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TRACEABLE RADIOMETRY UNDERPINNING TERRESTRIAL AND HELIO-STUDIES (TRUTHS): A BENCHMARK MISSION FOR CLIMATE

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I. INTRODUCTION

Sound policymaking requires high confidence in climate predictions verified against decadal change observations with robustly known accuracy. Yet, our ability to monitor and predict the future of the climate is inadequate as we currently do not possess sufficient accuracy in our observing capability to confidently observe the small but critical climate change signals that are expected to occur over decadal time scales. These signals are fundamental to assessing the accuracy of climate change projections made by models and for the unambiguous attribution of climate change.

There is a need to dramatically improve the absolute accuracy of in-orbit observation (factor of ten) if we wish to maximise our sensitivity to critical climate signals, mitigate the risks of gaps in the data record and provide the observations necessary to evaluate the accuracy of climate model predictions. To address this lack in our observing capability three critical measurements and their required accuracies were defined by the US National Research Council Decadal Survey, one of which was Earth reflected solar spectra.

Uncertainties in climate feedbacks, which are key to determine how the climate system will respond to a given forcing, are the primary cause for our current uncertainty in climate prediction. The most important of these in order of uncertainty in the magnitude of their contribution are: cloud feedback, temperature lapse rate/water vapour feedback, and snow/ice albedo feedback [1]. Understanding how these aspects of the climate system respond and evaluating the fidelity of the response in climate models is essential if we are to improve our understanding of how the climate will change and thus take action in a timely manner.

Solar radiation, reflected from the Earth-atmosphere system back to space, constitutes a powerful and highly variable forcing of the climate system through changes in snow cover, sea ice, land use, cloud and aerosol properties. Systematic, spatially resolved observations of the time series of the absolute spectrally resolved flux of near-ultraviolet, visible, and short wave-IR radiation returned to space by the Earth system, tied to international standards in perpetuity, underpin a credible climate record of the changing Earth system. In combination with establishment of the absolute spectrally resolved solar irradiance reflected from the Earth-atmosphere system to space, to address the above, it is essential to continue the long-term, time series of incident total solar irradiance (TSI), and enhance its climate value through improved accuracy, removing the current controversies and uncertainties due to instrumental variations and their linkage into a climate record. The addition of a high accuracy spectrally resolved measurement of solar irradiance, provides the means to link solar variation to climate processes: underpinning studies of atmospheric chemistry and facilitating retrieval of the full range of Earth system products at both top and bottom of atmosphere.

It should be noted that whilst global and zonal averages are all that are required for climate benchmarking, hyperspectral radiances are collected globally at the full instantaneous spatial resolution of the sensor (in this case ~50 m). This data can thus be utilised for the full range of applications typified by multi/hyper spectral imagers, but with significantly higher accuracy, at least within the temporal observational constraints of the mission, for example forests and the carbon cycle, agriculture and resource prospecting. As a minimum the high accuracy of TRUTHS can be used to validate and in most cases upgrade the calibration of other optical sensors through overpass opportunities and anchoring the measurements from dedicated reference test-sites.

II. CLIMATE BENCHMARKING

A. Definition

The term climate benchmark is employed to denote a high absolute accuracy SI traceable measurement of the state of the climate. Such a benchmark can be used as a reference point against which to evaluate change and assess the performance of climate models. The fidelity of the measurement must stand independent of the instrument characteristics, the sampling used or the time period sampled, thus as well as traceable absolute accuracy it needs to be well sampled in space and time such that uncertainties in sampling and natural

variability, which all affect the accuracy of the benchmark, are minimised.

To be useful the benchmark needs, as a minimum, to be sensitive to the most significant and uncertain climate change signals and capture their climate impact, and this sensitivity must be maximised to enable earliest possible detection. In addition, in order to provide a significant constraint, the benchmark needs to provide the means of distinguishing different climate signals. For example, in the case of cloud, forcing varies with cloud fraction, cloud optical depth, cloud phase and particle size. So whilst it is necessary that a model can produce the correct decadal change in, say, shortwave cloud radiative forcing it is not a sufficient constraint, it must be clear that it is achieved by the same type of cloud. The ideal benchmark would provide the means to understand the change observed: allowing attribution of any observed change to specific causes and providing the information necessary to evaluate the deficiencies of climate models in terms of their ability to link change to the responsible forcing and feedback mechanisms.

