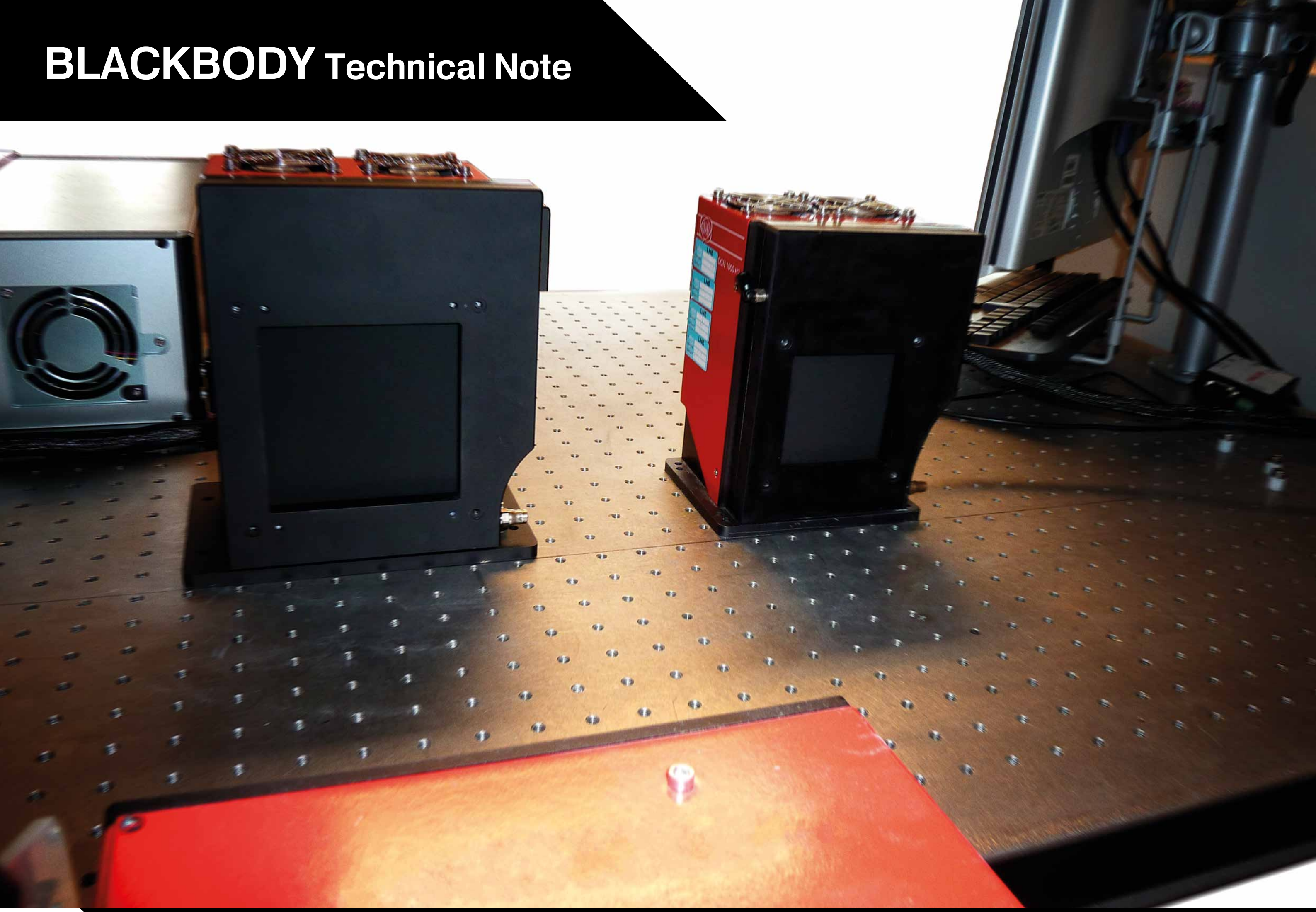
# **BLACKBODY** Technical Note



# THE CERTIFICATION CHALLENGE OF IR REFERENCE SOURCES

As Infrared cameras are commonly used for security and civilian applications (24/7 sensitive site surveillance, medical applications, hot spot detection on electrical power lines, energy waste in buildings, temperature measurement in heavy industry, thermal imagers for mobile phones...), many developments are carried out to improve their performance. Therefore, the thermal characterization of IR sensors is becoming critical and manufacturers have to rely on testing devices and procedures certified by metrological standards.

