Accurate radiometry from space: an essential tool for climate studies

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The Earth’s climate is undoubtedly changing; however, the time scale, consequences and causal attribution remain the subject of significant debate and uncertainty. Detection of subtle indicators from a background of natural variability requires measurements over a time base of decades. This places severe demands on the instrumentation used, requiring measurements of sufficient accuracy and sensitivity that can allow reliable judgements to be made decades apart. The International System of Units (SI) and the network of National Metrology Institutes were developed to address such requirements. However, ensuring and maintaining SI traceability of sufficient accuracy in instruments orbiting the Earth presents a significant new challenge to the metrology community. This paper highlights some key measurands and applications driving the uncertainty demand of the climate community in the solar reflective domain, e.g. solar irradiances and reflectances/radiances of the Earth. It discusses how meeting these uncertainties facilitate significant improvement in the forecasting abilities of climate models. After discussing the current state of the art, it describes a new satellite mission, called TRUTHS, which enables, for the first time, high-accuracy SI traceability to be established in orbit. The direct use of a ‘primary standard’ and replication of the terrestrial traceability chain extends the SI into space, in effect realizing a ‘metrology laboratory in space’.

Keywords: climate change; Earth observation; satellites; radiometry; solar irradiance

1. Introduction

(a) Background

Unequivocal attribution of the causes, consequential impact and effective mitigation/adaptation of change in the Earth’s climate is arguably the greatest challenge facing science today. The ‘Kyoto Protocol’ and ‘Copenhagen Accord’

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Figure 1. From IPCC [1], the variance in forecast temperatures of the Earth for emissions scenario A2 for a range of climate models.

exemplify the intense political, scientific and public debate associated with this issue. This is underpinned by the enormous cost implications of policy decisions based on forecasted impacts. However, these forecasts have significant uncertainty, with estimates of global temperature increases ranging from, at best, 2 to 5°C by 2100 (figure 1) [1]. Such a range could be the difference between the need for major new flood defences to prevent large land losses or maintenance/minor updates of the status quo. It is the duty of the science community to reduce this unacceptably large uncertainty in forecasts by finding and delivering the necessary information, with the highest possible confidence, in the shortest possible time.

The Intergovernmental Panel on Climate Change (IPCC) concludes that recent decades have revealed hallmarks of anthropogenic climate change, but the mix of natural variability and anthropogenic effects on decadal time scales is far from fully understood or measured, requiring significant improvements in accuracy [1]. Unequivocal attribution and the quantification of subtle fingerprint indicators are fundamental to our ability to reliably predict the impact and the development of appropriate mitigation/adaptation strategies. The uncertainty in climate prediction lies in the complexity of the models, our inadequate understanding of the Earth system and its feedback mechanisms, and the relatively poor quality of available data against which to test predictions on the necessary decadal time scales [2].

The data needed to benchmark and to test these models must be global in nature and collected over a sufficiently long time base with appropriate uncertainty to enable the identification of ‘change’ in a particular measurand above variance that could be caused by natural or ‘local’ effects. In general, this means that such measurements need to be considered on decadal time scales and collected from satellite-based instrumentation.

Terrestrial networks, collecting in situ data, will always be necessary to provide local validation of global observations and support detailed studies of the Earth system processes, e.g. air quality, carbon and hydrological cycles, etc. However, it is only remote and continuous observation of the Earth system by satellite that the key datasets, the essential climate variables (ECVs) identified by the Global Climate Observing System (GCOS) of the United Nations (http://www.wmo.int/pages/prog/gcos/publications/gcos-138.pdf), can ultimately be adequately addressed. In general, these ECVs (e.g. albedo, cloud cover, chlorophyll, etc.) are not measured directly but are derived from more
fundamental and familiar physical quantities, such as radiance, reflectance, transmittance, etc. The satellite instruments measuring these quantities utilize the full electromagnetic spectrum and in most cases passively, for example making use of the Sun as a source for reflectance/radiance/transmittance measurements.

A community workshop held in the USA in 2007 considered the needs of climate [3–5] and concluded that, in the optical domain, the critical underpinning measurands and the associated uncertainty requirements were:

— total solar irradiance (TSI) 0.01\% \,(k=1);
— solar spectral irradiance (SSI) 0.1\% \,(k=1);
— Earth-reflected solar radiance 0.3\% \,(k=2); and
— Earth-emitted infrared (IR) radiances (expressed in terms of resultant temperature) 0.1\,K \,(k=3).

This, and their priority, was reinforced in the decadal review carried out by the National Research Council of the USA [6].

Note that the uncertainties are expressed at different confidence levels simply to provide more convenient values for communication. It should also be noted here that the temperature of the Earth is expected to rise at the rate of approximately 0.2\,K per decade. National Metrology Institutes (NMIs) rarely disseminate radiation thermometer (spectral radiance) measurement uncertainties in this spectral region at uncertainties less than approximately 0.1\,K.

(b) Earth observation data quality

The advent of the European ‘Global Monitoring of Environment and Security’ (GMES, http://GMES.info) programme and that of the Group on Earth Observation (GEO) ‘Global Earth Observation System of Systems’ (GEOSS, http://www.earthobservations.org/geoss.shtml) have transformed space-based Earth observation (EO). While maintaining the need for scientific endeavour on a ‘best efforts’ basis, the drive for operationally delivered services to meet the needs of society, e.g. disaster monitoring, pollution detection and agriculture, has become a major commercial focus.

Fundamental to these initiatives is the recognition that the data products, services and conclusions arising from them are unlikely to be derived from a single source. They will instead rely upon the synergistic combination of data from all components of the EO sector, space, \textit{in situ} and airborne, in many cases derived from instrumentation developed and operated by different teams, countries and agencies. There are some good examples of how this process has been, and continues to be, successful, e.g. weather prediction. In this example, data assimilation techniques have been developed as a powerful tool to weight the relative contributions of various data sources. However, for many applications, such techniques cannot easily be applied, as the models are inadequate and the source data lack sufficiently reliable ‘quality indicators’ to allow the necessary discrimination and weighting to take place.

Coupling this with the availability of low-cost small satellites, such as those of Surrey Satellite Technology Ltd. (SSTL; http://www.sstl.co.uk/), has led to the emergence of new ‘space nations’ and the launch of privately financed commercial satellites, complementing those of the big space agencies. This rapid
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proliferation of data, data providers and, most importantly, users (or customers) has brought to the fore long-standing concerns over reliability and adequacy of the data’s quality and declared accuracy. Such issues have long since been resolved in conventional terrestrial-based industries through the adoption of rigorous quality assurance (QA) procedures underpinned by traceability to international standards and measures, e.g. the International System of Units (Le Système International d’Unités, SI). Although the space industry adheres to high levels of QA during manufacture of satellites and instrumentation, this is not always rigorously maintained during calibration activities or following launch.

The world’s space agencies have now identified this as a priority issue, which must be addressed if EO and the emerging applications market that it serves are to develop and flourish. However, the nature of space flight, e.g. launch vibration and harsh environment, causes unpredictable drifts in the instrumentation (particularly optical). This is further complicated by the inability, following launch, to regularly recalibrate instrumentation in any traceable manner. Establishing robust traceability in space has been identified as an essential element of any long-term strategy to improve data quality to a level where it fully meets the needs of society (see http://www.ceos.org; http://www.star.nesdis.noaa.gov/smcd/spb/calibration/icvs/GSICS for details and references) [3].

The most critical application area is of course ‘climate change’. Many of the key indicators of climate change require the detection of subtle changes over decades. In the solar-reflective (SR) domain (<2500 nm), this can be at the level of less than 1 per cent per decade, and in the IR 0.2 K per decade [1,5]. Because no existing EO optical sensor comes close to achieving this level of accuracy, strategies have been devised that seek to monitor change by maintaining an overlapping time series of measurements, wherever possible using similar heritage instrumentation. In this way, the often-large instrumental biases can be artificially removed from the data. It is widely recognized that the adoption of such a strategy brings with it an extremely high level of risk:

— any ‘data gap’ destroys the climate record;
— drifts within a mission lifetime are hard to evaluate and remove;
— innovation in technology is difficult to implement;
— reduced operational flexibility;
— requires long-term financial commitments; and
— data reliability and user confidence are poor.

