Adv. Space Res, 32: 2253-2261 (2003)

TRACEABLE RADIOMETRY UNDERPINNING TERRESTRIAL – AND HELIO- STUDIES (TRUTHS)

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ABSTRACT

The Traceable Radiometry Underpinning Terrestrial- and Helio- Studies (TRUTHS) mission offers a novel approach to the provision of key scientific data with unprecedented radiometric accuracy for Earth Observation (EO) and solar studies, which will also establish well-calibrated reference targets/standards to support other EO missions. This paper presents the TRUTHS mission and its objectives. TRUTHS will be the first satellite mission to calibrate its EO instrumentation directly to SI in orbit, overcoming the usual uncertainties associated with drifts of sensor gain and spectral shape by using an electrical rather than an optical standard as the basis of its calibration. The range of instruments flown as part of the payload will also provide accurate input data to improve atmospheric radiative transfer codes by anchoring boundary conditions, through simultaneous measurements of aerosols, particulates and radiances at various heights. Therefore, TRUTHS will significantly improve the performance and accuracy of EO missions with broad global or operational aims, as well as more dedicated missions. The provision of reference standards will also improve synergy between missions by reducing errors due to different calibration biases and offer cost reductions for future missions by reducing the demands for on-board calibration systems. Such improvements are important for the future success of strategies such as Global Monitoring for Environment and Security (GMES) and the implementation and monitoring of international treaties such as the Kyoto Protocol. TRUTHS will achieve these aims by measuring the geophysical variables of solar and lunar irradiance, together with both polarised and un-polarised spectral radiance of the Moon, Earth and its atmosphere.

INTRODUCTION

Understanding changes in the Earth's system is probably the most important challenge facing humankind and science today. It is the subject of international controversy, political debate, scientific review and public concern. Yet it remains contentious, ambivalent and equivocal. Scientists cannot agree on the conclusions they draw from their data – because the data itself may be equivocal! The ambition of the Traceable Radiometry Underpinning Terrestrial- and Helio- Studies (TRUTHS) mission is to resolve some of the data issues. In doing so, it will provide the benchmarks vital to a consensus interpretation and a common understanding. TRUTHS will underpin the data from past, present and future missions. There are political justifications for undertaking this mission – the Kyoto Protocol is a case in point – and there are commercial benefits. But the overarching need is scientific.

The Sun is the major external component forcing changes in the Earth system. We need long-term records of the Sun, other forcings *and* the system responses - changes in land albedo and land use patterns, etc. Yet, in the acquisition of long-term geophysical and solar quantities, the problem of maintaining a reliable absolute scale has proven to be almost insurmountable. Optical, electrical and mechanical components of instruments in space all contribute to changes in responsivity and wavelength that cause spurious trends in many, if not all, long-term climate and solar data sets acquired thus far.

While pre-launch sensor characterisation helps in evaluating the extent to which a sensor meets specifications, it is in the post-launch environment that the issues of radiometric calibration and traceability to SI units become critical. Science has an overarching interest in ensuring that data are of the highest quality, accuracy, and reliability available. The user community, which will draw the conclusions, need reliable information on the uncertainty associated with satellite-measured signals. Armed with that information, they can assess the accuracy of products generated by their algorithms and how useful they are to Earth resource and climate studies.

There are a number of examples of space-borne Earth observation missions with less than satisfactory accuracy, calibration, consistency, and stability of the higher-level data products that represent geophysical variables. Nevertheless, in recent years, several space agencies have responded to the more stringent requirements in this respect. Pathfinder projects were initiated to improve long-term historical time series and satellites with exceptional calibration were launched. A striking example of this was the seamless transition from the European Space Agency's (ESA) Earth Resources Satellites (ERS) ERS-1 to ERS-2 operation in terms of radar image calibration (level-1) and wind/wave products (level-2). NASA also has put great emphasis on calibration during the development of its Sea-viewing Wide Field-of-view Sensor (SeaWiFS) program and the Earth Observing System (EOS) spacecraft sensor systems. In particular, NASA engaged the support of the National Institute of Standards and Technology (NIST) to work with it and the instrument teams to develop and adopt a consistent and appropriate method of assessing and presenting uncertainties. They also developed dedicated transfer standards in order to carry out "round-robin" comparisons between the various instrument calibration teams, both within the US and elsewhere, so as to ensure equivalence. However, even after these rigorous activities, post launch biases between some of these sensors are much larger than expected. For example, the EOS Terra sensors MODIS (Moderate-resolution Imaging Spectroradiometer) and MISR (Multi-angle Imaging Spectroradiometer) differ by ~10% (based on initial in-flight calibration algorithms) when viewing a relatively simple (in terms of surface characteristics) desert target; (Abdou et al., 2002, Bruegge et al., 2002). Thus, there remain specific difficulties associated with optical sensors and their transference into orbit.

