheric measurements are performed simultaneously with the satellite overpass.

Different methods (Slater, 1987; Biggar, 1991 and Santer, 1992) are used:

The first is the *reflectance-based method* which requires an accurate measurement of the spectral reflectance of the ground target and measurement of spectral extinction depths and other meteorological parameters. The scattering and absorption in the atmosphere are computed using radiative transfer models and codes like 6S (Vermote, 1995) or more exact codes such as MODTRAN or that due to Herman and Browning (Herman, 1965). The code output is a TOA radiance value for a given ground reflectance. This radiance is compared to the average digital counts, from the image of the ground area measured, to give a calibration coefficient in units of counts per unit radiance.

The second is the *radiance-based method* . In this case, a well-calibrated radiometer is used to measure the radiance of the ground target at an altitude above much of the aerosol scattering. The radiometer can be mounted in a helicopter or light plane flying at about 3 K-m MSL (Slater, 1996), or in a high altitude-aircraft, E.G. an ER-2 at 20 Km (Abel, 1993). This radiance value is corrected for the residual scattering and absorption above the radiometer to give a TOA radiance. Again, a calibration coefficient can be computed using the radiance and image data.

The third is the *improved reflectance-based method.* It uses all the measured data from the reflectance-based method along with measurement of the ratio of diffuse-to-global spectral irradiance at ground level. This additional measurement helps to reduce the uncertainties in the aerosol model used for scattering computations.

These methods are used in an operational way for SPOT (Gellman, 1993) and Landsat (Thome, 1993). They will be used for EOS instrument (Bruegge, 1996b; Ono, 1996 and Slater, 1996) and the Vegetation camera on board SPOT4 (Thome, 1996). These sites are (or will be) also used for mid IR and thermal sensor calibration (Palmer, 1993; Slater, 1994 and Thome, 1994). They are mainly desert or semi-arid areas, but other targets can be used as grasslands (Teillet, 97) or smaller sites, but in this last case, adjacency effects have to be taken into account. (Richter, 1997).

Theoretically, the radiance method is the most accurate and its uncertainty has been estimated to be 2.8 % against 4.9 % for the reflectance based and 3.5% for the improve reflectance-based (Biggar, 1994). It is anticipated that the reflectance and radiance based methods will soon have uncertainties of 3.3% and 1.8% with the inclusion of improved equipment and techniques. The low value for the radiance-based method depends heavily on the calibration and stability of the airborne radiometer. The improved reflectance-based method, with the development of new instrumentation, can reach a precision of 2.8% (Slater, 1996). Moreover, as different teams are making these kinds of measurements with different instrumentation (and ground calibration of this instrumentation), some of the residual biases are being reduced. With the growth of joint field campaigns (Thome, 97), instrument and systematic errors introduced by improper field protocols are also being reduced, which promises further reduction in the above uncertainties.

Dark test sites are more suitable than bright areas for the calibration of ocean-colour sensors because the latter may give rise to sensor saturation, particularly in the summer months. Dark test sites may also be used to check the linearity of land-scanning instruments. Such sites (usually deep lakes, like Lake Tahoe in Nevada) are more sensitive to atmospheric correction but, through improvements in the methods, e.g. development of new instrumentation, an accuracy of the same order of magnitude as the one obtained for the bright sites may be achieved (Parada, 1997).

5.2 *Rayleigh scattering method*

At short wavelengths, the signal observed by the satellite, over deep oceans, is mainly due to Rayleigh scattering whose TOA radiance is easy to calculate theoretically (Teillet, 1990). The aerosol scattering component is added to this along with the surface contribution such as foam, in-water reflectance (ocean colour) and ocean glint. To reduce the influence of these parameters, and thus reduce the error in the radiance estimated for the scene, particular viewing conditions are chosen : deep oceans to reduce pollution, large viewing and sun angles to increase the atmospheric path and viewing in a westerly direction to avoid specular reflection. The aerosol component is deduced from the signal in the near IR band, where molecular scattering is negligible (Vermote, 1992). The other signal contributors, such as from: foam, in-water contributions and ocean glint are derived from models and ECMWF (European Centre for Medium Range Weather Forecast) data. The aerosol content, estimated in the near IR band, is transferred to the short wavelength bands using different aerosol models (Dilligeard, 1996).

