TRUTHS (TRACEABLE RADIOMETRY UNDERPINNING TERRESTRIAL- AND HELIO- STUDIES): A MISSION TO ACHIEVE “CLIMATE QUALITY” DATA

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ABSTRACT

Prediction of the magnitude, regional manifestation and societal impact of long term climate change rely upon the predictive capabilities of sophisticated and highly complex simulation models. The output of these models is the cornerstone of international and national efforts that guide the policy decisions that select effective mitigation and adaptation strategies.

These model predictions clearly need to be validated against an observational dataset. However, since the key indicators of climate change may only vary by a few percent per decade, the absolute accuracy of such an observational dataset also needs to be very small to allow robust detection of the underlying trend against the backdrop of natural variability. Current sensor in-flight accuracy is inadequate for this climate benchmarking goal.

TRUTHS (Traceable Radiometry Underpinning Terrestrial- and Helio- Studies) is a proposed mission that will provide a robust dataset of sufficient quality and accuracy through ‘on-board’ traceability to SI units, regularly re-established to guarantee it throughout the lifetime of a mission and thus capable of providing a climate benchmarking product.

1. 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 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.

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, it is essential to continue the long-term, time series of incident total solar irradiance and enhance its climate value through improved accuracy and add to it a high accuracy spectrally resolved measurement.

2. CLIMATE BENCHMARKING

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

Proc. ‘ESA Living Planet Symposium 2013’, Edinburgh, UK
9–13 September 2013 (ESA SP-722, December 2013)

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 a 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 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 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.

2.1. 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 §2.3.

We define three levels of benchmark products, each subsequent level adding to the requirements of the previous and providing additional scientific value. We summarise them in Table 1, but first we provide more detail and the scientific justification of the requirements and measurement implications.

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, which, together with an increasing degree of separation of the averages into different categories (and thus there is a reduction in the number of 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

- **Aim:** Provide a benchmark measurement of the climate state which is appropriate as a sensitive and robust measure of climate change. For the shortwave this comprises a high accuracy measurement of the spectrally resolved annual average reflected solar radiance.
- **Value:** Enables early and unambiguous detection of climate change. Can be used to evaluate the ability of models to correctly simulate change.
- **Product characteristics:** Reflected solar spectral radiance as a 10-15 degree zonal annual average, with additional value if there is some resolution in longitude for example 30 or 60 degree.
- **Measurement implications:** Absolute accuracy, sampling and spectral range need to be sufficient to capture the true zonal average total spectrally integrated solar reflectance to better than 0.3% (k=2), and the true zonal spectrally resolved reflectance with an accuracy between 0.3% and 1% (k=2) depending on wavelength, at a spectral resolution of between 8 and 25 nm (FWHM) over the spectral range 320/350/400-2300nm.

Level 2: Climate feedback benchmark
In addition to the above this would:

- **Aim:** Provide a benchmark for cloud radiative forcing and feedback determination and evaluation in models. Requires clear-sky, all sky and cloudy benchmark measurements of the climate state with additional value if these were separated into land / ocean scenes.
- **Added Value:** Enable measurement of the cloud feedback and if separated by land/ocean also surface albedo feedbacks. Enhance attribution analysis. Provide direct evaluation of the climate model surface albedo and cloud forcing and feedbacks enabling some diagnosis of model deficiencies and aiding improvement.
- **Product characteristics:** As before but separate averages for clear, all and cloudy, land / ocean with each separate average meeting the accuracy requirements given for level 1.
- **Measurement implications:** In addition to improved signal to noise ratio (SNR) requirements due to reduced averaging, places additional constraints on instantaneous accuracy and spatial resolution. These must be sufficient to accurately distinguish cloud and clear-sky such that these uncertainties do not impact on the overall average uncertainty requirements. Instantaneous spatial resolution between 250 m (or less) and 1 km is needed, with noise at this scale sufficiently low in appropriate regions of the spectrum to enable robust and accurate cloud identification, for example 0.5% noise on the instantaneous observation integrated over 600-700 nm.

