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 will present the TRUTHS mission and its objectives. TRUTHS will be the first satellite mission to calibrate its 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 Earth observation 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, and the Earth and its atmosphere.

Keywords: sensor calibration, terrestrial radiance, solar irradiance, vicarious calibration, test sites.

1. 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 themselves 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

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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%. 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 accomplish traceable measurements of unprecedented accuracy and, for the first time, directly to the SI scale. 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. 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 precision for the reliable detection and attribution of global change.

2. SCIENTIFIC JUSTIFICATION: THE SUN AND THE EARTH'S CLIMATE

2.1 Total Solar Irradiance

Solar radiation from the Sun is the driving force of the Earth's climate. Quantitative measurements of solar irradiance reaching the surface have been made for more than a century, based on principles little changed today. Angstrom constructed the first "absolute radiometer" in 1893, which compared the heating effect of solar irradiance to that caused by electrical power, and thus the first Electrical Substitution Radiometer (ESR). Independently, similar studies in the German national standards laboratory by Kurlbaum built an ESR for the measurement of more general optical radiation sources, e.g., lighting. Although technological improvements have been made over the years, the instruments in space today and in the foreseeable future to measure solar irradiance are based on this same technology. The many potential sources of error have meant that the uncertainties in measurements resulting from this technology, even terrestrially in National Metrology Institutes (NMIs), have remained at a few tenths of a percent. However, twenty years ago, the

United Kingdom's National Physical Laboratory (NPL) constructed a new type of ESR cooled to cryogenic temperatures, which reduced the uncertainty of measurements by more than a factor of 50 to a level of 0.005%. Such cryogenic radiometers (CR) are now in routine use as the primary standard in most of the worlds NMIs.[1]

Figure 1 shows predicted values of climate forcing by total solar irradiance (TSI)[2], including the range of uncertainty as an assumed background component. The solar-forcing is compared with two different projections of the net anthropogenic forcing: the IPCC 1995 IS92a scenario and an alternative scenario proposed by Hansen et al.[3]

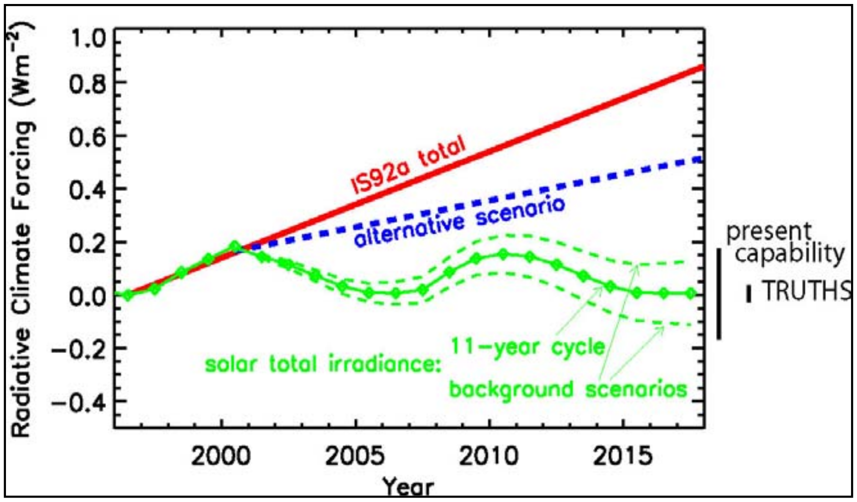

Figure 1. Predicted values of climate forcing by TSI.

Current space-based ambient-temperature radiometry lacks the accuracy to distinguish between future long-term solar trends. As illustrated in Figure 1, TRUTHS will provide the accuracy to enable this capability. Current databases lack sufficient accuracy to identify the long-term changes in TSI. To allow a firm conclusion requires solar irradiance measurements with a relative stability of better than 0.3 Wm^{-2} over a cycle timescale, i.e., with 0.02% in 11 years. In other words, the relative stability of the radiometers needs to be better than 20 ppm per year! The radiometers also need to provide uninterrupted, accurate observations of the Sun for this 11-year period (or at least ensure overlap with another mission).

