Prototype of Cryogenic Solar Absolute Radiometer and Transfer Radiometer for On-Board Calibration of Spectral Earth Imager

L. Zajiczek, R. Winkler, T. Hobson, P. Green, and N. Fox

1Earth Observation, Climate and Optical Group, National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW United Kingdom
2Current address: Surgical Robot Vision Group, University College London, London WC1E 6BT United Kingdom
3Current address: Stephenson Institute for Renewable Energy, University of Liverpool, Liverpool L69 7ZF United Kingdom

E-mail: nigel.fox@npl.co.uk

Abstract. We describe a prototype calibration system for the Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS) satellite mission. We outline the design and testing of key system components, including the Cryogenic Solar Absolute Radiometer (CSAR). CSAR is designed to make Total Solar Irradiance (TSI) measurements with a standard uncertainty of < 0.01% and provide SI-traceable calibration of a hyperspectral Earth imager (EI) over the wavelength range 320 nm – 2450 nm. The EI is designed to make Solar Spectral Irradiance (SSI) and spectral radiance measurements with a standard uncertainty of < 0.3%.

1. Introduction
The Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS) satellite mission intends to provide SI-traceable measurements of spectral Earth radiance and Solar Spectral Irradiance (SSI) within a standard uncertainty of < 0.3% and Total Solar Irradiance (TSI) within a standard uncertainty of < 0.01% [1]. The unprecedented accuracy of the mission’s measurement capability would not only provide benchmark climate monitoring but also offer reference calibration of other Earth observation satellites. Measurement traceability is provided by an on-board Earth imager calibration system anchored to the SI through the Cryogenic Solar Absolute Radiometer (CSAR). We present a flight-representative prototype of CSAR cooled by Airbus’ High Performance Stirling Cooler (HPSC) and a breadboard calibration system demonstrating a technology readiness level (TRL) of 5 – 6. We also present an engineering assessment of the feasibility and reliability of a space-qualified version of the TRUTHS payload.

2. Design of Payload Instruments
The payload of TRUTHS consists of three main components: an on-board primary standard CSAR, a hyperspectral Earth imager (EI) and a calibration system that anchors the EI measurements of spectral radiance to CSAR via a transfer radiometer (TR). A suite of power-stabilized single-wavelength laser diodes over the range of 320 nm to 2450 nm serve as anchor points in the calibration of the EI via the TR and an illuminated Spectralon diffuser target.
Laser light is collimated and directed into different instruments as needed during the calibration chain via a rotating roof prism arm (RPA). CSAR provides both TSI measurements and an absolute measurement of each laser diode’s optical power, calibrating the response of the TR at that wavelength. The diffuser is then illuminated by the laser light and the calibrated TR measures the radiance of the diffuser simultaneously with the EI, calibrating its response. Finally a white light source (incandescent current/voltage stabilized lamp, although as this is only used in a relative mode anchored spectrally this is less critical than would be the case if used as an absolute source) is used to illuminate the diffuser and the calibration of the EI is interpolated between the laser diode wavelengths over the entire spectral range. Lamps of this nature have been flown in space before, are widely used terrestrially and by their physics have relatively smoothly varying spectral irradiance. However, both in space and on ground the absolute level of the output and its absolute spectral shape is subject to variation, with the latter dependent on its nominal ‘Planckian’ temperature/emissivity although the latter will only result in a spectrally smooth and relatively small variation which can be anchored by fixed spectral (laser diode) calibration points. This type of lamp is A schematic of all major components in the payload is shown in Fig. 1 with a flow chart of the calibration chain shown in Fig. 2.

Figure 1. Schematic of calibration system.

Figure 2. Flow chart showing calibration chain of EI at each laser wavelength.

