

THE TRUTHS CRYOGENIC ABSOLUTE RADIOMETER TEST RESULTS

Stefan Schulze-Walewski ^{*a}, Lisa Gambicorti^a, Morad Masaoudi^a, Piet Belgraver^a, Loic. Nicolas^a, Patrick Lochmatter^a, Loic Nicolas^a, Antonio Casciello^a, Elisabetta Rugi Grond^a, Florian Reinhard^b, Manfred Gyo^b, Wolfgang Finsterle^b, A. Sabino^c, Clément Chauveau^c, Aisha Qadir^d, Alexander Upcott-Gill^d, Pierre Coste^d, Alessandro Zuccaro Marchi^e, Wilfried Glastre^e, Cyril Torreton^e, Andrea Marini^e

^aThales Alenia Space in Switzerland, Schaffhauserstrasse 580, 8052 Zürich, Switzerland

^bPhysical Meteorological Observatory/World Radiation Centre (WbRC), Dorfstraße 33, 7260 Davos Dorf, Switzerland

^cMicos Engineering GmbH, Überlandstrasse 129. 8600 Dübendorf, Switzerland

^dAirbus Defence and Space, Portsmouth, United Kingdom

^eESA ESTEC, Noordwijk, The Netherlands

ABSTRACT

TRUTHS (Traceable Radiometry Underpinning Terrestrial – and Helio – Studies) was a climate space mission of the European Space Agency (ESA), designed to enhance by an order of magnitude our ability to estimate the Earth radiation budget through direct measurements and to establish a “metrology laboratory in space” to create a fiducial (International System of units – SI traceable) reference data, setting the gold standard reference for climate measurements to cross-calibrate other sensors and improve the quality of their data. TRUTHS’ main objective was to establish a benchmark measurement as a reference of the current radiative state of Earth, against which future observations can be compared to, facilitating improved climate model validation, forecast accuracy, and rapid assessment of climate change and mitigation measures.

As the mission prime contractor, AIRBUS was responsible for implementing TRUTHS with two key instruments: the Cryogenic Solar Absolute Radiometer (CSAR) and the Hyperspectral Imaging Spectrometer (HIS) taking measurements of incoming as well as Earth reflected solar radiation, complemented by a novel onboard calibration system. TRUTHS’ instruments measure the incoming solar radiation and the Earth-reflected radiation allowing to determine the Earth’s energy balance.

CSAR is designed to measure both the Total Solar Irradiance (TSI) and the optical power from the Onboard Calibration System (OBCS) ensuring SI-traceable spectral radiance measurements with an absolute accuracy better than 0.3% ($k = 2$). Thales Alenia Space Switzerland has led the Swiss consortium responsible for the development and testing of CSAR.

The goal of providing SI-traceable means for measuring the total solar irradiance with an uncertainty of below 0.02%, as well as calibrating its sister payload - the Hyperspectral Imaging Spectrometer (HIS) - posed significant multidisciplinary engineering challenges.

We present the technologies selected to meet these stringent measurement goals, detail the design of the CSAR breadboard, describe its commissioning with the associated Ground Support Equipment (GSE), and report the results from the TRL6 test campaign conducted in a representative environment. The achieved performance will be evaluated against the specified requirements, with key conclusions drawn to guide future developments.

Keywords: TRUTHS, CSAR, absolute radiometer, cross-calibration

*Stefan.Schulze-Walewski@thalesaleniaspace.com, phone +41 76 822 96 51, www.thalesaleniaspace.com

1. INTRODUCTION

TRUTHS was an international climate observatory, first proposed by the UK Space Agency to ESA in 2019 and started to be implemented as an operational mission in the ESA EO programme proposals at the ESA Ministerial Councils in 2019 and 2022 [1], [2]. The development underwent Phase B2.

TRUTHS was conceived to fulfill the need, over a long operational period, of international cooperation and data interoperability among different worldwide missions. This is made possible by the capability to cross-calibrate with other satellites. It opens up an operational service for improving the quality of other optical satellites, either institutional (e.g., Copernicus and Eumetsat series), either commercial (new space). The improved efficiency of the use of space and data asset via one satellite that improves the performance of many others fit in the strategic view of making space assets interconnected. It is also noteworthy that cross-calibration of TRUTHS with other satellites will even improve past datasets. The traceability to SI units and rigorous uncertainty tracing will allow trustworthy measurements with an accuracy never reached before. TRUTHS' unique calibration system might be optimized / miniaturized and become a novel package for calibration of other optical instruments calibration. As complement in new space economy contest, smaller satellites might be optimized to fully rely on calibration from TRUTHS' data service and will allow to simplify new optical payload development.