The goal of TRUTHS is a bold radiometric endeavour. It aims to establish traceable measurements of unprecedented accuracy and, for the first time, directly to the SI scale in orbit. As described in this paper, it will make direct use of a terrestrial primary standard, a cryogenic radiometer (CR), adapted for use in space. The CR together with its associated calibration chain will provide, in space, a standard reference for measurements of both the Sun and the Earth. This novel "in-flight" calibration system makes it possible to dramatically improve the accuracy of measurements over existing planned missions, for example more than an order of magnitude for Earth spectral radiance. TRUTHS, and only TRUTHS for the foreseeable future, will provide the necessary advances to ensure that future Earth system data sets have sufficient radiometric long-term accuracy for the reliable detection and attribution of global change. The scientific case for improved measurements of the Sun and Earth are widely available in the literature, a summary focussed on the objectives of TRUTHS can be found in (Fox et al, 2003).

MISSION OBJECTIVES

TRUTHS is a satellite mission to make spectrally resolved measurements of input solar radiation, the energy that supports life on Earth, and reflected solar radiation to visualise and interrogate the surface with an accuracy ten times that of any other mission. It will characterise reference targets directly traceable to SI units to allow the transfer of TRUTHS accuracy to other Earth observation missions. It will also establish true traceability for sensors in-flight by avoiding bias and uncertainty caused by pre-launch calibration, storage, launch, and ageing by performing spectral and radiometric calibration of sensors in-flight directly against a primary standard. Thus, TRUTHS will provide underpinning tools to generate unequivocal data to enable scientists to advise policy makers to make decisions and take actions on sustainable development and climate change with confidence.

The mission objectives are as follows.

- To establish a set of reference sites and targets (land, water, Sun, and Moon) to act as calibration standards for next generation Earth observation sensors.
- To measure Earth hyper-spectral radiance (400 – 2500 nm) with polarisation information at high accuracy (0.1 %) at 20 m ground resolution.
- To simultaneously compare ground, aircraft, and space-based measurements of spectral radiance to improve accuracy and reliability of atmospheric radiative transfer codes.
- To determine Total Solar Irradiance (TSI) and Solar Spectral Irradiance (SSI) and their variance with uncertainties of < 0.01 and 0.1 %, respectively
- To demonstrate the use of self-calibration of radiometric properties of optical EO sensors in space.

SCIENTIFIC REQUIREMENTS

Earth Observation Data

Optical Earth observation sensors generally measure top-of-the-atmosphere (TOA) radiances, either relative to the Sun or by reference to SI through ground calibrations. In order for these signals to be used for studies of Earth and Ocean processes they need to be transformed into geophysical and biophysical products. A serious limitation in this transformation is the uncertainty of the input variables due to the uncertainty of the measurement. It might be presumed that, if several instruments view the same geophysical system and claim to measure the same physical property, they will all give the same result. However, this is rarely the case. As noted earlier, even new and sophisticated missions such as the NASA Terra platform's MISR and MODIS initially exhibited systematic biases between themselves in spectral radiances of the order of 10 %(Abdou et al., 2002, Bruegge et al., 2002). There are similar differences between these two instruments and other instruments such as the Landsat sensors. On the other hand, MISR and MODIS pre-flight claims and science goals demand 5 % or better. This calibration discrepancy is unacceptable and, without a strong, definite, reliable standard to benchmark against, can lead to dubious procedures to 'force' one instrument to match the other. Although it should be said that generally this "normalisation" process is usually carried out after the identification of a specific or potential source of "bias" from one of the instruments. Unless we undertake a mission like TRUTHS, it is hard to imagine any real synergy from the combination of results of sensors intended to be complementary.

