Overview and prospects of thermography in the Test Centre of the European Space Agency

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Abstract

Infrared thermography has been a cornerstone technology in the Test Centre of the European Space Agency since 2009, providing insights into thermal characteristics and behaviours of various aerospace components and systems. We explore the diverse applications of infrared thermography in spacecraft thermal vacuum testing. Looking ahead, we envision the future trajectory of infrared thermography at ESA, focusing on low temperature measurements and miniaturization. This paper aims to provide an overview of the past achievements, current capabilities, and future prospects of infrared thermography within the ESA Test Centre, underscoring its pivotal role in ensuring the success and safety of space missions.

1. Introduction

The European Space Agency (ESA) operates a Test Centre at ESTEC, in Noordwijk, The Netherlands; a unique place in Europe which is geared to perform environmental tests on large spacecraft and aerospace structures. The Test Centre includes a complete portfolio of test facilities to simulate the environmental conditions which are experienced by a spacecraft during its launch and operations. The harsh environmental conditions of space, i.e. vacuum, temperature extremes and solar illumination are simulated within thermal vacuum chambers. The Large Space Simulator (LSS) is the largest thermal vacuum test facility in Europe (**Figure 1**). For more information, please visit to our Virtual Tour [1].

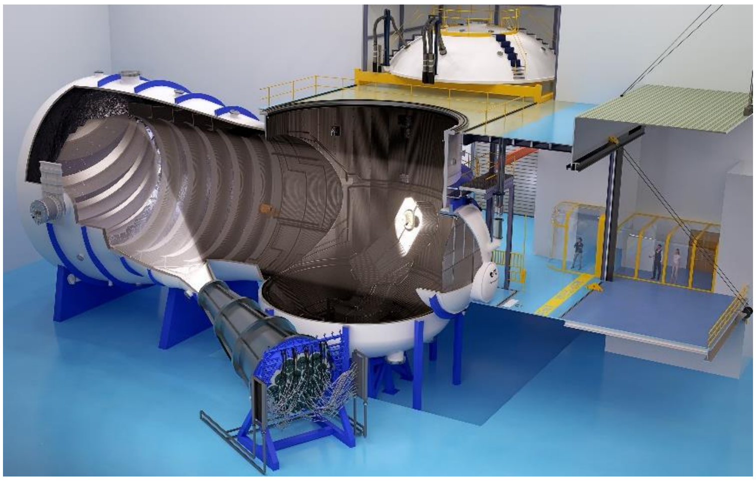

Figure 1 *Large Space Simulator (LSS)*

Spacecraft undergo thermal vacuum (TV) and thermal balance (TB) testing with the goal of collecting the data necessary for the verification and tuning of their thermal model as well as to assess the effectiveness of the thermal protections and thermal controllers. The latter being vital for the survival and correct functioning of a spacecraft.

During thermal-vacuum tests, the knowledge of the temperature distribution of the test article is required. Traditional thermal sensors, e.g. thermocouples or thermistors, are often complemented by thermal cameras. Infrared thermography offers reduced instrumentation time and detailed temperature mapping of external surfaces, providing contactless, instantaneous multi-point measurements of temperature.

The Engineering Services Section of the ESA Test Centre supports the test execution performing measurements and developing test instrumentation. Infrared thermography has been for years one of the major measurement capabilities of the Engineering Services Section supporting several of ESA's scientific projects. This paper reviews the history, current status, and future plans for infrared thermography in the Test Centre of the European Space Agency.

The first vacuum compatible thermography system of ESA was conceived in 2009, and used for the first time for GAIA [2] with the aim to be ready for BepiColombo and other, at the time upcoming, high solar intensity missions, e.g. Solar Orbiter and JUICE (**Figure *2*** and **Figure 3**).