The TRUTHS Cryogenic Solar Absolute Radiometer (CSAR) will reliably anchor the composite record of space-based observations to SI units at an uncertainty level of < 0.2 Wm^{-2} (0.01%) – better than the aforementioned requirement. Furthermore, the technology that TRUTHS will use does not suffer from the same systematic calibration biases of the room temperature radiometers previously used. This capability will ensure that a composite TSI record can be readily established at any time in the future through the flight of a similar instrument. This will be a unique benefit of the TRUTHS program, for previous re-flights of room temperature radiometers (e.g., the Active Cavity Radiometer Irradiance Monitor (ACRIM)) have shown that it has not been possible to achieve this low level of uncertainty with their technology (Figure 2).

The outstanding benefit will be the eradication of risk to the continuity of data. Presently, should there be any interruption, for whatever reason, to the continuity of TSI data, the 22-year composite of the space-based observations data set (one of the longest space-based reference sets we have) will be irretrievably lost. This will leave unanswered the question of the contribution of solar-induced forcing to the climate for many more decades, until a data set of sufficient time base can be re-established.

2.2 Solar Spectral Irradiance

TRUTHS will make direct measurements of the solar spectral irradiance (SSI) with unprecedented accuracy and wavelength resolution. The 0.0005 to 0.001 μm wavelength resolution of TRUTHS exceeds that of the SOLSPEC Solar Spectrum Measurement instrument and the Solar Radiation and Climate Experiment (SORCE), which have resolutions of a few to tens of nm depending on wavelength. TRUTHS data will help validate spectral variability models and the assumed characteristics of the variability sources. This validation will enable a better understanding of the sources of irradiance variations and thereby a better understanding of the climate system and causes of climate change.

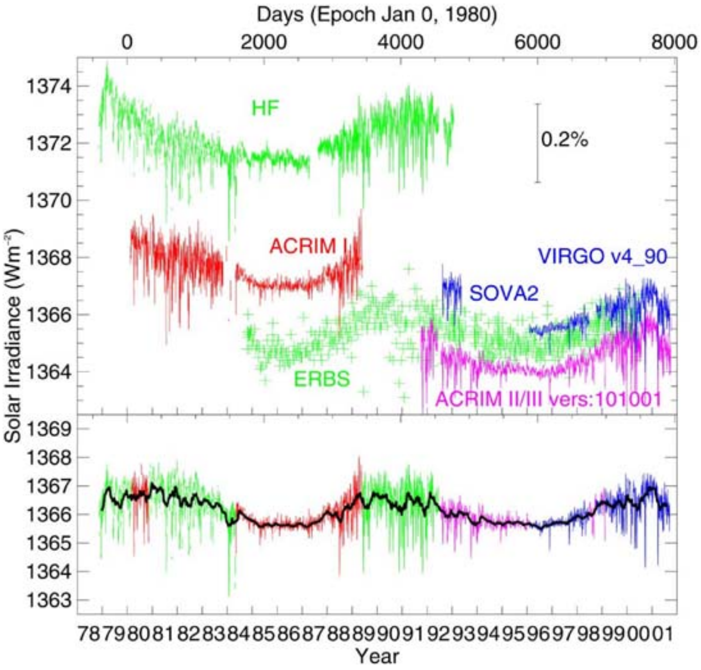

Figure 2. TSI record and its composite. Upper panel: data from measurements of TSI made from satellites showing the systematic biases of the individual missions. Lower panel: composite TSI obtained from the data shown in the upper panel by making adjustments to normalize the absolute levels of successive data-sets. It is the data set used to evaluate the effects of solar variability on the terrestrial climate. Although the two minima 1985/86 and 1996/97 show similar minimal levels, can this really be concluded from the data of the upper panel with any degree of confidence?

Absorption of solar radiation out to 4 μm makes a significant contribution to the atmospheric energy budget, but the lack of benchmark measurements of the Sun have inhibited progress in determining this important climate system parameter. There is controversy[4-8] over the amount of solar radiation absorbed by the Earth's atmosphere in both clear and cloudy skies.