It is often stated that absolute uncertainty of measurement is not critical for most EO applications. This statement is certainly true for many applications where a simple instantaneous set of data is required. However, as soon as any long term trend or quantitative information is required such as for climate change studies, then it is hard to rely on accuracy claims from a single instrument. It is also difficult to improve the accuracy of any of the correction or processing algorithms e.g. atmospheric transfer without having reliable high accuracy data to anchor the boundary conditions.

Sensor Calibration and Uncertainties

A space sensor, once launched to its designated orbit will provide data for many years. Even when it is considered that the space sensor is free of errors, the signal output cannot be regarded as stable over the entire mission duration. Due to possible degradation of the sensor's performance, it is necessary to monitor and understand the behaviour of the sensor until the end of the mission. Besides the sensor output, the data products also have to be evaluated and validated. Here, temporal variations in atmospheric transmission, solar geometry, and the time of the day may result in different data representations for the same ground target. This is why considerable science and engineering effort has been dedicated to the correction of these effects.

Earth observation data require a careful calibration and characterisation of the remote sensing instrument. All calibration and characterisation efforts are made to define the sensor's response (e.g., counts, voltage) to known and controlled signal inputs with the objective to describe (or characterise) the sensor in terms of its spectral response (wavelength, spectral band width), radiometric response (intensity of the input radiance, noise equivalent radiance), geometric response (different locations across the instantaneous field-of-view and/or entire field of view), differences in integration times or lens/aperture settings, polarisation sensitivity, and unwanted signals such as stray light and leakage from other spectral bands. All of these characteristics can vary over time. It is beyond the scope of this paper to outline these aspects of sensor characterization.

Approaches to sensor radiometric calibration have been well-documented (Dinguirard and Slater, 1999) and new methodologies continue to evolve.(Teillet, et al., 2001a and 2001b). Consistency between different sensors starts with uniform calibration of the individual sensors, including the development of a stable sensor, detailed and traceable pre-launch characterisation, and standardised in-orbit calibration. Post-launch radiometric calibrations can be based on reference to onboard standards, solar and lunar illumination, and/or ground-based test sites. With reliable sensor radiometric calibration in place, it then becomes possible to tackle other steps such as atmospheric correction, spectral characterization, and corrections for geometric effects on image radiometry. The objective is to enable the generation of consistent geophysical and biophysical products from dissimilar measurement methods and/or systems (Teillet, et al., 1997a and 1997b). The Committee on Earth Observing Satellites Working Group on Calibration and Validation (CEOS WGCV) was established as an entity to help meet this objective (http://www.wgcvceos.org/). All calibration exercises ultimately consist of cross-comparisons between instruments. Therefore, calibration devices themselves need to be at least an order of magnitude better than the sensors that need to be calibrated if they are to serve as a reference and benchmark. TRUTHS will achieve this order of magnitude improvement, at least for dedicated reference targets.

Vicarious Calibration

Similar to the on-board calibration, vicarious calibration is applied after launch of the sensor, using calibration sources in the form of natural/artificial sites on the surface of the Earth. These sites are imaged by the sensor under investigation and one or more well-calibrated sensors on various platforms (satellite, aircraft, or on the ground itself). After the selection of an appropriate homogenous ground site (such as dry lake beds or the open ocean), the comparison between the sensor data for these sites can be performed. Therefore, the atmospheric and directional reflectance effects of the site have to be taken into consideration for the reference sensor and the sensor under study. Allowing for differences in spectral band characteristics, the calibration coefficients (such as the gain coefficient) for the sensor under investigation can be updated. The best vicarious calibration methods currently predict uncertainty estimates approaching the 1.8 % level (Dinguirard and Slater 1999). Although feasible they require the adoption of improved instrumentation and calibration techniques. TRUTHS will reduce this uncertainty by a more than a factor of ten.