This method was apply to AVHRR (Fraser, 1986; Holben, 1990), SPOT (Dilligeard, 1996), POLDER (Hagolle, 1997 a) and will be applied to Vegetation (Vermote, 1992 and Briottet, 1997).

The accuracy depends on the input data and the accuracy to which the spectral bands are known. The uncertainty, in the blue bands, is between 2 ad 3.5% (Vermote, 1995, Hagolle 1997 a) and is more applicable to wide field-of-view instruments like POLDER because of their more frequent acquisition of suitable scenes. For narrow field-of-view cameras, like SPOT, it is harder to find regions with no cloud and a clear atmosphere. This, added to the fact that SPOT 1 to 3 do not have a "blue" band, leads currently to a 5% uncertainty (Dilligeard, 1996).

5.3 *Stable deserts*

Stable desertic sites have been used for the multitemporal calibration of satellite sensors (Holben, 1990; Kaufman, 1993 and Henry, 1993). Different areas in Ariabia and North Africa, of size 100 x 100 km^2, have been located (Cosnefroy, 1996) and their temporal instability without atmospheric correction, has been determined to be less than 1-2% over a year. This instability was verified by reference to METEOSAT and AVHRR images. In addition, four Algerian sites were also characterized by ground measurements (Cosnefroy 1997).

Assuming the TOA reflectance of the sites is perfectly stable, the temporal change of the instrument's sensitivity or it's calibration can be checked simply by comparing the change of the digital outputs. This also checks the stability of the on-board calibration sources. For example, SPOT operational instruments, since 1990, have systematically acquired images of some of these stable areas in North Africa. The processed data showed that the stability of the on-board lamp was high. The uncertainty of the method was shown to be less than 3% (Henry, 1993).

Furthermore these sites have been used to inter-calibrate different sensors, even when they did not overpass them on the same day, examples are SPOT and JERS1- OPS comparisons (Dinguirard, 1995). At a meeting of the Calibration/Validation Working Group of the Committee of Earth Observation Satellites (CEOS) in late 1996, it was agreed that an area in the Egyptian desert should be identified for such use by the international remote sensing community for sensor inter-calibration purposes.

5.4 *Clouds*

To get in-flight interband calibration, spectrally flat targets having a well known TOA spectral radiance are necessary. Very high altitude (10 Km) bright clouds are good candidates in the visible and near IR regions as they have a spectrally constant reflectance (Vermote, 1995). Such clouds are sufficiently high that corrections for the atmosphere are quite small, only Rayleigh scattering and ozone corrections have to be applied; aerosols and water vapour being concentrated at lower altitudes. These clouds have to be observed under suitable geometric conditions to avoid observation of hot spot and rainbow effects.

The method presently gives a 4% uncertainty for the inter-calibration of the POLDER spectral bands (Hagolle, 1997 a).

5.5 *Glitter*

Specular reflection over water (glitter) may be used to provide inter-band calibration in the same manner as the use of clouds described above. The instrument has to be pointed to view specular reflections. Then the difference is determined between the signal in the glitter area and the signal outside the glitter. The ratio of this difference between two bands is assumed to be only dependent on differential atmospheric absorption and scattering, which are easy to model. This is only true if the glitter area is not too large, i.e. wind speed at the sea surface is not too high, which leads to the compromise: choose wind speeds which are high enough to avoid signal saturation but not so high as to spread the glitter area too widely. Good conditions usually correspond to wind speeds between 2 and 5 m/s. This approach has to be performed over as many glitter images as possible, thus a mean aerosol model is sufficient (the knowledge of the aerosol type being the major source of error).

