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RATIOING METHODS FOR IN-FLIGHT RESPONSE CALIBRATION OF SPACE-BASED SPECTRO-RADIOMETERS, OPERATING IN THE SOLAR SPECTRAL REGION

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ABSTRACT

One of the most significant problems for space-based spectro-radiometer systems, observing Earth from space in the solar spectral band (UV through short-wave IR), is in achievement of the required absolute radiometric accuracy. Classical methods, for example using one or more sun-illuminated diffusers as reflectance standards, do not generally provide methods for monitoring degradation of the in-flight reference after pre-flight characterisation. Ratioing methods have been proposed that provide monitoring of degradation of solar attenuators in flight, thus in principle allowing much higher confidence in absolute response calibration. Two example methods are described. It is shown that systems can be designed for relatively low size and without significant additions to the complexity of flight hardware.

1. INTRODUCTION

1.1 Instrument calibration

Radiometers observing Earth from satellites are generally used to provide data on the spectral radiance of the target, which can then be used to derive a range of higher-level data products. Radiometric calibration of data is the process of converting raw data from the radiometer to Earth-radiance or Earth-reflectance data, using knowledge of the instrument response characteristics. Radiometric calibration of the instrument is needed to provide this response data. In general, instrument calibration is performed by providing a source of known spectral radiance, and recording the instrument response in terms of digital counts. User ambitions for absolute radiometric accuracy in the solar band, typically around 1% or better, have usually been relaxed to the few-% range in instrument specifications, since engineers have found it difficult to offer better than 5-10% accuracy at acceptable confidence levels.

Pre-flight calibration of the instrument usually includes measurement of radiometric response, at a full range of source radiance levels that are known and traceable to national standards. However, instrument response is expected to change significantly after pre-flight characterisation, so that some in-flight calibration measurements are usually considered essential. Typically, the response of the instrument will be measured at two radiance levels, in flight, to update the pre-flight response model. More radiance levels may be used to measure any changes in non-linear response coefficients, but this complexity is often considered unnecessary.

1.2 Solar region requirements

This paper is concerned mainly with methods for providing sources of known radiance for in-flight radiometric calibration of space instruments operating in the solar radiation band – UV through short-wave IR, up to about 3000nm. (At longer wavelengths, reliable radiances can be provided fairly easily by black-body radiators of known temperature.) A nominal-zero radiance level can generally be provided by observing a dark scene area (dark side of Earth or space), or by operating a shutter. The most significant problem is in providing a known upper radiance level, within the range of radiances typically reflected from the sun-illuminated Earth.

Vicarious calibration methods, described for example in [1], typically make use of bland ground areas as radiance references. Some selected sites are instrumented for ground-reflectance and atmosphere measurements at ground level, allowing computation of at-sensor radiances or reflectances using radiative-transfer models. More accurate at-sensor radiances can be derived, at higher cost, by direct radiance measurements from aircraft. Vicarious methods provide an alternative to expensive on-board calibration hardware, and are commonly used as an additional check, even where on-board sources are included. However, vicarious calibration alone has significant disadvantages, including limited absolute accuracy (see [2]) and infrequent updates. This paper continues the search for on-board sources that are reliable and affordable.

1.3 Sun-illuminated diffuser

The most common upper-radiance reference is a sun-illuminated reflecting diffuser, which provides radiances calculated from the product of solar irradiance with diffuser reflectance. Use of the sun is desirable partly to avoid a need for powerful calibrated lamps on board.

Radiance data based on use of the sun includes significant uncertainties in knowledge of the solar irradiance spectrum. However, an instrument using a sun-illuminated diffuser can be considered to be a reflectance-measurement system, comparing the reflectance of Earth with the reflectance of the diffuser as the basic physical reference. This is logically appropriate for most users, since the physical parameters that they need to derive – for example soil moisture content or leaf area index – are seen most reliably as effects on Earth reflectance, rather than on Earth radiance. Uncertainties in solar spectral radiance present problems only where there is a need to measure Earth radiance as a final product (for example in radiation-budget instruments), or to compare measurements with results from instruments that are calibrated without reference to the sun.