TRUTHS INSTRUMENTATION

The TRUTHS satellite comprises a suite of independently operable instruments, each largely based on existing designs to reduce risk and cost. The instruments are arranged so that they view out of opposite faces of the payload, such that the level of movement of the bus is minimised when switching from solar to Earth viewing mode. Most of the instruments sit on the solar viewing face, the exception being the Earth Imager (EI) and the filter radiometers (FR). The FRs can rotate to face both directions by means of a "wheel", the Filter Radiometer Transfer Wheel (FRTW) upon which they are mounted. Of those facing the Sun, only those directly interacting with it are exposed to it and these in turn have individual shutters to limit exposure and allow "dark readings" to be taken. The payload occupies a volume of <1 m^3, has a mass of 130 Kg, and has a peak power requirement of 185 W (this is dominated by the mechanical cooler of the Cryogenic Solar Absolute Radiometer (CSAR)).

In the limited space available in this paper, only a brief overview of the instrumentation is given in order for the reader to understand the critical design requirements. In particular, emphasis is placed on the unique on-board calibration methodology that allows TRUTHS to achieve and maintain its high radiometric accuracy.

Earth Imager (EI)

The TRUTHS EI will be a compact imaging spectrometer. It will measure Earth spectral radiances in a contiguous manner from 0.380 to 2.5 μm in 212 channels of nominal 10 nm bandwidths, although the last two channels at both ends will be of poorer signal-to-noise ratio. The ground resolution will be 20 m or better from a baseline operational altitude of 680 km in a pushbroom mode. The selection of centre wavelength and actual bandwidth, within the physical resolution limits of the spectrometer, can be selected from ground during the mission. The demanding specification makes use of existing designs and technology, based on a space-qualified upgrade of the Airborne Prism Experiment (APEX) aircraft spectrometer, under design as a generic calibration instrument for ESA.

In addition to the EI there will also be a group of four Earth viewing filter radiometers, each filter radiometer separating and measuring Earth reflected radiation in "s" and "p" polarisations. The spectral bands of these filters radiometers will be spaced across the visible spectrum so as to help analyse the atmospheric transmittance.

Solar Spectral Irradiance Monitor (SSIM)

The Solar Spectral Irradiance Monitor (SSIM) is most easily described as being a set of four diode array spectrometers with a common input. The input is via a small integrating sphere with a precision aperture illuminated by the Sun, so as to define irradiance. The spectrometers disperse the solar radiation on to the arrays to allow a spectral resolution of 0.0005 μm in the range 0.2 μm to 1 μm, and 0.001 μm from 1 to 2.5 μm. The use of linear diode arrays allows the integration time and thus the dynamic range to be varied. The use of a single common input port significantly aids the in-flight calibration procedure.

Spectral Calibration Monochromator (SCM)

The purpose of the Spectral Calibration Monochromator (SCM) is to provide monochromatic (0.5 nm bandwidth) tuneable radiation covering the spectral range of the TRUTHS instrumentation (0.2 to 2.5 μm) as a central part of the in-flight calibration system. This is achieved through the dispersion of incident solar irradiance by three linked double grating monochromators. The output of these monochromators is coupled into fibre optic bundles to aid distribution to the TRUTHS instruments. These bundles are terminated at their exit with a simple optical lens to allow the radiation to be imaged into the entrance optics of the various instruments. The principle design driver is the need for relatively high radiant power within the relatively narrow spectral bandwidth. Calculations show that, with the losses of practical systems, this will be in the range of 5 to 40 μW.