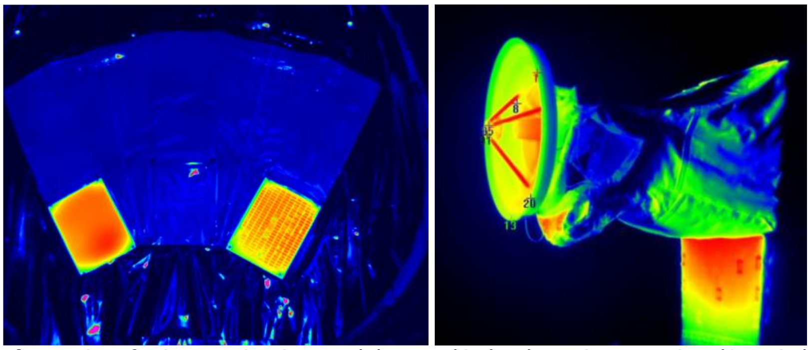

Figure 2 *Left: GAIA DSA STM. Right: BepiColombo HGAMA EQM (©TAS-I)*

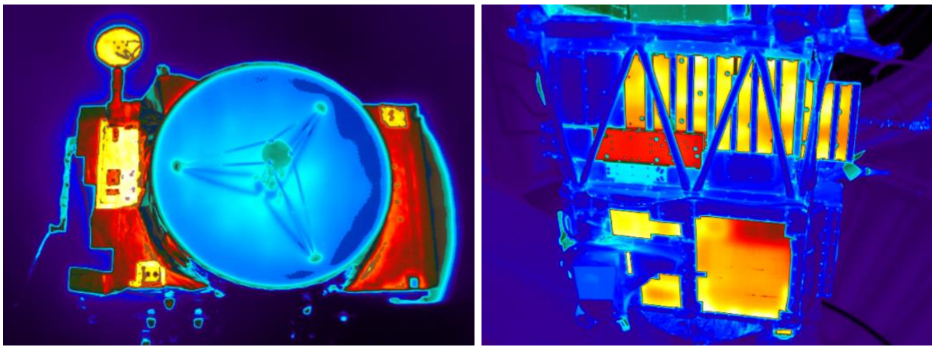

Figure 3 Tests of *JUICE and EarthCARE (©ESA/Airbus)*

The first camera system relied on commercial off-the-shelf (COTS) canisters to keep the cameras in ambient pressure. Over the years, the instrumentation has been updated with new cameras in canisters developed in-house and a retrofitted bolometer camera which can operate in vacuum without a canister. New capabilities were also added, e.g. the in-house measurement of emissivity. Most recently, the need has been identified for future measurements to be performed at low temperatures, i.e. down to -100 °C, and to calibrate cameras down to such cold temperatures.

2. Canister-based thermography systems

2.1. Legacy FLIR SC7600-based system (MWIR and LWIR)

Since its introduction in 2009, the canister-based infrared system using the FLIR SC7600 series cameras has been a fundamental asset of the ESA Test Centre [3] (**Figure 4**).