The only robust option to meet the exacting needs of the climate change community and also the emerging operational needs of the EO community as a whole is to ensure that all EO data and derived knowledge information products should be traceable to SI units and have with them an associated uncertainty estimate and/or ‘quality indicator’. Such requirements now pervade the strategy documents and recommendations of organizations such as the CEOS (Committee on Earth Observation Satellites), the GEOSS and the World Meteorological Organization (WMO) and have subsequently been passed down to the space agencies (see http://www.earthobservations.org/geoss.shtml; http://www.ceos.org; http://www.star.nesdis.noaa.gov/smcd/spb/calibration/icvs/GSICS for details and references). Many of these organizations and agencies
recognize not only that the space element needs to have exacting QA associated with it, but also that this must be embedded within the whole validation and data-processing chain. In response to this demand, CEOS has led the development of a new internationally endorsed Quality Assurance Framework for Earth Observation (QA4EO; http://QA4EO.org). This framework and its core principle, i.e.

All data and derived products must have associated with them a Quality Indicator (QI) based on documented quantitative assessment of its traceability to community agreed (ideally tied to SI) reference standards

are now being implemented throughout the world’s space agencies and the WMO. This principle is not revolutionary and is widely practised in most other commercial/academic sectors. In fact, there are many good examples of how this has been implemented in the EO community as well. However, rarely has it been comprehensive or applied in an internationally harmonious manner, making it difficult to identify and assess any differences in results. Therefore, QA4EO provides specific guidance to aid in the implementation and interpretation of the core ‘traceability principle’ (http://QA4EO.org).

Traceability to SI is the key underpinning requirement to enable such a QA infrastructure to function. However, to achieve ‘climate quality data’ also requires significant improvement in accuracy. The necessary improvement in accuracy to meet these requirements is not contained within any of the current planned missions of any space agency, although many have the necessary sensitivity and resolution. In fact, no strategy exists to enable optical-based sensors to establish and maintain traceability to SI in flight with any reliable uncertainty estimate, as required to meet the long-term needs of the EO community, and present sensors are an order of magnitude away from meeting the needs of the climate community. Until recently, it was hoped that NASA would proceed with the development of a mission called CLARREO (Climate Absolute Radiance and Refractivity Observatory; http://clarreo.larc.nasa.gov/) [6,7], which would seek to meet these objectives. However, budgetary reductions in 2011 have effectively put an indefinite delay on the mission at the time of writing this paper.

(c) SI traceability from space

Benchmark measurements of the Earth’s incoming and reflected solar radiances with unprecedented uncertainties (factor 10 improvement) tied robustly to internationally accepted physical standards of the SI in orbit are now time-critical (but achievable) and will allow indicators of decadal climate change and feedback processes (radiative fluxes, clouds, albedo, ocean colour) to be extracted from a background of natural variability. This paper will ultimately describe a small satellite-based mission called TRUTHS (Traceable Radiometry Underpinning Terrestrial- and Helio- Studies; http://www.npl.co.uk/truths) [8], which was first proposed to the European Space Agency (ESA) in 2002 and again in 2010, enabling high-accuracy primary SI-traceable calibration chains to be established directly in orbit for the first time and realizing the concept of a ‘standards laboratory in space’. TRUTHS is complementary to the CLARREO mission in observing the Earth’s reflected solar spectrum, while the CLARREO

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mission adds climate-accuracy SI-traceable observations of the full IR spectrum and global navigation satellite system radio occultation. In addition to collecting its own datasets—spectrally resolved radiances and solar irradiances—TRUTHS will also provide the catalyst (through provision of rigorous cross-calibration from space) to facilitate improvements in the accuracy of current and planned observation systems, enabling them to better meet the demanding challenges emerging from, for example, the new ESA Climate Change Initiative.

In this paper, where appropriate, we will for convenience use TRUTHS as the named example mission, but for many cases it could easily be substituted by CLARREO. In fact, it should be acknowledged that much of the example scientific justification case for the Earth viewing reflected solar spectral observations was largely originally developed by the CLARREO science team [7] and has been adapted for TRUTHS (§2b).

2. Uncertainty drivers for climate

The following sections provide an overview of a few of the key drivers, in terms of uncertainty and SI traceability, for decadal climate studies in the solar-reflective domain. These examples are illustrative of the measurement issues and are by no means comprehensive. Similarly, each example is not intended to be a full treatise on the issues related to the topic under discussion.

(a) Solar irradiance

(i) Introduction

Solar radiation, the driving force of the Earth’s climate, has been observed for many centuries, with quantitative measurements of solar irradiance being made for over 100 years. It is expected that variations in solar irradiance influence the terrestrial climate, but we do not yet fully understand how suspected long-term variations arise or how the climate system actually responds. Monitoring solar variations is therefore crucial, but the continuous record of space-based measurements since 1979, which have revealed solar irradiance variations of a few tenths of one per cent during the 11-year cycle, are as yet inadequate for the detection of long-term variations.

(ii) Instrumental biases

Solar radiative forcing on climate was qualified by the latest IPCC report [1] as ‘very low’ and ‘highly uncertain’. The small magnitude of the forcing is largely based on the satellite record derived over the last three decades. The analysis of the observation data [9] showed that, despite substantial scatter between different instruments (figure 2) [10], following normalization, the variability of the TSI from the minimum to the maximum of the solar activity does not exceed 0.1 per cent or approximately 1.4 W m\(^{-2}\), which translates into a direct radiative forcing of the Earth of approximately 0.25 W m\(^{-2}\). In reviewing the scale of instrumental variation in the non-normalized datasets and subtle differences that can be obtained using differing normalization strategies (figure 2), one is drawn to question the metrological reliability of this approach [11]. Even when accepting the above conclusions (which are probably reasonable), it is clear that, if any

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data gap were to emerge (i.e. failure to have at least two instruments operating in parallel) due to failure of an instrument or launch (as was the case of the recently anticipated GLORY mission of NASA), the full record would in effect be lost, or at best have a significantly increased uncertainty.

(iii) Solar radiometers

The instruments used to measure TSI in space (and on the ground) are all radiometers based on the principle of electrical substitution, comparing the...
heating effect of optical radiation with that of electrical power, which is a concept more than 100 years old [12]. These radiometers were first launched into space in the late 1970s. At a similar time, a group was incorporated by the WMO to form a World Standard Group (WSG) with a mean to be defined as the World Radiometric Reference (WRR) [13]. Similar instruments were also used in the NMIs to establish primary radiometric scales.

Quinn and Martin of the National Physical Laboratory (NPL) made a step change in the performance of this type of instrument through cooling to the temperature of liquid helium [14]. This cooling reduced many of the sources of uncertainty significantly, leading to more than a factor of 50 improvement in accuracy.

The significant benefit of cryogenic radiometry over optical radiometry in general was compounded with the design of a specific instrument optimized for spectral responsivity measurements [15] and its subsequent usage and development in a wide range of applications, as reviewed earlier [16,17]. It is perhaps notable that, although a preliminary design for a cryogenic solar radiometer capable of achieving 0.01 per cent uncertainty has been in existence since the early 1990s [18,19] and widely recommended for flight, to date, none has yet flown in space. The Cryogenic Solar Absolute Radiometer (CSAR) described in §4b(ii) brings the prospect of achieving this a step closer.

(iv) Solar variability on climate time scales

In climate terms, it is also important to note that solar activity during the past 30 years can be considered unusually high. A long-term proxy of solar activity is the solar modulation function, which shows that, in the past 50 years, the solar activity has been remarkably constant and at a 500-year maximum [20,21]. Therefore, we can clearly place no reliance, in terms of climate impact, on this rather short observation time series of 30 years, when we know that the Sun has varied dramatically over the past 400 years, emphasizing the importance of monitoring with sufficient accuracy to detect relatively subtle radiometric, but climatically dramatic, changes.
A notable minimum of solar activity (low sunspot number) occurred in the seventeenth century, e.g. the Maunder (1645–1715) (figure 3). Our estimate correlates well with the ‘Little Ice Age’ in northern Europe, indicating a strong linkage, confirmed by short-term correlations with solar irradiance observed during the 11-year solar cycles [22]. The first half of the twentieth century was characterized by an increase in solar activity, reaching a maximum (in terms of sunspot numbers) in the year 1957. Moreover, after five decades of high, but stable, solar activity, there is now growing evidence for a decline in solar activity in the near future [23,24].

While there is general agreement about how TSI has changed over time, there is scientific controversy about the magnitude. The TSI relative to the Maunder minimum had been determined to range from 0.7 to 6 W m\(^{-2}\) [25]. The obvious conclusion is that, despite considerable progress, we still do not have a reliable, commonly accepted value for the amplitude of the solar forcing. On the other hand, many attempts to simulate past climate changes and define the solar irradiance variability from climate simulations have also failed to give a unique and indisputable answer to the question about solar irradiance variability and its impact on climate.