Cryogenic Solar Absolute Radiometer (CSAR)

In terms of the TRUTHS mission objectives, the CSAR is arguably the most critical instrument of the payload. This is because it is responsible for providing the primary reference for the in-flight calibration of all the other TRUTHS instruments. The CSAR is an Electrical Substitution Radiometer ESR, where the heating effect of optical radiation is compared to that of an electrical heater. Operation at cryogenic temperatures (around 20 K in TRUTHS using the Astrium cooler) improves the specific heat capacity of the radiation or "heat" absorber allowing greater sensitivity and also the ability to build relatively large cavity absorbers to improve absorbtance of optical radiation. Pioneered by NPL 25 yrs ago, terrestrial Cryogenic Radiometers (CR) have become widely used as the primary reference standard for optical radiation measurements in most of the worlds National Metrology Institutes (NMI)(Fox 1996). The absorbing cavity of TRUTHS has an absorbtance of > 0.99999. The high absorbtance leads to two operational advantages for TRUTHS: firstly, a high absorbtance reduces uncertainty in correction when measuring TSI, for example, and, secondly, when used as a primary standard, it allows significant degradation of performance before effecting the uncertainty of the other instruments. This latter functionality is most easily visualised when one considers that the absorbing cavity of CSAR acts as the interface between optical and electrical measurements. In space, when using appropriate components, electrical measurements have been shown to be stable and robust, whereas optical components have tended to be subject to unquantifiable drifts and changes. In the CSAR, the only optical element is the cavity absorbtance, which can degrade by a factor of 100 and still achieve 0.1% uncertainty.

In the TRUTHS mission, the CSAR has two clear roles. The first is to measure TSI in a manner that is similar to ACRIM and VIRGO on the Solar and Heliospheric Observatory (SOHO) (although with higher accuracy). (Martin and Fox, 1994). The second role is as the primary reference standard to underpin the calibration of all the TRUTHS instruments and provide traceability to SI units. In addition to CSAR, there is also a package of ambient temperature ESRs from the World Radiation Centre/Physikalisch-Meteorologische Observatorium Davos (WRC/PMOD). The PMO radiometers include flight spares of those in VIRGO, allowing a direct comparison on board TRUTHS and thus a link back to the measurements of SOHO.

As a calibration reference, CSAR is required to measure the radiant power of the monochromatic radiation emitted from the SCM. This is of the order of 10 μW, significantly different than the 30 mW of TSI. Thus, the CSAR requires two types of absorbing cavity, one of much high sensitivity than the other. Measuring low radiant powers also requires sources of stray background radiation to be minimised, another advantage of cryogenic operation. The CSAR has been designed in such a manner to allow the two types of cavity to be intercompared, between themselves and with other redundant cavities to ensure a fully integrated and traceable system.

CALIBRATION STRATEGY FOR TRUTHS

The importance of the accuracy and traceability of all the TRUTHS instruments to the objectives of the mission makes pre-launch calibration on the ground a particularly important consideration, in addition to the on-orbit systems. This will be carried out directly against primary standards maintained at NPL, making use of its National Laser Radiometry Facility (NLRF) to fully characterize the spectral, polarisation and stray light characteristics of the various spectrometers. In addition, the CSAR itself will be compared to the NPL primary CR, whose performance has been compared with fundamental constants, the Stefan Boltzmann constant in particular.

Terrestrial Calibration Methodology

The terrestrial calibration methodology typically employed by an NMI such as NPL is shown in the left hand column of Figure 1. At NPL, a CR measures the radiant power in a monochromatic beam of radiation, from a laser, by comparing its heating effect with that of electrical power. Uncertainties of 0.001% can be achieved in this way. The now calibrated monochromatic beam is then used to illuminate a photodiode and thus determine its spectral response. This process is repeated at sufficient wavelength intervals (usually 0.05 to 0.1 µm) to allow interpolation of the slowly varying spectral response of the photodiode. These photodiodes can then be used to calibrate spectrally selective detectors (filter radiometers) using a similar monochromatic beam of radiation but making measurements at much finer spectral intervals. The filter radiometer (FR) can have narrow or broad spectral response functions, e.g., 0.001 µm for a monochromator or 0.01 µm for coloured glasses. The calibrated FRs are then used to measure directly the spectral irradiance or radiance of conventional polychromatic sources such as lamps. Often, the Planck radiation of an intermediate, high temperature (3500 K) black body (UHTBB) is used to interpolate finer spectral intervals for irradiance and radiance measurements, its radiant temperature having been previously determined using a group of FRs across the spectral region of interest. Uncertainties as low as 0.02% can be achieved in this way, although in practise the limitation is often the performance of the conventional standard lamp being calibrated.