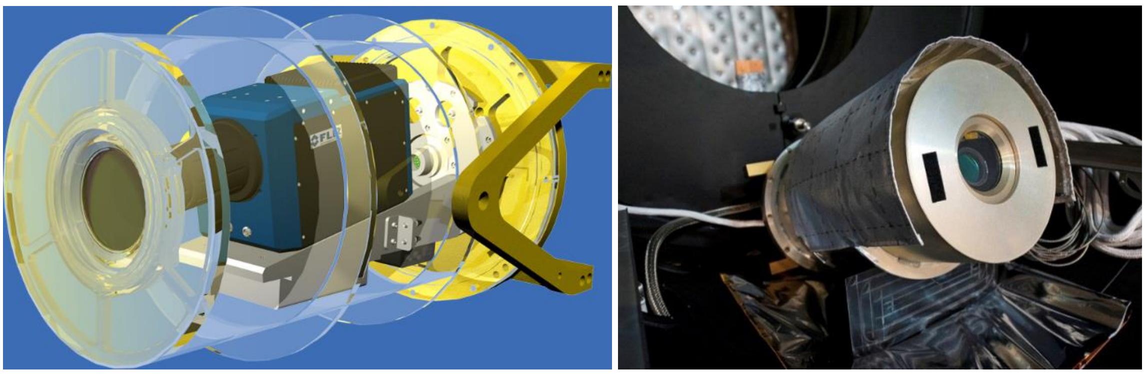

Figure 4 *Canister-based infrared system with FLIR SC7600 series camera*

The SC7600 series camera is installed in a canister for operations in thermal vacuum chambers (TVAC). The chamber's environmental temperature can range from -180 to +40 °C. Thermal control of the canister is by a heater and the circulation of gaseous nitrogen (GN2). Multi-layer insulation (MLI) is installed on the outside of the canister to insulate it thermally from the test chamber. The cameras have cooled detectors and motorized lenses, for remotely controlled focusing. Motorized focusing is a must because it is often required to re-focus the cameras during a test due to varying operating conditions. The cameras are available in both medium-wave and long-wave versions, MWIR and LWIR, respectively (**Table 1**).

Table 1. *Overview of technical specifications of FLIR SC7600 series cameras*

Wavelength		Resolution	Calibrated temperature range	Detector type	Max. frame rate
MWIR	3 – 5 µm	640 x 512	+5 to +350 °C	InSb	100 Hz
LWIR	7.85 – 9.5 µm	640 x 512	-20 to +150 °C	MCT	100 Hz

Multi Integration Time (IT) recording, called Superframing, is available. The camera is equipped with a motorized filter wheel. In case of solar simulation and MWIR camera, a 3 – 5 µm bandpass filter is used to filter out the solar simulator's light reflected into the camera. The cameras are calibrated together with the canister's window, while the window is mounted in a custom holder. The material of the window is matched to the type of detector, MWIR or LWIR. Up to three canisters can be used simultaneously, with two control racks. Communication with the camera is through optical fibres.

Recently, it has been observed that the cameras are exhibiting signs of aging. The operational lifespan of the camera is primarily constrained by its Stirling cooler. Moreover, their maintenance and operation are complex and costly. In 2025, a new-generation canister-based infrared camera system was introduced, replacing the SC7600 system (Section 2.2).

2.2. New FLIR A8581-based system (MWIR)

The FLIR SC7600 series cameras are being replaced by FLIR A8581 cameras (**Table 2**). These are also cooled cameras, having improved performance, e.g. higher resolution, and smaller volume. New, more compact canisters were designed in-house to protect the cameras from the environmental conditions of TVAC tests (**Figure 5**). The new canisters are largely compatible with the existing mechanical ground support equipment (MGSE) of the previous generation system. A new control rack has been deployed for housekeeping and infrared acquisition. The control rack provides temperature control, GN2 flow control, pressure measurement and power supply to the camera system.

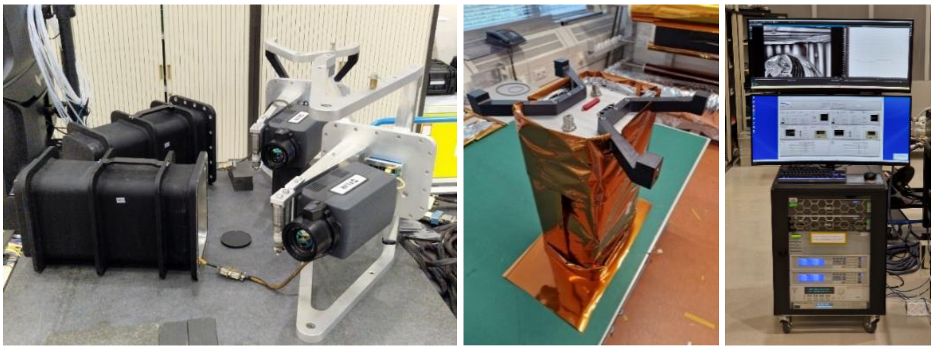

Figure 5 *FLIR A8581 cameras, canisters and control rack*

Table 2. *Overview of technical specifications of FLIR A8581 cameras*

Wavelength		Resolution	Calibrated temperature range	Detector type	Max. frame rate
MWIR	3 – 5 µm	1280 × 1024	-20°C to 350°C	InSb	45 Hz (GigE)

The chamber's environmental temperature can range from -180 to +40 °C. Thermal control of the canister is by a heater and gaseous nitrogen (GN2) circulation. Multi-layer insulation (MLI) is installed on the outside of the canister to insulate it thermally from the test chamber. The cameras have cooled detectors and motorized lenses, for remotely controlled focusing.