Several different types of diffuser have been investigated for use in space – see for example [3]. There is a general preference for reflecting diffusers, mainly because the polar reflectance distributions of reflecting diffusers tend to be more uniform than the polar transmission distributions of transmitting diffusers. The most significant problem in use of reflecting diffusers, as fundamental standards of reflectance, is that their reflectance is found to deteriorate thorough life, as reported for example in [4] and [5], typically by up to 10% in the visible region. The most significant of the identified causes of degradation is out-gassing of adsorbed volatile materials from diffuser bulk, and polymerisation of this material in sunlight, typically to form a brown film. This problem is significant particularly for reflecting diffusers, which tend to be porous. However, even without the difficulties imposed by operation in space, it has been found difficult to ensure diffuser stability; inter-comparison of measurements between standards laboratories [6], involving transfer of diffusers, has found differences approaching 2%.

Efforts have been made to minimise degradation in reflectance by improvements in preparation and protection of diffusers. In the MERIS mission (the MEdium Resolution Imaging Spectrometer on ESA's ENVISAT platform, [7]), effects of sun-exposure will be monitored effectively by comparison of signals from two deployable diffusers – one exposed less frequently.

The current concern is that control of diffuser preparation and environments cannot provide very high confidence in the calibration provided by a diffuser, at the precision desired by users. The basic problem is that, apart from vicarious calibration, there is no independent check for effects that have not been predicted, including human errors in manufacture, integration, storage etc. Use of two or more diffusers will improve confidence, but cannot remove concerns that there may be common-mode effects on the diffusers.

Multiple diffuser systems are also subject to the criticism that they occupy a large volume, since the diffusers must be deployed sequentially over the system aperture. This is less a problem for MERIS, which is a wide-field small-aperture system, than for other instruments for which the two-diffuser strategy may be considered – including for example the current SPECTRA development, which has a much larger aperture.

2 RATIOING RADIOMETERS

To address the problem of low-confidence in sun-illuminated diffusers, schemes have been suggested for detector-based monitoring of diffuser radiance. A set of simple filter-radiometers may be considered less susceptible than diffusers to degradation through life, but may introduce errors due to contamination of filter surfaces. The more elegant schemes, proposed by Kriebel and Reynolds [8] and by Palmer and Slater [9] propose direct comparison of the reference radiance with direct solar irradiance, using the same detection system for both measurements. In effect these methods provide direct measurements of the reflectance of the reference, and avoid errors due to uniform contamination of the detection system surfaces. (Non-uniform contamination is not compensated, but no calibration scheme is perfect.)

The main criticism of these ratioing methods is that they are fairly complex, requiring an additional sensor system with moderate spectral resolution, and a mechanism to provide alternate views of the reference and the sun. This paper describes schemes in which the on-board reference is calibrated using the main system optics and detectors.

3 DOUBLE DIFFUSER SYSTEMS

A radiometric calibration system suggested for use in the proposed ESA instrument SPECTRA (Surface Processes and Ecosystem Changes Through Response Analysis) is shown schematically in Figure 3-1. The SPECTRA hyperspectral instrument covers the spectral range 400nm to 2400nm at 10nm resolution.

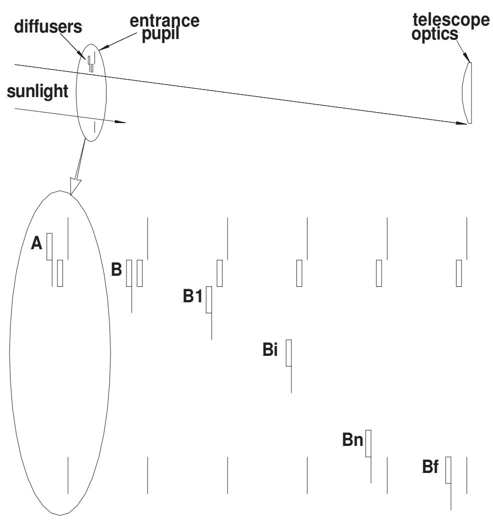

Figure 3-1 Ratioing method using 2 diffusers

The calibration system uses two transmitting diffusers located at the entrance aperture of the main instrument. A proposed design for the main instrument will have a rectangular external entrance pupil, typically 130mm across-track x 100mm along-track. The rectangular shape is selected partly to facilitate the calibration concept, but also partly to ease design of off-axis mirror optics in the main instrument. Both of the diffusers are rectangular strips, typically 10mm x 130mm. One is in a fixed location over one edge of the optics aperture. This area of the main-system aperture is used only for radiometric calibration. The second diffuser is tracked across the short dimension of the aperture by a linear movement.

During calibration measurements, the instrument is pointed close to the direction of in-coming direct sunlight – typically 6° from the sun direction. In this attitude, the instrument will receive no significant signal except for signal produced by scatter at the diffusers. Stray light will in principle be negligible, since no direct sunlight will fall on the first telescope mirror. Each diffuser may be produced as a ground surface on a wedge of fused silica, the wedge producing a 4° deflection of transmitted light, so that the diffusers operate close to the peak of the polar scatter distributions.

