Review of the Calibration of Radiometric Measurements from Satellite to Ground Level

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Abstract

This review discusses satellite sensor spectroradiometric calibration and mentions specific advantages and disadvantages of some of the commonly used methods. The importance of the use of several independent methods is stressed. Ground-based measurements and results are described for a reflectance-based, in-flight, sensor calibration method. Results are also presented for the reverse process, i.e. for retrieving ground reflectance from calibrated sensor data. Finally the magnitude of uncertainties in the ground and atmospheric measurements associated with the reflectance-based method and their combined effect on the uncertainty of the final in-flight calibration are estimated.

1. Introduction

This review is an extension of an earlier paper[1] that deals with the general needs and problems of radiometric calibration in remote sensing. Here the subject will be considered in terms of the reflectance-based calibration of satellite or aircraft sensors and the retrieval of reflectances from calibrated image data. By using the example of the reflectance-based method for satellite sensor calibration, the connection will be made between the following: the uncertainty in the absolute calibration of the reflectance factor of a field reference site; the accuracy of the required atmospheric measurements; and the influence of the assumptions that have to be made concerning the atmosphere. An appreciation of these factors is equally important in the reverse process of determining ground reflectances from absolutely calibrated sensor data.

Before discussing these subjects the methods available for the spectral, relative and absolute calibration of multispectral imaging sensors will be summarized.

Spectral calibration concerns the accurate determination of the wavelength shift in a spectral filter or the shift in the position of the dispersed spectrum along a linear- or area-array detector. Its importance is increasing, especially for filter systems, as the bandpasses of the filters become narrower and tailored to specific physical characteristics, such as atmospheric oxygen and water absorption features. Spectral calibration has not, so far, been implemented in multispectral space sensors.

Relative calibration concerns the determination of (a) the difference in response between the detectors in an array when they are exposed to the same irradiance level, (b) the change in the average response of the detectors in one band with respect to that of the detectors in another band, and (c) the change with time of the mean response of the detectors in each band. Relative calibration facilitates accurate comparisons of data (i) across an image, (ii) for band-ratio analyses, and (iii) as a function of time. The procedures used to date for relative calibration have provided adequate solutions to (i) and (ii), but none to (iii) and this has complicated the study of long term changes such as desertification.[2]

Absolute calibration provides the relationship between the input radiance level at the entrance pupil of the sensor and the number of digital counts this level gives rise to in the output digital image. It provides a way to monitor the change in response of the sensor with time and, with atmospheric correction, allows the determination of surface properties such as reflectance and chlorophyll concentration. The uncertainties claimed for the absolute calibration of multispectral imaging systems generally range from ±5 to ±10%.[3,4] In one case the *precision* has been estimated to be better than 97%[5] which augurs well for approaching this figure in absolute accuracy. Figure 1 provides further information regarding the various categories of, and ways to provide, spectral, relative and absolute calibration. Common problems that beset both relative and absolute calibration methods are also listed. These underscore the great difficulty in achieving low uncertainty in absolute calibration.

