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CEOI8 TRUTHS CSAR FINAL REPORT

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LYDIA ZAJICZEK
RAINER WINKLER
PAUL GREEN
THEO HOBSON
NIGEL FOX

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CEOI8 TRUTHS Calibration System Final Report

Lydia Zajiczek
Rainer Winkler
Paul Green
Theo Hobson
Nigel Fox
Earth Observation, Climate and Optical Group
National Physical Laboratory

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of Airbus by
Ben Dobke, Project Manager

Approved on behalf of NPL by
Rainer Winkler, Project Manager
Nigel Fox, Lead Scientist

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EXECUTIVE SUMMARY

1.1. OVERVIEW OF PROJECT

The Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS) satellite mission intends to provide SI-traceable measurements of spectral Earth radiance, Solar Spectral Irradiance (SSI) and Total Solar Irradiance (TSI) to within standard uncertainties of < 0.3 %, < 0.3 % and < 0.01 %, respectively. The unparalleled accuracy of TRUTHS' measurement capability would not only provide benchmark climate monitoring but also offer reference calibration of other Earth observation satellites, improving their performance and thus can be viewed as a cross-cutting element to Copernicus. The L1 global hyperspectral radiances can also be convolved to support a range of other applications including many biophysical ECVs and retrieval algorithm developments. The disruptive aspect of the mission stems from its inherent on-board SI traceability which is achieved through its on-board calibration system, anchored with a primary standard the Cryogenic Solar Absolute Radiometer (CSAR). The CSAR itself based on an original concept pioneered at NPL 30 yrs ago for laboratory applications and more specifically built as a first prototype for space in 2010 currently serving as a WMO reference for terrestrial solar irradiance located at the World Radiation Centre in Davos, Switzerland. The CEOI8 project's major deliverable was to increase the TRL of this concept through building a lab-based 'flight representative' prototype of CSAR (including coupling to Airbus HPSC space cooler) and a breadboard calibration system, both tested under vacuum, demonstrating technology readiness level (TRL) 5/6, as well as an engineering assessment of the feasibility and reliability of a space-qualified version of the TRUTHS payload and some consideration of implementation options. The work was extended to include more detailed mission analysis including ROM costings, together with a study to demonstrate achievable uncertainties when used in cross-calibration of spectrometer based sensors like Sentinel 3 OLCI.

All project objectives were achieved, providing demonstrable evidence that the mission could be readily implemented utilising heritage or low risk incremental technology developments and fully meet its performance goals.

1.2 TECHNICAL OBJECTIVES

Work Package 1 (Airbus)
Optimization of Airbus High Performance Stirling Cooler (HPSC)

- Analyse current performance and develop strategy for possible modifications to cooler
- Disassemble cooler, install new units (e.g. piston, bush) and reassemble
- Optimize operation frequency targeting improved performance at 30 K given expected heat load of CSAR instrument (approximately 1 W)

Work Package 2 (Airbus): Design and manufacture of CSAR cryostat and breadboard

- Design and build using flight consistent components a cryostat to house and interface CSAR with the HPSC to raise TRL of CSAR to 6
- Integrate HPSC with cryostat and characterise performance

Work Package 3 (NPL): CSAR instrument and cavity design and test

- Evaluate alternative black coatings for CSAR radiation measurement cavities e.g. VANTA black (carbon nano tube) at cryogenic temperatures
- Assess thermal performance of redesigned measurement cavities and sensors
- Assemble new CSAR design and integrate with HPSC and cryostat after delivery
- Develop design specification for measurement electronics for review in Work Package 5

Work Package 4 (NPL): Spectrally resolved in-flight calibration system of TRUTHS

- Design space layout breadboard of on-board system to calibrate a hyperspectral Earth imager (EI) via an on-board single-wavelength low power laser diode, CSAR and a transfer radiometer (TR)
- Procure and manufacture laboratory quality (vacuum compatible) prototype with space-upgradeable components including laser diode sources
- Test calibration system with CSAR/HPSC under vacuum