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 above two levels this would:

- **Aim:** Enable attribution of climate change and evaluate and improve the physics of climate models.
  - Provide more detailed information on cloud properties at the IFOV to enable compositing by cloud type for example.
  - Bestow SI traceable in-orbit reference calibration with absolute accuracy of 0.3% (2σ) over the mission lifetime for relevant existing sensors (solar reflective band) that can provide additional climate sensing capability and retrieval of physical parameters (e.g. CERES, GERB, VIIRS, MODIS and Geostationary imagers) and improve the accuracy, reliability and climate value of other 'operational' GMES type sensors e.g. Sentinel 2 and 3.
- **Added Value:** Enables the nature of feedbacks to be probed and understood. Significantly enhances the ability to evaluate models and improve model performance. Improves attribution analysis.
- **Product characteristics:**
  a) As for level 2, but maintaining accuracy for global, zonal or gridded composites for each cloud type classification identified in the instantaneous spectra, for example cloud phase/optical depth/height (depending on measurement characteristics).
  b) To act as an in orbit calibration standard requires the ability to provide sufficient space/time/angle matched data for the relevant instruments to overcome matching and instrument noise and determine instrument offset, gain, nonlinearity and sensitivity to polarization on the appropriate timescale (monthly or seasonal).
- **Measurement implications:**
  a) In addition to being more stringent in terms of signal to noise to meet the reduced amount of initial averaging at the product scale, there are stronger requirements on instantaneous accuracy above and beyond those of level 2 i.e. for a wider range of wavelengths. Within this benchmark level there is increasing scientific benefit in terms of our ability to attribute change and evaluate and improve model performance as instantaneous measurement capability increases.
  b) To act as a calibration standard for other sensors, spectral and spatial resolution and absolute accuracy in the relevant regions need to be appropriate to enable calibration of the sensor to 0.3%. Depending on signal to noise characteristics of both the reference sensor and the sensor under test this could require around 2000 samples (with an SNR of ~<50 although this can be reduced with increased SNR). Pointing capability and orbital configuration must therefore be appropriate to enable maximal number of matches (within 1° viewing angle and within ±5 minutes in time) to span different data configurations and encompass monthly / seasonal timescales.

2.2. 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

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 λ for < 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 <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	P90 precessing Nearly circular polar orbit at 609 km (±200 m) (61 day ground track repeat cycle) 90 degree inclination (±0.1) Period 5812.4 ± 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)		

scientific driver for the TRUTHS mission, however, this secondary objective is achievable with only a small number of non-critical additional technical requirements. The scientific value this secondary objective brings significantly outweighs the risk of the slight increase in complexity of the mission requirements. The key requirement modifications are discussed below.

For the reference calibration of other space assets from orbit the spectral resolution and sampling requirement is to match that of the other sensor such that the convolution of channel spectral response does not contribute a significant uncertainty to the cross-calibration. Table 3 indicates some of the potential cross-calibration sensors.

Studies by the CLARREO team summarised in [2] using high resolution Schiamachy data [3] have shown that 8 nm bandwidth and 4 nm sampling is the optimum needed to meet sensors other than spectrometers. In practise this resolution is only needed around bands of other sensors which are relatively well defined and broadly common e.g. Ocean colour bands.

Reference calibration increases the demands on spatial resolution requirements, (ideally of the order of 50-100m) and with the instantaneous SNR, with an optimal target for typical radiance levels being >100 to 300 (with the 300 being for the visible spectral range). Typical radiance levels in historical vicarious calibration studies have generally been stable high reflectance sites, such as deserts and ice fields resulting in this typical SNR requirement not being too onerous. Studies by the CLARREO team [4] have also shown that the ideal minimum swath is between 40 km and 100 km. 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. A study 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.

Table 2. Comparison sensor spectral & spatial resolution.

Sensor	Resolution FWHM	Spatial pixel size
MODIS	10-50 nm	250/500/1000 m
MERIS	7.5-200 nm (O_2-A band 2.5 nm)	300 m
VIIRS	15-80 nm	259 – 742 m
Sentinel 2	15-115 nm	10 m
CERES	N/A	16 by 23 km
AVHRR	60+ nm	1- 6 km

The 609 km orbit altitude is driven largely to reflect 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. Studies by the CLARREO science team suggest that two reflected solar instruments in 90° inclination at 609 km altitude (in perpendicular planes) orbit would provide sufficient sampling for all reference inter-calibration goals. Both instruments would need to operate on a pointing gimbal with azimuth and elevation degrees of freedom. Reference inter-calibration noise increases by a factor of $\sqrt{2}$ in going from two to one satellite. 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.