Thus a well-designed benchmark can serve several inter-related scientific goals:

- Provide an SI traceable observation of the climate state robust to gaps in the climate record.
- Provide observational climate change evidence as quickly as is feasible (limited by natural variability) with high absolute radiometric accuracy and high statistical confidence across a wide range of essential climate variables (ECVs).
- Provide the data critical to evaluate the ability of models to predict the nature of climate change, enabling a sufficient test to put the range of climate prediction uncertainty in context.
- Diagnose climate model deficiencies and improve the fidelity of their response.
- Attribute the change, distinguish the cause of the signal and diagnose response and feedback of critical climate components such as cloud, surface albedo and water vapour.

B. Climate benchmarking product requirements

The choice of observations made and how they are obtained needs to be carefully considered. Data with sufficient information to resolve the inadequacies of models and probe the complexity of climate signals is required. Additionally, sampling and the treatment of the data must limit the aliasing of sampling bias error and the impact of natural variability on our observations, as these constitute noise on our measurements outside the controls of instrument design. In this section we address the product requirements of an Earth reflected solar climate benchmark. The requirements for incoming Total Solar Irradiance (TSI) are much simpler and outlined in [9].

We define three levels of benchmark products, each subsequent level adding to the requirements of the previous and providing additional scientific value. The consequential observational requirements are summarised in Table 1, but first we provide an overview of their scientific justification.

The solar reflected benchmark requires an SI traceable measurement of the spectrally resolved Earth reflected radiance and incoming solar radiation with sufficient absolute accuracy to meet the product requirements stated in terms of reflectance.

The inescapable properties of climate change signals are that they are relatively small, broad scale and only emerge over long timescales; thus a benchmark doesn't require high spatial or temporal resolution, but rather only needs to provide a relatively low resolution global picture for an average year or season. Each level of benchmark is a large scale average, and the primary requirements on the accuracy are on these 'average products'. However, with each level there is an increasing complexity in the discrimination required by the instantaneous observations, increasing the demands on the instantaneous measurement and in particular its signal to noise ratio (SNR), which, together with an increasing degree of separation of the averages into different categories (and thus a reduction in the number of data points contributing to the average) will also increase the demands on the instantaneous measurement characteristics. Finally it must be remembered that the accuracy requirement on the benchmark products is relative to the true average, thus sampling error, including the sampling of year to year variability, as well as instrument absolute accuracy and noise or uncertainty in the categorisation of the averages all contribute to the overall uncertainty term.

Level 1: Baseline reflected solar benchmark: provides a benchmark measurement of the climate state which is adequate as a sensitive and robust measure of climate change and facilitates testing of predictions of climate forecast models. For the shortwave this comprises a high accuracy measurement of the spectrally resolved annual average reflected solar radiance. It comprises of 10-15 degree zonal (spectrally integrated and resolved) annual averages, with some resolution in longitude, for example 30 or 60 degree. Spectral resolution

of 8 – 25 nm bandwidth and overall accuracies of 0.3 to 1 % (k=2) over the range 340 to 2350 nm.

Level 2: Climate feedback benchmark: In addition to the above this would provide a benchmark for key feedbacks: Cloud and surface Albedo. Additionally requires separation of measurements to clear-sky, all-sky and cloudy and higher spatial resolution to <~500 m. This means that in addition to uncertainties in the averages, instantaneous noise must also be <0.5% in certain spectral regions, for example 600 to 700 nm, to ensure accurate cloud detection.

Level 3: Attribution and evaluation benchmark: There are two aspects to this, the first (a) is based on direct use of the benchmark and the second (b) on the climate information that can be provided if the benchmark instrument is used to improve the calibration of key climate instruments to meet decadal climate signal accuracy requirements. In addition to the benefits of level 1 and 2 this would enable attribution of climate change and evaluate and improve the physics of climate models and processes. In practise this means improving the spatial resolution and maintaining high accuracy (and SNR) at the Instantaneous Field of View (IFOV). In this way it can provide detail on cloud characteristics and surface properties for a wide range of climate and operational applications. It also provides the means to upgrade the performance of sensors such as CERES, VIIRS, Landsat 8 and the new Copernicus sensors on Sentinel 2 and 3, binning the spatial and spectral measurements of TRUTHS to match the footprint and signatures of the other sensors.