2.1. Cryogenic Solar Absolute Radiometer
The design of the onboard cryogenic radiometer is based on the terrestrial Cryogenic Solar Absolute Radiometer located at the World Radiation Centre in Davos, Switzerland. This instrument is used to measure direct solar radiation and as it is directly traceable to the SI, it is expected to replace the existing World Standard Group of independently-designed instruments in the near future [2]. Terrestrial cryogenic radiometers including CSAR are operated at temperatures between 10 K – 20 K which would be difficult to achieve with existing space qualified cryocoolers [3]. Airbus’ recently optimized High Performance Stirling Cooler (HPSC), based on the high-heritage Astrium 50-80K cryocooler, can readily achieve a 45 K cold tip temperature with a 1 W heat load. The terrestrial CSAR design was significantly modified to reduce its volume, mass, complexity, and crucially, surface area with the aim of reducing the heat load of the instrument to 1 W as shown in Fig 3.

Initial testing of the thermal response of the redesigned cavity at an expected operating temperature of 60 K yielded a time constant of $\tau = 165$ seconds and a sensitivity of 0.0004 %, well within the 0.01 % requirements of the mission. Rather than measuring the absolute change in temperature due to an introduction of optical radiation requiring several multiples of $\tau$ to stabilize, the cavity temperature was actively maintained by a PID loop. The absolute difference in electrical power through the cavity’s resistive heater before and after the introduction of optical radiation is equivalent to the optical power of the radiation source. This introduces additional instability due to the uncertainties of the current source output and control loop, but the reduction in measurement time allows for additional integration of cavity temperature measurements to measure the electrical power within the required uncertainty.
2.2. Calibration Breadboard

The transfer radiometer (TR) is an intermediate radiance-measuring instrument whose response coefficient is calibrated by CSAR at each laser wavelength. The large calibration range necessitates three detectors: a silicon (Si) photodiode for the ultraviolet-visible-near infrared portion of the range, a thermo-electrically cooled indium gallium arsenide (InGaAs) photodiode for the near and shortwave infrared and an extended range InGaAs detector for full calibration to 2450 nm. To ensure the radiance incident on the detectors was as uniform as possible for both viewing conditions and at all wavelengths, the TR was designed as a 50.8 mm diameter Spectralon integrating sphere with a single input port and three detector ports. The RPA is rotated into position between the TR’s input port and its radiance-defining external aperture for the response calibration. The diffuser target is illuminated via another 50.8 mm diameter Spectralon integrating sphere with two input ports and one output port. The RPA directs laser light into its first input port, and the output port radiance is collimated and directed onto the diffuser via a periscope as the integrating sphere is situated at a different height than the diffuser disk. Two different collimating configurations were investigated and are presented in Section 3.3. The TR measures the radiance of the illuminated diffuser target at a 45 degree viewing angle and with a similar field of view to the EI. The illuminating sphere’s second input port contains a white light source which is used for interpolating the EI calibration between the anchor wavelengths.

3. Prototype Assembly and Testing

A flight representative cryostat was thermally modelled and procured by Airbus to house the CSAR instrument and the HPSC. CSAR’s thermal performance was tested separately before being mounted to a larger vacuum tank housing the calibration system prototype; the assembled prototype inside the tank is shown in Fig. 4. As a first test, both a trap detector with an external aperture acting as an EI analogue and the TR viewed the illuminated diffuser disk at a 45 degree angle and its radiance was measured. A flat-panel light source was then illuminated with the same laser and placed directly in front of both instruments (approximately 5 cm away); its radiance was measured, and the ratios of the EI and TR radiance measurements for both configurations agreed to within 0.08 %.

3.1. Thermal Testing of CSAR

The HPSC achieved a minimum CSAR reference block temperature of 55 K which was in line with performance expectations. The measured cavity time constant and temperature sensitivity at a cavity temperature of 60.12 K were consistent with the thermal model presented in Section 2.1: \( \tau = 217 \text{ seconds} \) and a better sensitivity than expected (0.09 K/mW). The cavity was then stabilized 15 mW or 1.35 K above 60.12 K, with 15 mW being in excess of a typical TSI measurement. Typical excursions of the cavity temperature from its setpoint due to optical
radiation heating the cavity would be on the order of 1% – 5%. The stability of the cavity temperature after such an excursion is nominally required to be within 0.01% of this 15 mW uplift, and while the PID control loop was not able to achieve this stability criterion by itself, the temperature quickly stabilized to within 0.2%. The standard deviation of the cavity temperature measurements was just under 4 times the 0.01% requirement, meaning an additional integration time of 10 seconds or 20 samples at 2 Hz would be sufficient. For a worst case scenario of a 5% excursion, a cavity temperature stabilization achieving the required stability criterion took 38 seconds in total. The time needed to make a cavity power measurement would also add a finite but similarly small amount of time for an accurate optical power measurement.

