National Physical Laboratory

VERSION 1

ESR: EXECUTIVE SUMMARY REPORT

AUTHOR: WESLEY BOND WITH
VIVEK PANICKER
JAMIE MCMILLAN
MICHEAL HAYES
TECHNICAL LEAD: DR ROB SIMPSON

ESA CONTRACT: "ASSESSMENTS TO PREPARE AND DE-RISK TECHNOLOGY DEVOLOPMENTS – METROLOGY ENABLED THERMAL IMAGER FOR THERMAL VACUUM"

(ESA 4000125394/18/NL/BJ/ZK)

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Wesley Bond, Vivek Panicker, Jamie McMillan & Dr Rob Simpson
Engineering, Materials & Electrical Science
National Physical Laboratory

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

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1 INTRODUCTION

This Executive summary report is a deliverable for work package 9 of the contract “Assessments to prepare and de-risk technology developments – Metrology enabled thermal imager for thermal vacuum” between the European Space Agency (ESA) and the United Kingdom’s National Physical Laboratory (NPL) (ESA 4000125394/18/NL/BJ/ZK).

The entirety of the work carried out within the project has been summarised in this report as concisely as possible. The goal of this de-risking project was as follows: To raise the Technological Readiness Level (TRL) of a low Size Weight And Power (SWAP) thermal imager for thermal vacuum from a TRL of 2/3 to a TRL of 4/5. This included the aim to produce a thermal imager with a calibration uncertainty of ± 1 °C. These objectives were successfully achieved.

2 OBJECTIVES

The objectives of this de-risking activity were:

- Evaluate the current state of the art and use cases
- Setup a thermal vacuum testing facility at the National Physical Laboratory
- Assess operating temperature performance and vacuum outgassing properties of the thermal imager
- Calibrate the thermal imager in laboratory conditions
- Enable the long-term operation of the thermal imager in vacuum
- Calibrate the thermal imager from within the vacuum chamber using an external blackbody[*]
- Design and construct a vacuum compatible blackbody[*] for testing
- Perform a validation using the vacuum blackbody[*]
- Perform drift checks throughout the project to assess impact of vacuum exposure

[*] As used in this report a ‘blackbody’ is a high emissivity source, generally a temperature-controlled cavity with emissivity close to 1, of known temperature used to calibrate thermal imagers by providing the ideal measurement target.

3 STATE OF THE ART REVIEW AND THERMAL IMAGER SELECTION

The initial state of the art of review confirmed the benefits to accurate measurement of using a thermal imager without a windowed canister to contain it at atmospheric pressure – as currently used by ESA and other facilities as seen in Figure 1 – and the success of previous vacuum capable devices. These have been used both in ground-based testing and in orbit but the low uncertainty quantitative measurement, that this project offers, have been lacking. The key thermal and outgassing requirements were also identified in addition to numerous use cases for a final vacuum thermal imager device. These included vacuum testing key components such as heat pipes and telecoms panels in addition to studying temperature impacts such as thermoelastic deformation.

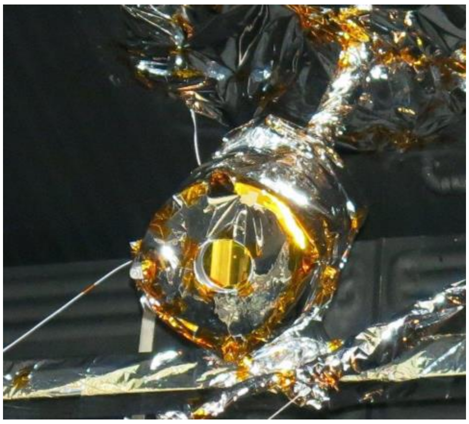

Figure 1: Canister with viewport for thermal imager connected by flexible hose [1]