Table 1. The measurement requirements summary, defined for the Benchmark Level 1-3.

Requirement	Level 1 benchmark	Level 2 benchmark	Level 3 benchmark
Spectral range	320/350/400 – 2300 nm		320 – 2300 nm
Spectral resolution	10 – 25 nm		8 nm FWHM (over key information regions typical of other EO sensors)
Spectral sampling	5 – 12.5 nm		2-4 nm
Absolute accuracy	0.001 in reflectance (0.3% relative to 0.3 average Earth albedo)		
S/N ratio	Better than 33 for $380 < \lambda < 900$ nm and better than 25 for $\lambda > 900$ nm, better than 20 for $\lambda < 380$ nm. (some degradation may be acceptable for level 1 benchmark pending studies). For Level 3 this is more optimally >100 and ideally >300 for the visible spectral range		
IFOV	1 km	0.25-0.5 km	Ideally <50-100 m for reference calibration
Polarisation sensitivity (for 100% polarised input)	< 0.5% (2σ) for wavelengths below 1000 nm (ideally <0.25%) < 0.75% (2σ) above 1000 nm Ability to distinguish all 4 Stokes parameters for a small subset of wavelengths in the visible provides some additional benefit regarding aerosol identification and quantification		
Orbit	<i>P90 precessing</i> Nearly circular polar orbit at 609 km (± 200 m) (61 day ground track repeat cycle) 90 degree inclination (± 0.1) Period 5812.4 \pm 0.25 secs (orbit maintenance requirement) RAAN = 0 or 180° (for level 3 benchmark reference inter-calibration)		
Swath width cross track	50 km minimum ideally 100 km or greater @ 600km		
Range of pointing	Nadir > 90% of time (120° limit)		Requires additional steerable single-axis rotation (gimbal/platform) for matching to other sensors. Nb some pointing likely to be required to allow both solar and Earth viewing (needed for technical implementation)
Estimated data rate	30 Mbytes/sec (uncompressed)		
Estimated data volume	Up to 1.25 Tbytes/day (uncompressed)		
Pointing Knowledge	Better than 0.1° (1 sigma) for nominal 609 km orbit (<3 x IFOV for reference calibration)		
Pointing accuracy	Better than 0.1° (1 sigma) for nominal 609 km orbit		
Jitter	Less than 0.1° over 0.1 second		
Stability	To maintain absolute accuracy requirement		
MTF	70% of energy within sampling distance square >95% within 2x sampling distance square		
Operation modes	Nadir data collection > 90% time, solar calibration		Lunar views. Additional inter-calibration of other on-orbit assets or targets of opportunity
Channel co-registration	As a minimum, better than the pointing knowledge		
TSI absolute accuracy	Total (0.2 to 30 um) integrated 0.01%		
Mission life	5+ year target (3 year min)		

C. On-orbit reference sensor product requirements

A significant component of the level 3 benchmarking product is the ability for TRUTHS to act as an on-orbit reference calibration sensor to bestow SI-traceable calibration onto other sensors. There should be no confusion that climate benchmarking is the primary scientific driver for the TRUTHS mission and its demanding performance specification. However, the scientific value this secondary objective brings significantly outweighs the slight increase in complexity of the mission requirements as discussed below.

Reference calibration of other space assets from orbit requires that any convolution to match the footprint (spectral or spatial) does not contribute a significant uncertainty. Studies by the CLARREO team summarised in [2] using high resolution Schiamaachy data have shown that 8 nm bandwidth and 4 nm sampling is the optimum needed to match sensors other than spectrometers. In practise this resolution is only needed for the spectral bands of other sensors which are relatively well defined and largely common e.g. Ocean colour bands.

Reference calibration for the full range of assets increases the demands on spatial resolution requirements, (ideally to $\sim <50$ m) whilst maintaining an IFOV SNR, for a typical target radiance level of >100 to 300 (the latter for the visible spectral range). Optimal targets have relatively high reflectance levels e.g. deserts, snow fields and the moon and so these SNR levels are not too onerous. Studies by the CLARREO team [3] have also shown that the ideal minimum swath is between 40 and 100 km to ensure sufficient overlap. The spectral, spatial resolution and SNR requirements, together with that for swath and IFOV exist within a trade-off space as defined by the spectrometer design, and specifically the limitation of available detectors. Studies recently performed by the TRUTHS science team, using the SSTL CHRIS-2 instrument as a baseline concluded these combined requirements could be achieved with low risk evolution of heritage instrumentation and are similar to the specifications of EnMAP for example. Work is in progress to design an optimal hyperspectral imager for TRUTHS and assess its likely performance.