3.1 Operation and theory – 2-diffusers

In position A (in figure 3-1), which is also used in normal imaging mode, the moving diffuser is out of the aperture of the instrument, and the fixed diffuser is masked. In this position, the instrument will nominally receive no light at the detectors, and will record offset signals that will be subtracted from subsequent calibration signals. This measurement, and other measurements discussed below, will be made separately for each resolved spectral waveband and for each spatially-resolved pixel, using the hyperspectral imaging capabilities of the main instrument.

In position B in the diagram, the moving diffuser is next to the fixed diffuser – the instrument will receive a signal (after offset correction) given by: $I.R_A.T_{AB}$. I is the solar irradiance, R_A is the whole-instrument spectral response to scene radiance measured through the fixed-diffuser aperture area, and T_{AB} is the diffuse transmission function of the combination of the two diffusers. In position B1 for the moving diffuser, the signal received by the instrument is given by:

$$I.R_A.T_A + I.R_{B1}.T_B$$

Here, T_A is the diffuse transmission factor of the fixed diffuser, R_{B1} is the whole-system response function for the aperture area occupied by the moving diffuser in location B1, and T_B is the diffuse transmission function of the moving diffuser. Signals are recorded for locations of the moving diffuser, numbered i = 1 to i = n, that fill the useful aperture of the instrument. These signals will be summed to give:

$$n.I.R_A.T_A + I.T_B.\Sigma R_{Bi}$$

Finally, with the moving diffuser out of the aperture (in position Bf, with f>n), the signal from the fixed diffuser alone will be recorded: $I.R_A.T_A$. The n signals from the fixed diffuser alone can then be subtracted from the total of signals produced by the moving diffuser to give: $I.T_B.\Sigma R_{Bi}$.

The signal $I.R_A.T_{AB}$, produced by the two diffusers together at location A, will be divided by the signal generated only by the fixed diffuser, giving the ratio: T_{AB}/T_A. This ratio will be compared with the same ratio measured pre-flight using a sun simulator: T_{ABg}/T_{Ag}. At this point we assume temporarily that the shapes of the polar distributions of diffuse transmission, produced by the two diffusers, are not changed between pre-flight and in-flight measurements. The principle change expected will be in absorption, varying with wavelength but uniform in its effect on the polar scatter distributions. We can therefore write, for each resolved waveband:

$$T_A = C_A.T_{Ag} \;,\; T_B = C_B.T_{Bg}, \text{ and}$$

$$T_{AB} = C_A.C_B.T_{ABg}$$

where C_A and C_B are the absorption factors for the fixed and moving diffusers, associated with contamination etc. after pre-flight calibration. Taking the ratio of T_{AB}/T_A measured in flight to the corresponding value measured on ground, gives $T_{AB}.T_{Ag}/(T_{ABg}.T_A) = C_B$.

The method therefore yields a measure of the change of diffuse transmission for the moving diffuser, produced by any change in the moving diffuser after the pre-flight measurements This will include any effects of out-gassing and contamination and any radiation darkening or other bulk effects. The change for each diffuser is measured independently of any changes in the other. Because ratios of signals are used, separately for pre-flight and in-flight measurements, the results are also independent of any changes in source irradiances and main-instrument response.

We can therefore confidently use the measured value C_B for change in diffuse transmission of the moving diffuser, to update the pre-flight characterisation of the moving diffuser. T_B is now known with acceptable accuracy and – more importantly – with very good confidence, so that the instrument response to scene radiance, $T_B.\Sigma R_{Bi}$, can be computed from the sum of moving-diffuser readings, given knowledge of the solar irradiance I. As for conventional diffuser systems, the instrument response to Earth reflectance, $(T_B/I).\Sigma R_{Bi}$, can be derived without accurate knowledge of the solar spectral irradiance.

The simple theory given above applies separately to each resolved spectral band of the main instrument, since signals will be measured in all bands. The calibration method therefore provides the full spectral response of the instrument.

The method (like most other diffusre methods) is subject to errors if contamination or aging effects produce changes in the shapes of the polar diffuse distributions of the diffusers. In this case, changes in the ratios of diffuser signals cannot be assumed to be related only to absorption losses. However, it will be possible to make limited checks on the polar transmission characteristics of the diffusers by varying the sun angle with respect to the instrument, and comparing the results with similar data measured pre-flight with a sun-simulator.

