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TRUTHS: Towards the in flight calibration of a hyperspectral imager to SI traceable standards.

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ABSTRACT

TRUTHS (Traceable Radiometry Underpinning Terrestrial – and Helio- Studies) is a hyperspectral climate mission which, with the support of an on board calibration system traceable to national standards, will enhance our understanding of the Earths changing radiation budget by an order of magnitude.
The payload being developed by consortium led by Airbus UK includes three major subsystems: a hyperspectral imager capable of high resolution spatial and spectral lunar and earth measurements, a cryogenic radiometer with three high precision temperature controlled cavities traceable to national standards and a transfer system to convert this calibration into one of diffused radiance for comparability with measurements made with the hyperspectral imager.
The on board calibration system also includes a solar monochromator and a range of mechanisms and distribution optics to enable the calibration sequence and the required modes of the instrument.
This paper will summarise the design concept for the on board calibration chain developed during the Phase A/B1 instrument studies carried out in 2020-2022. The presentation will discuss the main engineering challenges and tradeoffs and the outlook and development plan for the Phase B2CD programme will be presented.
Keywords: Calibration, Remote Sensing, Hyperspectral

1. INTRODUCTION

TRUTHS (Traceable Radiometry Underpinning Terrestrial – and Helio- Studies) is primarily an operational climate mission with the main objective of establishing a reference baseline measurement (benchmark) of the state of the planet, against which future observations can be compared. This will both allow climate model improvements and forecast testing and provide observational evidence of climate change including mitigation strategies in the shortest time possible. The TRUTHS mission aims to

1. Enhance by an order of magnitude our ability to estimate the Earth radiation budget through direct measurements and
2. Establish a “metrology laboratory in space” to create a fiducial (International System of units – SI traceable) reference data set to cross-calibrate other sensors and improve the quality of their data.

To this end, TRUTHS will primarily measure the incoming & outgoing energy from the climate system, including the spectral fingerprint needed to observationally attribute climate processes, with an accuracy needed to detect climate trends in a shortest time frame. For this purpose, the satellite will host a Hyperspectral Imaging Spectrometer (HIS) capable of providing an accurate, continuously calibrated, dataset of spectrally resolved solar and lunar irradiance and Top of Atmosphere (ToA) Earth-reflected radiance in the near-UV/Visible/NIR/SWIR (320 to 2400 nm) waveband. By incorporating in the satellite a space-adapted primary SI-standard (Cryogenic Solar Absolute Radiometer - CSAR), as part of an innovative On-Board Calibration System (OBCS), the HIS aims to achieve an unprecedented radiometric accuracy of better than 0.3% (improved by a factor of ten with respect to other missions).

The satellite will be deployed through a VEGA-C launch from CSG on a LEO (~600km) polar, non-sun synchronous, orbit. Such a precessing orbit enables the full diurnal cycle to be observed and provides multiple opportunities to co-align with other satellites and transfer its calibration to them; the orbit, together with the HIS design, allows to provide global, continuously sampled nadir observations of the Earth.

TRUTHS has an operational timescale of 5 years with a target of 8 years. The mission is currently within a Phase B1 extension phase with an anticipated launch date in 2030. This paper presents the payload design and calibration methodology at the end of phase B1.

2. PAYLOAD ARCHITECTURE

The TRUTHS payload architecture is shown in Figure 1 and contains three main instruments or sub-assemblies:

1. The HIS (Hyperspectral Imaging Spectrometer). The HIS consists of a 4 freeform mirror telescope and a dispersive imaging spectrometer imaging onto a cooled MCT detector and is the main instrument on-board TRUTHS mission. This paper focuses on the TRUTHS calibration chain, for more information on the HIS, see [1]
2. The Cryogenic Solar Absolute Radiometer (CSAR) is the SI-traceable primary standard, able to measure both Total Sun Irradiance (TSI) and the optical power coming from the OBCS with an absolute accuracy compatible with the mission needs.
   The CSAR is an electrical substitution radiometer consisting of three identical measurement cavities and a reference block mounted within a cryostat. The CSAR cavities are designed to each be capable of absorbing 99.99% of incident solar radiation with a minimized thermal time constant. The availability of three cavities then allows for degradation monitoring and redundancy.
   To achieve the high absolute accuracy requirements, the reference block is connected to the cold tip of a cryocooler which maintains the block at 60K. Irradiance measurements are performed by monitoring the power within the CSAR thermal control system required to maintain this temperature.
3. The On Board Calibration System (OBCS) is the intermediate between the CSAR and the HIS, providing light input to the HIS with calibrated spectral radiance traced to the CSAR measured power. This system is discussed in more detail in the following section.