These lamps are then used to disseminate radiometric scales to users for calibration of, for example, Earth observation instrumentation. Most satellite instrumentation would be calibrated using a traceability chain similar to this. However, the number of steps after the final calibration at an NMI may of course vary considerably as indeed could the consequent traceability, since there is often no formal comparison or independent review to evaluate the uncertainties achieved in the final application.

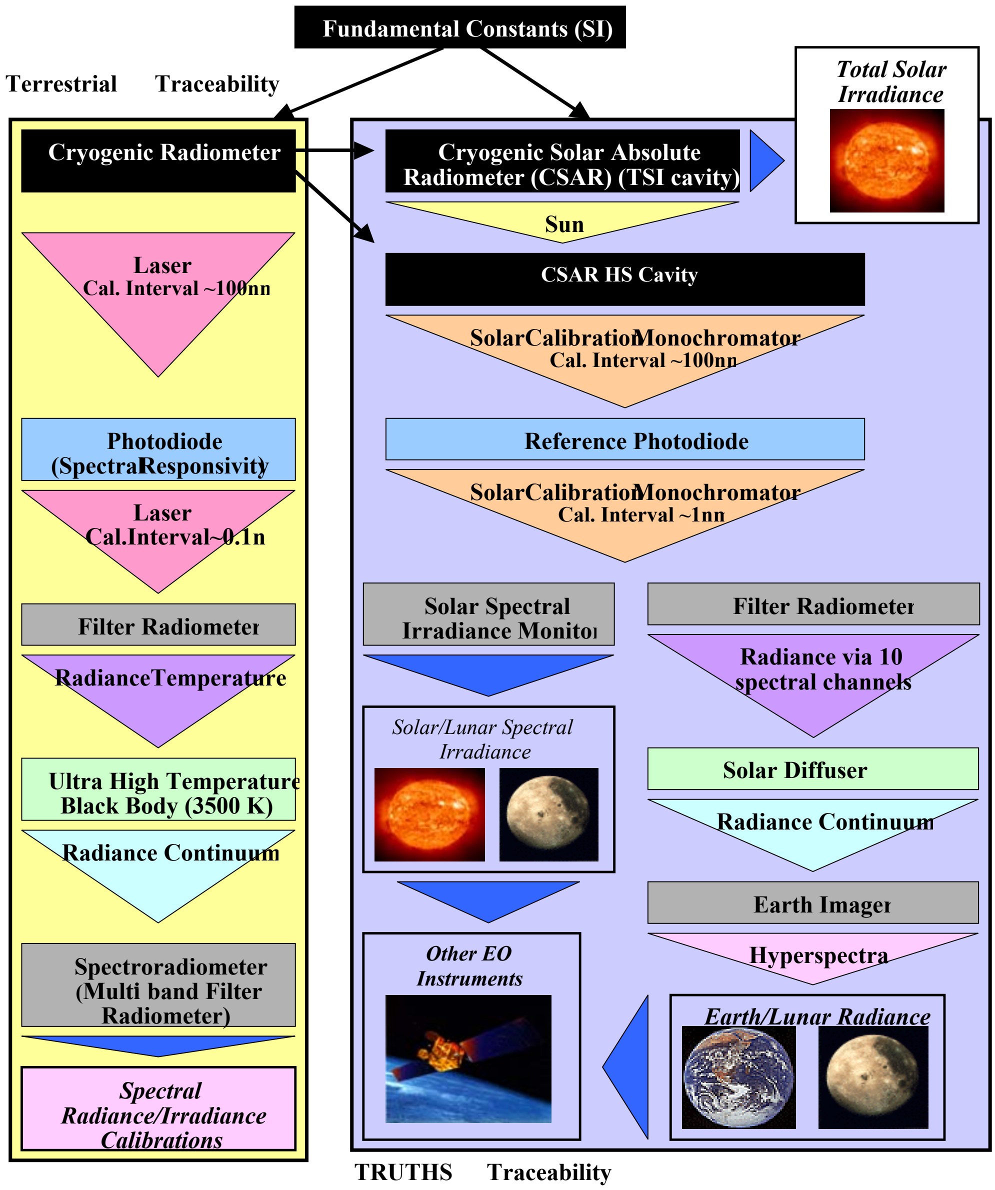

Fig. 1. Calibration traceability chain for TRUTHS contrasted with that of an NMI.