3.2. End-to-End Calibration In Situ

The CSAR cryostat was mounted to the testing vacuum tank’s viewing port and an end-to-end calibration was carried out at a single wavelength (785 nm). Once the cavity temperature was stabilized, CSAR measured an input optical power of 1.266 mW ± 0.001 mW with a standard uncertainty of 0.08%. Laser light was then coupled directly into the TR and the Si detector voltage was measured at 7.07 V ± 0.04 V (with 105 amplifier gain), yielding calibration coefficient of 0.179 mW/V ± 0.006 mW/V with a standard uncertainty of 0.3%. The illuminated diffuser radiance was measured by the TR’s Si detector to be 0.417 V ± 0.004 V (with 109 amplifier gain). The EI analogue measured a signal of 0.601 V ± 0.002 V, which is consistent with its larger field of view compared to the TR. Given the known diameters of the TR input aperture and external aperture as well as their separating distance, this gives a radiance of $L_{\text{diff}} = 0.025 \text{ W m}^{-2} \text{ sr}^{-1}$. This value was validated by estimating the input power to the illuminating sphere that would generate an irradiance of this magnitude on the diffuser, assuming that radiance and irradiance are roughly equivalent for a Lambertian source:

$$P_{\text{input}} = \frac{L_{\text{diff}} A_{\text{spot}} A_{\text{sphere}}}{M A_{\text{port}} \theta}$$

The collimation angle can be estimated from the collimating lens’ clear aperture of 45 mm and focal length of 170 mm as $\theta = 0.77$ rad. Assuming a Spectralon reflectance of 95% and a port fraction of 5% gives a sphere multiplier $M = 10$. For a diffuser spot 40 mm in diameter, a sphere diameter of 50.8 mm and an output port 11 mm in diameter, the input power required to generate a diffuser irradiance of 0.025 W/m2 is approximately 1.3 mW, which is in good agreement with the value measured by CSAR.
3.3. Uniformity of Illumination

Two critical aspects to generating uniform diffuser illumination are the collimation of the illuminating sphere output and laser speckle. The use of single-wavelength (and thus highly coherent) laser sources resulted in observed speckle patterns on the diffuser. The use of a multimode optical fibre to deliver all wavelengths of the laser diode array allowed for vibration of the fibre to mix the spatial modes, reducing the coherence and the speckle inhomogeneity. Adding a separate de-speckling element would introduce unwanted complexity, but fortunately the HPSC’s compressors continuously vibrate at a frequency of 36 Hz. The multimode fibre was wrapped around a vibrating element and the illuminated diffuser was imaged with a 12-bit CCD camera. The illumination with and without 36 Hz vibration are shown in Fig. 5 using radiation from a 530 nm laser diode. The speckle generated with no vibration showed up to 20% variation in signal (ratio of RMS to mean), while the maximum variation was 1.15% with vibration (note that some of this residual noise is due to the performance of the CCD camera, We expect that with optimized winding of the fibre maximizing spatial mode mixing the non-uniformity of the speckle pattern will be further reduced (subsequent as yet to be published measurements using a different facility at NPL have indicated that the effect of speckle on the calibration of a spectrometer can be reduced to <0.1%). It should be noted that whilst the size of the speckle features will change as a function of wavelength, the use of the mode scrambling in the optical fibre and the various independent diffusing elements serves to minimize the effect of this spectral dependency on the overall calibration uncertainty. Measurements are still to be performed to quantify any residual spectral effects.

![Figure 5.](image_url) (left) Image of speckle pattern generated on diffuser. (right) Image of diffuser illumination with fibre vibrated at 36 Hz.