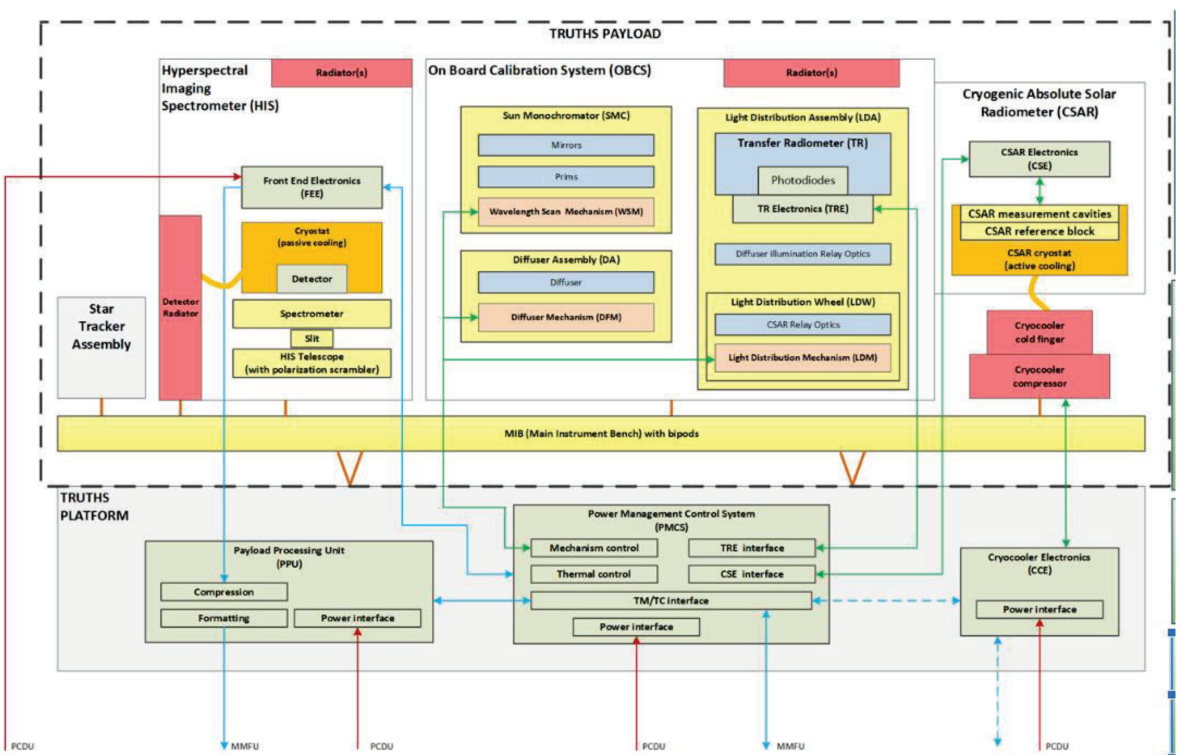


Figure 1: Payload architecture at the end of phase B1

2.1 On Board Calibration System (OBCS)

The OBCS is made of 3 subassemblies: the Solar MonoChromator (SMC), the Light Distribution Assembly (LDA) and the Diffuser Assembly (DA). For reference, the optical signal chains available within the OBCS is shown in Figure 2.

The SMC takes incident solar radiation and generates an output beam with a narrow spectral bandwidth around central wavelengths selectable through a Wavelength Scan Mechanism (WSM).

The LDA distributes the optical beam coming out of the SMC to either the CSAR (for absolute beam power measurement), the Transfer Radiometer or the HIS (via the diffuser) as determined by the calibration sequence. Within the LDA, the optical beam is transported out of the SMC through a periscope on the Light Distribution Wheel (LDW) actuated by the Light Distribution Mechanism (LDM) The LDA has several stable positions which can direct the beam towards one of the CSAR cavities or the TR, without modifying the beam power and polarization, or to the diffuser through relay optics. The fixed LDA structure also supports the relay optics to alternatively illuminate the diffuser directly from solar radiation (without the SMC). The LDW also acts as a shutter for the Total Sun Irradiance (TSI) and Sun Spectral Irradiance (SSI) measurement optical paths.