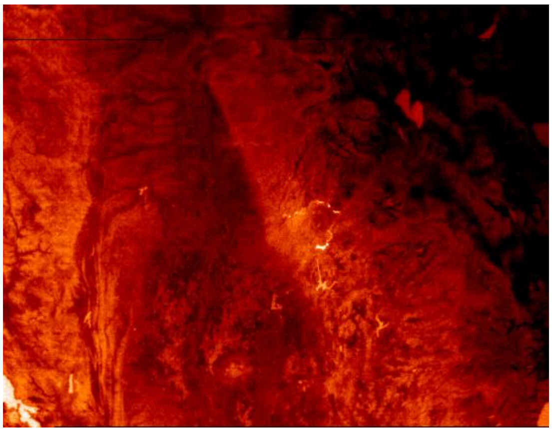

Figure 2: Thermal image of wildfire (centre) taken with Tau 2 (low SWAP Model produced by FLIR) thermal imager in orbit [2]

3.1 THERMAL IMAGER SELECTION

Based on the current and future requirements for a thermal vacuum compatible quantitative thermal imager the FLIR Boson was selected due its strong specifications across the board and lack of drawbacks [3]. The Boson thermal imager model selected is about 30 × 30 × 40 mm in size and weighs 44 grams. An CAD (Computer Aided Design) representation and our modified version in situ in the vacuum chamber are seen in Figure 5 and Figure 6 respectively.

4 HARDWARE

4.1 SETUP OF NPL FACILITY

The next stage was the setup of a small thermal vacuum facility at NPL, this was developed with the capacity to reach a vacuum level of less than 1×10^{-4} mbar (High vacuum) and temperatures in the range of -40 °C to 125 °C and this capability was confirmed with testing. Similarly, key components for the project such as the infra-red transparent window, that the thermal imager can take measurements though; USB feedthrough for connectivity and temperature sensors (Figure 3) were installed. These were also tested and calibrated and required.

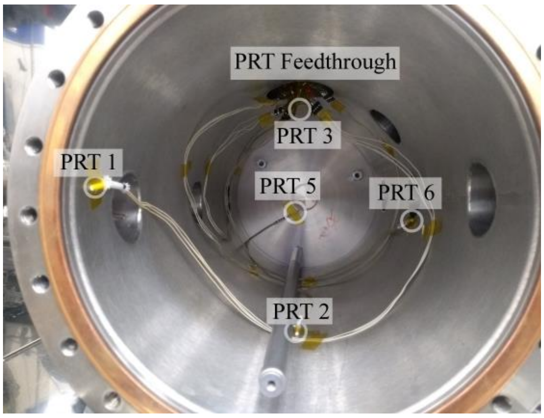

Figure 3: Vacuum chamber interior showing thermometer locations (PRT = Platinum Resistance thermometer)

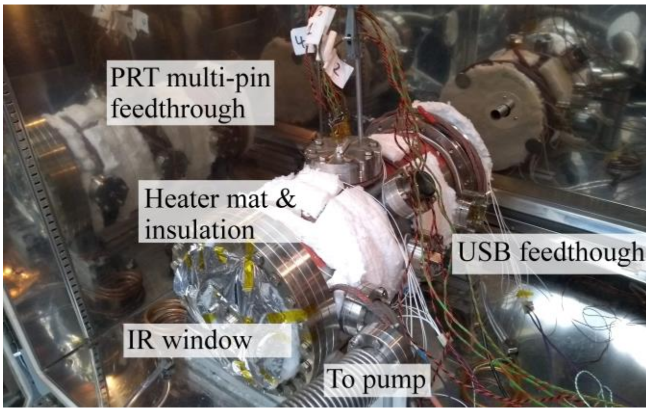

Figure 4: Annotated image of vacuum chamber setup within climatic chamber

4.2 ADAPTION OF THERMAL IMAGER

The initial breakdown of the device identified that the replacement of the thermal gap pad with a vacuum qualified one and the removal of the O-ring seal around the lens mount were key to reducing outgassing, so these changes were made.

Figure 5: CAD of 32° Lens FLIR Boson

Figure 6: Boson in chamber with final radiative modifications in place

The Boson began with an initial maximum operational vacuum temperature of 48.5 °C (with this value being the temperature of the vacuum chamber walls). Connecting the thermal imager directly to the vacuum chamber wall, rather than thermally isolate it, showed a Boson temperature decrease of 2 to 3 °C and adding radiative heatsinks around the thermal imager showed a temperature decrease of 1 to 2 °C. The main impact however was generated by turning on the frame averager, which in essence halves the frame rate from 60 Hz to 30 Hz. The workload on the CPU was therefore reduced resulting in a temperature decrease in operating temperature of 8 °C. This resulted in a final maximum operating temperature of 60.3 °C.