Multi Integration Time (IT) recording, called Superframing, is available. The camera is equipped with a motorized filter wheel. In case of solar simulation, a 3 – 5 µm bandpass filter is used to filter out the solar simulator's light reflected into the camera. The camera is calibrated together with the canister's window (CaF2), while the window is mounted in a custom holder. Up to two canisters can be used simultaneously, with a single control rack. Communication with the camera is through Ethernet, which shall improve reliability compared to the optical fibre communication of the SC7600 based system.

3. Canister-free thermography system, based on FLIR A655sc

The canister-based infrared systems introduced in Section 2 deliver cutting-edge performance in terms of resolution, sensitivity, accuracy and measurement temperature range. On the other hand, their bulky canisters and cable harnesses make their installation complex and, in some cases, represent a limitation for their use. Complementing the capabilities of the canister-based systems, a canister-free solution has been developed in-house and supported several test campaigns successfully [4]. The canister-free solution is reducing the complexity of the installation and operation. The reduced volume and mass ensure more flexible positioning around the test specimen. The lack of GN2 flushing means simpler operation and reduced risk of leakages. Due to the camera not looking through a window, standard calibration can be applied, i.e. avoiding expensive and time-consuming special calibration procedures.

The canister-free infrared system is based on the FLIR A655sc camera (**Figure 6**). The camera's uncooled bolometer detector is sensitive in the long-wave IR range (7.5 - 14 µm), with a resolution of 640 x 480 at a maximum of 50 Hz. The camera is equipped with a motorized lens, allowing for remotely controlled focusing. The standard calibrated temperature range is -40 to +150 °C or +100 to +650 °C.

***Figure 6** FLIR A655sc camera*

The camera had been retrofitted in-house to be compatible with the environmental conditions of thermal-vacuum testing of spacecraft. The main requirements for retrofitting were to continuously operate in a vacuum environment, in the temperature range between -180 to -40 °C, while keeping the camera in its operational temperature range of -15 to 50 °C. Additionally, the camera shall operate in vacuum at +20 °C for at least 10 minutes without overheating.

To thermally insulate the camera from the test specimen and the thermal chamber, most of the camera is wrapped in a 10-layer MLI blanket. Apart from the lens on the front side, there are no warm parts of the camera visible to the test item. The backside of the camera, where the connectors are located, is an MLI-free, black anodised, octagonal-conical aluminium part (**Figure 7**). This part is directly coupled with the PCB stack, and it is meant to act as a radiator by removing the heat generated by the camera. A dedicated control rack is responsible for supplying power to the camera and the heaters installed on the camera body and lens.