Work Package 5 (Airbus/NPL): Implementation and reliability considerations
- Assess potential TRUTHS deployment options, i.e. on standalone satellite or on board the International Space Station (ISS) through model of CSAR
- Perform feasibility study of CSAR flight electronics
- Evaluation of start and end TRL of project technologies

Work Package 7 (Airbus): System engineering and costing for implementable mission.
- Evaluate platform implementation options for TRUTHS payload and orbit
- Consider thermal, power, data transmission for TRUTHS preferred orbit
- Establish ROM cost for mission based on above analysis

Work Package 8 (NPL sub contract to D Lobb): Upgrade design of Earth Imager following feedback from ESA EE9 review.
- Review design with view to simplification (two detectors) and spectral band splitting
- Upgrade design and associated modelling stray light analysis
- Technical specifications of optical sub-systems

Work Package 9 (NPL): case study on reference calibration for spectrometer based sensors e.g. OLCI of Sentinel 3.
- Evaluate uncertainty contributions for cross calibration of Sentinel 3 with TRUTHS
- Initial evaluation of suitability of a range of test sites other than deserts

1.3 OVERVIEW OF TECHNICAL PROGRESS

The optimization of the HPSC progressed as expected, with several upgrades being made to the system after disassembly. The cooler was re-assembled, baked out and tested, achieving an un-optimized cold finger temperature of 47 K with a 1 W heat load. Some optimization resulted in a another 2 K improvement; a potential further optimization of 1-2 K is considered possible. A helium leak during performance testing and optimization required a seal replacement, a re-fill of the helium supply and a bake-out. This added a small delay to the expected delivery of the HPSC and cryostat to NPL. The design and manufacture of the cryostat also went smoothly, and integration with the HPSC was successful, as shown in Figure 1. Collaboration between Airbus and NPL during the design process meant the eventual integration of the cryostat with the calibration system’s vacuum tank was also successful.