Further investigations are obviously needed, and from the observational side, the only way is to obtain a very long-term time series (more than 30 years) of the TSI with high precision and absolute uncertainty better than 0.01 per cent. All estimates of the solar influence on the climate will eventually depend on this experimental determination and can only be achieved by robust SI-traceable calibrations.

(v) Solar spectral irradiance

Measurements of TSI as described above can give a good indication of the overall impact on the Earth’s climate, but in reality it is of course the variation in the spectral distribution of radiation within the TSI that controls the detail of the climatic impact. Thus, an accurate estimate of solar radiative forcing requires knowledge not only of changes in the incoming irradiance at the top of the atmosphere but also of the influence of variations in UV on stratospheric temperature and composition [26]. Much larger fractional changes take place at shorter wavelengths than for the integrated visible portion of the spectrum [22]. Variances in solar UV influence the ozone distribution and the heating rates in the stratosphere [26,27] and subsequently affect the radiation propagation to the troposphere in a nonlinear manner, which varies with latitude and season.

A recent analysis by Haigh et al. [28] showed that observed changes in SSI collected by the Spectral Irradiance Monitor (SIM) instrument [29] (more than four times greater reduction in UV between solar maximum and minimum than expected but with an increase (!) in visible radiation) would lead to an overall warming of the planet, when all existing expectations would predict the opposite.

(vi) Summary

Long-term observation of the Sun’s radiation on the Earth, total and spectrally resolved, at uncertainties of 0.01 and 0.1 per cent, respectively, is critical to ensure that we can fully account for the effects of all natural variability when
monitoring climate and the results of any mitigation strategies. This can only be achieved through robust traceability to SI. The uncertainty levels required, which are commensurate with those of primary scales at NMIs, mean that we have to take instruments based on the same concepts as the terrestrial primary standards, i.e. cryogenic radiometry, into orbit. It is long overdue for deployment in space to remove the issues and controversy associated with existing climate datasets. Robust SI-traceable instruments can, in principle, be flown on occasions to provide an anchor for simpler lower-mass instruments, in this way reducing the high risk and cost associated with guaranteeing overlapping missions.

(b) Reducing uncertainty in climate forecasting

(i) Constraining climate models

Currently, there is significant variability between the predictions of different models of the effects and consequences of climate change (figure 1), mainly driven by a factor of 3 uncertainty in climate sensitivity of the equilibrium response of the climate system to a given level of anthropogenic radiative forcing from greenhouse gases, aerosols and surface albedo changes [1]. Climate change feedbacks (processes that amplify or retard the planetary response to a radiative forcing) are the biggest source of uncertainty in the current understanding of climate, and in determining future climate change [30]. The uncertainty in climate feedback directly impacts the uncertainties associated with the projected temperature change [31].

The largest single uncertainty component is the cloud feedback, and particularly the climate feedback from low-level cloud [32]. The second largest feedback uncertainty (though approx. a factor of 2 smaller) is from the combination of water vapour and temperature lapse rate feedbacks [32]. The other major climate forcings are albedo (snow, ice, land cover), aerosols and solar irradiance, all of which have significant modelling uncertainties and therefore need high-accuracy observations to be better constrained. All these forcings require benchmarking for future studies.

(ii) Cloud feedback on climate

Clouds can amplify or counteract global warming; current climate models show a range of amplification values from close to zero to up to 60 per cent [32]. The global distribution and radiative properties of clouds are likely to alter in response to global warming, which could have several different feedbacks on the surface temperature. For instance, during day-time, reduced coverage of low-level cloud would result in less reflection of solar radiation, and increased warming [30]. Thus, detecting a long-term trend against high natural decadal variability needs high-accuracy observations of cloud properties.

Reducing the uncertainty associated with climate prediction by a factor of 2 would require observation stability of 0.5 per cent per decade for visible spectral radiances and 0.3 per cent per decade for broadband SR radiances [33] (approx. a factor of 10 better than is currently achieved). This thus needs high-accuracy spectrally resolved observations with high stability over decadal time scales to test the capability of different climate models in accounting for the various

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cloud feedbacks (also dependent on cloud type). Spectral resolution of 10–20 nm is needed for cloud-phase and cloud-type characterization, for observing the transition zone between cloud and clear sky, and for seeing the effect of aerosol on cloud formation. For reflected solar radiation, the differences between spectral signatures in cloud fraction change and in cloud optical-depth change are very similar. Therefore, sufficient spatial resolution (<500 m) is required to allow cloud masking. A cloud fraction analysis would then allow determination of cloud radiative forcing (CRF) (all-sky minus clear-sky), which is needed for cloud feedback [34]. It would also help in identifying decadal change of all-sky versus clear-sky properties, when an all-sky spectrum change alone might not be sufficiently discriminating.

On a global mean basis, the changes are small but critical: a 1 s.d. of about 0.3 W m\(^{-2}\) K\(^{-1}\) for net and SR CRF. The recent IPCC AR4 report [1] predicts about 0.2 K per decade change for the next few decades, or an order-of-magnitude change of 0.06 W m\(^{-2}\) per decade for SR CRF. Given the global mean value of SR CRF of 50 W m\(^{-2}\), this is a relative uncertainty of approximately 0.12 per cent \((k = 1)\) or 0.25 per cent \((k = 2)\).

The same conclusion can be derived by an alternative (order-of-magnitude) approach. Expected anthropogenic radiative forcing of the climate system is expected to be approximately 0.6 W m\(^{-2}\) per decade for the next few decades [30]. A 25 per cent cloud feedback would amplify or dampen this forcing [30] by approximately 25 per cent, or roughly 0.15 W m\(^{-2}\). This change would be 0.3 per cent of the average SR CRF of 50 W m\(^{-2}\).

(iii) Optimizing uncertainty

Although accuracy requirements derived from expected climate signals are useful, a much more rigorous approach was recently developed by the CLARREO science team [7], which established a model to determine the optimum uncertainty needed from a sensor, taking account of all observational aspects, i.e. instrument drift, sampling, seasonal variation, etc., in order to detect a trend in a climate parameter above a background of natural variability in a given time frame. Of course, there are fundamental limits to the accuracy of measuring climate trends, which can be set with reference to the perfect climate observing system following the methodology of Leroy et al. [35].

Figure 4 presents the results of such an analysis for the CRF example using the proposed operational characteristics of TRUTHS and CLARREO. The details can be found in Wielicki et al. [7].

Figure 4 shows that there is a strong dependence of climate trend accuracy on the TRUTHS calibration accuracy. An accuracy of 0.3 per cent \((k = 2)\) shown as the indicated blue line provides trend accuracy within 20 per cent of a perfect observing system (black line), and time to detect trends within 15 per cent of a perfect system. The upper horizontal red dashed line is the observed signal if the feedback factor was 100 per cent, and the lower green dashed line is for the signal if the CRF feedback effect was at a level of 50 per cent. Such feedbacks, if they exist in the climate system, will amplify climate change, and it is critical to determine from observations if they exist. It is clear from figure 4 that the TRUTHS requirement of 0.3 per cent \((k = 2)\) is optimal. Further improvements
in accuracy are hindered by the limit of natural variability (the perfect observing system, black line), and reduced accuracy rapidly increases the time for society to detect moderate to large cloud feedbacks.

For an accuracy change from 0.3 to 1.2 per cent, the time to detect cloud feedback increases by almost a factor of 2. Society would need to wait an extra decade for accurate climate sensitivity information to facilitate difficult policy decisions concerning the implementation of rigorous and potentially costly mitigation and adaptation strategies. We conclude that a TRUTHS relative accuracy of 0.3 per cent \((k = 2)\) is required to observe decadal changes in cloud feedback. Of course, a similar analysis can be carried out for other climate-sensitive feedbacks.

\((c)\) Establishing SI traceability for the Earth observing system

Although every effort is made to ensure that any pre-flight calibration and characterization of a satellite sensor can be relied upon and is traceable to SI units, when the instrument is operational in orbit, it is well known that for optical
sensors this is rarely if ever the case. The high vibration of launch and sensitivity to contamination of optical coatings and surfaces make some form of post-launch calibration, or at best validation, an essential component of any mission. Some sensors have on-board calibration systems to offer the prospect of direct calibration, but often these are themselves subject to the same sorts of issues as the instruments themselves, particularly in the solar-reflective spectral domain. For the thermal IR, blackbody radiators, which for practical (mass/size) reasons may not have quite as good emissivities as the standards used on the ground, are probably reasonably good at providing some level of in-flight performance monitoring. With effective design, these might be considered to offer a sufficient level of ‘SI traceability’ for operational missions, as they are relatively insensitive to most of the common degradation mechanisms.