The conclusion from many, but certainly not all, studies is that more absorption occurs than is predicted by models. However, for clear skies there is a divergence of opinion: some[9] consider that there is no evidence for an anomaly while others[6, 8] estimate an absorption anomaly between 4% to in excess of 10%. Much of the earlier work on the clear-sky absorption anomaly was carried out using standard broad-band radiometers. Now, growing attention is being directed towards spectrally-resolved measurements of the near-IR radiation field at the surface with collocated measurements of the atmospheric state and comparisons with model calculations[10, 11]. Previous measurements of the spectrally-resolved solar irradiance have concentrated on the ultra-violet. The near-infrared is quite different: the long-term variability is comparatively small so the absolute radiance level becomes the critical factor. Presently, there is no benchmark for this, which leads to uncertainty in the quantification of the atmospheric absorption of solar radiation. This quantity is one of the most basic parameters determining the nature of the Earth's climate. Since all of the models are based on theoretically-derived spectra, experimental data to validate and or modify the models is essential.

Uncertainty levels of < 1% would provide some benefit, although 0.1 % would give significantly more confidence. TRUTHS will resolve this issue through measurement at a high spectral resolution of 0.001 μm and a high absolute accuracy of 0.1 %. This should be sufficient to meet the needs of current atmospheric models. The complementary missions of SOLSPEC and SORCE will both measure SSI in this spectral region, but neither will achieve the required spectral resolution, being some 10 to 30 times wider than TRUTHS and, at least in the SOLSPEC case, a factor of 50 times lower in accuracy.

3. SCIENTIFIC JUSTIFICATION: THE EARTH AND REFLECTED SOLAR RADIATION

3.1 Earth Observation Data

The processes that take place within the continental biosphere play an important role in climate change and environmental degradation. Traditionally, complex global models have been used to address these issues. These models use a large number of variables and parameters to describe the biophysical and geophysical processes. Surface characteristics in particular directly govern the processes. Therefore, it is critical to describe accurately the surface characteristics if the interaction between the surface and the atmosphere is to be better understood, modelled and predicted, and if we are to take the proper actions to mitigate undesirable effects. When the uncertainties of surface variables are compounded in the models, the extended 'solution space' leads to only moderate to poor accuracy. To ameliorate this situation, independent information has to be applied to control or constrain the models. This information could come from independent ground-based estimates of surface characteristics, but the spatially distributed character of land-surface processes, their large spatial heterogeneity and their highly dynamic character, require remote sensing observations to access the surface characteristics that drive the processes of interest[12]. Indeed, there are growing expectations on the use of Earth observation data to support key decisions by governments and industries concerning the sustainable development of our resources and the good stewardship of our environment. This puts increasing pressure on advanced technologies to deliver information that can be proven to be reliable. The measurements concerned may document small changes in key terrestrial parameters and they may extend over many years. Careful characterisation of the sensor systems used to make these measurements becomes a critical element. One of the most revealing and challenging disciplines concerns the measurement of solar reflected radiation from the Earth's surface.

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 as the independent information for surface characterization, 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 exhibit systematic biases between themselves in spectral radiances of the order of 10 %. 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 3 % or better. This calibration discrepancy is unacceptable and, without a strong, definite, reliable standard to benchmark against, leads to dubious procedures to 'force' one instrument to match the other. 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.

3.2 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[13] and new methodologies continue to evolve.[14, 15] 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.[16, 17] 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.

3.3 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 yield uncertainty estimates approaching the 1.8 % level through the use of improved instrumentation and calibration. TRUTHS will reduce this uncertainty by a more than a factor of ten.

4. 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 prelaunch 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 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 hyperspectral 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 Earth observation sensors in space.

5. TRUTHS INSTRUMENTATION

The TRUTHS satellite comprises a suite of instruments each largely based on existing designs to reduce risk and cost and independently operable (Figure 3). The instruments are being 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. The filter radiometers 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.