The 609 km orbit altitude (table 1) is largely driven by the needs of reference calibration. Many EO sensors operate in 700+ km orbits and a large height gap between the relative orbits allows a longer orbital dwell time to maximise overlap times for simultaneous cross-calibrations, however, too low an orbit increases drag and impacts the fuel requirement.

Additional requirements are placed on orbital configuration and pointing ability. To minimise sampling noise to the sub 1% level necessary to achieve the required accuracy, 2000 samples (for a nominal SNR of <50) matched to within 1° in viewing angles and 5 minutes in time for each of the data configurations (scene spectral properties, polarisation, view angles etc.) is required. A pointing capability to ~ 1 km and a knowledge to $<3x$ the IFOV is required to ensure a representative spatial matching can be made with the sensor under test.

D. Solar irradiance product requirements

The measurement requirements for Total Solar Irradiance (TSI) are relatively easily defined and with the exception of the absolute accuracy needed to meet the climate benchmark criteria are based on best practise from existing heritage instruments e.g. VIRGO on SOHO. Similarly for solar spectral irradiance other than spectral resolution (where <1 nm is desired in the UV) the requirements are similar to those for Earth reflectance and lead us to the prospect of using the same hyperspectral imager for both applications. In this case, we use the native spectral resolution of the spectrometer together with long staring solar views to improve limitations posed by SNR.

III. HERITAGE SENSOR TECHNOLOGIES

A. Current state-of-the-art

One immediate question would be whether the climate benchmarking product requirements could be achieved with current sensor capabilities i.e. is the novel TRUTHS SI-traceable method necessary. The majority of past, current and planned future missions are not designed for climate benchmarking, but rather to investigate specific processes or obtain specific retrieval products. Could these sensor concepts be adapted in a low risk way to climate benchmarking? As already discussed, the hyperspectral imager instrument requirements in terms of swath, coverage, spectral & spatial resolution and instantaneous SNR do not require a significant advancement in technology. The demanding aspect of a climate benchmark mission concept is in the instrument calibration accuracy, its traceability to SI and the maintenance of these strict accuracy requirements throughout the mission lifetime. For any sensor data to be used as part of a climate record, the sensor measurements should be stable and traceable with an estimate of the uncertainties which must be below the

detection threshold for that record.

Current optical imaging sensors fall into two categories; filter radiometers and spectrometers. Filter radiometer-based sensors are unable to fulfil the climate benchmark role as they do not give the full required spectral coverage requiring significant modelling to interpolate nor do they have the required accuracy with at best uncertainties at beginning of life being no better than a few %.

Spectrometers can deliver the required spectral range (250-2500 nm) at high spectral resolution but again are limited in terms of SI-traceable accuracy to typically 2 to 5% dominated by radiometry. Reducing calibration uncertainties in the top-of-atmosphere radiometric measurements is clearly the technologically disruptive innovation provided by TRUTHS which distinguishes it from its peers allowing climate quality data.

The limitations in current calibration methods are not in our understanding of the calibration equation (the relationship between observed radiance and digital signal recorded and processed by the sensor), which while invariably complex can be well characterised pre-launch. The limitation is in the simplified linear relationship, typically resulting in a gain and offset term and the derivation and monitoring of these values on-orbit. The transition from air to vacuum, pre-flight storage and the harsh launch environment all lead to changes in the calibration parameters that means the pre-flight values cannot be guaranteed in flight, and with much evidence to show that they can change significantly.

Current on-board calibration methods are usually referenced to the reflectance factor of a white lambertian diffuser, with pre-flight calibrated accuracies typically of 1-2% ($k=2$) (although uncertainties a factor of ten lower than this are achievable). Calibration to radiance is reliant on a reference solar irradiance e.g. [4], with an associated accuracy of ~2%; clearly, in need of significant improvement to attain the 0.3% required for climate benchmarking. However, the largest concern with this method is lack of reliability of measurements of degradation of the diffuser panel. This is often coupled with the application of a degradation model e.g. [5] that assumes an exponential form; however the coefficients in this model vary from sensor to sensor and mission to mission and need to be determined on-orbit, ideally through an SI-traceable method.