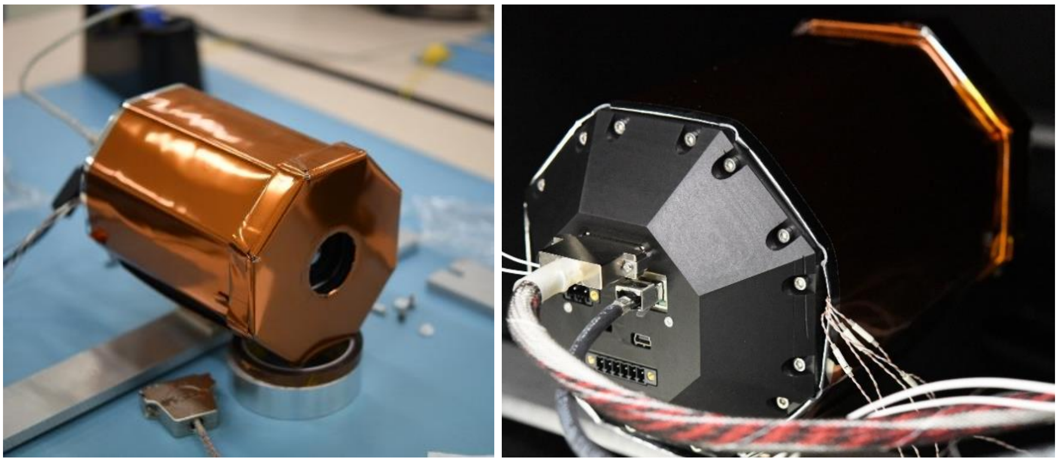

***Figure 7** Retrofitted canister-free IR camera FLIR A655sc*

There is an ongoing effort to calibrate our cameras in vacuum, particularly for the low temperature range down to -100 °C. For details see Section 5.1.

4. Measurement of emissivity

The knowledge of the emissivity of the test item is important to accurately measure their temperature. Emissivity varies with temperature, incident angle and wavelength. Two emissivity measurement benches are available in the Test Centre of ESA. Performing the end-to-end measurement of emissivity in house allows to perform thermography with better accuracy than if the emissivity was simply adjusted during a test based on the knowledge of temperature values by contact sensors.

One of the emissivity measurement benches of the Test Centre of ESA allows for the adjustment of the sample's angle. This device has got a measurement temperature range between 20 - 180 °C and inclination angle between 0 - 45° (**Figure 8**).

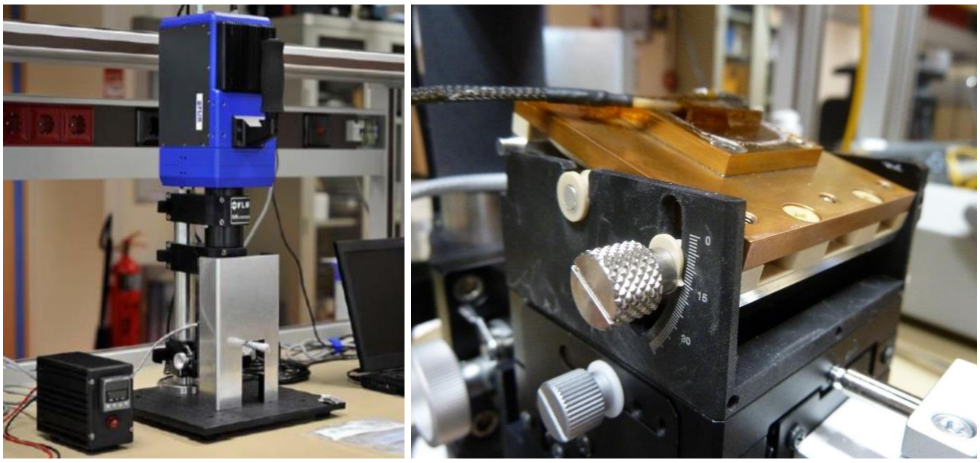

Figure 8 *Tiltable emissivity bench, 20 – 180 °C*

Another emissivity bench has got a higher temperature range, 20 - 450 °C, but without the option to change the angle of the sample (**Figure 9**). A mechanical system composed of a spring and a magnet allows the support to open and the sample to be exposed to the camera lens.