However, sensors operating in the solar-reflective domain (<2500 nm) are a very different issue. Here, various on-board approaches have been and are being used, including the flight of relatively fragile ‘standard lamps’. More commonly, diffusers illuminated by solar irradiance to establish a Lambertian radiance ideally capable of filling the sensor field of view are employed. Knowledge of the diffuser reflectance and solar irradiance allows full in-flight calibration. Even in the absence of reliable values for these, if they can be relied upon to be stable, then they can at least monitor and provide a correction for drift. In practice, SSI, although reasonably stable in the short/medium term, is only known to at best a few per cent in an absolute sense. Similarly, diffusers degrade with time, particularly when exposed to sunlight. Effort is of course made to limit exposure, in some cases, e.g. Medium Resolution Imaging Spectrometer (MERIS) of ESA (http://envisat.esa.int/instruments/meris/), using multiple diffusers. These methods have never claimed to be more accurate than a few per cent. Thus, although the best of these are probably adequate for many operational applications, none are really sufficient for the needs of long-term studies such as climate.

All satellite operators use some alternative vicarious method (or often a collection of methods) to attempt to establish some level of confidence in the satellite observations and, if appropriate, on-board calibration systems. These approaches are briefly reviewed below but none at present can come close to the uncertainties needed for climate. However, if they could be validated, and in some cases calibrated, by a sensor in orbit of sufficient accuracy, spectral and spatial resolution, then the uncertainty of these methods could be reduced. This would allow the establishment of an operational global calibration system capable of upgrading the performance of existing sensors (which usually have adequate sensitivity but not accuracy) and of facilitating a ‘global climate observing system’ rigorously tied to SI units. The TRUTHS satellite (http://www.npl.co.uk/truths) described in this paper and its sister CLARREO (http://clarreo.larc.nasa.gov/) are designed for this very purpose.

(i) Vicarious calibration

Post-launch vicarious calibration relies on the use of remote targets that are calibrated or characterized independently of the sensor under test, e.g. Earth targets. Historically, the most commonly used approach has involved specifically identified test sites. Many ‘test sites’ have been identified and
used. Some are characterized by local survey teams, with a few of these now permanently instrumented, providing automated information on their properties to Web-based servers. These form the basis of a potential operational calibration network called Landnet, which follows an earlier concept called GIANTS [36]. Others are too remote to visit directly (e.g. the Moon [37,38] and some North African/Arabian deserts [39]) but instead use regular observations by satellites or ground observing stations to build a database of knowledge of their properties. A catalogue of all test sites has recently been established by the United States Geological Survey (USGS) for CEOS and is accessible through the Cal/Val portal (http://calvalportal.ceos.org/cvp/web/guest), operated by ESA for CEOS and GEO. In the case of optical imaging sensors, such sites (targets) exist for both land and ocean, and a subset has been formally endorsed by CEOS to serve as international reference standards.

Vicarious calibration methods can be used not only to establish absolute values on the radiometric performance of a sensor and relative ‘band-to-band’ performance but also to facilitate sensor-to-sensor bias evaluation, and they are not limited to fixed sites; e.g. the use of Rayleigh scattering over the ocean [39] is also a well-established method.

(ii) Sensor-to-sensor cross-calibration (reference inter-calibration)

The concept of reference inter-calibration in its broadest sense is not new, nor specific to space. In fact, the principle is widely practised and underpins SI traceability and the measurement system as a whole. When reviewed in detail, there can be and are a number of approaches that can be followed to implement it, often bringing slightly different information to aid in analysis, e.g. different spectral characteristics, dynamic range, etc.

In all cases, the instrument under test is presented with a ‘signal’ from a ‘reference standard’, which is similar in characteristic to that which it normally observes. However, a prerequisite is that the appropriate characteristic of the ‘reference standard’ is well characterized/quantified or defined (calibrated) by some independent SI-traceable means, e.g. the test sites mentioned above. For this to be useful, the property of the ‘reference standard’, as observed by the instrument under test, must be sufficiently stable compared to when it was originally calibrated, or at least any change quantified. In the ideal case, the ‘reference standard’ is calibrated at the same time as or close to (approx. ±10 min) the time that it is observed by the instrument under test; this is generally called simultaneous nadir observation. However, for most standard orbits, this does not happen very often, and so pointing of the reference sensor may be necessary, and ideally an orbit chosen that has frequent cross-over opportunities, i.e. a 90° polar precessing orbit.

Of course, the calibration can only be as good as the sensor under test. For example, the reference sensor, e.g. TRUTHS, can only define with high accuracy the radiometric characteristics of the spectral radiation that it observes and is then observable by the sensor under test. If the sensor under test is not well characterized, has unknown or drifting spectral characteristics, limited signal-to-noise ratio capabilities, poor stray light, etc., then TRUTHS is unlikely to provide significant help, other than to provide known values to constrain, test or monitor drift. However, if the sensor is relatively stable,
as most now are, is well characterized pre-flight and only lacks knowledge of radiometric gain and traceability, then TRUTHS will be able not only to validate performance but also to improve the overall accuracy significantly, in some cases bringing them up to the levels needed to make decadal climate quality measurements.

3. A benchmark mission for climate: a metrology institute in space

(a) Introduction

Section 2 has presented an outline science case based on a few example topics highlighting the urgent need to make high-accuracy SI-traceable ‘benchmark’ measurements of the Earth–Sun system. It has alluded to the prospect of satellite missions capable of fulfilling that role, e.g. TRUTHS and CLARREO. This section will introduce one of these missions, TRUTHS, and its unique in-flight calibration strategy.

The overall concept of TRUTHS can be summarized as:

a mission to measure, SI-traceably and with an unprecedented accuracy, the interaction of solar radiation with the Earth as a benchmark reference to enable the detection of decadal climate change.

TRUTHS will also enhance the performance and traceability of other EO systems to deliver additional societal benefits, and, in some cases, ‘climate quality’ data products, from existing instruments.

TRUTHS will achieve this objective using two independent but complementary methodologies:

— direct sampling of key climate-specific fingerprint signatures as baselines from which future change can be detected;
— facilitating performance improvements in other observing systems, satellites and others, to enable them to collect better ‘climate quality’ data through reference inter-calibrations.

These objectives drive the specification of the mission and, although there is a wide range of potential observables, the overall mission driving characteristics—instrument and platform—can be relatively easily defined. While demanding high performance and, in some cases, adaptations, the requirements are not pushing technology beyond the established and already proven state of the art for space instrumentation. Thus, this paper will not dwell on the details of the instrumentation, but will only seek to highlight any key characteristics to aid the reader to understand the concepts.

The key to the mission’s success lies not in the complexity or novelty of its observational instruments, nor in the platform, but in the innovative in-flight calibration system and the effective transfer of state-of-the-art terrestrial primary calibration and SI traceability methodologies into space. The TRUTHS mission will fly the radiometric capability of a national measurement institute into space. In this way, it will be able to act like a calibration or ‘standards laboratory in space’—TRUTHS will be SI traceable by design.

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The key challenge to this mission and thus one where we will concentrate our efforts in terms of explanation is the ability to achieve SI traceability at uncertainty levels a factor of 10 below what has been achieved to date. We will seek to show how this step change is not in practice as radical as it might initially appear, but rather the result of simply taking the calibration chain directly into orbit. In fact, when the methodology that will be described here was first introduced into national standards laboratories, some 25 years ago, a similar step change of more than a factor of 10 was also achieved. It is worth noting that this goal to achieve high SI-traceable accuracy is also being pursued in the USA by NASA for the complementary mission CLARREO, although the technical approach they are pursuing to achieve this is very different. In the CLARREO case, the IR traceability aspects of the mission mimic the traceability routes of national standards laboratories, with the onboard reference standard being a gallium melting point blackbody. The SR route differs significantly and relies on some key measurements from other missions. Ideally, both missions and all their components would fly simultaneously, allowing the establishment of a climate and calibration constellation and some inter-calibrations at very high accuracy. However, a minimal partnership would see the combination of IR elements from CLARREO and SR from TRUTHS.