The TRUTHS payload contains

- a cryogenic solar absolute radiometer (CSAR) and
- a hyperspectral imaging spectrometer (HIS) as well as
- a novel onboard calibration system (OBCS)

In phase B2, the CSAR (Cryo Solar Absolute Radiometer) design was carried out in 2023-2024 (cf. [1]) and the BB TRL6 testing was performed. In this paper, the testing of the CSAR TRL6 bread-board (BB) is described.

2. CSAR OVERVIEW

The underlying principle of the CSAR is that of an electrical-substitution radiometer: the temperature of a Cavity black body is kept in constant thermal imbalance with respect to a reference block by means of a closed control loop actuating an electrical heater. The radiation heating the black body when the shutter is open is being substituted by the electrical heat when the shutter is closed. The difference in applied electrical power between the two states equates to the radiation power to be measured. The measurements are performed using a compensating Cavity in bridge configuration and operated at cryogenic temperatures. TRUTHS CSAR is operating at a higher temperature compared to studies presented in [3], [4].

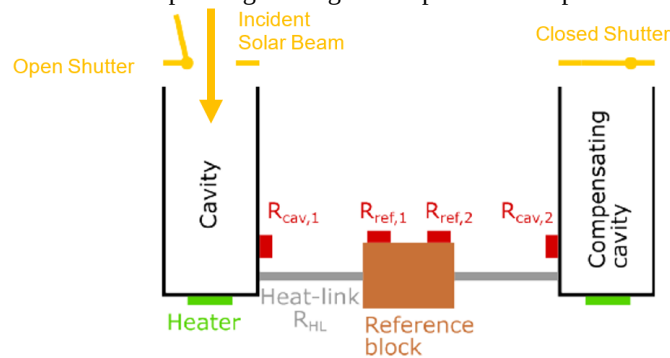


Figure 1 Measurement Block with two cavities, with one of them acting as compensating Cavity

The CSAR functional block diagram is reported hereafter (cf. Figure 2):

- The Control Electronics Box (CEB) providing the primary-to-secondary power conversion for the proximity electronics and each Cavity's Front End Electronics (FEE), the Telemetry (TM) and Tele-Command (TC) management, housekeeping data (HK) acquisition and proximity electronics control, as well as shutter operation during measurement cycles.
- The proximity electronics provide the control and measurement function of the Cavity FEE. The Cavity FEE is controlling the temperature of individual cavities, of the reference block, and of the Precision Aperture. It also provides an accurate measurement of the power delivered by the Cavity heaters through the metrology of internal voltages and currents.
- The Cryostat Cover Plate containing the Precision Aperture to shape the incident sun beam to the required dimension for the TSI measurements, a shutter to cover the line of sight of the individual cavities while not in use and related monitoring of shutter position, temperature and Precision Aperture temperatures.

- The measurement cavities with related temperature sensors and heaters using resistors.
- The field of view limiting apertures to limit the incident beam FoV and suppress background as much as possible
- The reference block with related thermistors and heaters to control the reference block temperature.

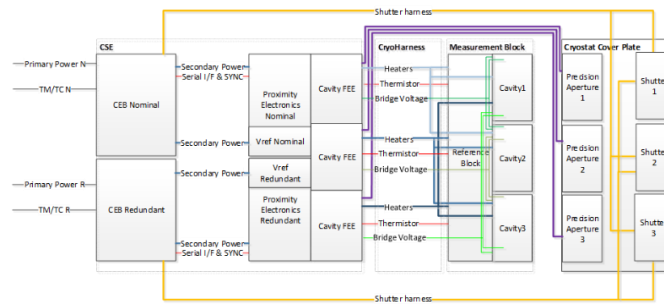


Figure 2 CSAR functional block diagram

3. VERIFICATION SETUP AND OBJECTIVES

The CSAR breadboard was tested in a dedicated verification setup Figure 3 at ESA/ESTEC premises, under vacuum at its operational cryogenic temperatures. The Cryo-GSE developed by Thales Alenia Space in Switzerland, houses the CSAR breadboard along with the Cover Plate from Thales Alenia Space in Switzerland and the Measurement Block from PMOD. The optical unit, which includes the laser source and measurement components, was positioned outside the chamber. The primary objective of the test campaign was to demonstrate Technology Readiness Level (TRL) 6 for the critical functions of the CSAR unit.

The verification setup of the CSAR breadboard is used for:

- monitoring the relative displacements (with respect to temperature) of the Cavities w.r.t. Field-Limiting Apertures / Precision Apertures and anticipating the Line-of-Sight (LoS) drift of each radiometric channel.
- checking the pre-compensation loads applied on the CSAR mechanical structure, calculated to guarantee a proper co-alignment of radiometric channels once in cryogenic conditions.
- supporting its alignment when the Measurement Block is installed in the Cryostat. The Cryostat Cover Plate on the other side is maintained at ambient temperatures and can be removed to allow the observation of the front face of the Measurement Block through a window.
- correlating the theoretical thermal model of the CSAR with respect to the reality in order to validate all sources of uncertainties linked to thermal design.
- alignment measurements using a motorized microscope as part of the equipment commissioning
- performing functional testing in the TSI configuration introducing a representative optical power stimulus
- performing sensitivity testing in the Continuous Acquisition mode using electrical stimulus.