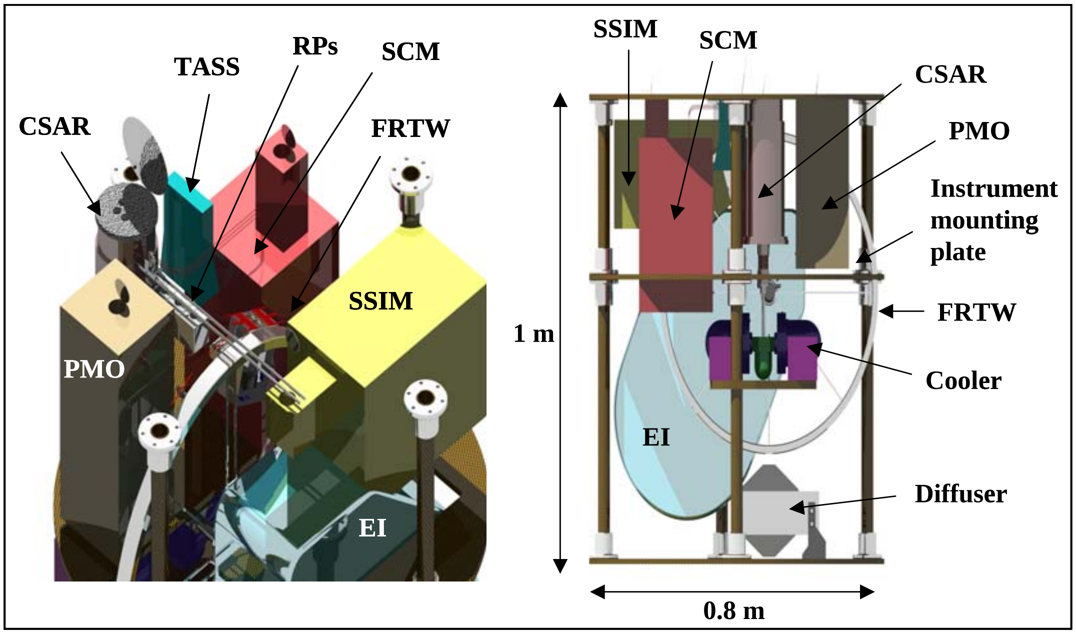

Figure 3. Schematic diagram of TRUTHS instrumentation.

5.1 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.

5.2 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.

5.3 Spectral Calibration Monochromator (SCM)

The purpose of the Spectral Calibration Monochromator (SCM) is to provide monochromatic (0.0005 µm 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.

5.4 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 ESR with an operating principle similar to those described in Section 2.1, 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. 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 (Variability of Solar Irradiance and Gravity Oscillations) on the Solar and Heliospheric Observatory (SOHO) (although with higher accuracy).[18] 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's Physikalisch-Meteorologisches Observatorium Davos (WRC PMOD). These 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.

6. 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.

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.

6.1 Terrestrial Calibration Methodology

The terrestrial calibration methodology typically employed by an NMI such as NPL is shown in the left hand column of Figure 4. 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.

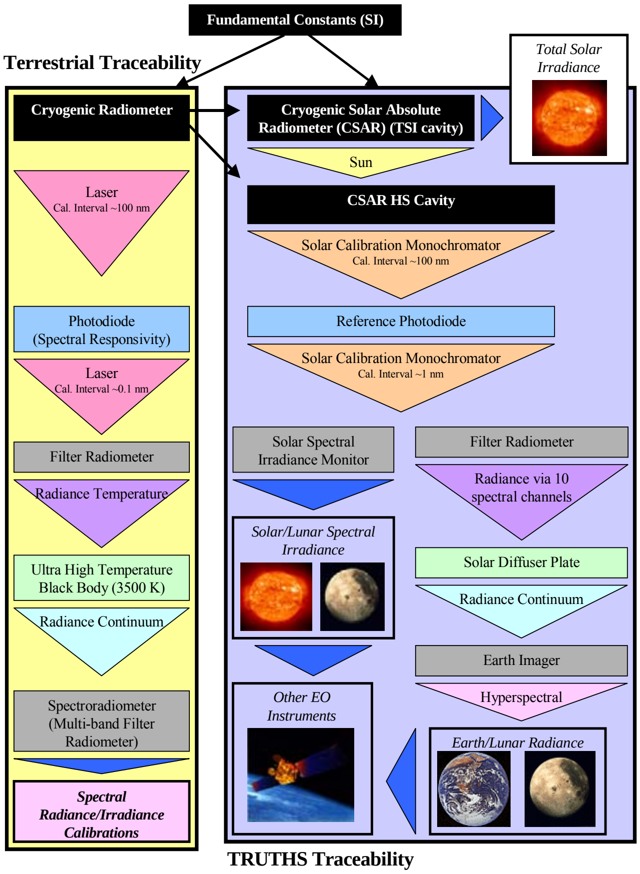

Figure 4. Calibration traceability chain for TRUTHS contrasted with that of an NMI.