Strategies, such as a monitor detector, the use of multiple diffusers (as employed on MERIS) or comparison against a stable reference site (such as a vicarious calibration site on the Earth or the moon) allow the monitoring of diffuser degradation to some extent, but these methods are neither SI traceable or can be performed to an accuracy level necessary for climate benchmarking studies.

With on-board calibration sources it should be possible to achieve uncertainties <3% ($k=1$). Maintaining and achieving uncertainties below 3% is only possible if the source is actively monitored. In-flight monitoring techniques have been deployed with some degree of success (e.g. MERIS, MODIS-A) to provide an on-board calibration stability of <1%. However, even these techniques rely on assumptions about their stability and cannot claim to be fully traceable to SI. Achieving VIS-SWIR spectral radiances at the 0.3% uncertainty level clearly demand advances in on-board monitoring methods.

B. Sensor vicarious cross-calibration

Even with on-board calibration systems it is generally necessary to verify the radiometric accuracy is achieved on orbit by independent means. There are a number of techniques available to provide a vicarious calibration of a satellite sensor. Although techniques have been developed to monitor the calibration using stable reference sites, these are based on an assumption of the long-term stability of the sites being $<\pm 1\%$ per decade which has not yet been independently verified. A recent review paper [6] provides an overview of many of the techniques available and their current status. The paper [6] shows that the accuracy of such activities is limited to approximately 1% in the stability of an individual sensor and 2-3% in cross-calibration depending on spectral band and similarity of the spectral response function of the spectral bands of the compared sensors.

Limitations to vicarious calibration activities include:

- No or limited direct traceability of measurements to SI.
- Primary test-sites do not cover full dynamic range of the sensors
- Sites not always available – especially moon, clouds.
- Site characterisation usually traced to satellite measurements and/or radiative transfer modelling, so reference instrumental effects are convolved with the ground truth and dependant on historical sensors calibration.
- Differences in viewing geometry and spectral characteristics can introduce significant errors if unaccounted for – particularly for bands with strong spectral features

- Limited availability of instrumented sites
- Very few opportunities for simultaneous observations so additional noise from atmospheric changes

A study by Lukashin [7] has developed the uncertainty attainable in sensor inter-calibration using an ideal reference sensor and simultaneous nadir observations concluded that in favourable observation conditions and with adequate polarisation distribution models a radiometric uncertainty of 0.3% (1σ) could be achieved in the target sensor. By limiting the cross-calibration measurements over well characterised vicarious sites, the combination of this technique with those discussed in [6] could potentially reduce the number of required samples from that described in the benchmark level 3 requirements.

In conclusion, the main limitation for climate benchmarking is the radiometric calibration. Current diffuser monitoring and vicarious techniques are inadequate for benchmarking and $<1\%$ is unattainable without a change in traceability methods.

IV. TRUTHS INSTRUMENTATION

A full description of the instrumentation employed on TRUTHS is beyond the scope of this paper but a brief summary of the key instrument is included here to aid in the outline description of the novel calibration method, more details can be found elsewhere [8].

A. Cryogenic solar absolute radiometer (CSAR)

The Cryogenic solar absolute radiometer (CSAR) is the heart of the TRUTHS mission [8], providing the means to establish SI traceability in orbit. CSAR (and laboratory cryogenic radiometers) are based on the simple principle of ‘electrical substitution’, where optical power incident on a black (spectrally neutral) absorbing surface will cause a rise in temperature of the disk, which is sensed by a thermometer. With the optical power shut off, the same temperature rise is then established by passing a current through an electrical heater attached to the disk. The electrical power used to create that temperature rise can be equated to the optical power, and since electrical power can be measured with relative ease, the optical power can be determined through the substitution of electrical power.

Although similar instruments are already used in space to measure TSI, this mission will be the first to fly such an instrument, cooled to cryogenic (~ 20 K) temperatures, using an Airbus cooler. Cooling such instruments in terrestrial laboratories ~ 30 years ago led to a step change reduction in radiometric uncertainties of nearly a factor of 100 and are now the primary standard of choice at most of the World’s National Metrology Institutes. CSAR will be the primary standard providing SI traceability for the calibration of all on-board optical instrumentation. This standard will provide traceability to SI to an absolute accuracy of 0.1 % ($k=2$). In addition to serving as a primary standard for radiance and irradiance, CSAR will also provide measurements in its own right: Total Solar Irradiance (TSI) at an uncertainty of 0.02 % ($k=2$), a factor of ten better than the currently operational ambient temperature radiometers.