Key challenges encountered in the design of the Cryo-GSE included:

- **Maintaining precise thermal conditions:** The Cover Plate needed to be held steady at 12°C, while the Measurement Block required a cryogenic temperature of 67 K. Both units had to maintain these temperatures consistently, with minimal thermal gradients across their surfaces. This was achieved by mounting the Cover Plate on a thermally controlled support bracket and enclosing the Measurement Block within a thermally regulated Copper Case ("Cold Screen") connected via a thermal strap. Additionally, the Measurement Block was linked to a second thermal strap to ensure effective temperature control.

- **Providing mechanical support with minimal interface loads:** The Cover Plate was supported using flexed interfaces to minimize mechanical stress, while the Measurement Block was mounted using three pairs of thin sheet metal bipods arranged in an isostatic configuration, ensuring stable support with low interface loads.

- **Ensuring stable optical alignment throughout thermal transitions:** All optical elements on both the Cover Plate and the Measurement Block needed to maintain precise alignment during cooling from ambient to operational temperatures. At the same time, the design had to allow injection of a representative sun beam into the CSAR system and enable observation of the optics from outside the chamber by the optical unit. To observe and characterize the optics on the underlying Measurement Block, an initial test was performed prior to installing Cover Plate in a subsequent test phase.

The Cryo-GSE design successfully implemented and utilized during the CSAR test campaign is shown in Figure 3.

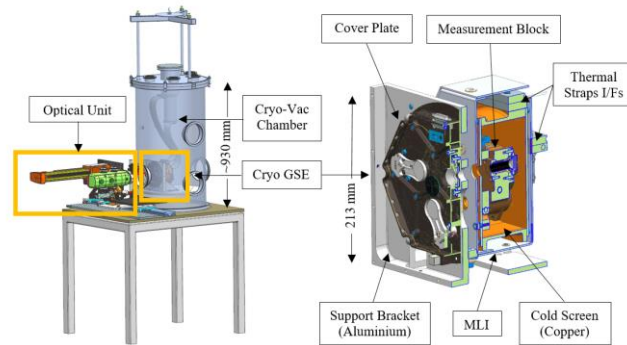


Figure 3 Overview of verification setup (left) of BB CSAR and Cryo-GSE (right) located within a cryo-vacuum chamber.

The respective hardware implementation of the Cryo-GSE setup for the primary test configuration, used to verify the Measurement Block and CSAR, is shown in Figure 4.

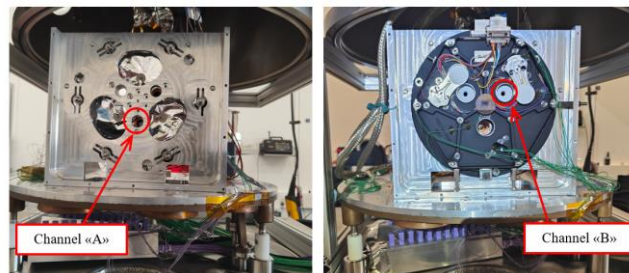


Figure 4 Cryo-GSE setup with Measurement Block test setup (left) and complete BB CSAR including Cover Plate (right)

The following objectives have been established for verifying the CSAR BB, focusing on demonstrating TRL6 Critical Function (CF) and technologies with an emphasis on testing:

- CF1: Demonstrate that the Cavity subsystem (Cavity + coating + heat link + flange) can sustain the full MAIT process and meet environmental constraints without performance degradation (absorptivity or unusual particle fallout, CSAR BB Test).
- CF2: Demonstrate the manufacturing of the Precision Aperture (PRA) with the intended profile, including control of the land profile of the PRA centre hole (CSAR BB PRA component tests).
- CF3: Demonstrate that the harness, particularly the copper wire thermistors, can withstand cryogenic temperatures (CSAR BB Test).
- CF4: Demonstrate that an SI-traceable PRA surface measurement within the accuracy required by the performance budget is feasible at +20°C (CSAR BB PRA component tests).
- CF5: Demonstrate that the Coefficient of Thermal Expansion (CTE) of a built PRA can be measured with the required accuracy (CSAR BB PRA component test).
- CF6: Demonstrate that Field of View Limiting Aperture (VLA) center position relative to the reference block interface frame does not exhibit any hysteresis when subjected to thermal cycling (CSAR BB Test).
- CF7: When the Cover Plate is integrated into the Cryo-GSE at cryogenic temperature, demonstrate that the positions of both the VLA and the PRA decenter can be determined with the correct uncertainty relative to the same external reference frame (CSAR BB Test).
- CF8: Demonstrate that the absorptivity of the coated Cavity can be measured at ambient temperature with the required accuracy for the spectrum of 320–2400 nm and for solar radiation (TSI budget, CSAR Cavity sample tests).
- CF9: Demonstrate, through review of available data that the reflectivity remains unchanged within measurement accuracy w.r.t. possible water absorption (Cavity sample tests).
- CF10: Demonstrate the capability for SI traceability of the shunt resistors on-ground (CSAR BB electronics tests).
- CF11: Confirm the contributors to electrical-optical equivalence using a step-and-stare optical beam (slightly divergent) and verify sensitivity to beam lateral displacement relative to the bottom of the Cavity (CSAR BB Test).
- CF12 Continuous Acquisition Mode (CAM) demonstration using electrical stimulus (CSAR BB Test).