3.2 <u>Variants and limitations of the diffuser method</u>

The ratioing method can in principle use either reflecting or transmitting diffusers. It is also possible to invent schemes using multiple diffusers or a complete integrating sphere. (For example, the ratio of signals recorded before and after removing one segment of an integrating sphere can in theory provide a measure of the sphere reflectance, assuming uniform degradation.) However, the key advantage of a system using transmitting diffusers is that it can be very compact, due essentially to the near-straight-through light paths, with simple movements.

Use of small diffusers moved across the aperture, is not essential to the ratioing concept, but provides two potentially significant advantages: (a) it provides a very compact arrangement and (b) it ensures that the aperture is never blocked, so that the instrument function is not totally destroyed by a failure of the mechanism. These advantages must be traded against a need for multiple measurements to derive the full-aperture response of the instrument.

The method tends to be limited to systems with relatively small fields of view, since high-gain diffusers (providing narrow polar scatter distributions) are needed to provide adequate signal levels. The method is also limited to use in systems that can be pointed near-directly at the sun – typically for instruments mounted on dedicated agile platforms, but also for systems with a regular view of sun in normal operation, for example in geostationary orbit.

There are multiple trade-offs in detailed design of the concept. As described, the system can be very compact, using a diffuser movement comparable with the aperture width. If a larger movement is accepted, the moving diffuser can be carried in a full-aperture mask, which provides better elimination of stray light, while pointing directly towards the sun, and of course a shutter facility that may be required for other reasons. Larger movements can also be used to introduce full aperture transmitting diffusers, which can simplify the measurement procedure and allow larger fields of view to be filled.

4 WINDOWS METHOD

A system using multiple images of the sun is indicated schematically in figure 4-1. The on-board reference consists of two flat windows. Each of the two windows will typically comprise 2 or 3 flat parallel plates of silica, without coatings. The two windows are inclined at an angle typically in the order 1°.

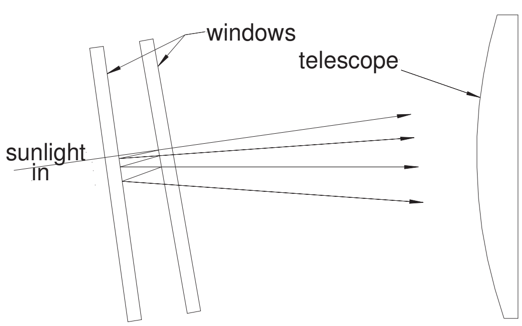

Figure 4-1 Ratioing method using windows

For absolute radiometric calibration, the instrument views images of the sun transmitted by the windows. It is necessary for the main instrument to record images of at least two of the multiple sun-images produced by reflections between the two windows, using the instrument field or pointing capability.

4.1 Operation and theory - windows

The sun images received through the windows by direct transmission and by multiple reflections have radiances:

$S.T_1.T_2$,
$S.T_1.T_2.R_1.R_2$
$S.T_1.T_2.(R_1.R_2)^2$
$S.T_1.T_2.(R_1.R_2)^3$, etc.

where S is the radiance of the sun, T_1 and T_2 are the direct transmission factors of the two windows, and R_1 and R_2 are their reflectance factors (including all surfaces in each case).

The direct radiance of the sun is 5 orders of magnitude above the typical measurement range of Earth-observing instruments, which will not therefore be able to record the direct image or (probably) the images produced by two and four reflections. However, the sun image radiances scale down by successive factors $R_1.R_2$. The numbers of plates in the two windows may for example be adjusted such that $R_1.R_2$ is in the region 0.025, so that the image produced by six and eight reflections are within a normal Earth-radiance range. These two images will be recorded by the main instrument. The ratio of the two results (or of any other two neighbouring images) will be calculated, giving an exact value for $R_1.R_2$, for each resolved spectral waveband of the main instrument.

It will also be necessary to measure the direct transmission of the windows – $T_1.T_2$. This will include any additional attenuation for the direct view that may be included for convenience, for example by adding a filter glass or a sieve plate. In cases where the windows are deployed across the view direction of the main instrument, this measurement will typically be performed by recording images of the Earth seen with and without the windows, and taking a ratio. Where pointing optics are used to view through the windows, it may be more difficult to measure direct transmission using Earth or moon images; methods will depend on detailed orbit and platform factors – for example platform agility may sometimes be used.