V. IN-FLIGHT CALIBRATION METHOD

The calibration method for the TRUTHS Earth Imager (EI) has simplified from that described in [8] and is now a three step process. The SI primary standard ‘traceable’ cryogenic radiometer (CR) power measurement capability is transferred via a monochromatic based source to a simple transfer radiometer (TR) and from there, using the same source to provide a known radiance field to overfill the entrance aperture of the EI via a Lambertian diffuser plate. The stepwise process is shown schematically in Fig. 1.

It should be noted that in an attempt to make clear the basic steps the schematic representations are not necessarily intended to represent a real or even close to real layout, only the concept. For example, in some cases there may be additional turning mirrors or optical elements to help practical engineering implementations but it should be noted that these will not impact the overall traceability concept or its ability to achieve the required uncertainties.

Step 1: A stabilised (temperature and current control) suite of low power laser diodes (LD) is used as a source, its power measured by the cryogenic radiometer (CR) and then used to calibrate the response (to power) of the TR, under filling its two field of view (FOV) defining apertures. (The TR is a small integrating sphere, with integral semiconductor photodiodes, Silicon and InGaAs, viewing the diffusely illuminated wall), removing any sensitivity due to alignment. This step requires the LD output to be stable in wavelength and intensity during the time period for the measurement <1 minute. Studies indicate this should present no problem. The output of the LD is moved between the two instruments using for example, a mirror or optical

fibre. **The result of step 1 is a TR calibrated for spectral response (and spectral radiance response, through knowledge of the FOV geometry) for a discrete set of monochromatic wavelengths.**

Step 2: The LD output is expanded to create a uniform illumination of the diffuser, providing a radiance source which can be viewed by the TR (once rotated) and the EI. This is achieved by under-filling the input aperture of the irradiance sphere (IS), which provides a convenient means to homogenise and uniformly expand the LD beam. The previous measurement in step 1, together with knowledge of the geometry of the TR two FOV defining apertures allows the TR to measure the reflected monochromatic radiance of the diffuser plate. The diffuser now provides a known source of radiance, to calibrate the EI at each of the LD wavelengths. An independent measure of the IS throughput is not needed, just short-term (seconds) stability of the LD & IS combined system and consistency of the LD wavelength used in step 1. **The result of step 2 is the EI calibrated for spectral radiance at a number (typically ten) of discrete monochromatic wavelengths across its spectral range, directly traceable to the CR.**

Step 3: A lamp (with a smooth spectral output) illuminates the diffuser and is viewed by the EI. This provides a means to interpolate the spectral radiance calibration between the LD wavelengths. Although the lamp output will change, this will largely be in terms of absolute level and/or relatively smooth and small spectral variation. The absolute level and spectral shape is anchored by the LD calibration points on the EI.