4. COVER PLATE ASSEMBLY VERIFICATION

The Cryostat Cover Plate accommodates

- the shutters and Hall effect sensors to confirm their state,
- the Precision Aperture assemblies including their mounts and - fixations,
- the Cryostat cover base-plate and cover to hold all constituting elements,
- the reference cube and spheres for accurate Precision Aperture alignment and alignment traceability.

The Cryostat Cover Plate contains a Precision Aperture that shapes the incident solar beam to the required dimensions for TSI measurements. The Precision Aperture is intentionally overfilled, meaning the beam exceeds the Precision Aperture size. Consequently, the TSI measurement is computed as the ratio of the power entering the Cavity to the surface area of the Precision Aperture. To minimize its contribution to the uncertainty of the irradiance measurement, the area of the Precision Aperture must be determined with a precision better than 50 ppm ($k = 2$).

Key challenges encountered in the design of the Cryostat Cover Plate included:

- Maintaining the alignment of the three Precision Apertures within the thermal environment of the Cryostat Cover Plate relative to the CSAR reference frame.
- Mitigating the incident solar beam power during TSI measurements to reduce thermal gradients in both the Cryostat Cover Plate and the Precision Apertures.
- Minimizing the impact of thermal distortion on the individual Precision Apertures, ensuring that any deformation does not affect their area and thereby compromise the absolute accuracy of the TSI measurement.
- Integrating relevant alignment features into the Precision Apertures to enable verification of their position relative to the CSAR reference frame, using information derived from the Measurement Block.

Accurate measurement and characterization of the Precision Aperture's CTE and its area are critical to achieving the instrument's required operational accuracies. Results from the BB PRA tests indicated a measurement uncertainty of 47 ppm, which remains within the target defined by the radiometric budget but exceeds the more ambitious goal of 30 ppm. The achieved land uncertainty of $2.4 \mu\text{m}$ is within the radiometric budget limits, successfully meeting objectives CF2 and CF4. The CTE verification included an uncertainty analysis of the PRA's impact on system sensitivity, aiming to rely on standard measurement techniques to fulfill objective CF5.

Following verification of the shutter operation timing, a preliminary metrology inspection was conducted on the Cover-Plate. The objectives were to:

- Verify the positions of the PRA-Assemblies.
- Ensure proper concentricity among the PRA, and PRA-Baffle (Figure 5).

This verification utilized contactless metrology equipment and was performed in two stages:

- First, a Digital Measurement Microscope was used to assess the alignment of the PRA relative to the PRA-Baffle (Figure 5).
- Second, a 3D-Scanner and a Laser Tracker were employed to measure the alignment of Channels B and C relative to the Cover Plate reference features.

The alignment verification was successfully completed at ambient temperature prior to integration into the Cryo-GSE, in preparation for the CSAR verification.

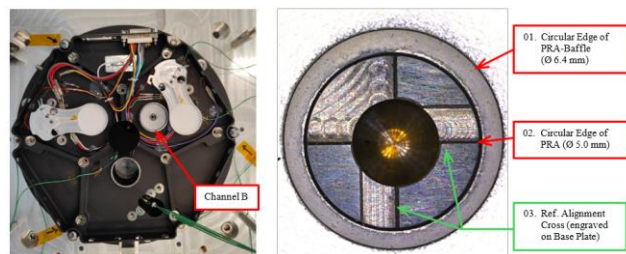


Figure 5 Cryostat Cover Plate cover assembly (left), verification of Precision Aperture (PRA) alignment on Channel B, observed under a Digital Microscope (right)

5. MEASUREMENT BLOCK OPTO-MECHANICAL VERIFICATION

The Measurement Block comprises three View Limiting Apertures (VLA), three Cavity assemblies, the reference block, the cryo harness and associating interconnecting elements (Figure 6).