Infrared reference sources are key elements of thermal imager test bench. Measured results are highly dependent on blackbodies characteristics, such as the temperature accuracy, the emissivity, the thermal uniformity and stability. Consequently, HGH has developed a testing bench for accurate calibration and measurement of uniformity of infrared sources based on a low noise radiometer mounted on translation stages. This bench delivers a reliable thermal map of any blackbodies and performs an accurate calibration through a comparison method.

## 1. DEMANDING CHARACTERISTICS OF BLACKBODIES

New applications recently appeared requiring an accurate knowledge on uniformity.

Among these applications is the thermography for research applications using high end thermal cameras including large cooled detectors. The measurement is made at short focusing distance and the contrast between the measured phenomena and the background is so small that the camera non uniformity correction has to be done in the same condition as the testing condition, i.e. by focusing the image of the large emissive area of the blackbody at the same average temperature as the sample on the detector of the camera.

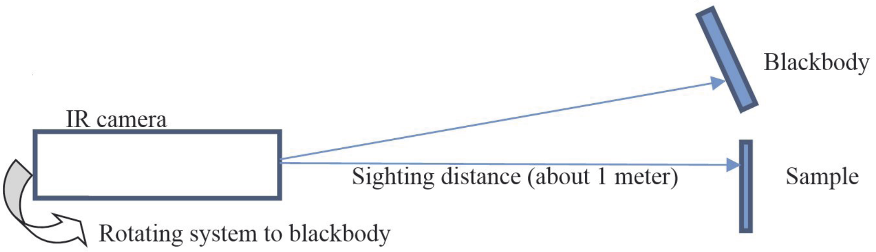


*Figure 1 New non uniformity correction procedure*

New concerns also appeared on the uniformity of high temperature cavity blackbodies. A great non-uniformity of the radiation at the output aperture of these sources leads to a great uncertainty on IR sensor calibration. This non-uniformity is hardly measured due to small cavity diameter and high radiation level. A maximum non-uniformity of 1% of temperature peak to peak is now expected by the major thermal imager manufacturers over a 25 mm diameter aperture.

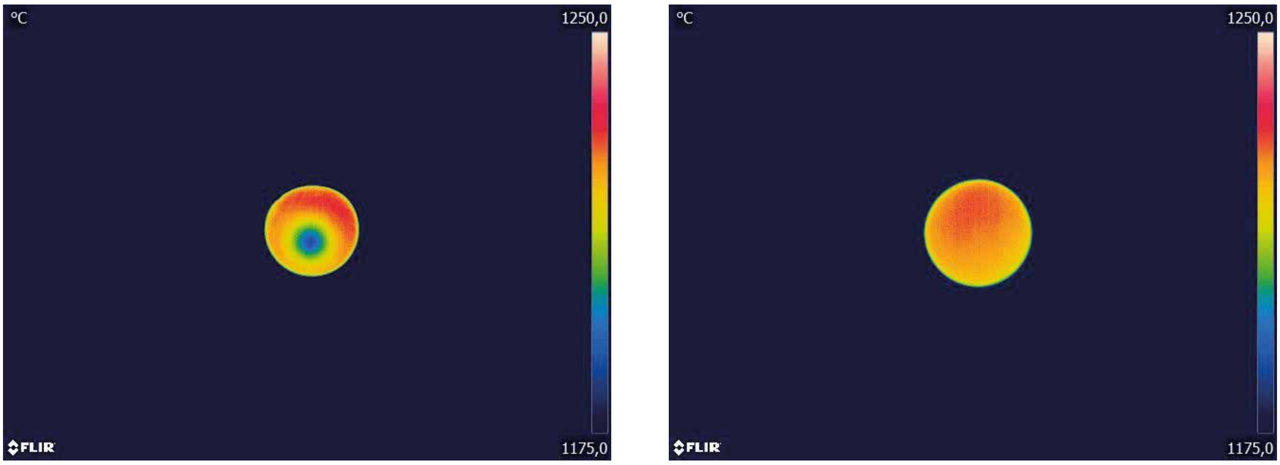


*Figure 2 Example of unacceptable (left) and acceptable (right) cavity uniformity*