TRUTHS is implemented through a small agile satellite platform with two perpendicular observation axes—Solar and Earth viewing (figures 5 and 6). The majority of observation time is allocated to global nadir spectrally and spatially resolved measurements of Earth-reflected solar radiation for decadal
climate change benchmarking. A nominal 5–10 min per day is allocated to solar observations (total and spectrally resolved). In addition, the agile platform enables:

— near-simultaneous angularly co-aligned observations for sensor reference calibrations;
— multi-angular measurements of specific targets for reference inter-calibration of sensors (surface and Moon); and
— multi-angular measurements of specific targets to support ‘process studies’.

The very high radiometric accuracy required by TRUTHS means that it seeks to be largely self-reliant in most of its key measurands and thus includes the instrumentation required to provide the information to retrieve the atmospheric parameters (e.g. aerosols, water vapour) required to account for radiation propagation losses in the atmosphere.

(b) Requirements

Table 1 provides a summary of the driving requirements for a benchmark decadal climate mission. For reference calibration, the spatial requirement is driven by the sensors targeted for calibration. Most climate-focused sensors have relatively large spatial footprints, as the objective is generally global-averaged measurements rather than local, while, increasingly, many operational satellites have relatively high spatial resolution of a few tens of metres or less. This suggests that the emphasis should be on high spatial resolution provided it does not compromise the other measurements.
Table 1. Characteristics of the key measurands needed to meet the needs of decadal climate studies. Note that the Earth/Moon radiance also represents the requirements needed to provide reference calibration to other EO systems.

<table>
<thead>
<tr>
<th>key parameters</th>
<th>spectral range (μm)</th>
<th>spectral resolution (nm)</th>
<th>spatial resolution (m)</th>
<th>estimated accuracy 2σ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSI</td>
<td>0.2–30</td>
<td>total</td>
<td>n.a.</td>
<td>0.02</td>
</tr>
<tr>
<td>SSI</td>
<td>0.2–2.5</td>
<td>0.5–1</td>
<td>n.a.</td>
<td>0.2</td>
</tr>
<tr>
<td>Earth/Moon radiance</td>
<td>0.32–2.45</td>
<td>4–10</td>
<td>&lt;500</td>
<td>0.3</td>
</tr>
</tbody>
</table>

(c) Scientific payload

Three separate instruments on-board TRUTHS deliver the above science objectives. In some cases, more details are provided later, but to provide an overview of the mission concept, they will be briefly introduced here.

(i) TSI (0.2–30μm)

Measurement is provided by an instrument called CSAR. In essence, this instrument has a similar operational principle to those already used to measure TSI in space, e.g. PMOD VI on-board VIRGO, TIM on SORCE, etc., and as described in §2a(iii). The CSAR compares the heating effect of optical power with that of electrical power. However, CSAR, through cooling to cryogenic temperatures of approximately 20 K, reduces uncertainty by more than 10 times over the typical ambient instrument. It is also the same operating principle as that used at the NMIs for establishing primary radiometric scales.

(ii) SSI (0.2–2.5μm)

This is measured on TRUTHS by the Solar Spectral Irradiance Monitor (SSIM). In simple terms, this instrument consists of a spectrally dispersing element to enable solar radiation to be dispersed onto a detector, e.g. a linear array detector. In our baseline concept, the SSIM consists of two gratings and two array detectors to enable simultaneous collection of spectrally resolved solar irradiance and operates in a passive staring mode, removing any movements. The exact design of this instrument can take many forms, including a spectrally scanned system, but all aspects can be delivered by heritage components and concepts and contain no significant risk. There are many examples of such instruments used in space and on the ground for similar spectral irradiance-based measurements.

(iii) Earth spectral radiance (0.32–2.45μm)

This is measured on TRUTHS by an imaging spectrometer baselined to be an upgrade of the ESA aircraft imager APEX (http://www.apex-esa.org/), but again could be based on many other existing designs and instruments. Our instrument uses prisms to disperse the radiation and provides the opportunity

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for full continuous spectral sampling of a scene. This Earth imager (EI) samples the Earth, in our case, at 40 m GIFOV (geometric instantaneous field of view) and with a swath of 40 km, driven by the availability of existing detector technologies. In normal operational mode, it views the Earth at nadir but can be rotated by the spacecraft to make observations at multiple angles. It can provide in-flight switchable spectrally resolved radiances at bandwidths from approximately 1 nm, but normally these will be integrated to around 10 nm. The EI is designed to have a low sensitivity to polarization but contains a means to check and quantify this in orbit. The number of spectral bands and spatial resolution transmitted to the Earth is changeable in flight to maximize the trade-off between ‘useful information’ and data transfer rates. For example, high spectral and spatial information is useful over land, but less so over the ocean or cloud, where coarser spatial resolutions are more than adequate; and similarly, other than in a few specific spectral bands, high spectral resolution is also unnecessary. However, even when optimizing these observational criteria, we anticipate a data collection of some 4500 Gbits d\(^{-1}\).

(d) Satellite platform

The instruments described above form the key science payload and are mounted on a small agile pointable satellite platform in a 90° precessing polar orbit (see schematic configuration in figure 6). The payload is configured so that the entrance ports of the solar instruments, CSAR and SSIM, are on one axis and the EI is perpendicular to them. Operationally, the satellite will alter its orientation so that the solar instruments have approximately 5 min observing time per day. For the remainder, the satellite will point the EI to the Earth, largely at nadir but also occasionally (per orbit) off-nadir to co-locate with another sensor (to provide a calibration) or to make angular measurements on specific targets.

The total payload mass for a fully redundant system is approximately 160 kg and the peak power requirement is less than 200 W.

(e) The ‘in-flight calibration system’

This is the key technological innovation within TRUTHS and is designed to enable direct traceability to an SI primary standard in orbit at unprecedented uncertainties. This calibration system again consists of three instruments, although one is common to the science payload. The heart of the calibration system is the primary standard. In TRUTHS, this is the CSAR outlined above and described in detail in §4b(ii), and the key operational principle is the same as for TSI measurements. However, when performing as the primary standard, we need in this case to measure the power of monochromatic radiation and not of TSI. The spectrally dispersed radiation is significantly lower in power than direct sunlight and so for these measurements a cavity with higher (approx. 100 \times) sensitivity has been incorporated into the CSAR and serves as the primary SI standard, able to measure the power in a monochromatic beam of radiation with an uncertainty of less than 0.1 per cent.

Once the power of the monochromatic beam of radiation is determined, it can be used as a known input to provide calibrations and traceability to other optical instruments. For example, it could be used as an input to SSIM instead of the Sun, allowing an absolute calibration of the instrument at any or each wavelength.
In practice, this is carried out on TRUTHS through an intermediate instrument called a polarizing transfer radiometer (PTR; see §4f), which in turn also provides the calibration to the EI (see §3c(iii)).

The source of the spectrally dispersed solar radiation on TRUTHS is the spectral calibration monochromator (SCM; see §4c). This instrument disperses incident solar radiation using (in our baseline) a diffraction grating. The SCM includes an optical fibre delivery system as a single integrated instrument. In use, the CSAR and other instruments measure the output power of the optical fibre bundle that is translated between them.

The final instrument in the TRUTHS calibration system is the PTR. This instrument is relatively simple in nature and provides the means to act as a short-term secondary standard to minimize measurement time with the CSAR and also to provide calibrations of the EI. The PTR is a transfer detector including both broadband and spectrally filtered detectors. Monochromatic radiation from the SCM can enter the PTR and provide spectral calibration of non-filtered photodiodes traceable to CSAR.

In a secondary step, the output of the SCM can be measured by these detectors in the PTR before being used to calibrate the SSIM. In a similar way, the filtered detectors of the PTR can be calibrated across their spectral bandpass using radiation from the SCM. The PTR is mounted on a small simple rotation device, which can rotate the PTR so that it views towards the Earth viewing axis and measures the radiance in spectral bands of a reference source—a solar diffuser and/or the Moon or Earth reference site. The source is simultaneously viewed by the EI to provide full SI traceability to that instrument.

In TRUTHS, the PTR has been configured to serve a secondary purpose, as it will also be able to measure s and p polarizations separately. In this way, the PTR can also provide information on the state of the atmosphere, particularly aerosol optical depth, for atmospheric correction. TRUTHS has two PTRs for redundancy.

The above calibration system mimics that used terrestrially in NMIs, with the exception that, instead of the SCM as a source of tunable radiation, on the ground, tunable laser sources are generally used. In addition, it is more convenient to use a high-temperature blackbody as an artificial source of continuum radiation rather than the Sun. The traceability chain is described in more detail in §4.