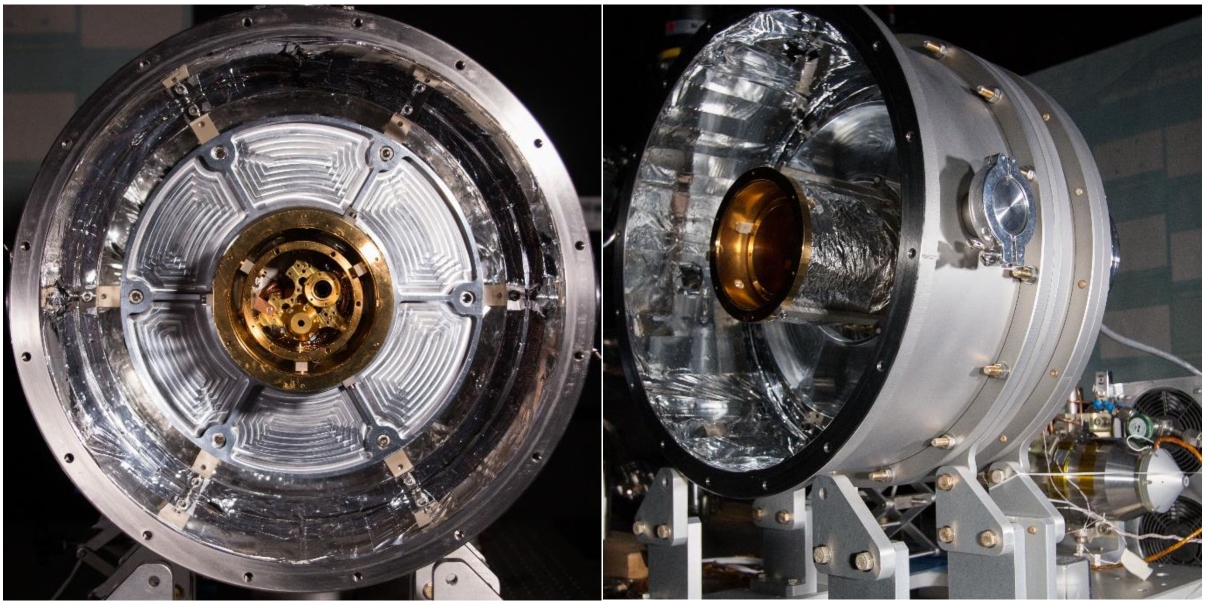

Figure 1 (Left) CSAR instrument mounted on cold tip of HPSC inside cryostat. (Right) Side view showing integration of HPSC into cryostat.

The CSAR redesign reduced the mass (by a factor of two) as well as the complexity of the instrument, and reduced the surface area to minimize the heat load wherever possible given the limited cooling power of the HPSC. The reflective performance of VANTA black (carbon nano tube) coating was investigated at cryogenic temperatures and was found to be suitable with no significant deviation from ambient temperature. Measurement cavities were then procured with this coating. A cryogenic test bench based on a 'high power' ground-based cryocooler was used to test the performance of the redesigned cavity assembly at different operating temperatures to allow greater flexibility in base temperature as 30 K with a 1 W load was likely to be an optimistic target. One potential issue with operating at a temperature above 30 K is an increased measurement time, which if too large is undesirable in the context of regular TSI measurements and EI calibrations. An active cavity configuration (means of operationally taking the measurements) was tested and found to greatly improve the temporal performance of cavity measurements removing detrimental effects of increased time constant. The procurement and manufacture of CSAR introduced some scheduling delays as some parts were initially outside of tolerance, but CSAR was wired successfully in time for integration with the HPSC and cryostat. A small redesign of the flexible heat link between the HPSC cold tip and CSAR's reference block is required for future implementations as only one heat link could be fitted due to access; thermal modelling assumed two heat links. Despite this, a minimum CSAR temperature of 55 K was achieved with minimal optimization of the HPSC operation settings. The active cavity configuration was tested at 60 K and achieved a stability of ± 0.01 % after the introduction of power into the cavity typical of TSI measurements. Although initially a target of 30 K as operational temperature was desired, evaluation and optimisation of the cavity and operational mode of CSAR means that temperatures up to 60 K are acceptable and allow all science goals to be achieved, although with a slightly longer integration time.

The TRUTHS calibration system primarily consists of a transfer radiometer (TR) that is calibrated by a suite of single-wavelength, low power stabilized laser diodes and CSAR. A schematic of the calibration chain is shown in Figure 2. The absolute optical power of each laser diode is measured with CSAR, and the same optical power then illuminates the TR (an integrating sphere with photodetectors) and the response is calibrated in V/W. The integrating sphere serves to homogenise the radiation and remove sensitivity to alignment. The same laser light then illuminates a Spectralon diffuser plate, which is viewed simultaneously by the calibrated TR and the EI instrument that is being calibrated. In detail, the laser first enters a small integrating sphere to homogenise the radiation and the output of the sphere is then imaged on to the diffuser plate This calibration sequence is repeated for each laser wavelength over the range of 355 - 2004 nm. The TR has a view limiting aperture mounted in front of it to allow a geometric field of view to be defined in conjunction with a second aperture and consequently a measure of radiance.