2.3. Total solar irradiance (TSI) product requirements

The measurement requirements for 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. They require continuous observations of the Sun for at least 5 minutes a day. In observing the Sun, heritage practise indicates that the defining aperture for irradiance should be a nominal 5 mm in diameter (although providing it fully under-fills the solar disc this is again not critical). Knowledge of where within the solar disc the aperture is pointing is required to ~2 arc secs (easily achieved through existing sensors) with pointing accuracy and stability only required to 0.1 degree.

The only mission driving requirement is an absolute radiometric accuracy of 0.02% in the total integrated solar irradiance product.

3. HERITAGE SENSOR TECHNNOLOGIES

One immediate question would be whether the climate benchmarking product requirements could be achieved with current sensor technologies, and whether the novel TRUTHS SI-traceable method is necessary. The majority of past, current and planned future missions are not designed for climate benchmarking, but designed to investigate specific processes or obtain specific retrieval products. Could these sensor technologies 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 the TRUTHS 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 in providing climate records, 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 sensors fall into two categories; filter radiometers and spectrometers. Filter radiometer-based candidate sensors are unable to fulfil the climate benchmark role as they do not give the full required spectral coverage. Bands with significant radiative contribution that are not directly measured would require determination by model simulation, both reliant on the models being tested (denigrating the independence of the benchmarking activity) and generating unacceptably large uncertainty contributions. The on-board calibration of filter radiometers typically result in uncertainties of the order of at least 1-2% (k=1) and are insufficient for the climate benchmarking product by an order of magnitude, with the degradation of filter transmissions and drifts in centre wavelengths being some of the key contributions to the radiometric uncertainty achievable.

Spectrometer sensors generally do provide the full required spectral range (250-2500 nm) at high spectral resolution, examples include: GOME-2, TROPOMI & Sentinel-5 UVNS. Typically sensors are in sun-synchronous orbits are not capable of providing the sampling required, but this issue could potentially be addressed, with low risk, by deploying similar sensors in the required orbit; however, a second more fundamental radiometric uncertainty limitation would also have to be overcome. Typical on-board calibration radiometric uncertainties for these spectrometer sensors of 2-6% (k=1); an order of magnitude worse than the radiometric accuracy requirements. Reducing calibration uncertainties in the top-of-atmosphere radiometric measurements is clearly the main technological challenge for TRUTHS.

The limitations in current calibration methodologies 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.

Current calibration methodologies are primarily referenced to a white diffuser BRDF, with pre-flight calibrated accuracies typically of 1-2% (k=2) as a reflectance standard. Calibration to radiance is reliant on a reference solar irradiance e.g. [5], 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 methodology is the degradation of the diffuser panel. Diffuser panel degradation is not generally well monitored over the lifetime of the mission and in many cases a degradation model is employed, e.g. [6] that assume 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. A direct method of monitoring diffuser ageing is necessary to account for the variations in the diffuser BRDF with time if the 0.3% (k=2) accuracy requirement is to be achieved.

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 to address the assumptions in current monitoring techniques.

3.1. 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, even these are based on an assumption of the long-term stability of the sites being <±1% per decade which has not yet been independently verified. A recent review paper [7] provides an overview of many of the techniques available and their current status.

Current sensor cross calibration activities focus on TOA reflectance not radiance, relying on spectral radiance data derived from SOLSPEC solar spectral irradiance measurements to calculate radiance data. The contributions to the TOA reflectance are varied and complex, with the dominant sources of uncertainty being: atmospheric contribution, site BRF, temporal variations, site spectral variations. To minimise these effects in a vicarious site inter-comparison, the same view and solar illumination angle is used for both sensors, combined by viewing a temporally stable site limiting the main variability to the atmosphere. However, experience 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 spectral band SRF similarity between the compared sensors.