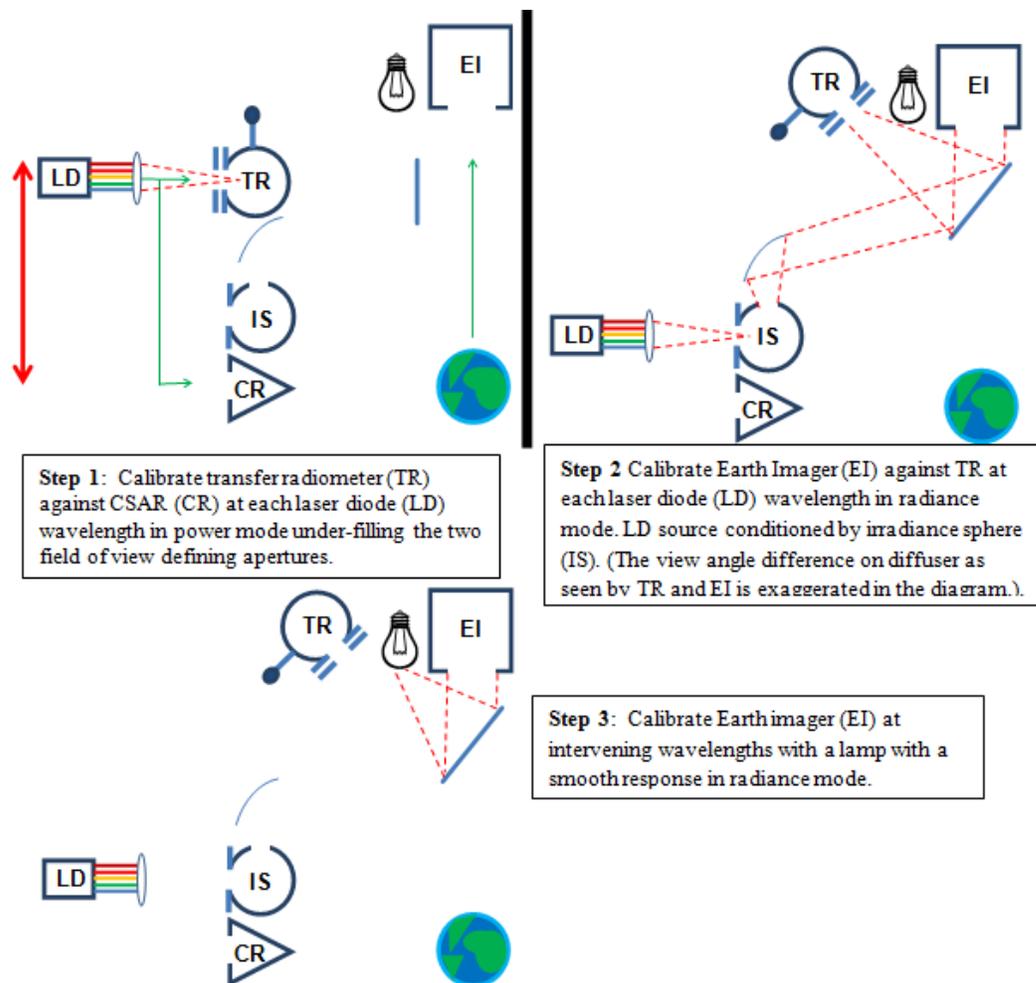


Fig. 1. The TRUTHS traceable on-board calibration methodology.

It should be noted that the TR and diffuser used in steps 1-3 never need to be exposed directly to sunlight, thus limiting the solarisation degradation of these components. **The result of this step is a fully spectrally calibrated EI.**

A similar set of steps can be shown for the use and calibration of the EI for measuring solar spectral irradiance, but the page limit of this paper prohibits its inclusion here.

VI. CONCLUSIONS

The science requirements of a climate benchmark have been described and from these a resultant set of technical mission requirements have been derived. Many of the underlying studies to identify the specific requirements are based on studies carried out by colleagues in NASA for a sister mission called CLARREO. The resultant requirements have been summarised with varying levels of detail dependent on their criticality and uniqueness to this benchmark missions goals. Some are considered more suitably addressed during phase A studies.

The key conclusion is that the mission's technical requirements are challenging in one aspect only, that of absolute SI traceable uncertainty, with most other radiometric/geometric aspects already demonstrated in other heritage missions. However, achieving the uncertainty requirement does have implications for other aspects of the mission and these should not be ignored or underestimated during the design phase. We demonstrate realistically how this uncertainty can be achieved with relatively low risk technologies and methods through adoption of a novel on-board calibration system. This calibration system which mimics that performed on the ground is based on already bread-boarded and tested methods using space qualified components and could be readily developed for space flight. The only elements of this system not yet fully space qualified are the full range of low power laser diodes. However, it is not considered that these would present a high risk and their relative size allows significant protection and the potential for a high degree of redundancy.

The mission's principle measurement instrument, an imaging hyperspectral spectrometer, is largely an evolutionary upgrade to the heritage CHRIS instrument of SSTL (originally SIRA) and presents little risk. Additional considerations are inevitable for a more rigorous SI-traceable on-orbit calibration, e.g. stray-light and temperature control, but there is little that requires novel technical development.

In summary, the urgency of a climate benchmark mission is such that early implementation is imperative and TRUTHS offers a means to achieve that for solar spectral domain and in doing so provides a means to upgrade the performance of the whole Earth Observing system.

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