The Transfer Radiometer (TR) is the intermediate instrument which converts the monochromatic measurement made by the CSAR to a diffused radiance measurement effectively allowing the SI traceable calibration to be transferred over to the HIS.

The TR is mounted, along with the CSAR, to the LDA and is made up of an Integrating Sphere to collect either the SMC output beam (through the LDW optics) or the light from the diffuser and photodiodes with associated acquisition electronics (TRE). There are 3 types of photodiode to cover the full wavelength range with some overlap: one Si photodiode for UV-VIS, one InGaAs photodiode for NIR and one extended InGaAS photodiode for SWIR.

The signal ratio between the two optical inputs which the transfer radiometer is required to measure (from the diffuser or from the SMC) is several orders of magnitude. This results in the requirement for a large linear dynamic range within the transfer radiometer detection chain. This is achieved through the use of dual gain electronics with the gain ratio calibratable using a diaphragm or a rotating shutter. At the lowest signal, the SNR does however become limited. Further work is currently underway within the B1 extension phase to explore an evolution of the transfer radiometer concept to avoid this issue.

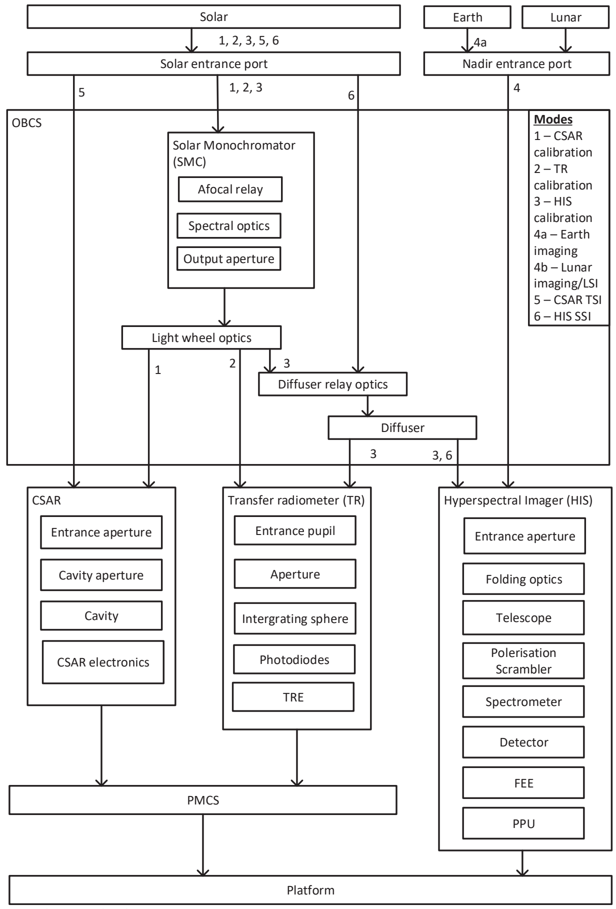


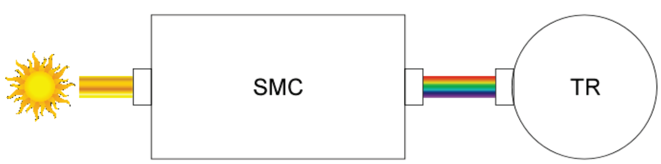
Figure 2: Payload optical and electrical signal chains

3. CALIBRATION METHODOLOGY

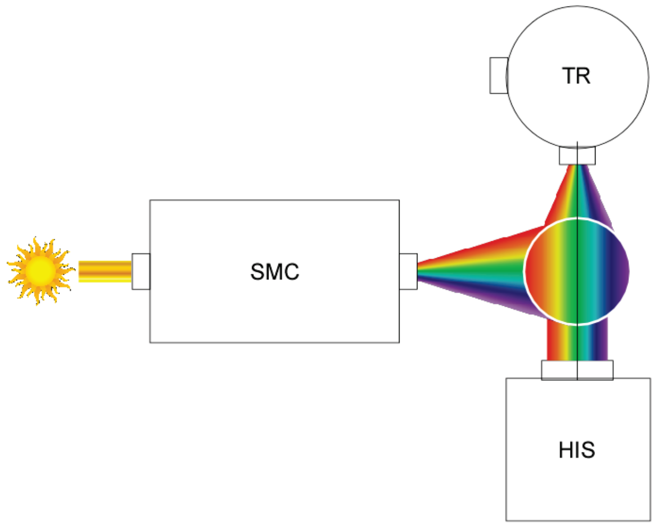
For each single wavelength, the in orbit calibration of the HIS gain is performed in four steps:

1. Calibration of the SMC output power with the CSAR at the corresponding wavelength.

2. Measurement of the same SMC spectral output power by the transfer radiometer.



3. Measurement of the diffused radiance of the same SMC spectral output beam by the HIS and transfer radiometer.



4. Calibration of the HIS gain through processing of the preceding measurement data.

The detailed calibration sequence is as follows:

a) The spacecraft is oriented such that the entrance aperture of the Solar MonoChromator is facing the sun. An intermediate field stop is located at the intermediate point of the entrance afocal telescope within the SMC to remove signal fluctuations due to spacecraft instability or orbital variations, see Figure 3.
b) The LDW is rotated such that the SMC output illuminates the CSAR input port.
c) The wavelength scan mechanism (WSM) is moved to the start wavelength.
d) The CSAR shutter is opened and the SMC output beam power measured. The duration of this measurement is allocated to be less than one minute (objective 30 s) and sets a maximum limit for the cavities required thermal time constant.
e) The LDW is rotated such that the SMC output illuminates the TR position.
f) After stabilisation a TR measurement is taken on the TR photodiodes.
g) The WSM moves to next wavelength and the LDW is rotated back to CSAR position.
h) Steps d) to g) are repeated for each required wavelength
i) The LDW and diffuser are rotated to allow the SMC to illuminate the diffuser
j) The complete wavelength range is scanned continuously by the WSM while the diffuser radiance is measured continuously and simultaneously by the HIS and the Transfer Radiometer.

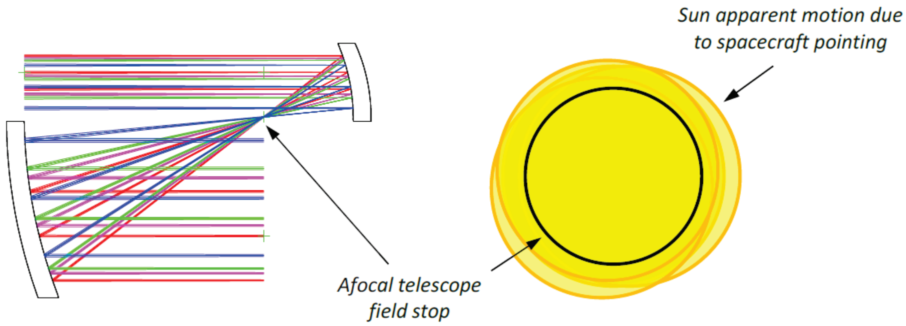


Figure 3: Implementation of afocal array field stop.

This calibration sequence utilises the WSM in step and stare mode for the CSAR measurements, where a subset of wavelengths covering the complete range are measured one after the other. An alternative solution is to operate the WSM in continuous mode while performing continuous measurements of the CSAR (then of the TR). By scanning, the SMC output slowly but continuously varies over the complete useful wavelength range, the CSAR optical input power is continuously changing and the CSAR never reaches a steady state (except at start and end of the scan). The processing is then based on the characterisation of the CSAR dynamic behaviour that allows, by calculation, to retrieve the actual input power. This method overcomes the limitation of step and stare mode where only a fixed number of wavelengths can be measured in a reasonable timeframe requiring interpolation between the measured points. However the continuous acquisition mode is a new methodology not yet applied or demonstrated before therefore its accuracy is unproven.

The payload design currently allows for both methods of calibration. Further work is underway in the B1 extension phase to further model, analyse and test the accuracy of the continuous acquisition mode.

Further challenges existent with this calibration methodology include the requirement for very accurate knowledge of the transfer radiometers geometric etendue as well as the complex numerical processing required to deconvolute the individual SMC spectral outputs from the spectral channels of the HIS detection chain. This is essential because the measurements by CSAR and TR will mix several spectral channels due to the SMC output beam not fitting exactly within the HIS spectral channels. The validation of this processing has been successfully initiated in phase B1 and shall be resumed in the B1 extension phase.

REFERENCES

[1] Mero, B. et al Status of the Design, Accommodation and Performance of the TRUTHS Hyperspectral Imager at the End of Phase B1, 2022