The mass production of IR sensors for smartphones and human body temperature sensors require the simultaneous calibration of a complete set of sensors. This calibration is made by presenting a unique large emissive area blackbody to a set of sensors: typical configuration is 8/9 IR sensors simultaneously calibrated using a 180x180 mm$^2$ blackbody. The maximum required difference of calibration from one sensor to another is 0.1°C at 42°C. This specification is directly transferred to the non uniformity specification for the infrared reference source.

Consequently, the above applications requires the blackbody manufacturers to develop new methods for measuring the uniformity of blackbodies and, if necessary, improving their manufacturing process.

These requirements on uniformity are combined with a legitimate knowledge requirement of reliable certification of the absolute radiated temperature value. Accurately measuring the temperature of the emissive plate or cavity through the use of calibrated thermometric sensors gives only an estimative value of the actual radiated temperature: this thermometric measurement doesn't take into account some hardly evaluated though important sources of error such as:

- The quality of the thermal contact between the sensor and the emissive plate or cavity
- The temperature difference between the location of the sensor and the emissive surface
- The emissivity of the emissive surface

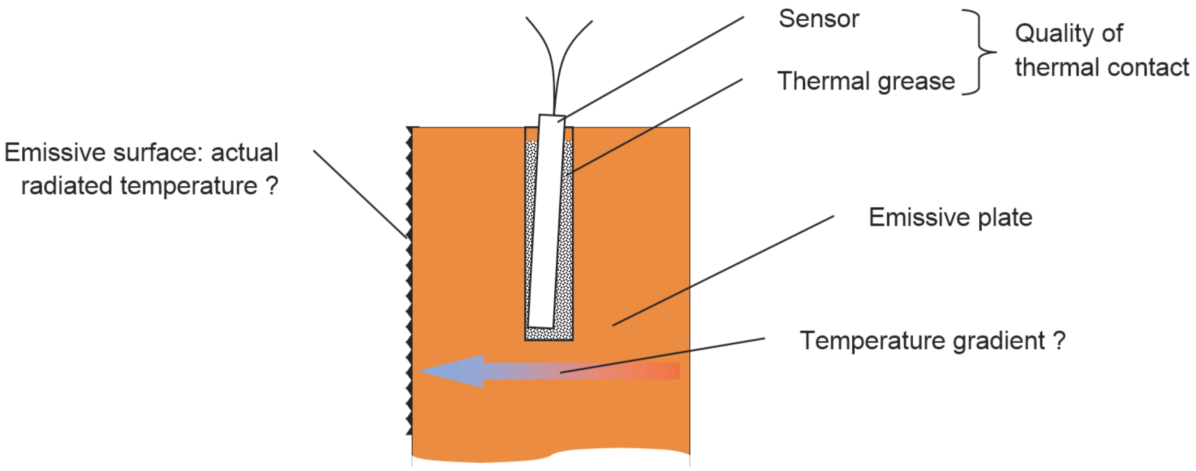


*Figure 3 Sources of error on the thermometric temperature measurement*

As the only displayed parameter is the temperature given by the sensor, calibrating a blackbody consists in calculating the relationship between the radiated energy and the temperature of the sensor. Consequently, this radiated energy is expressed by the temperature this source would have if it was a true blackbody, i.e. with an emissivity of 1. The calibration consists in defining the radiated or «apparent» temperature as a function of the measured or «displayed» temperature.

Of course, since the apparent temperature is measured through an optical sensor, the above function is valid only over the spectral range of the optical sensor.