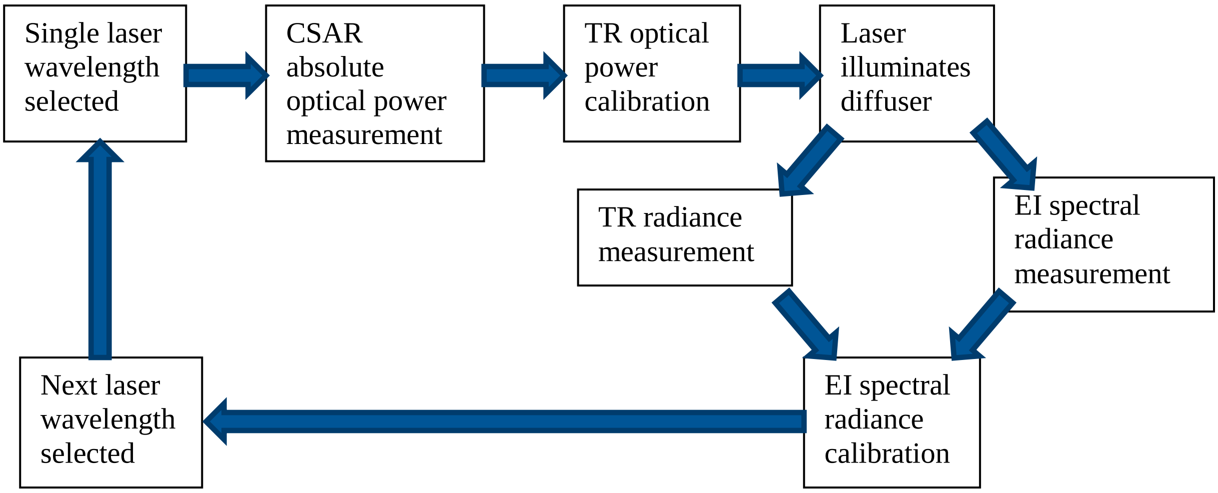

Figure 2 Schematic showing calibration chain of TRUTHS calibration system.

A CAD model of the prototype is shown in Figure 3, with the CSAR and EI instruments not visible. The laser light is collimated and directed into each of the instruments via a rotating roof prism arm. The diffuser is illuminated via an illuminating sphere, which is also equipped with a spectrally smooth white light source for interpolation of the spectral EI calibration between the diode wavelengths.

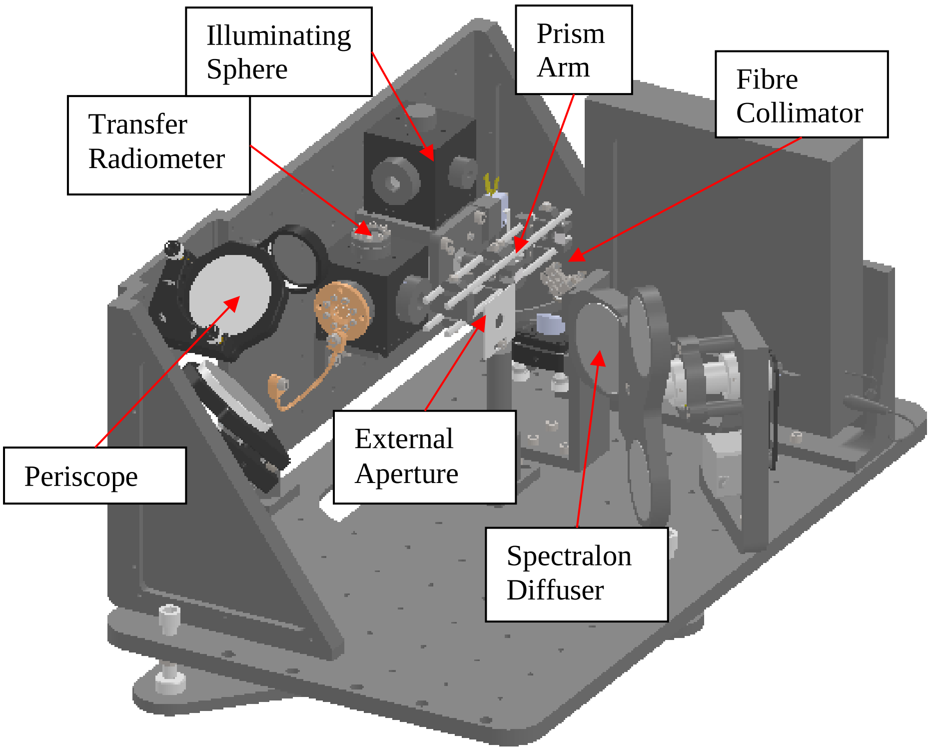

Figure 3 CAD model of prototype calibration system. CSAR is viewable in one of the positions of the prism arm behind the back plate of the system, while the EI would view the diffuser at a 45 degree angle.