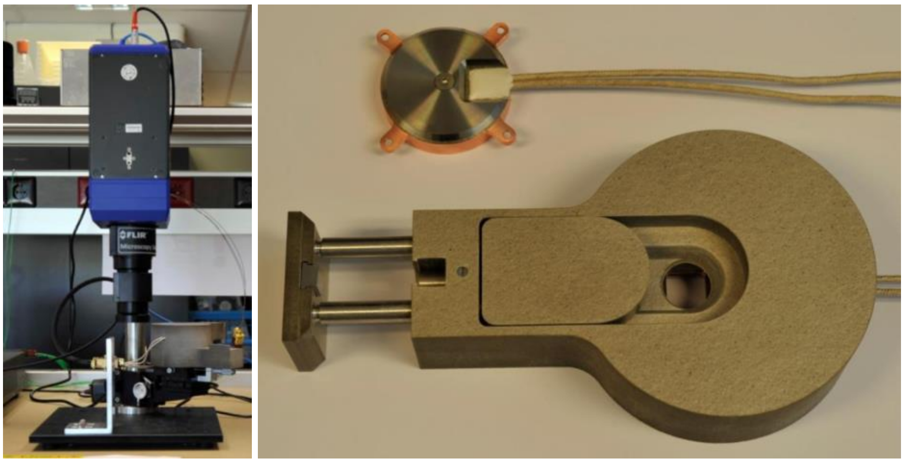

Figure 9 *Fixed angle emissivity bench, 20 – 450 °C*

The temperature of the sample is stabilized in a closed environment before abruptly exposing it to the camera, minimizing the cooling effect of the environment. The calculation of the emissivity can be performed once two images of the sample, taken at two different temperatures, have been acquired using the same integration time.

The two emissivity measurement benches are currently compatible with the FLIR SC7600 series cameras. The modification of the two stands to accommodate the new cooled camera, FLIR A8581, is currently being evaluated.

5. Ongoing activities in the field of thermography

5.1. In-house calibration in vacuum, low temperature thermography

The calibration of an infrared camera is typically performed by the manufacturer, down to approximately −20 to −40 °C. An extension of the calibration range would be beneficial as more and more ESA missions are expected to require measurements at much lower temperatures. Therefore, the Test Centre of ESA is interested in advancing the field of low temperature thermography for testing, down to -100 °C. Low temperature thermography could be useful for others in the fields of extra-vehicular activities (EVA), robotic exploration, space stations, lunar and arctic research.

There are two main limitations to low temperature thermography. The first one is the low amount of radiation emitted by the measured surface. The parasitic fluxes can be comparable in magnitude or even larger than the signal itself. This limitation can be overcome by having a calibration setup in which the amount of the parasitic fluxes is controlled and quantified. It has already been demonstrated in a previous study [5] that the range of the infrared temperature measurement can be extended down to -100 °C using commercial uncooled microbolometer cameras. The second limitation is the lack of calibration facilities for such cold temperatures. Performing an in-house calibration using a longwave infrared (IR) camera (Section 3) in combination with a thermal vacuum compatible blackbody can help to overcome this limitation. As result, the calibrated temperature range of the camera can be extended to colder temperatures than the standard factory calibration range.

A large-surface, calibrated and TVAC-compatible blackbody (HGH ECN100V7) is available in-house. It has an emissive surface of 190 x 190 mm and emissivity of 0.99. The temperature control of the blackbody's emissive surface is by liquid nitrogen (LN2) flow and resistive heaters, in the -163 to +150 °C range.

The activity reported in [6] is building on the lessons learned during the previous study [5]. It is proposing a methodology to extend the calibration range of infrared cameras down to −100 °C with a known uncertainty. A thermal-vacuum test campaign was performed to explore this method, identifying two scenarios: calibration prior the test (close-range calibration) vs. in-situ calibration and measurement.

In the close-range scenario, the camera was calibrated while the blackbody covered the entire Field-of-View (FoV) of the camera. A 10-layer MLI cover was installed around the camera and the blackbody to minimize parasitic fluxes (**Figure 10**). The camera was characterized by determining the non-uniformity and standard deviation over the whole image and smaller regions of interests (ROI) of the whole detector.

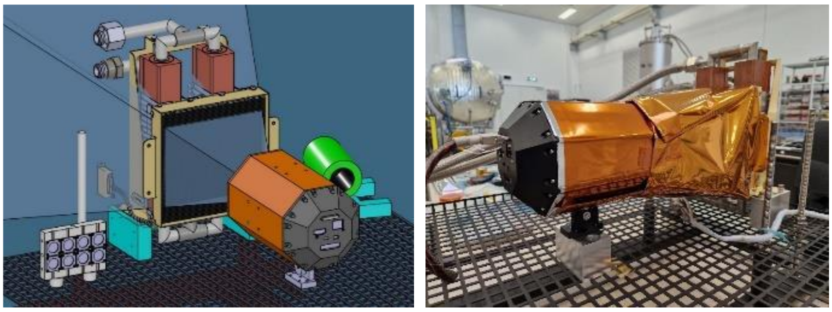

Figure 10 *Close-range calibration*

In the in-situ scenario, the camera was calibrated whilst also performing measurements (**Figure 11**). In this test configuration, another blackbody and representative material samples were also in the field of view of the camera. The blackbody being further away from the camera, the influence of the blackbody's temperature on the camera was minimized. On the other hand, no spatial calibration was achieved.