The ratio measurements of $R_1.R_2$ and $T_1.T_2$ allow the sun-radiance attenuation of any of the multiple-reflected sun images to be calculated precisely. The radiance of a selected sun image can then be used for absolute calibration of the instrument. For calibration in terms of radiance, it is necessary to assume knowledge of the solar radiance. But as before, the instrument can be calibrated as an Earth-reflectance monitor without knowledge of the average solar spectral radiance.

The measurement is again independent of the true values of transmission and reflectance of the windows, and hence very insensitive to any effects of contamination, radiation darkening etc. In this case, it is not strictly necessary to rely on any pre-flight characterisation of the windows (although the operation of the system would of course be checked pre-flight).

The radiance of the sun is not uniform over the disc, so that it will be necessary to make corrections for readings taken at points that do not represent the average. This may in principle be done by integration of the image over the whole disc, but may alternatively make use of relative radiance distributions measured from ground.

In general, the method will be used to calibrate the instrument as a reflectance-measurement system. Earth reflectance will be given by:

$$E = \pi.s_e/(s_s.\Omega)$$

where s_e is the signal from Earth (after offset correction), s_s is the average sun signal allowing for the computed attenuation, and Ω is the angular subtense of the sun. The absolute solar spectral radiance or irradiance is not required, but the relative distribution of radiance over the sun disc must be used to correct s_s.

4.2 Variants and limitations - windows

The transmitting windows can, where convenient, be substituted by a mirror with a single window, as indicated in figure 4-2. In this case, the radiances of multiple sun images are given by $T^2.R_m$, $T^2.R_m.R^2$, $T^2.R_m^2.R^3$, etc., where T and R are the transmission and reflection of the window, and R_m is the reflectance of the mirror. The ratio of an appropriate pair of neighbouring images gives $R_m.R$, and two images of Earth – direct and via the mirror, give the single-pass value $T^2.R_m$. The radiance attenuation of any sun image can therefore be calculated.

Flat mirrors or deflecting prisms can be added to the light path, where this is convenient to provide the required views of multiple sun images. Filters – neutral or coloured – can also be added to the light path to provide adjustments to the maximum transmitted spectral radiances. The modification in throughput produced by added mirrors and/or filters will be measured by the direct transmission measurement, typically using Earth as a source.

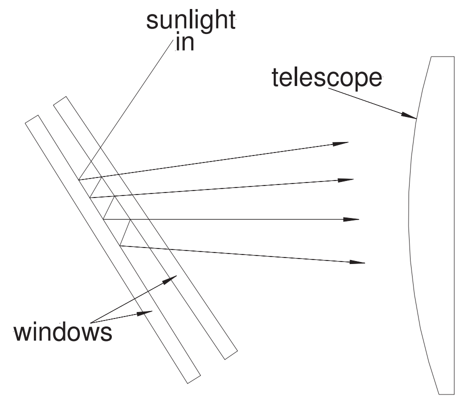

Figure 4-2 Ratioing concept with mirror and window

In general, the sun image will not be large enough to fill the field of view of the sensor, and will not therefore usually provide absolute calibration for the whole instrument field, unless the sun is scanned over the field. It will usually be desirable to include a flat-fielding sub-system that will provide radiance filling the instrument field. Measurements from the flat-fielding system can then be used to extend absolute calibration across the instrument field.

The flat-fielding system can for example be a simple sun-illuminated diffuser. The source for flat-fielding is required to produce a distribution radiance that is uniform with angle across the instrument field – or of known relative angular shape. However, it is not necessary for the absolute radiance of the flat field source to be known, since this information is provided for a limited part of the field by the windows. It is therefore reasonable to use collimation optics – a simple lens or mirror – with the diffuser to reduce the necessary size of the diffuser and its' sun-illumination window.

Figure 4-3 shows how a set of calibration functions, plus a shutter, may be provided using a single mechanism. The rotary mechanism carries (a) a transmitting window for absolute calibration, (b) a concave mirror, which can be moved into the field of the main instrument in alternate rotational positions.