4. Radiometric calibration of an optical sensor

(a) Traceability chain

A typical radiometric traceability chain from an NMI can be described schematically by the left-hand panel in figure 7.

— The primary standard, the cryogenic radiometer, establishes a scale of spectral responsivity, through the calibration of a photodiode. The cryogenic radiometer first measures the radiant power in a monochromatic beam; in this case a fixed-wavelength laser, e.g. argon ion, can be used. Uncertainties of less than 0.005 per cent can be achieved in this way [15].
— The now calibrated monochromatic beam is then used to illuminate a photodiode and thus determine its spectral response. This process
Figure 7. Calibration traceability chain for TRUTHS (right) contrasted with that of the typical terrestrial traceability of an NMI (left).

is repeated at sufficient wavelength intervals (usually 0.05–0.1 m) 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, FRs) using a similar monochromatic beam of radiation but making measurements at much finer spectral intervals using
Accurate radiometry from space

A tunable laser, e.g. a titanium sapphire. The FR can have narrow or broad spectral response functions, e.g. 0.001\(\mu\)m for a monochromator-based instrument or 0.01\(\mu\)m for one based on coloured glasses [40].

— The calibrated FRs are then used to measure directly the spectral irradiance or radiance of conventional polychromatic sources such as lamps [41–43]. Often, the Planckian radiation of an intermediate, ultra-high-temperature (3500K) blackbody (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.

The monochromatic source used for this traceability chain is typically a laser. Lasers provide high radiant power and monochromaticity of easily measured and potentially tunable wavelength, and are optically well defined and controllable. However, they are not very portable and require significant power for operation and thus are not suitable for space flight.

This traceability chain is quite simple and can allow spectral radiance measurements to be made with uncertainties less than 0.05 per cent. In principle, this traceability chain and its resultant uncertainty can be used to calibrate an instrument bound for space. In practice, this is rarely carried out using this primary stage of the traceability chain and thus to this level of uncertainty, because of additional challenges that have to be faced, e.g. the physical size of the sensor, level of ‘cleanliness’ and need for vacuum operation. However, the readiness to accept this increased uncertainty is underpinned by the acknowledgement that any laboratory calibration uncertainty is unlikely to be maintained in space and thus achieving an uncertainty of a few per cent pre-launch, while still very challenging, is usually set as the target. This uncertainty level allows additional steps and thus uncertainty to be added to the traceability chain to accommodate the challenges described above. For example, large-aperture integrating sphere sources can be built to fill the aperture of the sensor under test but considerable effort is required to make them spatially uniform; windows can be used on vacuum tanks but these need to have a known transmittance and are a source of inter-reflections and stray light.

It should however be noted that the drive for improved pre-flight accuracy is leading to new efforts at NMIs to reduce the length of the traceability chain and adapt the primary methodologies so that they can be more easily transported to the calibration facilities: vacuum tanks and clean rooms, located at sensor manufacturers (http://www.emceoc.org).

However, of greater potential interest is the realization that this complete traceability chain can actually be replicated directly on-board a satellite in space, allowing similar uncertainties to be achieved, tied robustly to SI. This space-based traceability chain is described in the right-hand column of figure 7 and is the heart of the TRUTHS satellite.

The major difference between the two traceability chains is that in TRUTHS the monochromatic radiation is not from a laser but instead is spectrally dispersed solar radiation from a monochromator, the SCM. Lasers are too large and power hungry for space applications, at least where multiple wavelengths are required. Only short-term stability (<1 min) of the radiation from the SCM is required. Any
long-term degradation of the SCM optics is calibrated out each time it is used, as the output beam power from the optical fibre delivery system is referenced to the on-board primary standard cryogenic radiometer, the CSAR.

Similarly, the spectral radiance response of the Earth viewing imager (EI) is calibrated in orbit through the measurement of solar irradiance reflected from a solar-illuminated diffuser plate instead of a high-temperature blackbody. This procedure is in common use, e.g. by MERIS (http://envisat.esa.int/instruments/meris/). However, in contrast to other EO missions, the spectral radiance of this system is measured directly in orbit using a group of FRs contained within the PTR 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 FRs (gain and shape) can be routinely measured in flight using radiation from the SCM traceable to the CSAR. The PTR can be rotated between the calibration plane and the EI by means of a simple rotation device (figure 5). The resultant uncertainty in this process is dominated by the signal-to-noise ratio caused by the relatively low power emitted through the SCM. As the CSAR itself has an uncertainty of less than 0.01 per cent, the overall uncertainty is likely to be less than 0.1 per cent in radiance, more than an order of magnitude better than any other EO mission. Although this may seem optimistic to the relatively conservative space instrumentation community, 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 nearly 30 years ago [15–17].

The in-flight calibration procedure described above does not of course reduce the need for normal detailed pre-flight characterization of the sensor 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 uncertainty that the TRUTHS calibration methodology addresses, through the regular recalibration, ‘in flight’, of its instrumentation against an essentially electrical, as opposed to optical, standard.

Some of the critical elements of this traceability chain will be described below, highlighting and contrasting differences between the terrestrial and space equivalent versions where appropriate.

(b) Primary radiometric standard: cryogenic radiometer

(i) Terrestrial primary standard

Most NMIs have adopted the cryogenic radiometer as the primary standard for all optical radiation measurement quantities [16,17,44,45]. The cryogenic radiometer is an extension of the concepts of the electrical substitution radiometer (ESR), summarized in §2a(iii) [14,16], which were independently developed by the metrologists Ångström [46] and Kurlbaum [47]. Cooling the technology to cryogenic temperatures (<30K) reduces uncertainty levels to less than 0.01 per cent (95% confidence) as first shown by NPL in the 1980s [14] due primarily to better equivalence between electrical and optical power and the ability to build a large cavity to absorb optical radiation while maintaining a reasonable sensitivity.
Accurate radiometry from space

Cryogenic radiometers are now the primary standard of choice for NMIs. Different designs and operators have been compared showing equivalence less than 0.02 per cent, generally limited by the transfer standards used in the comparisons [44,48,49]. The use of a mechanical cooling engine instead of the need for liquid cryogens made possible the practical possibility of flying such an instrument into space [18,19]. It subsequently resulted in a terrestrial version, which has formed the basis of the NPL primary radiometric scales for the last 15 years and has been commercially exploited for use in other NMIs around the world [50].

(ii) Space-based primary standard—CSAR

The space-based radiometer follows exactly the same principles as that for the ground. As both are already required to operate in vacuum, the principle differences relate to adaptation for vibration, redundancy and the specific operational characteristics required for the space application, e.g. different power levels and irradiance. Its configuration for space flight is shown in figure 8, where the radiometer head is attached to the cooling system by a flexible connector to aid configuration on the spacecraft platform. This cooling system is shown here consisting of two Astrium 10K coolers (http://www.astrium.eads.net/en/equipment/ 10-k-stirling-cycle-cooler.) for redundancy, but only one is needed and used during operation.

Figure 8. Representation of the CSAR. The radiometer head sits on the twin cooler cold platform via a flexible cooling link. Note that the orientation and location of the radiometer head with respect to the cold platform is fully open. (Online version in colour.)
TRUTHS will have a cryogenic radiometer (CSAR) with two different types of cavity shown schematically in figure 9. The high-power cavities will measure TSI directly. As the TSI cavities are optimized to measure power levels close to 30 mW, they do not have sufficient dynamic range to measure the relatively low-intensity monochromatic radiation from the SCM. This is done instead using high-sensitivity cavities (optimized for 10 μW to 1 mW), which serve as the primary references and provide traceability to SI for all the other instruments on TRUTHS: SSIM, EI and PTR.

The cavity absorptances are approximately 0.99998 and spectrally flat, allowing measurements in any spectral band. The only additional source of error in the space environment, which is different from those on Earth, is potential degradation of the cavity. But with such high absorptance, considerable degradation would be required before any change would be observed and have impact on the overall uncertainty, particularly for applications where it is used as a primary standard for other instruments. CSAR will minimize any residual sensitivity to this degradation by providing four primary cavities for TSI measurements operated in an exposure time-limited sequence. It will have two high-sensitivity cavities to ensure redundancy. A small (approx. 0.8 mm) aperture will be used to allow direct comparison between the two types of cavity in orbit. This aperture, positioned in front of each type of cavity in turn, will bring the detected solar power down to a level within the dynamic range of both cavities. The absolute area of this small aperture does not need to be known as it will be common and only relative measurements are required.