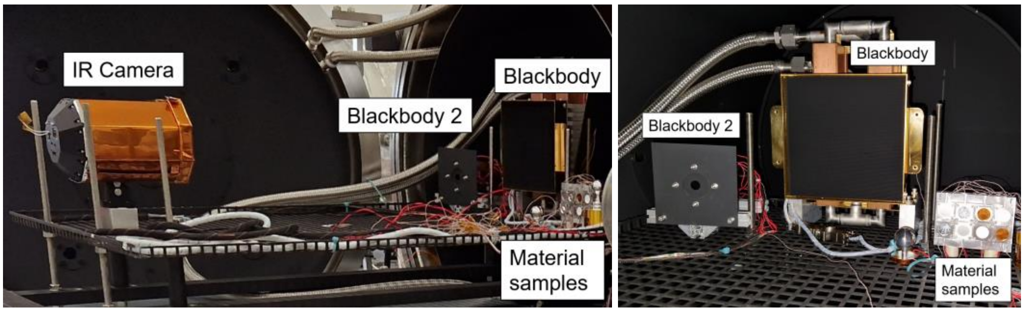

Figure 11 *In-situ calibration*

It has been concluded that the calibration method, close-range or in-situ, can be selected based on test needs.

The difference between factory and user calibration is highlighted on **Figure 12**. The curves differ the most at cold temperatures, on the left side. Extrapolating the factory calibration curve below −40 °C would result in considerable measurement errors.

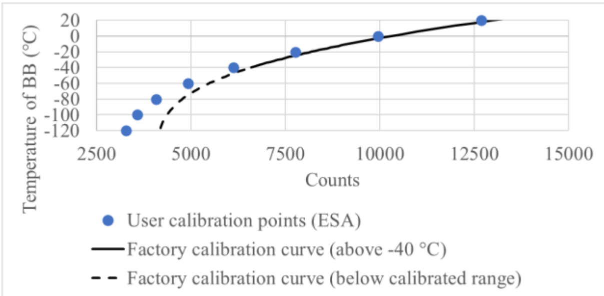

Figure 12 *Low temperature user calibration curve example*

Some internal trials have been successfully performed to measure the −100 °C shrouds or walls of a TVAC chamber, utilizing the low temperature user calibration method described above.

An upcoming activity aims to independently validate our low temperature thermography measurement method and create an associated uncertainty budget. Validating our measurement method aims to ensure the reliability and accuracy of thermographic data, which are essential for the integrity of our research and missions.

5.2. Correction of the apparent temperature recorded by infrared cameras, TEDMAP 3D:

Depending on the test setup, self-reflections and external reflections may significantly reduce to accuracy of temperature measurements by thermography. [7] details a past activity to map the geometry of the test specimen and thermal test environment; to model the surface temperatures and emissivity variations of the structures and materials; and to use this model to correct the apparent temperatures recorded by the thermal camera.

The method proposed in [7] is an iterative process (**Figure 13**). The initial temperature value is either the apparent temperature by thermography or a temperature reading by a contact sensor. Ray-traced simulations follow, where the temperature is varied incrementally until the ray-traced simulated image matches the real thermal image. The result is then the real surface temperature map.