TRUTHS Calibration Methodology.

An analogous calibration procedure is proposed for TRUTHS illustrated in the right hand column of Figure 1, alongside the NMI methodology on the left hand side. The main difference is that TRUTHS will use solar radiation dispersed by a grating monochromator and a SCM for spectral responsivity calibrations instead of lasers. Only short-term stability of the radiation from the SCM is required. Any long-term degradation of the SCM optics is calibrated out each time it is used, since the output beam power is referenced to the onboard primary standard cryogenic radiometer, the CSAR.

Similarly, the spectral radiance of the EI is calibrated in-orbit through a measurement of solar irradiance reflected from a solar illuminated diffuser plate instead of a high-temperature black body. This procedure is in common use, e.g., by the Medium Resolution Imaging Spectrometer (MERIS) on Envisat. However, in contrast to other Earth observation missions, the spectral radiance of this system is measured directly in-orbit using a group of filter radiometers calibrated using the SCM. This practice removes errors due to drifts in spectral shape and absolute level caused by ageing or contamination.

In TRUTHS, the complete spectral response of the filter radiometers (FR) (gain and shape) can be routinely measured in-flight using radiation from the SCM traceable to the CSAR, the FR being rotated between the calibration plane and the EI by means of the FRTW. In a similar manner, the polarisation filter radiometers are also calibrated. The resultant uncertainty in this process is dominated by signal to noise caused by the relatively low power emitted through the SCM. Since the CSAR itself has an uncertainty of < 0.01 %, the overall uncertainty is likely to be < 0.1% in radiance, more than an order of magnitude better than any other Earth observation mission. While this may seem optimistic, this step change reduction in uncertainty is similar in magnitude to that obtained when NMIs started to introduce CRs into their terrestrial calibration chains 20 yrs ago.

The in-flight calibration procedure described above does not of course reduce the need for normal detailed pre-flight characterisation of the sensors characteristics e.g. stray light, out-of-band, linearity etc. However, in most modern EO optical instrumentation the dominant uncertainty in the quoted error budget is "radiometric calibration" and its maintenance over mission life. It is this source of error which the TRUTHS calibration methodology addresses, through the regular recalibration, "in-flight", of its instrumentation against an essentially electrical standard.

It should be noted that errors in atmospheric transmission correction and other retrieval algorithms are likely to limit the overall uncertainty achievable by TRUTHS for specific measurands. However, the inherently accurate and reliable TRUTHS data will be essential inputs allowing such algorithms to be improved.

UTILIZATION

The instrumentation on board TRUTHS will provide data to the science community interested in the variation and absolute level of input solar radiation, both integrated as TSI and spectrally resolved. It will also of course provide accurate multi-angle, high spatial resolution spectral radiances of the Earth for studies of Land and Ocean processes. However, the nature of its orbit and high data collection rate prevent it from making truly continuous measurements of the Sun or global coverage of the Earth. These have to be performed by other dedicated missions. However, although possible to incorporate the TRUTHS calibration concept on these missions a similar benefit can be accrued by using TRUTHS as a reference. It can be used to transfer its solar calibration to other solar viewing instruments through simultaneous viewing. Similarly, it can transfer its spectral radiance calibration to other missions through the calibration of reference targets e.g. the Moon or Earth deserts. Providing these reference targets are stable or drifts/solar viewing angle differences between a TRUTHS overpass and another mission can be characterised/monitored, then these targets can transfer the spectral radiance coefficients determined by TRUTHS to other missions, removing the need for their own independent in-flight calibrations systems. Such a process will obviously require care in matching pixel size and spectral bands but can be achieved since the TRUTHS data is hyper-spectral and is at 20 m resolution.