4.3 CONSTUCTION OF VACUUM BLACKBODY

A vacuum blackbody cavity was constructed for use in the in projects final in vacuum validation. This was built from vacuum compliant materials and has a temperature uncertainty of 0.48 °C (k = 2).

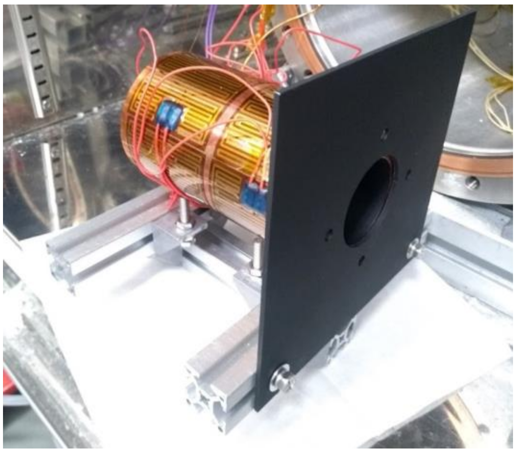

Figure 7: Front view of blackbody in front of chamber, black painted aperture plate and cavity are visible

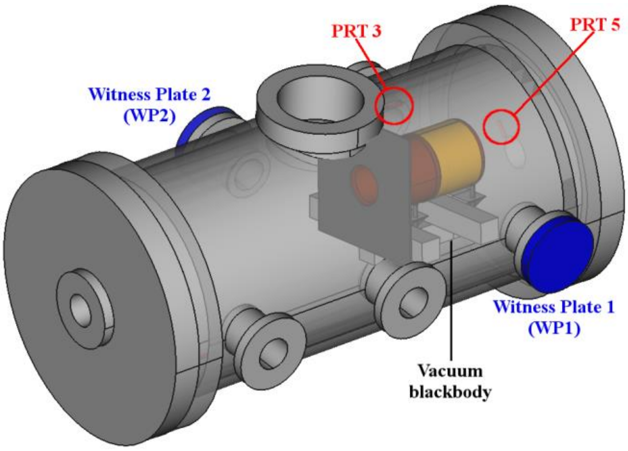

Figure 8: Diagram showing position of vacuum blackbody for outgassing

4.4 OUTGASSING

Before the Boson was used in vacuum an outgassing assessment was carried out employing conditions as similar as possible to the ESA standard. [4] [5] As such there was a 24-hr conditioning period before and after vacuum. The reduced temperature outgassing took place at nominally 90 °C over the course of 72 hours at a vacuum pressure of 5.3×10^{-4} mbar. The total mass loss was measured was 0.04% compared to the 1% limit of the standard and the Collected Volatile Condensable Material (CVCM) mass increase was 0.003% compared to the 0.1% of the standard. An outgassing was also performed on the vacuum blackbody with the CVCM witness plates showing a combined mass increase of 0.012 grams, a tiny fraction of the mass 2993 gram mass of the blackbody.

5 TESTING

5.1 LABORATORY

The Boson thermal imager was calibrated in the lab whilst the vacuum setup was taking place. This showed an off the shelf uncertainty of 5.6 °C to 6.2 °C under various conditions and a number of improvements that could be made for the in vacuum calibration were identified. Key thermal imager performance metrics such as the amount of noise in the thermal image and non-uniformity were also assessed and the Boson showed acceptable off the shelf results, with improvements to be made where possible.