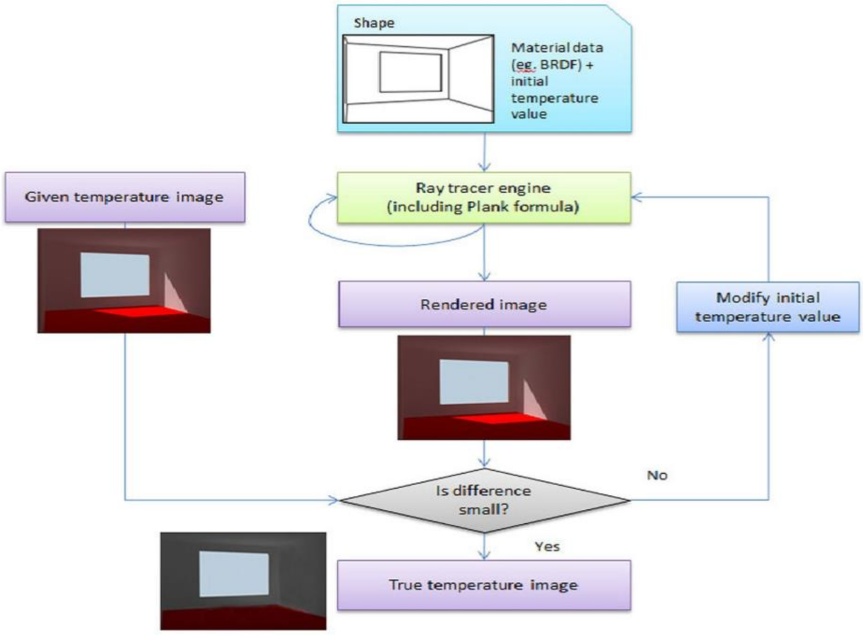

Figure 13 *Iterative process to calculate the real surface temperature (NPL)*

Figure 14 shows how this method works in practice. A test setup included samples of different materials, temperatures and geometries. Three infrared cameras were used to calculate and visualize the real surface temperature map.

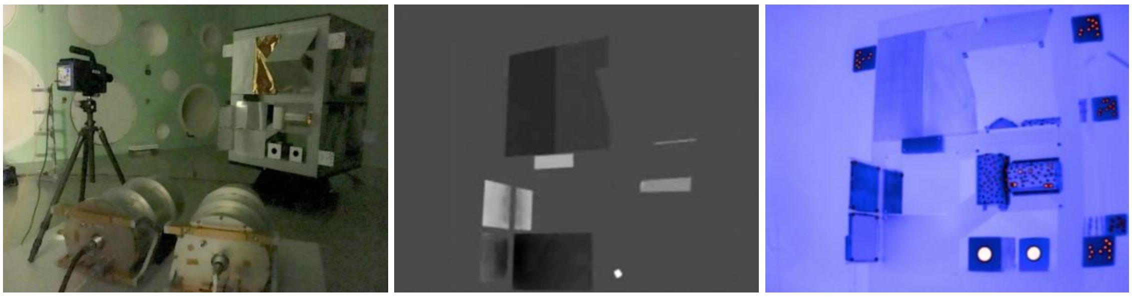

Figure 14 *Left: Test setup. Centre: Ray-traced image. Right: Camera IR image (NPL, ESA)*

A new software tool, TEDMAP 3D, has been recently developed to improve IR temperature measurements and integrate thermo-elastic deformations with temperature maps (**Figure 15**). It is a Spatial Software Tool for the projection of Thermal and Meta Information onto 3D point clouds. The main functionalities of TEDMAP 3D are the following:

- Performing ray-tracing and finding the true corrected temperature
- Point cloud displacements
- Projecting the IR temperature on 3D geometry
- Best fitting of shapes to 3D point clouds

In the near future, TEDMAP 3D is expected to enhance the way thermal test data is reported and analysed.

Figure 15 *TEDMAP 3D*

6. Conclusions

Over the years, the Test Centre of the European Space Agency has accumulated extensive experience in the field of infrared thermography for spacecraft testing. Complete systems were developed in-house, enabling thermographic measurements in the challenging environmental conditions encountered in thermal-vacuum chambers. On-going and future activities have been highlighted, including low temperature thermography and a new software tool to improve the measurements by correcting the apparent temperature taking into account the 3D scenario.

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