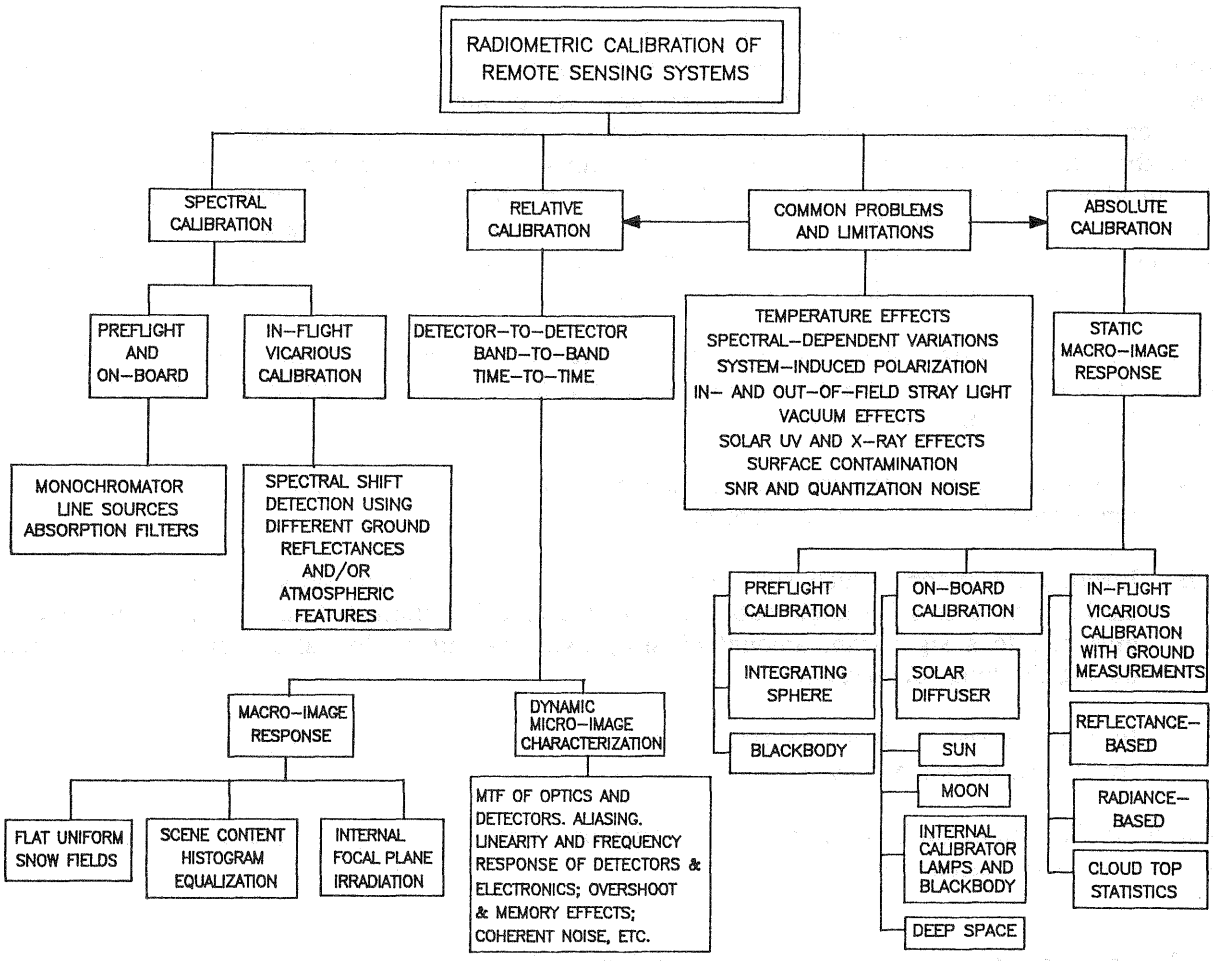

Figure 1. Classification of radiometric calibration procedures.

2. Advantages and disadvantages of methods for absolute calibration

Preflight calibration: This provides an important check of the system's overall radiometric response and serves as a benchmark against which to compare changes in the system's performance. It is inadequate as the only calibration, as in the case of the Advanced Very High Resolution Radiometer,[6] for the following reasons:

A. Unknown changes are likely to occur to the response of the sensor during launch and orbit insertion, invalidating the prelaunch calibration.

B. The operational conditions in orbit are difficult to simulate in the laboratory. This is particularly true of the viewing geometry in orbit which can introduce considerably more scattered light into the sensor than does the conventional laboratory calibration arrangement.[7]

Internal calibrator: Internal calibrators are most useful for relative calibration purposes for the following reasons:

A. No internal calibrator system to date has illuminated the whole of the entrance pupil and the entire field-of-view to provide complete end-to-end sensor calibration.

B. In some cases the stability of the calibrator is questionable, for example the solar-illuminated fiber-optics system in the SPOT Haute Resolution Visible (HRV) cameras.[4]

However, the internal calibrator does play the important role of monitoring the absolute calibration, albeit in a relative sense, at more frequent intervals than the methods discussed below. In the case of whiskbroom scanners, it is usually at the end of each scan, which is several times a second. Any changes in response during an orbit, for example due to thermal cycling, can then be closely monitored.