This method, applied to inter-calibrate the spectral bands of POLDER is estimated to have between 1 to 2% uncertainty (Hagolle, 1997 a and b).

5.6 *Lunar observations*

The stability of the reflectance of the moon is extremely high; unfortunately its radiance is not and its value is probably not now known to better than ±15% at any time during a lunar month. Although the relative radiance of the moon is known more accurately, probably to about ±5%, this is too high an uncertainty for calibration purposes. Fortunately, a long term program, of greater than four years duration, has been started to properly characterize, not only phase-angle but also libration variations to obtain an uncertainty, in an absolute sense, of about ±2% relative to national radiometric standards, (Kieffer, 1996, Wildey 97). The moon can be used (i) to check the in-flight stability of a solar diffuser and (ii) to provide a direct calibration of the sensor.

(i) In this case, the sensor is pointed at the moon and allowed to scan over its surface. The total integrated radiance of the moon is then determined by summing pixels over the face of the moon and into space until the signal counts are zero. The scan rate over the disc should be held steady at a known rate. The sensor then views the diffuser and the ratio of signals is taken. These measurements are repeated roughly every 28 days, making sure that the scan rate over the lunar disc is the same as it was the month earlier. Any change in the ratio of the measurements is a measure of the degradation of the diffuser. A source of error in this procedure is the change in lunar phase angle between the two measurements. The problem is that the phase angle changes by about 1° for every satellite orbit, and the rate of change of the lunar radiance can be significant for such a change in phase angle, depending on the time in the lunar month. For example, a measurement at 4° phase angle (a desirable phase angle to use) provides a radiance about 1.7 times that at 22.5° phase angle. If the phase angles for each monthly observation cannot be made identical then data from Kieffer must be used in order to make the necessary correction.

Note that this is perhaps a more appropriate use of the moon than for absolute calibration, described in (ii) below, because the moon is a small source compared to the earth-viewing case, thereby possibly introducing an error due to the so-called size-of-source effect, and its reflectance is low, about 0.07 in the visible. It therefore does not meet the first of the calibration desiderata mentioned in the Introduction.

(ii) The first part of the above procedure can be used for an absolute calibration of the sensor. Here the sensor again scans the lunar disc and the counts are integrated over an area larger than that of the disc to account for stray light, edge effects, detector cross-talk etc.. Care must be taken to adjust the scan rate across the surface so as not to over or under sample the lunar image. The integrated DCs from the sensor are divided by the number of pixels covering the lunar surface. Average radiance per pixel from Kieffer are then used that match the phase and libration angle of the observation. The ratio of lunar image DCs per pixel to lunar radiance per pixel then gives a point on the sensor's calibration curve.

Table 2 summarizes the performances (uncertainties) and constraints of the different vicarious methods :

6. CONCLUDING REMARKS

Preflight, an instrument can be accurately and comprehensibly calibrated but as changes in its characteristics can occur on orbit, such as spectral response drifts, sensitivity decreases etc.., on-orbit checks are necessary.

In order for absolute calibration methods to be as accurate as possible, light sources need to be very stable and accurate with respect to national standard laboratory references. Moreover, these light sources must be used in conditions that simulate, as closely as possible the scene viewing conditions. In this respect, on-board devices using internal lamps, which do not project light through the entire optics, do not fulfill these conditions : first they do not have an appropriate spectral distribution, being weak in the blue, and second, they do not simulate operational viewing conditions. Solar diffuser panels are better candidates, with the advantage of being available anytime and not perturbed by the atmosphere as are vicarious methods. A disadvantage is their possible degradation in the space environment. Some form of stability monitor needs to be employed (Slater, 1991). Vicarious methods, using natural sources, are fully representative of the normal scene viewing conditions as they use images of selected natural targets. Their inaccuracy is limited by the ground measurements and/or the validity of the atmospheric radiative transfer models, the main error being the aerosol model and the directional reflectance effects.

New remote sensing instruments like MISR and POLDER will help to improve our knowledge of aerosols and directional effects and thus the modeling will be improved. Furthermore, continuing efforts to improve laboratory standards and field instrumentation will make the reflectance- and radiance-based vicarious methods more accurate.