The uniformity of the diffuser radiance with despeckling was directly measured with a trap detector and external aperture having a deliberately small field of view to avoid averaging of any non-uniformity. The variation in radiance was 30% for a change in lateral position of 10 cm, and the diffuser radiance measured with a field of view similar to the TR/EI at different distances and positions showed variations of up to a maximum of 0.25%. The original design used a single fluorite lens to collimate the output light of the illumination sphere, and this configuration was generating a divergent collimated beam and introducing aberrations to the wavefront, resulting in a non-uniform illumination profile. A second optical element was then introduced immediately after the output port of the sphere in a Galilean beam expander configuration, and the non-uniformity was reduced from 30% to approximately 1%. It is expected that further improvement in uniformity can be achieved with a lens configuration that balances aberrations.

4. Reliability and Feasibility Analysis

The reliability of the TRUTHS payload was calculated as $R = 0.971$ and 0.955 and for a 5 year and 7 year mission respectively, based on redundancy provided by backup measurement cavities and laser diodes. No critical areas for development were identified. The estimated reliability figures were considered adequate for the level of complexity involved. The main reliability drivers were identified as the HPSC drive electronics, displacer and compressors, the TR detectors and the on-board computer controlling CSAR. It was determined that the TRUTHS control electronics can be constructed with space-qualified components meeting all performance requirements. The uncertainty budgets of the lab-based calibration system and the predicted final design for all wavelengths from around 400 to 2000 nm are given in Table 1, outside of this spectral region the uncertainty may increase a little due to performance of sources and detectors.
Table 1. Uncertainty budget for calibration system (400 to 2300 nm).

| Component                  | Prototype | Final Design |
|----------------------------|-----------|-------------|
| Laser diodes               | 0.3 %     | 0.07 %      |
| CSAR                       | 0.08 %    | 0.02 %      |
| TR                         | 0.3 %     | 0.08 %      |
| Aperture geometry          | 0.17 %    | 0.02 %      |
| Illumination uniformity    | 0.25 %    | 0.02%       |
| Total                      | 0.4 %     | 0.1 %       |

The uncertainties for the laser sources were provided via testing through the MetEOC-2 project, and the space-qualified laser diodes are known to have improved power stability. The higher uncertainties for the CSAR and TR measurements were due to a loss of 75% of the available laser power; the necessary addition of a port aligner between the CSAR cryostat and the testing vacuum tank increased the distance between the reflective collimator and the CSAR port, and divergence of the collimated beam necessitated using a smaller core fibre to allow the entire beam to pass through CSAR’s input aperture. This constraint will not be present in the final design and as such the signal-to-noise ratio will improve by at least a factor of 4. Finally, the aperture geometry uncertainty can be reduced through pre-flight calibration and the uniformity of the diffuser is expected to improve with optimized despeckling of the fibre and improved design of the collimation optics.

5. Summary and Future Work
A lab-based prototype of the calibration system was used in vacuum to calibrate an EI analogue instrument via the redesigned space CSAR. Testing indicates that the uncertainty for TSI measurements is within 0.01%, and the uncertainties for SSI and spectral radiance are expected to be within 0.1%. Analysis also suggests that a space-qualified system can be built to within the specifications and achieves sufficient reliability criteria. Some further work is required before a space-qualified design can be achieved, including the following:

- Procure and test a passive laser conjoiner, e.g. a waveguide rod or hexagonal fibre.
- Optimize diffuser illumination optics and fibre winding to improve diffuser uniformity.
- Introduce an imaging spectrometer as a closer Earth imager analogue.

Acknowledgments
This work was funded by the UK space agency through its Centre for Earth Observation Instrumentation (CEOI) and the Metrology for Earth Observation and Climate project (MetEOC-2), grant number ENV55 532 within the European Metrology Research Programme (EMRP). The EMRP 533 is jointly funded by the EMRP participating countries within EURAMET.

References
[1] Fox N, Kaiser-Weiss A, Schmutz W, Thome K, Young D, Wielicki B, Winkler R and Woolliams E 2011 Accurate radiometry from space: an essential tool for climate studies 369 Phil. Trans. R. Soc. A 4028–4063
[2] Walter B, Finsterle W, Mingard N and Soder R 2015 Cryogenic absolute solar radiometer (CSAR) Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center Annual Report 11
[3] R Radebaugh 2009 Cryocoolers: the state of the art and recent developments J. Phys. Condens. Matt. 21 16