Solar diffuser: A solar diffuser is a near-lambertian panel that can be deployed in front of the sensor to illuminate the entire entrance pupil and image plane with diffusely scattered solar radiation. It is used while the sensor is sunlit but on the dark side of the terminator. It does not suffer from the aforementioned shortcomings of an internal calibrator and is therefore a promising candidate for an on-board absolute calibration system. The problems with its use are the accurate determination of: (a) the solar incidence angle on the panel, and (b) the spectral bidirectional reflectance factor of the panel. The latter is of concern because of the high probability that the panel's spectral bidirectional reflectance factor will change with time under direct, high-energy, UV and X-ray solar irradiation. No method has yet been devised to monitor this change reliably.

Lunar observation: An image of the moon acquired within a $\pm 4^{0}$ phase angle, when the lunar surface radiance is most constant, has been suggested as an accurate method for absolute calibration.[8] The problems with this approach are:

A. Our knowledge of the radiance of the moon at the < 5% uncertainty level over the spectral range from 0.4 to 2.5 μm is suspect.

B. Imaging the moon, which subtends 6×10^{-5} sr at the sensor, does not simulate imaging the earth. The 3-sr solid angle subtended by the earth's illuminated surface and atmosphere may give rise to a significant amount of stray light that alters the calibration but is not detected during the lunar observation.

C. In many cases a lunar observation will require a substantial change to the attitude of the spacecraft, always a cause for concern.

In spite of these shortcomings, an occasional lunar observation would provide a useful calibration check for the reasons discussed below.

3. The need for several independent calibration methods

The uncertainty inherent in an absolute calibration method can not be determined reliably. Repeated calibrations can provide a measure of the precision of a method and from an error analysis an overall uncertainty can be predicted. But neither of these approaches can account for systematic errors that were not anticipated by the designer of the calibration procedure.

The only way to develop a reliable measure of the uncertainty is to calibrate a sensor using several independent, precise calibration methods. If the calibration results all agree, to within the precision of the different methods, then there can be confidence that the precision represents the accuracy of the absolute calibration. Examples of these and other reasons for the use of several redundant methods for absolute calibration are provided below.

4. Reflectance-based calibration and surface-reflectance retrieval methods

The reflectance-based method for aircraft- and spacecraft-sensor, absolute radiometric calibration has been described in detail elsewhere.[5,9] As shown in Figure 2, it consists of the following steps:

A. Determination of the average reflectance factors, for the sensor's spectral bands and viewing angle to nadir, over a flat, homogeneous, well-marked ground site at the time the sensor acquires an image of the site.

B. Determination of the spectral optical depths and gaseous transmittances of the atmosphere at the time the sensor images the ground site.

C. Use of (A) and (B) above, with assumptions regarding aerosol characteristics and exoatmospheric irradiance, in a radiative transfer code[10] that accounts for multiple scattering, to predict the radiances in the spectral bandpasses of the sensor.

D. Location of the marked ground site in the various multispectral images acquired by the sensor. Determination of the average number of digital counts (DCs) in the image of the site in each band.

E. Calculation of the ratio of the DCs to the spectral radiance within each band to provide a single point calibration for each bandpass.