The typical best expectable uncertainties (expanded coefficient $\sigma$=2) are

- Over the 3-5 µm range:
  - Below 0°C: 1.5°C
  - From 0°C to 150°C: 1°C to 0.4°C
  - From 150°C to 1000°C: 0.6°C to 3°C
- Over the 8-14 µm range:
  - Below 0°C: 0.8°C
  - From 0°C to 150°C: 0.1°C to 0.5°C
  - From 150°C to 600°C: 0.5°C to 3°C
  - From 600°C to 1000°C: 3°C to 5°C

## 2. RANGE OF APPLICATIONS

The specifications of the tool able to accurately measure the non uniformity and to calibrate infrared reference sources must take into account the constraints of the 3 usual families of blackbodies ([3]):

- Low temperature extended area blackbodies, which temperature is set from approximately -40°C to more than 150°C
  - Dimensions: square, from less than 50 mm to more than 300 mm,
  - Temperature temporal stability: less than 0.005°C,
  - Expected residual non uniformity: about 0.1°C rms at 50°C.
- High temperature extended area blackbodies, which temperature is set from above ambient temperature up to 600°C
  - Dimensions: square, from less than 150 mm to more than 500 mm,
  - Temporal stability: less than 0.05°C,
  - Expected residual non uniformity: 1% peak to peak of temperature.
- High temperature cavity blackbodies, which temperature is set from above ambient temperature up to more than 1200°C
  - Dimensions: 25 mm diameter,
  - Temporal stability: less than 0.1°C,
  - Expected residual non uniformity: 1% peak to peak of temperature.

The bench must be then able to cover a wide range of radiation levels, though having a very low thermal resolution for each level. In addition, it must be able to measure the uniformity of very wide emissive surfaces while having a high enough spatial resolution to check the non uniformity of small cavity blackbodies. It is important to notice that, for all sources, the temporal stability is negligible compared to the expected residual non uniformity and calibration uncertainties.

## 3. DESCRIPTION OF THE B3 BENCH

Since the thermographic equipment available on the market such as thermal cameras do not give reliable and satisfying results (see [2]), HGH has developed a specific bench named B3 Bench to perform accurate measurement of uniformity and radiometric calibration of blackbodies. This tool is made by the combination of a single element radiometer mounted on a motorized XY translation assembly (see fig. 4).

*Figure 4 Overview of the B3 bench*

The uniformity measurement procedure is achieved by scanning the emissive surface of the IR source under test. A software automatically acquires the radiometric signal from the radiometer while controlling the position of the radiometer through the XY translation assembly.

The calibration procedure is made by the repeated, successive and automatic comparison of the radiation of the IR source under test and the radiation of a reference blackbody previously calibrated by an NMI thanks to CMC registered at the BIPM.