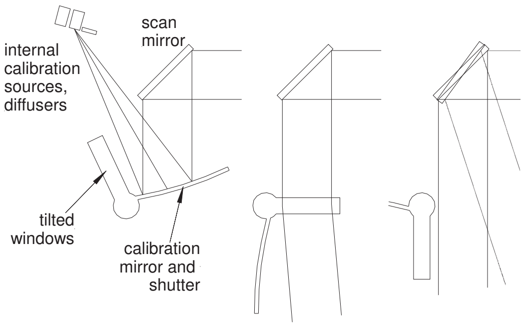

Figure 4-3 Deployment of separate components for absolute calibration and flat fielding

In a third position, both these components are moved out of the instrument field, so that it can view Earth directly. This arrangement is proposed for an instrument viewing Earth from a three-axis stabilised platform in geostationary orbit. Absolute calibration will be performed, with some assistance from platform agility, when the sun appears close to the Earth, so that multiple sun images can be viewed through the windows. In the same time-frame, the concave mirror will be deployed – it will act as an effective shutter, preventing over-heating of the instrument via the main system aperture. It will also collimate light from small sources, including a sun-illuminated diffuser used for flat-fielding, and wavelength calibration sources.

Other methods to provide flat-fielding, or to validate a diffuser, will often be feasible. For example, for some instruments large volumes of normal image data may be analysed to detect errors in the relative spatial response function.

As in the case of the two-diffuser concept, the feasibility of the windows method will depend on detailed instrument design and mission parameters. Near-direct views of the sun, provided by platform agility or pointing mirrors, will generally be required, except where normal attitude and orbit provide occasional sun views in appropriate directions.

5 SIZE AND COMPLEXITY

The size and complexity of the calibration system described in section 4 above may be compared with that of a conventional system using sun-illuminated diffusers.

It is usually recommended that the sources used for absolute calibration, flat fielding and wavelength calibration shall fill the aperture of the system, to avoid errors due to non-uniform transmission and wavelength-definition across the aperture. The sizes of external sun-attentuators therefore tend to scale in all cases with the size of the optics aperture. The size of the rotating system in Figure 4-3 will be similar to the size of a carousel of diffusers – possibly including a rare-Earth-doped diffuser for wavelength calibration – in a conventional non-ratioing system. Transmitting diffusers tend to provide more compact arrangements, however, since reflecting diffusers are normally viewed at oblique angles.

For the type of instrument indicated in Figure 4-3, with a scan mirror, it is in principle possible to use the scan mirror to view solar attenuators of any kind, provided that the orbit and attitude constraints of the platform allow suitable relative sun angles to be accessed. In practice, a separate movement tends to be favoured for conventional diffuser systems, since this allows the diffusers to be covered when not in use. Attenuator stabity is unnecessary for the ratioing method, so that it is easier to dispense with a separate mechanism. (The scheme shown in Figure 4-3 includes a calibration mechanism for a range of reasons, including a desirable limit on scan-mirror travel and a convenient shutter facility.)

6 CONCLUSIONS

Basic ratioing methods have been described for absolute radiometric calibration of space-based spectro-radiometers. The methods use different types of sunlight attenuator – diffusers or reflections from glassy plates – to provide reference radiance.

The relevant parameters of the attenuators – diffuser scatter characteristics or specular reflectance – are measured in flight, using the main instrument optics and detectors, by taking ratios of signals recorded in different configurations. In-flight measurements of the solar attenuators will provide much-improved confidence in absolute calibration with respect to the sun, since existing systems rely essentially on stability of solar-attenuator parameters after pre-flight characterisation.

The suggested arrangements do not require additional detection systems. In general, a movement is required for calibration measurements, to view attenuators in sun-light. However, the movements required are not more demanding than movements used in existing in-flight calibration systems.

The essential optical components suggested for the ratioing methods – ground fused silica and simple uncoated silica plates – are unlikely to present significant development problems. They are in fact likely to be more stable in their essential characteristics than the porous reflecting diffusers used at present. The ratioing methods will provide reliable measurements of effects of contamination etc., but will in practice be expected to demonstrate that very little changes have occurred.

However the suggested methods will require some development effort, mainly because the concepts are new and must be investigated in detail. There will be resistance to a change from present practice – generally using sun-illuminated reflecting diffusers. Reflecting diffusers may in fact have adequate stability, given stringent production control and protection on ground and in flight. The basic criticism of simple one- or two-diffuser systems – that there is no accurate independent check in flight – is also a reason for their acceptance: no-one can prove that they are not stable. But this is not an argument that should be accepted without question.

7 ACKNOWLEDGEMENTS

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Study on Radiometric Requirements for Hyperspectral Applications, ESA Contract No. 13245/98/NL/GD, completed 2001.

The diffuser concepts have been developed further by TNO in a recent phase A study for ESA on the SPECTRA mission. The windows concept has been further developed in a study for BNSC under the Newton programme, performed in a collaboration between Astrium, Sira and University of Liecester:
GeoSCIA Design Study, completed 2002.

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