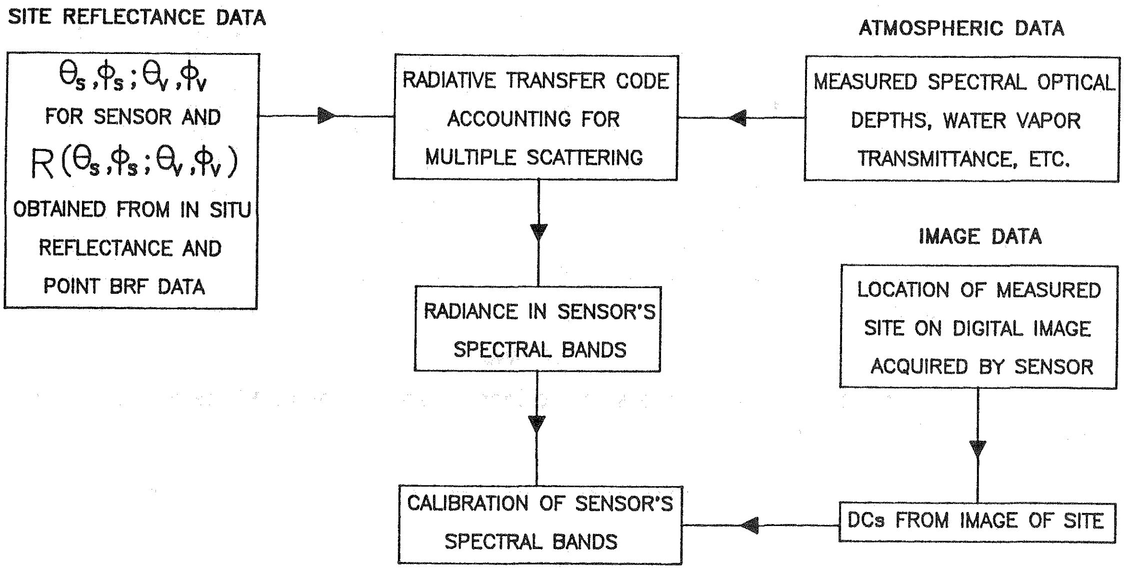

Figure 2. The reflectance-based method for aircraft- and spacecraft-sensor radiometric calibration.

Figure 3 shows the results of six calibrations of the Landsat-5 TM at White Sands, New Mexico, USA using this reflectance-based method, referred to as CODE in the figure. It shows the agreement between the calibrations over a 32-month period and the indications of a decrease in the response of the sensor with time. Figure 4 compares the results of the reflectance- and a radiance-based method, referred to as CODE and HELI, for TM at White Sands on 1985:10:28. HELI refers to helicopter-mounted, calibrated-radiometer, measurements of the surface from an altitude of 3 km above sea level. The CODE and HELI results are also compared to the preflight calibration (PRE) and the internal calibrator (IC) results for that date. These comparisons provide good examples of why several independent calibration methods are useful in analyzing the results, as follows:

A. The good agreement between the three independent in-flight methods shown in Figure 4, particularly in the first three TM bands, indicates that an absolute uncertainty of less than ±5% has been attained.

B. The identification of a difference between two, or more, independent methods may help diagnose a change in the condition of the sensor. For example, in Figure 4 the results in general show that TM was more sensitive preflight than in flight and that the internal calibrator results correspond to an instrument of greater sensitivity than the reflectance- and radiance-based results would indicate. Two conclusions can be drawn: first, the sensitivity of TM has decreased since the preflight measurements and second, part of the decrease appears to be due to a decrease in the reflectance of the scan mirror and image-forming optics and part due to a loss in sensitivity of the filters, detectors and electronics.

C. An analysis of the differences between two precise methods might expose an inadequacy or error in one of the methods which then can be corrected to improve the accuracy of future calibrations and measurements. For example, in Figure 4, the band-4 result for the reflectance-based method (CODE) is lower than any of the other results in that band, whereas