Limitations to vicarious calibration activities include:

- No direct traceability of measurements to SI.
- Sites do not cover full dynamic range of the sensors
- Inter-comparisons usually assume a simple ratio between sensor calibration and reference that is not always the case.
- 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 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 [8] 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 0.3% (k=1) 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 [7] 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.

4. TRUTHS INSTRUMENTATION

A full explanation of the SI-traceable calibration chain employed on the satellite for the TRUTHS mission is beyond the scope of this paper. The key components are described, summarising their primary application.

4.1 Cryogenic solar absolute radiometer (CSAR)

The Cryogenic solar absolute radiometer (CSAR) is the heart of the TRUTHS mission [9], providing the means to establish SI traceability in orbit. CSAR (and laboratory cryogenic radiometers) are based on the simple electrical substitution approach, where optical power incident on a black absorbing surface will cause a rise in temperature of the disk, which is sensed by a thermometer. With the optical power then shut off, the same temperature rise 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.

This mission will be the first to fly such an instrument, cooled to cryogenic temperatures, in space. CSAR will be the primary standard for radiant power and irradiance measurements providing SI traceability for the calibration of all on-board optical instrumentation. This standard will provide traceability to the International System of Units (SI) to an absolute accuracy of 0.1 % (k=2). Apart from serving as a primary standard for radiance and irradiance, CSAR will also provide science measurements in its own right of Total Solar Irradiance (TSI) with an accuracy of 0.02 % (k=2), a factor of ten better than the currently operational ambient temperature radiometers.

4.1 Earth Imager (EI)

A hyperspectral imager for measuring the Earth-reflected solar radiance and solar spectral irradiance (via the irradiance sphere).

4.2 Diffuser plate (DP)

A near-ideal Lambertian reflector viewed by the Earth Imager and Transfer Radiometer, additionally illuminated by a broadband lamp, as implemented in a number of heritage missions.

4.3 Low power Laser diode suite (LDS)

A suite of stabilised low power laser diodes (6 to 10 within the 340-2300 nm spectral range) will be used on board as a source of stable monochromatic light. The exact wavelength is not critical, so high TRL commercially available devices can be sourced. Each laser diode will include integrated collimating optics to allow a power measurement by the cryogenic radiometer and transfer radiometer.

4.4 Transfer radiometer (TR)

The transfer radiometer is a simple integrating sphere mounted broadband solid-state photodiode detector system. (One detector sensitive to the UV-VIS-NIR spectral region from 320-1000 nm, and a second detector sensitive to the SWIR from 800-2300 nm.) Equipped with a pair of apertures of known area and separation, the TR will be mounted on a simple rotating arm that allows its view to switch from the laser diode suite to the reflected radiance from the diffuser. The transfer radiometer will allow the conversion between power, irradiance and radiance calibration together with physical movement to transfer the CSAR calibration to the Earth Imager-viewed diffuser.

4.5 Irradiance sphere (IS)

The irradiance sphere is a simple integrating sphere to pre-condition the laser radiation to assist in the creation of a uniform radiance source on the diffuser plate as viewed by the TR and EI, and allows the EI to perform the dual role of measuring Earth-reflected solar radiance and solar irradiance.

At the centre of the instrument remains a hyperspectral imager and diffuser calibration target, the addition of the CSAR cryogenic radiometer, a suite of sources and a few additional simple elements is all that is needed to provide the all important on-board SI-traceability and reflector degradation monitoring without the modelling and performance assumptions that have limited previous missions.

5. CONLUSIONS

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 three 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 largely 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 any 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 spectrometer, is largely an evolutionary upgrade to the heritage CHRIS instrument of SSTL (originally SIRA) and presents little risk. Additional component are inevitable for a more rigorous SI-traceable on-orbit calibration, but there is little that required novel technical development.

In summary, the urgency of a climate benchmark mission is such that early implementation is imperative and TRUTHS is that route in the solar spectral domain.

6. REFERENCES

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ACKNOWLEDGEMENTS

The authors would like to acknowledge funding from the UK Space Agency via the Centre for Earth Observation Instrumentation and the National Measurement Office of the BIS Department of the UK.