The calibration system was procured, manufactured and assembled. Testing of individual components indicated performance was within specifications, with some final design decisions pending regarding signal levels in the NIR channels and a space-suitable laser conjoiner. The laser diodes were procured and tested for power and wavelength stability by external colleagues through the EU MetEOC-2 project. The calibration system was then installed in the vacuum tank and coupled to CSAR and the

HPSC as shown in Figure 4. A higher minimum CSAR temperature of 70 K was achieved due to problems with the vacuum chamber, and laser power measurements were made as part of an end-to-end calibration. An uncertainty budget of 0.12 % was assessed for the eventual space-qualified calibration system based on the components tested in the lab-based prototype, which is approximately a factor 3 better than required.

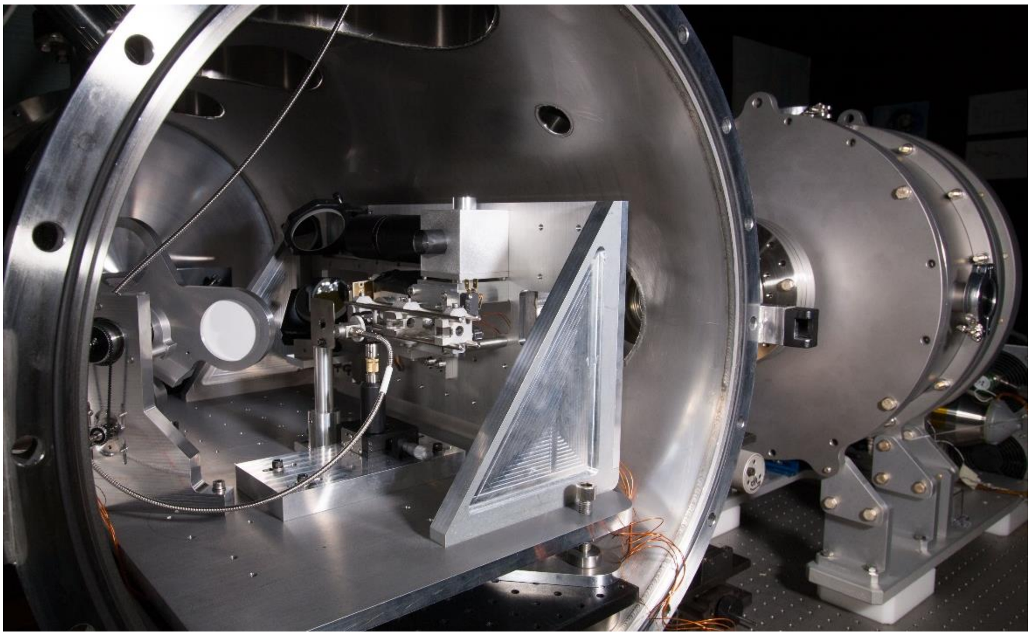

Figure 4 Photograph of calibration system prototype installed in vacuum tank and coupled to CSAR cryostat and HPSC.

The possibility of an ISS implementation was assessed, and found that the Columbus-EPF SDN ISS site was the most suitable for an actively or passively cooled TRUTHS payload until the ADS Bartolomeo addition is built, where more options exist. Finally, an assessment of the feasibility and reliability of the TRUTHS mission was carried out. It was determined that it is possible for the TRUTHS control electronics to be constructed entirely with space-qualified components, with all performance requirements being met. The reliability of the CSAR instrument was calculated as R = 0.971 for a 5 year mission, and 0.955 for a 7 year mission based on the 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 in CSAR and the calibration system, but better estimates could be made with improved reliability data for the laser didoes from the manufacturers or through testing. The main reliability drivers were identified for a 5 year mission as