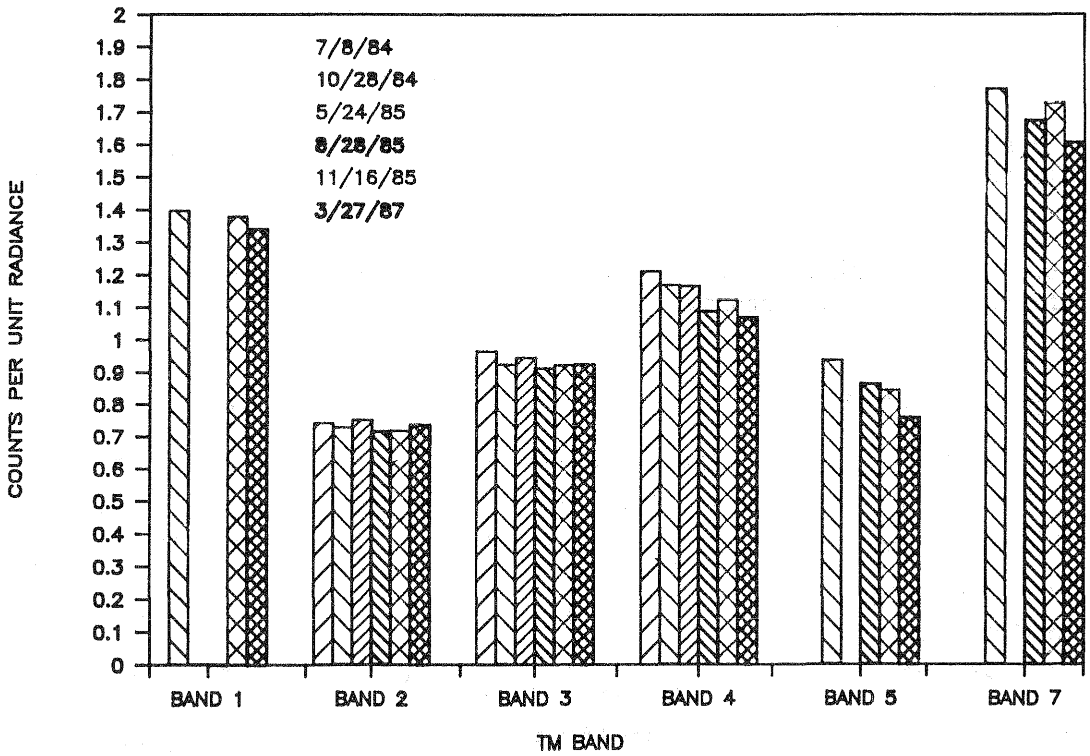

Figure 3. Calibration results for the solar reflective TM bands at White Sands for six days over a 32-month period.

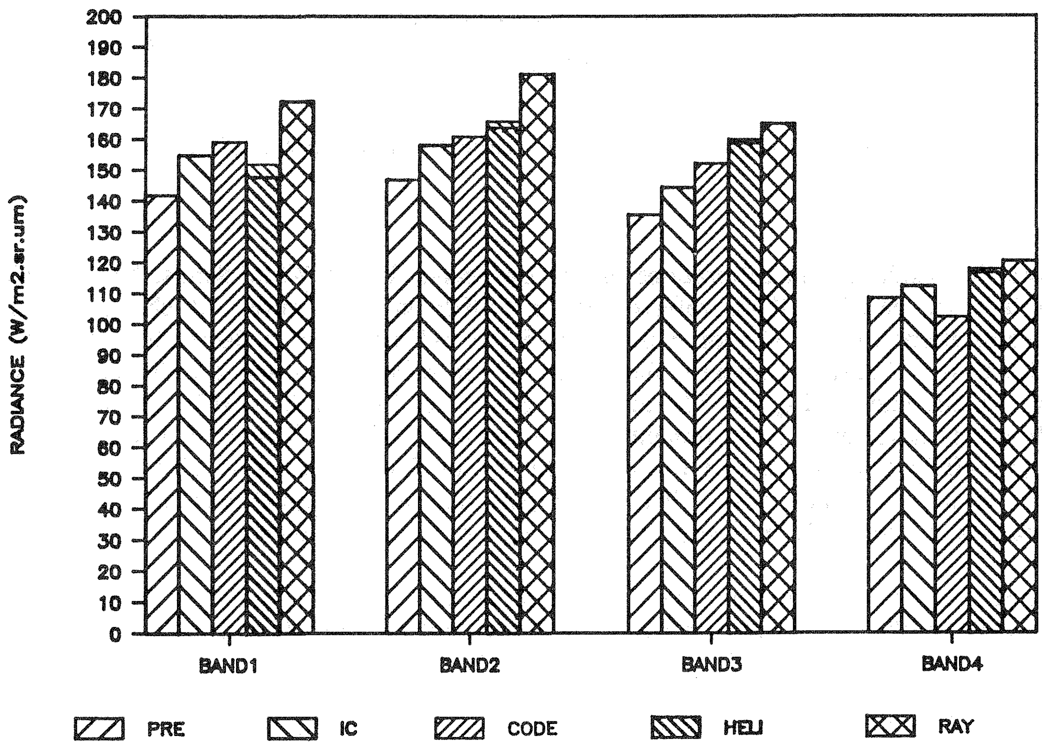

Figure 4. Comparison between the preflight (PRE) calibration of TM and the calibration results at White Sands on October 24, 1984, from the internal calibrator (IC), and reflectance- and radiance-based methods (CODE and HELI). The tips at the tops of the HELI bars are additions to account for the atmosphere above the helicopter. The calibration based on a Rayleigh atmosphere and ground reflectance measurements is shown as RAY.

in the other bands it is of intermediate value. This gave rise to a re-examination of the reflectance-based method in band 4 and the realization that the procedure resulted in an overcorrection for water vapor.[11] With a recalculation of water vapor absorption, the result in band 4 more closely matches the helicopter result, providing a more accurate method both for calibration and reflectance retrieval in band 4.