The design of the Measurement Block needed to address the following challenges, which were verified during the BB test campaign:

- Minimizing thermal gradients between the three cavities to maintain symmetry between measuring and compensating cavities.
- Optimizing electro-optical equivalence with respect to the beam diameter within the cavities and the cavity heater, to minimize uncertainties in the radiometric budget.
- Pre-compensating the position and tilt of the measurement cavities relative to the CSAR reference axis to ensure CSAR's optimal alignment with the Sun (TSI measurement) and OBCS (HIS calibration) at cryogenic temperatures.

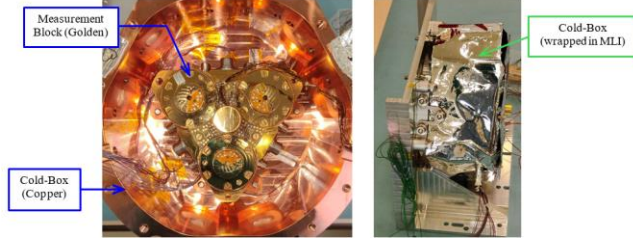


Figure 6 Measurement Block installed into Cryo-GSE cold box (backside view) and integrated into the L-bracket (right)

To characterize the spectral reflectivity of the cavities, the “Cavity effect” C_{ce} and its uncertainty u_{ce} is measured at different discrete wavelengths. C_{ce} is the ratio of the reflectivity of a flat sample, representative of the Cavity coating, to the reflectivity of the Cavity itself. This factor can be used to scale the spectral reflectivity $R(\lambda)$ and its uncertainty $u_R(\lambda)$ of the flat sample, which was calibrated by a National Metrology Institute (NMI). The spectral reflectivity of the Cavity is then $R_c(\lambda) = \frac{R(\lambda)}{C_{ce}}$ and the corresponding uncertainty

$$u_{R,c}(\lambda) = R_c(\lambda) \sqrt{\frac{u_{C_{ce}}^2}{C_{ce}^2} + \frac{u_R^2(\lambda)}{R^2(\lambda)}} \quad (1)$$

Incorporating features for alignment verification both before and after cooldown to cryogenic temperatures enables accurate determination of the VLA orientation and position within the alignment budget of the Precision Apertures located on the Cryostat Cover Plate.

The total spectral reflectivity of the cavity assemblies (CF8) was verified in a separate test setup at three distinct wavelengths (532, 808, and 1064 nm) using an integrating sphere.

The verification of the alignment during the BB test focused on collecting XY displacements induced by cryo-cooling shrinkage on the Cryo-GSE. These displacements were measured specifically on Cavity A, using a digital microscope equipped with a long working-distance objective (WD = 300mm). To track the movements of Cavity A interior, a bare metallic inner surface marked with three black crosses at the bottom was implemented (on the blank Cavity). To verify the motions of the Measurement Block components, the following features within the Cavity A channel were monitored during thermal cycling between ambient temperature and cryogenic temperatures and vice versa:

- 2x cross-marks inscribed on the cavity bottom
- VLA Aperture
- Cold-Screen Aperture (part of Cold Screen)
- L-Bracket Aperture

The chosen method for displacement measurements uses raw images captured by the microscope, which are analyzed through an image cross-correlation technique. In brief, the image processing software takes a reference pattern as input and searches for it in each image acquired during the test sequence (cryogenic or ambient temperature). The resulting XY position corresponds to the point of maximum correlation, indicating where the reference pattern is most likely located.

Figure 7 overlays the X-displacements of the L-bracket aperture, the Cold Screen aperture, and the VLA aperture measured during the cryo-vac testing, alongside the corresponding displacements predicted by FE analysis. The test results and the FE predictions exhibit very similar characteristics. However, the experimental setup shows some additional drift throughout the test campaign (for instance, a slight mismatch between the initial and intermediate ambient temperature positions), which is not captured in the FE analysis.

The tilt of the cryogenic setup was measured by placing a mirror at the position of Cavity C. The angular drift recorded over two cycles to cryogenic temperatures remained within 150 μrad .

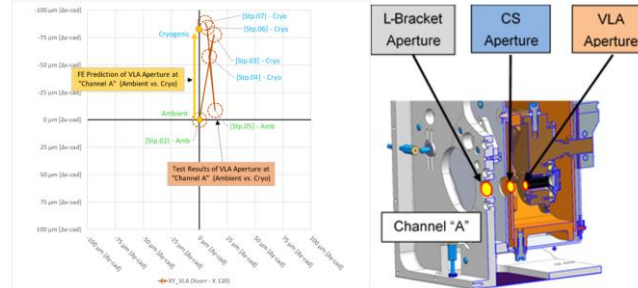


Figure 7 Overlay of XY displacements measured on the CSAR Cryo-GSE vs. predictions by Analysis