6.2 TRUTHS Calibration Methodology.

An analogous calibration procedure is proposed for TRUTHS and is illustrated in the right hand column of Figure 4, 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 (gain and shape) can be routinely measured in-flight using radiation from the SCM traceable to the CSAR, the filter radiometers 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 cryogenic radiometers into their terrestrial calibration chains 15 yrs ago. 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.

7. UTILIZATION

7.1 Central Ground Processing

Each individual TRUTHS instrument will have some level of independent operational control hardware, e.g., movements, detector, integration times, etc. However, the main control software and in-flight data pre-processing will be performed in a central TRUTHS processor. This processor and associated software will control calibration cycles, apply correction coefficients to digital counts from the individual instruments (based on inputs from the ground), apply time stamps to data, control spectral bandwidths (for EI), and provide interface between individual instruments and the on-board data storage (prior to download) and also for ground commands. Downloaded data will be separated into instrument-based data streams. Each stream will have its own ‘housekeeping’ information handled by a data de-multiplexer. Individual data streams will be sent electronically for processing to their respective sites: EI data to the University of Zurich, ambient radiometer data to WRC-PMOD, and all other data to NPL. A central office at a location to be determined, the Reference Test-site Secretariat (RTS), will coordinate network activities, standardised data processing, and archiving and dissemination of data internationally. Coordination of site and mission calibration work will create greater efficiency, reduce costs, and improved synergy. TRUTHS will do this to the benefit of the international Earth observation community and it has been included in the mission specifications.

7.2 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[19]. 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[14, 20].

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 some common instrumentation and standard methodologies.

Ideally, TRUTHS should utilise one or more test sites for each continental region, providing a variety of brighter and darker targets and options for year-round coverage. Initially, five possible ground reference sites have been identified (additional ocean sites will be selected during early mission phases). Four of the five have bright surfaces - only the rangeland site can be considered darker. The five test sites are (with central coordinates in North latitude and East longitude in degrees):

- Railroad Valley Playa (+38.48, -115.66) homogeneous and consisting of compacted clay-rich lacustrine deposits forming a smooth surface compared to most land covers.[14]
- Newell County Rangeland (+50.30, -111.64) flat, grazed rangeland characterised by slowly varying phenology and uniform vegetation cover over large tracts of land.[21, 22]
- Tinga Tingana (-29.00, +139.83) desert consisting of low, light-coloured sand dunes with less than 5 percent vegetative cover.[23]
- Dunhuang (+40.20, +94.43) homogeneous flat region in the Gobi desert with an alluvial surface formed by a mixture of gravel, sand and dust.[24]
- Dome C (-75.00,+123.00) large region characterised by a fine-grained, cold, uniform, and flat snow surface. Its off-axis location around 75 degrees South makes it possible for most if not all polar-orbiting Earth observation satellites to image the site.

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. The Newell County rangeland site is an experimental one that has only recently been studied.[21, 22] Although it is a vegetated target, it has potential as a darker reference surface at visible wavelengths with good spatial uniformity characteristics. The current list of candidate test sites is not an exhaustive one and it suggests that additional test sites are needed to achieve a more global distribution.

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. TRUTHS will add value and in particular provide instrumentation specially calibrated against the NPL primary standard using its UHTBB and NLRF. Field checks will be made using high accuracy transfer standard sources. Thus, uncertainties approaching 0.1% will be achieved for surface spectral reflectances or radiances. Given the current state of the art in such vicarious calibrations, this uncertainty may sound challenging. However, the dominant source of uncertainty is the linkage to SI. It is the direct calibration against primary standards provided by TRUTHS that will reduce this uncertainty.

8. 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 aid in this effort. 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 potentially 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 Earth observation 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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