One of the most important applications of absolute calibration is in the retrieval of ground reflectance. The following demonstration of this application was conducted at Maricopa Agricultural Center (MAC) in Arizona on four days during a 16-month period, simultaneously with TM image acquisitions.[12] In Figure 5, ground reflectances as determined by absolutely calibrated TM data are compared to ground reflectances as determined by an aircraft radiometer 150 m above the ground. The dashed line is the 1:1 line upon which all points should fall in the absence of an atmosphere.

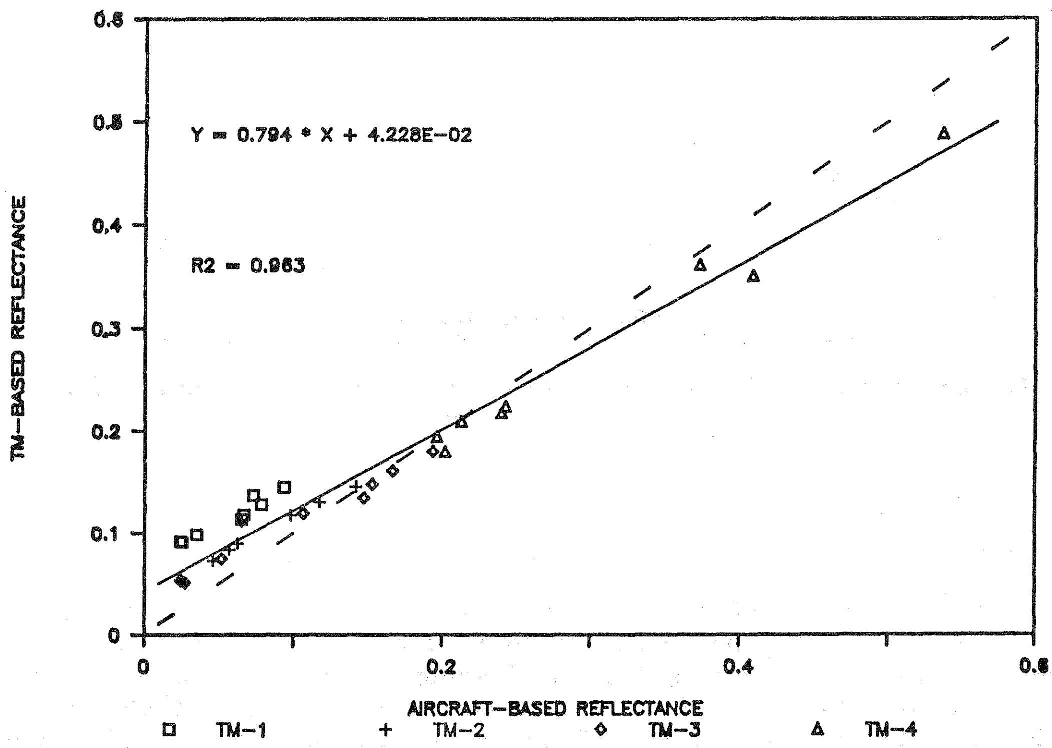

Figure 5. TM-based reflectances without atmospheric correction compared to reflectances obtained from low altitude aircraft measurements conducted nearly simultaneously with the TM image acquisitions.

As expected, the low-reflectance data derived from TM band-1 show a substantial departure above the 1:1 line due to atmospheric path radiance and, at high reflectances, atmospheric absorption brings the points below the line. Figure 6 shows the results after atmospheric correction, where the atmospheric measurements and a radiative transfer code are the same as those used for calibration purposes at White Sands.[5] The much closer fit to the 1:1 line in Figure 6 compared to Figure 5 is obvious and the equations on the graph provide quantitative evidence of this. Statistical analysis shows that the 1 σ deviation of the reflectance values from the 1:1 line in Figure 6 is ± 0.008 and that this appears to be fairly constant over the reflectance range from 0.02 to 0.58.