Calibration Test Sites

Among the various approaches to ensuring long-term radiometric consistency of Earth science data records and information products is the systematic and timely use of a small but global network of calibration test sites permanently established to acquire benchmark data sets. A global instrumented and automated network of test sites as envisaged within the TRUTHS mission will facilitate efforts towards a next-generation Earth observation capability by means of improved coordination of activities worldwide, innovation through a higher degree of interaction and synergy, and greater awareness of the critical role of calibration (Teillet et al., 2001c). To date, such vicarious or ground-look calibration has been labour intensive and far from systematic, standardized or permanent. Spatially and spectrally extensive ground reference data together with atmospheric characterisation will make it possible to update and improve the radiometric calibration of any satellite sensors that image the test sites with spectral bands in the solar reflective spectrum (Teillet, 2001a, Dinguirard et al., 1999).

The use of “standard” ground reference calibration test sites as a means of cross-calibration and validation of satellite sensors is well established. In many cases, dedicated campaigns have been organized using teams supported by the respective instrument. In some cases, particularly atmospheric chemistry applications, use has been made of existing ground networks of validation equipment. In the case of land imagers, some test sites have become recognized ‘standards’, e.g., White Sands alkali flats and Railroad Valley playa in the Central USA and La Crau in Southern France. These and other sites have been well characterized and shown to be relatively homogeneous spatially and temporally stable. However, significant differences can be observed by different sensor teams when using the same target area for vicarious calibration activities because of biases originating from subtle differences in methodologies, instrumentation and calibration traceability. Such biases can also occur for networked sites although these can be reduced by the use of common instrumentation and standard methodologies. Each site will require a common set of automated instrumentation, including Sun photometers; standard meteorological parameters; video images of the site in real time; downwelling solar irradiance; and surface spectral reflectance/radiance. All instruments would be automated and transmit data independently. Year-round availability is a difficult criterion to meet due to rain or snow that can occur even in regions that are almost always clear. However, having a global network of essentially interoperable test sites obviates this.

Data from the ground will correlate with absolute information from TRUTHS such that the satellite sensors need only be stable (easier to achieve than absolute calibrations). To ensure this, site non-uniformities will need to be known and activities to achieve this have been or are in progress by various teams at all sites. The TRUTHS mission will add value to this process using instrumentation calibrated directly against the NPL primary standard using its UHTBB and NLRF. Thus, uncertainties approaching a few tenths of a percent will be achieved for surface spectral reflectances or radiances (subject of course to ground homogeneity). Given the current state of the art in such vicarious calibrations, this uncertainty may sound challenging. However, the dominant source of uncertainty in present error budgets is the linkage to SI. It is the direct calibration against primary standards provided by TRUTHS that will reduce this uncertainty.

CONCLUDING REMARKS

The US and Russian space agencies have discussed the possible use of the International Space Station to host a set of primary reference instruments to perform a similar task. TRUTHS could achieve the same goal, earlier, and at lower cost and less risk. Its use of a dedicated small satellite mission with a suite of instruments calibrated in-orbit directly against a primary standard based on more stable electrical units will provide a better result as well. The TRUTHS mission will establish a set of calibrated reference targets, Sun, Moon and Earth sites. These sites can then be used to transfer the TRUTHS calibration to other EO sensors. TRUTHS would constitute a major international resource in the search for an understanding of the Earth’s systems. In addition to this metrological goal, TRUTHS instruments will also provide operational scientific data for Solar and Earth studies.

The ambition of TRUTHS is clear. The factors that influence its specification - the instruments, their requirement and their performance - lie in the needs of current and projected applications. These needs embrace biophysical and geophysical quantities, the direct measurands of radiance and irradiance and, importantly, the underpinning and often limiting transformation algorithms. Appreciation and understanding of these factors support and strengthen the very need for TRUTHS. They bring into sharp focus the advantages of solar and Earth system science programs to society in general and climate change in particular.

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Manuscript received 10 December 2002; revised 18 April 2003, accepted 27 April 2003.