6. MEASUREMENT BLOCK ELECTRICAL VERIFICATION

To enable CSAR operation, the Measurement Block and Cavity temperature control loops require commissioning and parameterization. A 10 mW heating power step was applied to the reference block, and the resulting change in the reference block bridge voltage was recorded. The step response follows an exponential curve (Figure 8), indicating that the reference block can be thermally modelled as a first order system

$$G(s) = \frac{1}{Cs+K}.$$

The amplitude of the response corresponds to the apparent conductive thermal interface (or “heat-link”) K , while the time taken to reach $1 - e^{-1} \approx 63.2\%$ of the step height is the time constant. This time constant depends on the heat capacity C of the reference block and is given by: $\tau = C/K$.

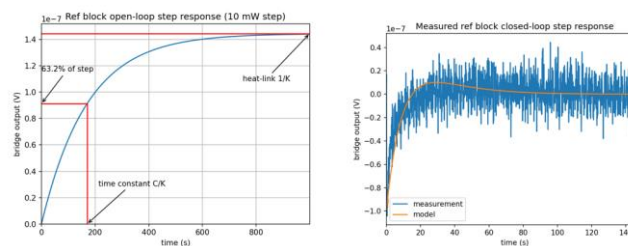


Figure 8 Reference block open-loop step response (left), Reference block closed loop step response (right)

Similarly, the Cavity controller has been commissioned and its noise performance was measured, Figure 9.

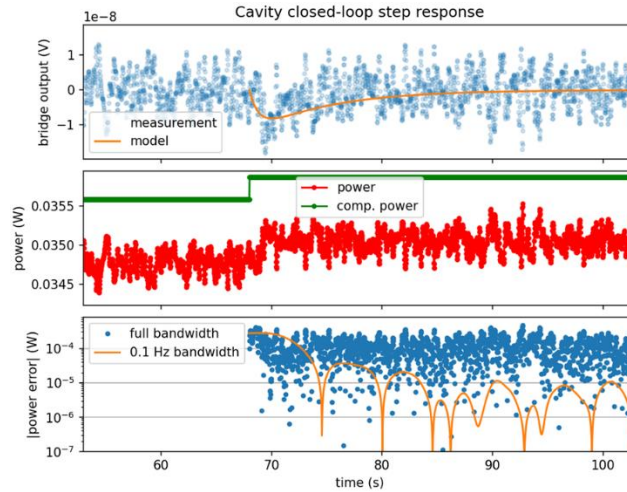


Figure 9 Cavity controller closed loop performance

The successful demonstration of CF12, the Continuous Acquisition Mode, has been performed using electrocical disturbances on the compensating cavity, which is operated in open loop and extracting the measured correction from the measurement cavity, thus verifying the instrument accuracy in presence of disturbances on the cold screen and the cold finger.

7. CSAR INTEGRATION AND VERIFICATION

The prior verification on the Cover Plate, the Measurement Block opto-mechanical verification, and the Measurement Block electrical verification are prerequisites for the CSAR verification. The pre-tested components of CSAR were integrated into the Cryo-GSE.

Measurements were conducted on the Cryo-GSE without the Cover Plate to determine the positions of the optical elements (VLA) relative to the L-Bracket prior to Cover Plate integration (Figure 10). Data from 3D Scanner measurements (using Leica LAS, with Leica T960-MR) were then used to precisely align the Cover Plate with the L-Bracket and Measurement Block within the Cryo-GSE. The resulting alignment on the measurement channel B – particularly the in-plane biases of the PRA placement – accommodates the expected shrinkage of the Measurement Block during cool-down to cryogenic temperatures. The achieved uncertainties on the concentricity are $\pm 20 \mu\text{m}$.

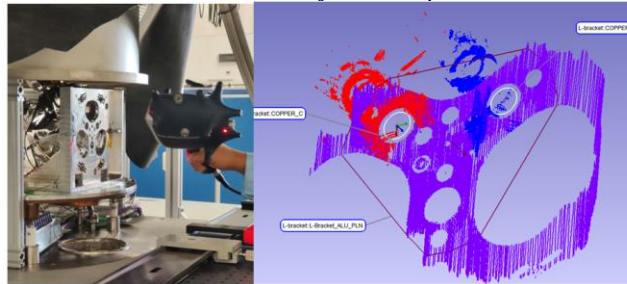


Figure 10 Front Face scan of L-bracket in Cryo-GSE setup (left) and obtained map (right)

After cool-down to operational temperatures, the setup shown in Figure 11 was used to verify the electrical-optical equivalence. The optical setup located outside the chamber enables to position the laser beam, allowing it to be directed onto the bottom of the Cavity. Additionally, the setup permits adjustment of the beam diameter to under-fill the Precision Aperture during this test.