Note that this result is for near-uniform areas which were visually selected and registered with great care and for which any residual positional mismatch between the TM and aircraft samples gave rise to negligible error in the results. When several non-uniform, entire fields at MAC were analyzed in this way, without the benefit of visual selection, the departure from the 1:1 line was 0.022 (1 σ). Finally note that no attempt was made to correct for the adjacency effect (atmospheric crosstalk) or sensor errors (the computer compatible tape images used were uncorrected for detector-to-detector variations within a band, the band-average absolute calibration being used in all cases).

Based on the results shown in Figure 6, it appears that ground reflectances can be retrieved from absolutely calibrated, atmospherically corrected, TM data to an accuracy of ±0.01 over the reflectance range from 0 to 0.6, at least for the first four TM bands.

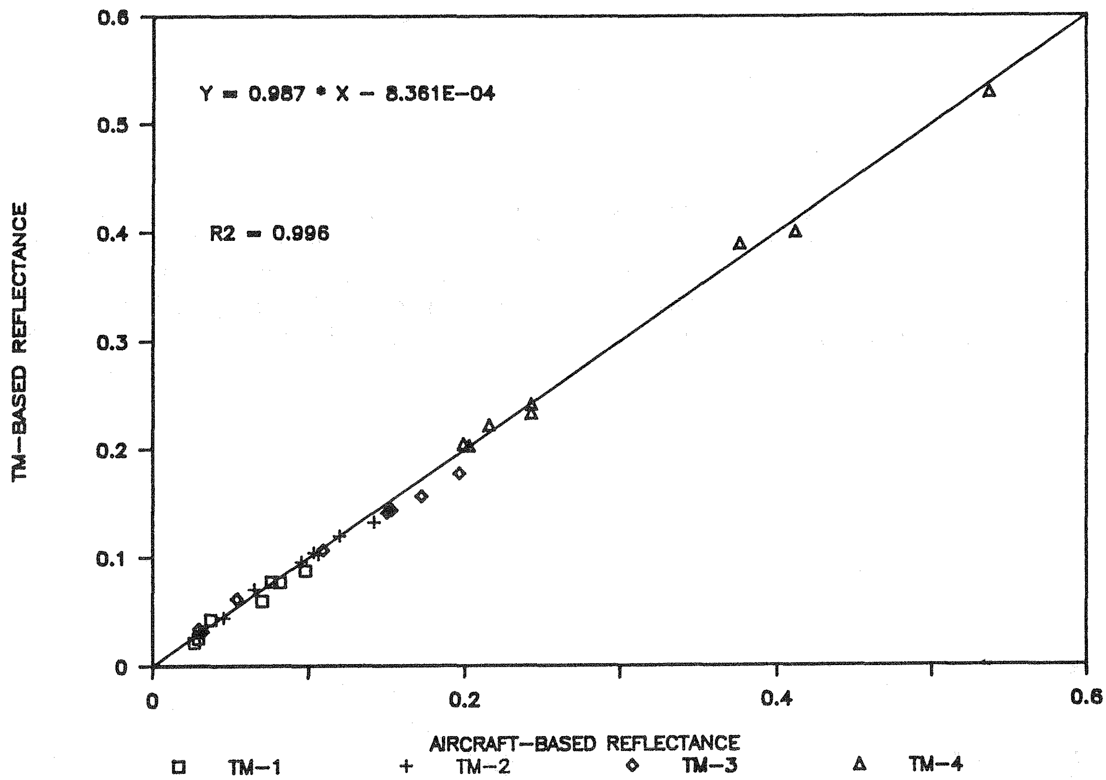

Figure 6. Same as Figure 5 but with atmospheric corrections based on the use of a radiative transfer code that used measured optical depths as inputs.