For traceability of irradiance (units: W m$^{-2}$), a defined detector area is also required. The TRUTHS CSAR will have five reference apertures, any one of which can be used with any of the cavities. The aperture areas will be calibrated traceably to the metre on the ground, and then cross-compared in the space environment (in an exposure time-limited sequence), using either direct solar or monochromatic radiation from on-board the spacecraft. The uncertainty planned for TRUTHS (for TSI) is less than 0.02 per cent ($k = 2$) and as a primary standard...
Table 2. Estimated uncertainty budget of CSAR.

<table>
<thead>
<tr>
<th>source of uncertainty</th>
<th>spectral–VIS uncertainty (k = 2) (%)</th>
<th>spectral–UV and IR uncertainty (k = 2) (%)</th>
<th>total solar irradiance uncertainty (k = 2) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>measurement of electrical power</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>area of defining aperture</td>
<td>0.010</td>
<td>0.010</td>
<td>0.008</td>
</tr>
<tr>
<td>cavity absorptance</td>
<td>0.010</td>
<td>0.010</td>
<td>0.004</td>
</tr>
<tr>
<td>diffraction correction</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.020</td>
</tr>
<tr>
<td>scattered light</td>
<td>0.006</td>
<td>0.006</td>
<td>0.004</td>
</tr>
<tr>
<td>random noise</td>
<td>0.010</td>
<td>0.020</td>
<td>0.002</td>
</tr>
<tr>
<td>total</td>
<td>0.03</td>
<td>0.04</td>
<td>0.024</td>
</tr>
</tbody>
</table>

less than 0.2 per cent (although we anticipate significantly better; table 2), a factor of 10 less stringent than that already proven on the ground, for TSI [51,52,53] and for spectral responsivity [16,17].

The full performance characteristics of CSAR, which is the heart of the TRUTHS concept, is currently being tested on the ground for terrestrial measurements of TSI. A fully working terrestrial CSAR has been manufactured and used to make comparisons against the WSG [54]—the group of (ambient-temperature) electrical substitution radiometers that maintain the WRR [13]. The terrestrial CSAR was designed to fully meet the requirements of TRUTHS and can largely be considered an engineering model of the space application [54]. Only the TSI cavities are required for the WRR comparison, but the instrument has been built to include also the high-sensitivity (SI traceability) cavities as well. Further, the instrument has been built to space standards (e.g. with space-compatible materials, with a design able to withstand launch vibrations and accelerations). The instrument design specification is also based around the relatively limited cooling power available from space refrigerators, although terrestrially it is being used with a non-space cooler and so effort has been made to degrade the effective performance of this cooler so that it can truly replicate space operational conditions. On the ground it also has to operate in a vacuum enclosure.

(c) Source of monochromatic radiation on TRUTHS

Monochromatic radiation is provided on TRUTHS by the SCM. This instrument disperses solar radiation using (in our baseline concept) a grating. We have chosen to use three monochromators, each optimized for different spectral regions, stacked together with a common drive shaft. Spectrally dispersed radiation from each grating (monochromator) is then coupled into an optical fibre bundle, which, through arrangement of the fibres, converts radiation from a rectangular slit into a circle that can then be imaged into a near-collimated beam using a lens. This fibre can be translated along an optical axis without significant change to its bending radius and thus throughput. The SCM together with the optical fibre delivery system should be considered as a single integrated instrument. The output of the optical fibre bundle is measured by the CSAR and used to calibrate the other instruments.
Figure 10. Spectral radiant power transmitted through SCM and fibre (through SCM in 0.5 nm bandwidth). (Online version in colour.)

In the short time scale between measurement of the SCM by CSAR and its use with another instrument (<60 s) there is no significant change in the output of the Sun, so the power will be constant. However, as the mission progresses, the throughput of the SCM, including the optical fibre, is likely to deteriorate, but this degradation will be calibrated out every time it is used. The anticipated signal of the SCM can be seen in figure 10.

(d) Transfer radiometers in standards laboratories

In NMIs, the cryogenic radiometer is used to calibrate the spectral responsivity of a solid-state transfer detector, e.g. a silicon photodiode. Solid-state transfer devices have a faster response than a cryogenic radiometer and can therefore be used over a wider spectral range more quickly. Also, it is easy to add an aperture (or apertures) to a transfer detector and therefore convert from power responsivity to irradiance or radiance responsivity and they are highly portable. On TRUTHS, the PTR will be used for the same reasons—a faster method of achieving full spectral coverage, to convert from power to irradiance and radiance responsivity, and to transfer from the solar viewing axis to the Earth viewing axis of the satellite.

An ideal transfer standard should:

— be spectrally predictable (so that calibrations at a few wavelengths can provide full spectral coverage),
— be stable between calibration and use,
— possess good linearity and uniformity, and
— be insensitive to geometrical changes (e.g. the addition of an aperture should not change the power responsivity).

The most commonly used transfer standard (for the important spectral region 300–900 nm) is the silicon trap detector [55,56]. Over this spectral region, it was shown [55,56] that the internal quantum efficiency of certain types of photodiode is near unity and therefore the intrinsic responsivity is directly proportional to wavelength. The reduction from unity for the external quantum efficiency is almost entirely due to specular reflectance. Therefore, by arranging silicon photodiodes in a ‘trap’ configuration (where the light specularly reflected from one photodiode reaches the next) and combining the output currents, a device
with predictable spectral responsivity directly proportional to the wavelength can be obtained. The spectral responsivity of trap detectors in the spectrally linear region can be predicted without calibration to within 0.05 per cent, and this performance (across the full spectral range) can be improved to 0.01 per cent by calibration against a cryogenic radiometer at a handful of wavelengths [55].

In the IR region, photodiodes have not performed well in a trap configuration [57] (radiometric uncertainties approx. 0.3%), primarily due to poor (low) shunt resistance, small size and spatial non-uniformity of their internal quantum efficiency. Therefore, alternative detectors have been developed using integrating spheres [58–60].

With a silicon trap detector, only a very small number of calibration wavelengths are required, as the relative spectral responsivity is predictable. With sphere detectors, more calibration wavelengths are needed to account for the potential spectral reflectance changes of the sphere. However, with a smoothly varying sphere reflectance and smoothly varying spectral responsivity of the detector (as in the case with the TRUTHS PTR), interpolations can still be performed between relatively widely spaced spectral calibrations.

\( e \) Filter radiometers in standards laboratories

Cryogenic radiometers are, by requirement and design, ‘black’ (they absorb radiation in a spectrally unselective manner). Solid-state transfer detectors, while not ‘black’, also respond over a wide spectral region. In order to obtain spectral information, it is necessary to introduce wavelength selectivity. By combining photodiodes with spectrally selective filters (and apertures: one, for irradiance, or two, for radiance), a device known as an FR is created. FRs are key instruments at any NMI in the measurement of spectral radiance or irradiance. FRs can have broadband filters (for example, to mimic the human eye response curve—a photometer) or narrowband filters. The latter are already in common usage as the basis for many space imagers.

A set of FRs with different central wavelengths and appropriately narrow bandwidths (approx. 10–20 nm) can be used to measure the spectral radiance or irradiance of a smoothly varying source of optical radiation directly. This is used to realize the primary spectral irradiance scale of several NMIs [41–43], where, for example, the irradiance of a tungsten lamp is determined at the wavelengths of the interference filters and then interpolated in the intermediate region using an appropriate smoothly varying model of the lamp’s spectral irradiance.

Other NMIs, including NPL, Physikalisch-Technische Bundesanstalt (PTB) and the National Institute of Standards and Technology (NIST), use FRs to determine the thermodynamic temperature of a blackbody as the basis of their (more accurate) spectral irradiance scales [61]. Because the blackbody’s spectral radiance can be entirely described by its temperature (through Planck’s law), a single FR reading is sufficient to determine the entire spectrum. In the early 1990s, NPL pioneered the absolute radiometric measurement of blackbody temperature (filter radiometry) with measurements of the transition temperature of fixed-point blackbodies (the freezing temperature of metals at around 1000°C) and measured the radiance of these blackbodies with uncertainties of 0.06 per cent \((k = 2)\) [62]. Today, the radiometry and thermometry communities are using the same techniques to calibrate novel high-temperature fixed points as references for
Figure 11. Schematic of NPL’s FR calibration facility. (Online version in colour.)

high temperature measurement (approx. 3000°C). Radiometric uncertainties of 0.1 per cent (95% confidence) in the measurement of blackbody radiance are now relatively straightforward [63,64].