The electrical-optical equivalence verification aims to confirm that the Cavity is insensitive to beam displacement on the Cavity bottom, specifically with respect to the heater misalignment between the Cavity heaters and the incoming optical beam. To minimize diffraction effects, a beam diameter smaller than the Precision Aperture was selected. However, during the test campaign, demonstrating electro-optical equivalence proved challenging due to several factors: the influence of the Cryo-GSE optical window, diffraction of the beam at the Precision Aperture of the Cover Plate, and inherent laser

beam properties. As a result, the expected flat Cavity response with respect to the incoming beam position could not be clearly demonstrated, limiting thus the conclusiveness of the CF11 demonstration.

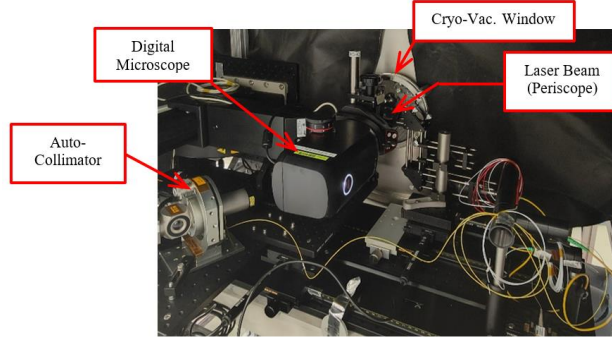


Figure 11 Optical Setup in front of Cryo-GSE

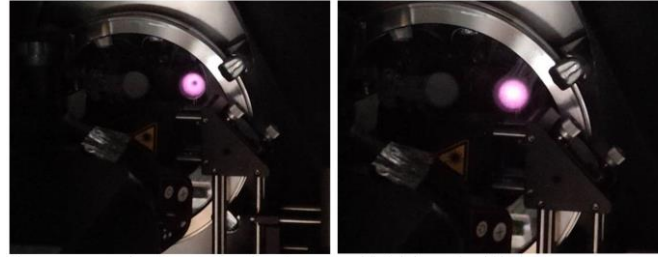


Figure 12 TSI operation of CSAR- Channel B : Shutter Opened (left) / Shutter Closed (right)

After completing the electro-optical verification, the simulated Total Solar Irradiance measurements were performed. The setup was modified to use a larger beam to overfill the Precision Aperture while keeping all alignments.

Figure 12 shows the power applied to the measuring Cavity during closed shutter cycles. The circular footprint of the TSI laser beam fully covers the white PRA-Baffle of Channel-B. Although the laser emits near infrared radiation at 980 nm (invisible to the naked eye), the intensity on the PRA-Baffle is sufficiently high for the digital camera to detect the NIR light, which appears as a pinkish glow in the image.

The plots in Figure 13 illustrate both the repeatability of the measurements - evidenced by the similarity of the different curves - and the time required for the signal to stabilize. The plot on the right presents the standard deviation of the same signals, where each data point corresponds to the standard deviation calculated from that time point until the end of the shutter cycle, defined as $std_after(t) = std(power([t: 75s]))$. This analysis is useful because once the signal converges to the background noise level, the standard deviation remains constant. In this case, convergence occurs around $t = 40$ s. Note that the increased variation towards the end of the cycle results from the decreasing number of samples used to compute the standard deviation.

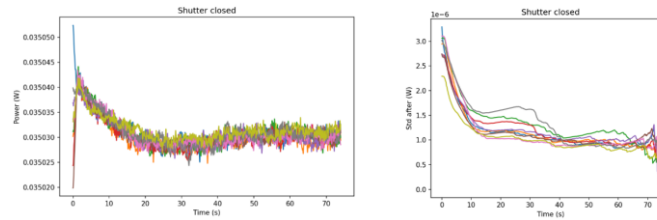


Figure 13 Electrical power applied to the cavity heater during shutter closed cycles. At $t = 0$, the shutter transitions from open to closed.

Figure 14 shows the corresponding data for shutter-open cycles. Unlike the closed-shutter case, the signal does not converge. This behavior is believed to result from fluctuations in the light source that exceed the measurement noise over the duration of a shutter cycle.

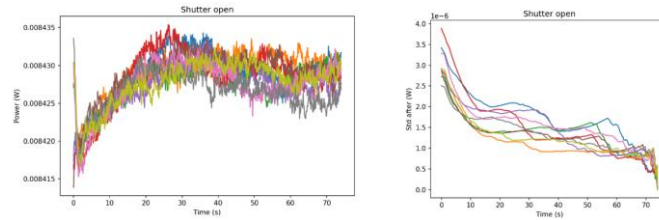


Figure 14 Electrical power applied to the cavity heater during shutter open cycles. At $t = 0$, the shutter transitions from closed to open.