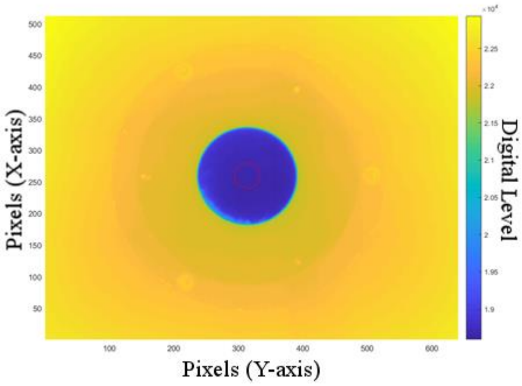

Figure 9: -40 °C blackbody calibration point at 300 mm distance

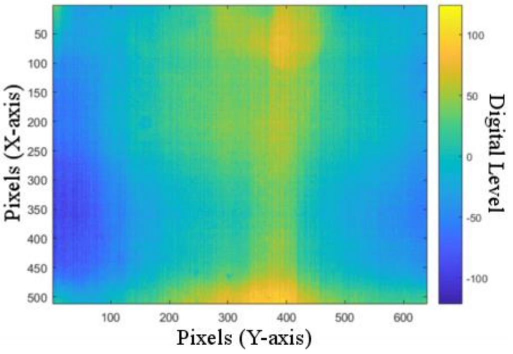

Figure 10: Thermal image non – uniformity at 50 °C

5.2 VACUUM – EXTERNAL BLACKBODY

The main calibration of the Boson thermal imager could now be carried out and this was done under vacuum conditions at -35 °C, 10 °C and 54 °C, when viewing a blackbody at seven temperatures from -15 °C to 140 °C. This resulted in three calibrations for each temperature uncertainties between 0.75 °C and 1.05 °C. The project goal of an instrumentation uncertainty of ± 1 °C was therefore met. An assessment was also carried out which showed the current total application uncertainty was 4.1 °C at a known thermal imager temperature, an uncertainty which was dominated mainly by the non-uniformity in the image.

The calibration at different thermal vacuum temperatures also showed that there was a clear change in the temperature measured by the thermal imager due its changing internal temperature. This shift however showed a repeatable correlation between thermal imager temperature, and the apparent change in a target of known temperature. As such this variation can be corrected for.

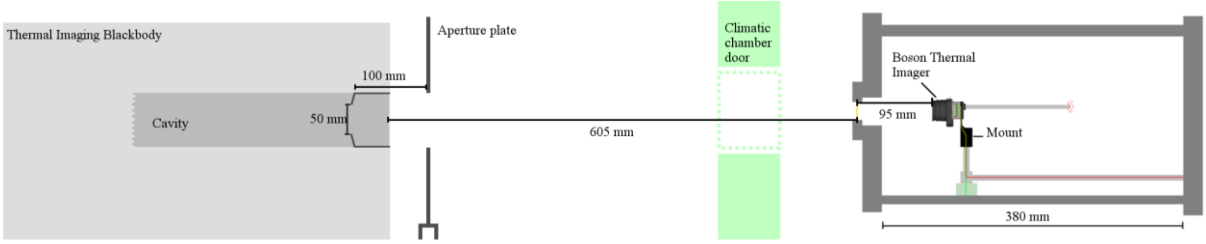

Figure 11: Calibration set up showing the path from thermal imager within vacuum chamber to Thermal imaging blackbody

5.3 VACUUM – INTERNAL BLACKBODY

The in vacuum validation took place with target temperatures ranging from -30 °C to 140 °C across the three vacuum chamber temperatures of -33 °C, 11 °C and 52 °C. The calibration uncertainty for vacuum calibration was calculated to be between 2.7 °C and 5.6 °C across the temperature ranges measured. This higher result is due mainly to the higher blackbody uncertainty and the temperature changes it caused within the vacuum chamber. Both of which can be improved in future for superior results.