FRs can be calibrated in power mode (under-filled), in irradiance mode (with a single aperture over-filled) or in radiance mode (imaging within a large uniform source). In all cases this is done with a monochromatic source. For broadband FRs, such a source can be obtained using a lamp-illuminated monochromator. For higher stability, stronger signal and better wavelength definition, a laser-based source can be used (figure 11). Such a source can be obtained by illuminating a small integrating sphere with a tunable laser, fed through a vibrating fibre to remove speckle [40,65]. Traceability to SI comes via the trap detector, which is itself calibrated for spectral power responsivity against the cryogenic radiometer. An aperture is added to the trap to convert this from power responsivity to irradiance responsivity.

Pre-flight calibration of any instrument, including those intended for space, can also be carried out using this approach.

(f) Transfer radiometers on TRUTHS

The TRUTHS PTR (figure 12) combines the functions of the transfer radiometer and FR used at NMIs to transfer traceability from a primary standard to a measurement instrument. In essence, we describe here a PTR that consists of an integrating sphere to ensure uniform and spatially insensitive collection of optical radiation from a range of sources, and a small group of solid-state detectors, some spectrally filtered, to defined bandpasses that can view the
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Figure 12. Conceptual design of PTR. (Online version in colour.)

radiance of the internal sphere walls. The PTR (figure 12) is mounted on a simple rotation device, which can rotate the PTR so that it views towards the Sun or Earth viewing axis, thus providing traceability from the CSAR to the EI (figure 5).

When viewing a small (point) source, the instrument acts as an irradiance mode sphere-based transfer detector. The silicon (200–1100 nm) and InGaAs (1000–2500 nm) detectors provide full spectral coverage as intermediate reference detectors to allow detailed spectral interpolation between more widely spaced calibration points made with the CSAR. The instrument (entirely under-filled in power responsivity mode and with the internal aperture over-filled in irradiance responsivity mode) provides the fast, spectrally smooth, portable detector needed to transfer traceability from the CSAR to the other instruments.

The PTR (figure 12) consists of a housing of two apertures—a polarizing beam splitter and two spheres (each illuminated by a different polarization state). The detectors are mounted on a thermo-electrically cooled housing block that sits on the sphere and views the sphere wall, well away from the input port or the first reflection. The Si and InGaAs detectors have smoothly varying spectral responsivities and the reflectance of the sphere (and transmittance of the beam splitter) is also smoothly varying spectrally. This means that the power (under-filled) responsivity of the instrument can be calibrated at a few wavelengths against the cryogenic radiometer using the SCM. For calibration transfer, the instrument can also be calibrated in irradiance mode by over-filling the second aperture. These solid-state reference detectors are then used to transfer the calibration to the SSIM through a similar process, but in this case between the PTR and the SSIM.

The PTR is also an FR. In addition to the unfiltered solid-state detectors, a number of spectrally filtered detectors are also mounted in the temperature-controlled block. In this case, the PTR can effectively use the SCM to
self-calibrate between the reference detectors and FRs, as both see the same radiation. The SCM only needs to spectrally tune over the bandwidth of each FR and its response compared with that of the reference photodiode.

The PTR can then rotate between the solar axis (its self-calibration mode) and the Earth viewing axis: see figure 5, where it can view sunlight diffusely reflected from a diffuser plate, which can be deployed in front of the EI. The PTR effectively measures the spectral radiance of the diffuser, which is then subsequently used as a ‘standard source’ to calibrate the EI.

This Lambertian diffuser, typically made from Spectralon, will be calibrated for full spectral reflectance during the pre-launch calibration. As Spectralon has high and nearly spectrally flat reflectance properties, and any degradation will not exhibit sharp spectral features, it is not necessary to measure the radiance with high spectral resolution. Therefore, measurements in a few spectral bands will be sufficient.

The PTR can also view the Earth or Moon simultaneously with the EI as alternate transfer sources, for both redundancy and integrity checks. The polarized nature of the instrument and choice of the spectral filters allows the PTR also to be deployed in an off-nadir view, pointing (approximately 50°) to the fore of the imager during normal observation mode. This provides essential additional information to aid in the determination of aerosol optical depth and atmospheric correction.

The mission baseline has two identical PTRs (each on a separate rotation arm) partly for redundancy and also to provide additional spatial information on the diffuser for the characterization of the EI. The SSIM can also view targets such as the Moon and can be used to provide another internal cross-check on calibration.

Figure 13 shows a block diagram of the traceability chain for TRUTHS in terms of its measurement of Earth spectral radiance. Note that in this paper we have not described all the steps in any great detail, e.g. wavelength calibration.

5. Summary

Climate change is the most critical issue facing mankind today. The enormous cost implications of policy decisions based on forecasted impacts resulting from the predictions of a warming Earth demand that the science community finds and delivers the necessary information with the highest possible confidence in the shortest possible time. The challenge to the metrology community is equally severe.

The IPCC [1] concludes that the mix of natural variability and anthropogenic effects on decadal time scales is far from fully understood or measured, requiring significant improvements in accuracy. Unequivocal attribution and quantification of subtle fingerprint indicators from this noisy background are fundamental to our ability to predict climate reliably and use appropriate mitigation/adaptation strategies. The uncertainty in climate prediction lies in the complexity of the models, our inadequate understanding of the Earth system and its feedback mechanisms, and the relatively poor quality of available data against which to test predictions on the necessary decadal time scales.
Establishing rigorous SI traceability to the key measurands underpinning the ECVs, with sufficient accuracy, is a central pillar to achieving this goal. The satellite community has over the years developed a number of strategies to support this objective, but as yet all fall dramatically short of the required accuracy, forcing the adoption of high-risk philosophies seeking to monitor ‘change’ through normalization of overlapping datasets. While pre-flight calibrations can be made traceable, the harsh environment of space following the shock of launch means that few, if any, of the radiometric ground calibrations can be relied upon in space. Efforts to recover some of the information can be carried out using a variety of post-launch methods, but none have sufficient accuracy to meet the needs of climate.

This paper has described the only real solution available to the EO community, i.e. to establish high-accuracy SI traceability in flight, on-board the spacecraft. One mission, TRUTHS, which is designed to achieve this for the solar-reflective domain, has been described in some detail. Its sister CLARREO complements this in the solar-reflective domain and extends the capability into the IR spectral region.
TRUTHS would become ‘a standards laboratory in space’ providing directly traceable measurements of unprecedented accuracy (factor of 10) in SI units, in orbit, through the deployment of a primary radiometric standard and associated calibration methodology. This unprecedented accuracy will establish benchmark measurements for the detection of decadal change in the most sensitive (but least understood) climate radiative forcings, responses and feedbacks in the solar-reflective domain.

With spectrometer resolution sensors of unprecedented accuracy, TRUTHS can observe climate-relevant processes related to the atmosphere, the oceans and the land surface. TRUTHS’ observations will test and advance the development of climate models, allowing more accurate climate change hindcasting and forecasting. In addition, TRUTHS’ measurements of ground-based reference sites (and the Moon) will allow retrospective improvements to the calibration of existing satellites and their data.

TRUTHS/CLARREO will provide an in-orbit standard for reference intercalibration for other EO satellite instruments (with benefits for both science applications and operational services). The TRUTHS and CLARREO missions are planned to fly in an orbit that allows frequent ‘cross-overs’ with other in-flight sensors. Together with their own pointing capabilities, and ability to match spectral and spatial resolution, the high calibration accuracy and SI traceability will transfer to other sensors through simultaneous observations of a target.

SI-traceable observations at climate change accuracy from different instruments can then be objectively linked to a common baseline time series even if no sensor-to-sensor overlaps are available. Had an in-orbit calibration observatory similar to TRUTHS/CLARREO already flown, this benefit would exist now. Delaying the installation of such a system reduces the value of the climate records and creates the constant risk of data records being lost completely should an overlap be lost. The full value of TRUTHS/CLARREO will be gained in the future, when a series of small platform in-orbit calibration instruments anchor EO time series, providing the highest possible confidence in any observed trends and at relatively low cost.

The realization of SI-traceable measurements in orbit is achievable now and time critical. This ‘grand challenge’ project between the metrology and Earth/climate science community must become a priority if society is to reap the commercial benefits of EO, but more fundamentally, without it, policy-makers will be acting blindly in their efforts to ensure long-term sustainability and growth within an ever-changing climate.

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