In Figure 15, the sections of the shutter cycles where the signal has stabilized are extracted to evaluate the TSI measuring capabilities of the instrument. The plot displays the electrical power applied to the measuring cavity minus the electrical power applied to the compensating cavity during shutter-open cycles (blue). For shutter-closed cycles (red), the same difference is shown with the addition of the average estimated optical power (~ 26 mW).

The average “power value” of approximately 1 mW observed in this plot is not relevant for performance analysis; ideally it would be zero. This offset arises due to heat-link asymmetries, an imperfectly balanced Cavity bridge, and controller limitations.

The horizontal black lines indicate the mean of the final 35 seconds of each cycle with $k = 2$ error bars. The closed shutter cycles exhibit relatively constant mean values across cycles, suggesting converged signals and a thermally stable system. In contrast, the open shutter cycles show greater variability despite similarly narrow error bars. This variability indicates fluctuations in the light source power on the order of several μ W during these measurements.

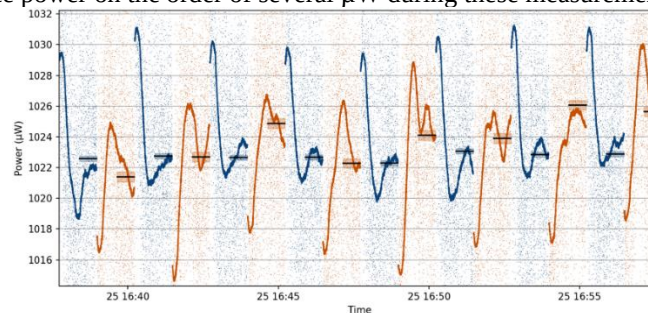


Figure 15 Analysis of TSI measurements with 75s-75s shutter cycles

8. CSAR INTEGRATION AND VERIFICATION

TRUTHS (Traceable Radiometry Underpinning Terrestrial – and Helio Studies) was an operational climate space mission of European Space Agency (ESA), scheduled for launch in 2030. Its primary objective was to improve our ability to estimate the Earth radiation budget by an order of magnitude through direct measurements. Additionally, TRUTHS aimed to establish a “metrology laboratory in space” to provide fiducial, International System of Units (SI)-traceable reference data.

This paper summarizes the TRL6 results of the Cryogenic Solar Absolute Radiometer (CSAR), demonstrating the successful validation of its critical functions:

- Opto-mechanical alignment of Cryo-GSE, Measurement Block and Cover Plate
- Derivation of the time constants for the Cavity and the Measurement Block
- Measurement noise characterization
- Simulated Total Solar Irradiance (TSI) tests
- Shutter operation and synchronization with the FEE
- Sensitivity tests for disturbances affecting the cold screen, cold finger, and Cover Plate

Improvements identified for the CSAR relate to optical design updates for coating to minimizing the impact on aperture diameters, qualification and delta-measurement of coating properties and refinement of integration steps to confirm accessibility to markers during instrument integration. Electrical design updates comprise better shielding sensitive signals to further reduce the noise, optimization of gain selection, separation of functions for signal generation of measurement

block and cavity to remove interdependencies. Wiring improvements and routing optimization for the cryogenic part of the measurement bridges for simplified interconnection and replacement of cavities. Additionally, in the future, special attention should be given to the Optical Ground Support Equipment (OGSE) and the illumination setup of the Cavity to minimize the influence of optical elements along the optical path from the source to the Cover Plate entrance channel. In particular, efforts should focus on reducing diffraction effects and enhancing source stability to minimize temporal variations in the optical power delivered by the source.

ACKNOWLEDGMENT

The activities are carried out under a programme of and funded by the European Space Agency (ESA). The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

We extend our sincere thanks to the prime contractor, ADS UK, for their leadership and invaluable collaboration throughout this project. Additionally, we appreciate the contributions of our industry partners, particularly PMOD and MICOS, whose support was crucial to the successful completion of the CSAR activities.

REFERENCES

- [1] https://www.esa.int/Applications/Observing_the_Earth/TRUTHS
- [2] <https://space.oscar.wmo.int/instruments/view/csar>
- [3] Martin, J.E., Fox, N.P. Cryogenic Solar Absolute Radiometer - CSAR. *Sol Phys* 152, 1–8 (1994). <https://doi.org/10.1007/BF01473175>
- [4] Martin, J.E., Fox, N.P. (1994). Cryogenic Solar Absolute Radiometer — CSAR. In: Pap, J.M., Fröhlich, C., Hudson, H.S., Tobiska, W.K. (eds) *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-0950-5_1
- [1] Schulze-Walewski, Stefan, Gambicorti, Lisa, Masaoudi, Morad et al. 2025/07/28, The TRUTHS cryogenic solar absolute radiometer (CSAR), 10.1117/12.3071591