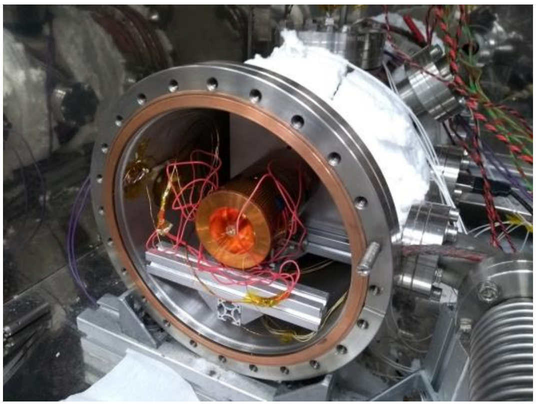

Figure 12: Vacuum blackbody in position at front of thermal vacuum chamber

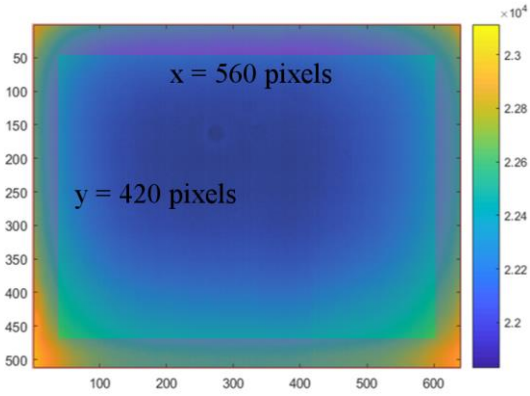

Figure 13: Non-uniformity with preferred measurement area highlighted (50 °C blackbody)

5.4 GAIN CALIBRATION

The Boson thermal imager has the capacity for adaptive filters to be applied to its imaging pipeline. These can correct errors such as any non-uniformity in the image and the change in the measured temperature due to the temperature of the thermal imager itself. The main filter for this is the ‘lens gain filter’ which needed to be calibrated in vacuum in order to reduce the thermal imager uncertainty under thermal vacuum conditions. This in-situ calibration proved successful and the gain filter provided a good ability to reduce the non-uniformity variation due to operation in a vacuum environment.

A need for thermal imager internal temperature correction was also established, as in section 5.2, as the internal temperature interpolation of the FLIR Boson is not employed on the lens gain calibration.

5.5 CHECK FOR DRIFT IN THERMAL IMAGER

During the course of the project drift checks were carried out on the FLIR Boson at 50 °C, 80 °C, 110 °C and 140 °C using a simple flat plate blackbody. The first one took place in tandem with the initial calibration and the final one six months later after the final vacuum operation had taken place. A total of nine drift checks took place between the Bosons modifications and 1800 hours of vacuum exposure and none showed a change from the mean digital of more than 0.9 °C. This is a good result and no long-term drift in the thermal imager due to vacuum exposure was identified.

6 CONCLUSIONS

In conclusions the initial objectives of the project as set out have been achieved. A good thermal imager selection was made that was then successfully assessed and adapted for thermal vacuum, with the Boson showing the ability to operate across a range of vacuum temperatures without long term drift. In addition, a low uncertainty calibration was carried out which is an excellent starting point for the future improvements to come. Vacuum calibration has also been validated and valuable lessons about vacuum calibration were learned.

Other aspects such as the uncertainty of the thermal imager in use show clear routes to improvement – via a correction based on thermal imager temperature and a gain filter calibration within vacuum – which again the ground work has been laid for. Similarly, an outgassing assessment of the thermal imager was carried out to the best of NPL’s ability, with the excellent results requiring more rigorous confirmation.

Taking a more general look ahead our modified Boson thermal imager has shown excellent potential for numerous uses in thermal vacuum and the routes to continued improvement in measurement – and towards a final device – are clear. In addition, no major issues were found when using the thermal imager canister free in a thermal vacuum environment, and those already identified such as outgassing and higher operating temperature were addressed. These two factors combined make the development of a vacuum ready thermal imager a clear goal for continued research.

7 REFERENCES

[1] *Temperature measurement in thermal-vacuum tests for spacecraft qualification – possibilities for infrared thermography,* Daniel Döring, Christian Spiessberger, Peter Jens Hein, 2016

[2] *Year in Space for the CUbesat MULtispectral Observing System: CUMULOS,* Dee W. Pack, Christopher M. Coffman, John R. Santiago, 33rd Annual AIAA/USU Conference on Small Satellites 2019

[3] https://flir.netx.net/file/asset/12673/original

[4] ASTM E 595- 93 “*Standard test method for Total mass loss and collected volatile condensable materials from outgassing in a vacuum environment*”

[5] ECSS-Q-ST-70-02C *“Space product assurance: Thermal vacuum outgassing test for screening of space materials”*