- HPSC drive electronics (R = 0.9876, non-redundant)
- HPSC displacer and compressor (0.9969 & 0.9977 respectively, non-redundant)
- On-board computer controlling CSAR, (R = 0.9939, 2-for-1 cold redundant arrangement)
- Calibration system transfer radiometer (R = 0.9985, non-redundant)

Following feedback from a proposal made to EE9 an updated design and performance/stray light analysis was carried out for a potential Earth Imaging spectrometer, originally designed in CEOI 7 project. The design took advantage of improved detector performance which allowed a single HgCdTe detector array to span the spectral range from 2.4 um to 420 nm enabling a much simpler (two detector) imager to be realised without any compromise on performance. This new design removed earlier criticisms related to the novel use of a knife edge mirror to split the spectral bands on to different detectors and also any potential concerns on band to band co-registration for applications where higher spatial resolution was of importance i.e. > ~420 nm.

An extension to the study demonstrating the ability of TRUTHS to transfer its calibration and improve the performance of multi-spectral sensors like Sentinel 2 was carried out to account for spectrometer based sensor like OLCI of Sentinel 3. This study showed that, with the exception of bands near atmosphere absorption features, a similar performance improvement can be obtained over deserts and other targets. This work is the subject of a publication.

In addition to accommodation studies for the ISS the project undertook a relatively detailed system engineering based analysis of how the mission could be implemented on board a candidate ESA compliant ADS platform. The study considered, power, thermal, mass and data transmission requirements for the mission taking account of the relatively novel non-sun-synchronous orbit. The analysis showed that the mission could be accommodated on the smallest of the ADS standard platforms, Astrobus-S with relatively minor low risk updates to increase power and radiators to remove excess payload heat. Although data rate is relatively high it was shown to be compatible with a single download station based at Svalbard. Unfortunately, the positive results from this latter extension to the project was only partly completed in time for the final EE9 proposal submission. An overall ROM cost for the mission was determined at £133.5M including 20% margin but excluding launch and operations. This was broken down by key elements and presented in individual reports but the detail is subject to commercial considerations.

1.4 FINDINGS

In summary, the overall mission has been shown to be technically ready for implementation with no high risk developments required. The novel aspects of the mission, the on-board calibration system has been built and demonstrated at breadboard level under vacuum for all heritage elements and at a more detailed 'engineering model' level using flight consistent hardware for the most critical element the CSAR. The CSAR V2 having a factor 2 reduction in mass over the first prototype and coupled, in this project, to an upgraded ADS HPSC and can be considered at TRL 5/6. The demanding performance objectives of the mission (TSI 0.01% and Earth spectral radiances of 0.3% have been shown to be achievable with the on-board calibration system demonstrated with some margin at 0.12%.

A systems engineering analysis of the mission and in particular, the platform element and its operational mode, has similarly shown to be fully consistent with the capabilities of the smallest ADS platform even in a non-sun-synchronous orbit. Subject to resources being available TRUTHS could be ready for launch in 4-5 yrs as either a national (bilateral) or ESA managed mission.

Some further work is required, and in some cases underway, to optimise the payload before it can be considered a fully space-qualifiable design but none has any real associated risk, and would be considered normal at this stage of a mission development before implementation of a formal phase A/B.

- Improved shielding of CSAR/calibration system interface to reduce heat losses and reduce operating temperature of CSAR
- Redesign of the thermal link between CSAR and the HPSC cold finger
- Assessment of the dark current fluctuations of the NIR photodetector in the TR, possibly necessitating laser diode modulation in this wavelength regime
- Procurement and testing of space-qualifiable laser conjoiner i.e. with no moving parts
- Integration of white-light source for EI calibration interpolation
- Optimisation of uniformity of diffuser illumination
- Test calibration system with imaging spectrometer (not in vacuum)
- Breadboarding of Earth Imager