5. Uncertainty analysis

There are many factors that influence the uncertainty of measurements related to sensor calibration and reflectance retrieval. Because surface and atmospheric conditions depend so much on location, and sensor limitations vary with the type and design of sensor, an analysis of the uncertainties in the general case has not been attempted. However, based on measurements taken at White Sands, Edwards Air Force Base and MAC for the calibration of TM, an uncertainty can be estimated corresponding to the extremely favorable conditions at these sites. Table 1 lists the sources of uncertainty, and estimates of their minimum values (1 σ RMS), related to the radiance at the entrance pupil of the sensor, under the broad categories of **reflectance measurements, atmospheric measurements, radiative transfer code uncertainties**, and **sensor-dependent effects.** Clear sky, high visibility (greater than 100 km) conditions have been assumed.

6. Conclusions

Under the best conditions, the results from Table 1 indicate that the root sum square of the uncertainties in the reflectance-based absolute calibration method is ±4% (1 σ). This represents the uncertainty in the predicted radiance level at the entrance pupil of the sensor. It assumes the use of the alkali-flats area at White Sands as the reference site, calibration in the visible and near IR, careful attention to all the items in Table 1, and clear atmospheric conditions. When these conditions are not met, the uncertainties will increase. Examples are: (i) in the range 2 to 2.5 μm the uncertainty in our knowledge of the reflectance factor for halon is double its value of 0.5% in the 0.3 to 2 μm range,[14] (ii) radiometers are more temperature sensitive in the 1 to 2.5 μm range than in the visible and near IR,[15] (iii) a decrease in visibility corresponds to a decrease in the single scattering albedo and greater uncertainty associated with the assumption of aerosol refractive index or phase function,[16] and (iv) as the reference site becomes less lambertian, reflectance measurement and code modeling uncertainties increase.

Accounting for our knowledge of the radiometric artifacts of a well-characterized sensor, in this case TM, the overall uncertainty, again under the best conditions, increases from ±4% to ±5% (1 σ). This is a strong function of wavelength and prevailing conditions. For example: (i) TM has been

Table 1. Magnitudes of sources of uncertainties in reflectance-based calibration and reflectance retrieval.

Uncertainties in the spectral reflectance factor of the reference site:	
Sampling errors due to an insufficient number of data points	0.3%
Site location errors caused by misregistration of the digital image with respect to the measured non-uniform site.	0.3%
Uncertainties in the absolute bidirectional reflectance factor of the field reference panel due to uncertainties in its calibration and ageing effects.	1.5%
Radiometer-related errors:	1%
Ill-defined field-of-view.	
Non-nadir pointing of the radiometer when collecting data over a non-lambertian site.	
Sensitivity variations with temperature.	
Light reflected from a nearby object causing errors in radiance measurements.	
Errors in the determination of atmospheric spectral optical depths and gaseous transmittance:	
Errors in spectral optical depths:	0.5%
Pointing inaccuracies of the solar radiometer.	
Temperature effects on the solar radiometer response.	
Solar-radiometer-calibration stability if the intercept value on the Langley plot is to be used.	
Diffuse sky radiance correction at short wavelengths.	
Data reduction error due to inappropriate data point rejection in the analysis of Langley plots.	
Errors in gaseous transmittances:	
Uncertainties in the data collection procedure	1%
Uncertainties in the atmospheric transmission codes used.	1%
Atmospheric radiative transfer code uncertainties:	
Inherent uncertainties in the codes	1%
Uncertainties in some assumptions needed for code input or final analysis, e.g. exoatmospheric solar irradiance.	1.5%
Sensitivity to the aerosol scattering phase function	2%
Accounting for non-lambertian surfaces	1%
Accounting for the atmospheric adjacency effect	1%
The effect of polarization, higher the shorter the wavelength.	1-5%
Satellite-sensor-related errors:	
Inadequate signal to noise ratio	0.3%
Definition of spectral bandpasses or responses	1%
System-induced polarization that can vary as a function of scan or pointing angle.	2%
Residual stray light effects, in spite of calibration under well-simulated conditions.	1%
Image effects.[13]	
Nonlinearities in the A/D converter	1%
The memory effect	1%
Within-scan droop	0.5%
Scan-correlated shifts	1%

shown[17] to be less stable in the two bands at 1.6 and 2.2 μm than in the visible and near IR, and (ii) several of the response uncertainties relate to the magnitude of scene reflectance changes.

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