An error analysis of current methods indicates that their uncertainties fall in the 2 to 3% range. This level of accuracy is, in some cases, insufficient for the user community, especially for ocean colour and some agriculture applications. So further work has to be done to meet the challenging demands of these disciplines.

An unified approach appears necessary, using the sun as reference, for all optical sensors, this is appropriate as they are designed to work in the solar-reflective range. In one approach, a sun-illuminated screen of accurately known small apertures is placed in front of the sensor's aperture during flight (Lobb, 1997). Another approach makes used of a single sun-illuminated small aperture, (Markham, 1996). A third uses a full aperture solar diffuser that is used both preflight and in-flight for calibration purposes (Slater, 1991; Palmer, 1991 and Baudin, 1996)

In this last case, preflight, on-board and vicarious calibration can use the same source via diffuse reflectance panels (Slater 95). The BRDFs of the different diffuser panels must be inter-compared by round-robin laboratory exercises. In the case of satellite sensors that use an on-board solar diffuser, there will be no need for such a comparison. In this case, the total diffuser-sensor system can be calibrated preflight using solar radiation (Biggar, 1993b).

For the unified approach to work, all users have to agree to reference the same exo-atmospheric solar spectral irradiance values. At present, different values are in use (Thekaekara, 1970; Iqbal, 1983 and Neckel, 1984) and the results of potentially more accurate measurements are under processing (Thuiller, 1997).

With this unified approach, inter-calibration of different sensors will be easier. Although, differences in directional, spectral and scale-factor effects will still have to be modeled in order to correctly account for the difference in viewing conditions (sun and view angles effects, spectral band differences and differences in ground resolution). In the same way, sensors effects (non linearity, stray light, MTF...) have to be accounted for when applying the calibration to complex scenes.

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Table 1. Comparison of on-board calibration systems

On-Board Systems	Advantages	Disadvantages
Lamps : SPOT, Vegetation, ASTER	Through total optical system Very stable Available on command	Not full aperture Low signal at shorter wavelengths
Lamps : Landsat TM	Very stable Recorded at the end of every scan line	Filters, detectors and electronic only Low signal at shorter wavelengths
Diffuse solar panels : MERIS, MODIS, MISR, SeaWiFS, ETM+, MOMS-2P, MOS	High signal throughout solar reflective range Full aperture	Possible degradation Given position on orbit
Sun+pinhole: MSS, ETM+	High signal throughout solar reflective range	Same as above Not full aperture
Sun + fibre optics : SPOT	Same as above	Same as above Difficult to characterize preflight

Table 2. Uncertainties summary for vicarious calibration methods

Methods /type of Calibration	Uncertainties	Contraints
Test sites : Absolute	actual : 3.5 % (reflectance-based) 2.8% (radiance-based) expected : 2.8 % and 1.8%	- Expensive - Needs ground experimentation - Needs good atmospheric conditions - Specific sensor programming in most cases
Rayleig : Absolute	depends on the wavelength actual : 5% for SPOT Xs1 2 to 3.5 % for POLDER blue bands	- Specific geometric conditions - Needs very good atmospheric conditions - Not applicable to longer wavelengths - Easier with large FOV (greater occurrence)
Stable deserts : Multi-temporal	actual : 3% expected : 1% with BRDF	- Specific programming - Needs non-cloudy images
Clouds : Inter-band	presently : 4% on POLDER (to be improved)	- Specific images of high clouds - Needs suitable geometric conditions
Glitter : Inter-band	1 to 2% on POLDER	- Specific geometric conditions - Wind speeds between 2 - 5 m/s, no clouds
The Moon : Multi-temporal	expected : 1%	- Does not provide calibration near top of dynamic range for land-observing sensors - Specific programming and viewing conditions
Absolute	expected : 2%	- As above - More radiometric verification needed - Requires low uncertainty calibration of the moon