## 3.1 Description of the radiometer

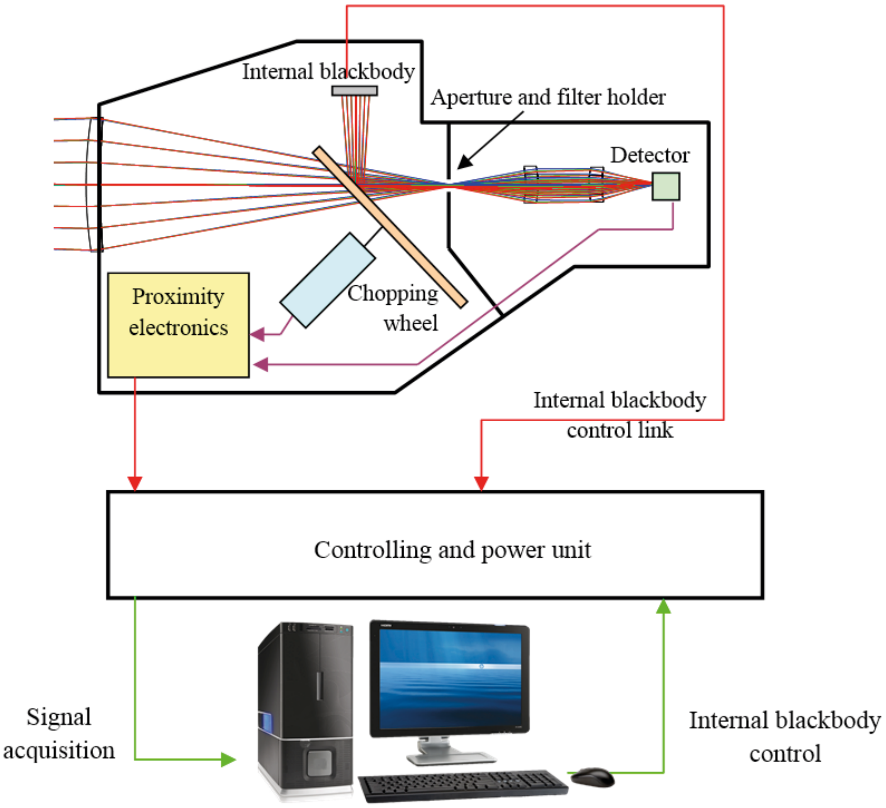


*Figure 5 Operating sketch of the radiometer*

The radiometer is made by a single element detector cooled by thermoelectric element. The optics focuses the emissive plane of the IR source under test on the detector sensitive plane. The testing distance between the radiometer and the IR reference source under test is about 0.3 m.

An intermediate focusing plane defines the position of an aperture hole. A filter holder is located close to this intermediate focusing plane: neutral filters are inserted here to adapt the signal level of high temperature sources to the sensitive range of the detector.

As the single element detector is not sensitive to continuous signal, a chopping wheel modulates the radiometric signal. This chopping wheel also reflects the radiation of an internal blackbody. Consequently, the radiometer signals is proportional to the difference between the radiant flux emitted by the source under test and the radiant flux emitted by the internal blackbody which temperature is measured in real time by the software.

$$Signal = k \cdot \left(Radiance_{source}(\Delta\lambda) - \frac{dR_{BB}}{d\lambda}(T_{int\ BB}, \lambda) \cdot \Delta\lambda\right) \tag{1}$$

Where $\frac{dR_{BB}}{d\lambda}(T, \lambda)$ is the radiance of a blackbody given by the Planck’s law. The temperature of the internal blackbody may be adjusted to match the average signal delivered by the source under test: this procedure increases the dynamic range of measurement in order to improve the thermal resolution of measurement on small temperature changes of the source under test. This function is particularly dedicated to the test of low temperature blackbodies. A preliminary calibration procedure allows the calculation of k.

The radiometer signal is also calibrated using a Reference Blackbody linked to International Primary Standard before each campaign of measurements. The Reference Blackbody model depends on the temperature range used for the radiometer. For example, in case of high temperature range, the radiometer, including its appropriate neutral density, is calibrated using a high temperature cavity Reference Blackbody. Assuming that the tested sources are greybodies over the spectral range of the radiometer, this calibration phase defines the parameters of the Sakuma Hattori formula:

$$Radiance_{source}(\Delta\lambda) = \frac{A}{e^{\frac{B}{T+273} + \frac{C}{(T+273)^2}} - D} \tag{2}$$

Through the combination of equations (2) and (3), the radiometric temperature of the IR source under test is displayed.

### 3.2 Scanning method: uniformity measurement

Thanks to the XY translation stages, the radiometer successively delivers the radiometric temperature of different points of the emissive surface of the IR source under test. An optimized network is consequently defined depending on the dimension of the emissive area of the source under test. Here are some examples:

- For a 25 mm diameter cavity blackbody: network of 11 x 11 measurements with a step of 2.5 mm. This network takes into account the dimensions of the radiometer spot into the source aperture plane, i.e. 5 mm. To avoid edges effect, the edges measurements are removed from the uniformity calculation:

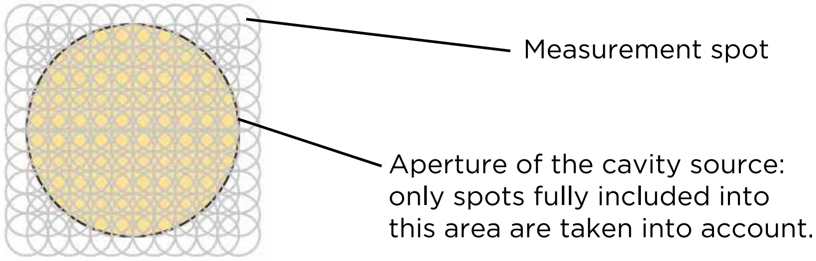


*Figure 6 Spot network for a 25 mm diameter cavity blackbody*

- For a 180 x 180 mm$^2$ extended area source: network of 11 x 11 measurements with a step of 15.5 mm. The spots at the edges are fully included into the emissive surface area. Hence, all the spots are considered for uniformity calculation. The approximate duration of the measurement procedure is 10 minutes: a tighter network increases the duration of the procedure in an approximate proportion with the number of measured spots (here 121).

### 3.3 Scanning method: calibration procedure

The blackbody under test and the reference blackbody are both set and stabilized to the same temperature. Thanks to the XY translation stage, the radiometer aims successively at the center of the blackbody under test and at the center of the reference blackbody, measuring successively apparent temperature on the blackbody under test (BBUT) and on the reference blackbody. This procedure is repeated 10 times for each temperature point.

The difference between 2 successive measurements is calculated for each couple of measurements and the average and standard deviation of these differences are computed. The average of these differences is the apparent temperature difference between the reference source and the BBUT.

| Aimed source | Temperature set (°C) | Measurement number | Measured value (°C) |
|---|---|---|---|
| Reference | 20 | 1 | 20,127 |
| BBUT sn 431 | | 2 | 20,040 |
| Reference | | 3 | 20,125 |
| BBUT sn 431 | | 4 | 20,031 |
| Reference | | 5 | 20,133 |
| BBUT sn 431 | | 6 | 20,023 |
| Reference | | 7 | 20,144 |
| BBUT sn 431 | | 8 | 20,035 |
| Reference | | 9 | 20,136 |
| BBUT sn 431 | | 10 | 20,049 |
| Reference | | 11 | 20,139 |
| BBUT sn 431 | | 12 | 20,023 |
| Reference | | 13 | 20,137 |
| BBUT sn 431 | | 14 | 20,033 |
| Reference | | 15 | 20,134 |
| BBUT sn 431 | | 16 | 20,046 |
| Reference | | 17 | 20,122 |
| BBUT sn 431 | | 18 | 20,036 |
| Reference | | 19 | 20,145 |
| BBUT sn 431 | | 20 | 20,045 |

*Table 1 Example of raw measurements at 20°C for the reference blackbody and the low temperature BBUT serial number 431*

| | Temperature set point (°C) | | | | |
|---|---|---|---|---|---|
| Difference between measurements number | 0 | 20 | 50 | 80 | 150 |
| 2 and 1 | -0,385 | -0,086 | 0,156 | 0,356 | 0,790 |
| 4 and 3 | -0,282 | -0,094 | 0,167 | 0,338 | 0,901 |
| 6 and 5 | -0,337 | -0,109 | 0,189 | 0,384 | 0,893 |
| 8 and 7 | -0,311 | -0,109 | 0,174 | 0,392 | 0,846 |
| 10 and 9 | -0,317 | -0,087 | 0,130 | 0,350 | 0,691 |
| 12 and 11 | -0,304 | -0,116 | 0,213 | 0,353 | 0,702 |
| 14 and 13 | -0,348 | -0,104 | 0,158 | 0,375 | 0,706 |
| 16 and 15 | -0,396 | -0,088 | 0,199 | 0,324 | 0,746 |
| 18 and 17 | -0,262 | -0,086 | 0,167 | 0,380 | 0,680 |
| 20 and 19 | -0,345 | -0,100 | 0,162 | 0,306 | 0,738 |
| Average difference (°C) | -0,33 | -0,10 | 0,17 | 0,36 | 0,77 |
| Standard deviation (°C) | 0,04 | 0,01 | 0,02 | 0,03 | 0,08 |

*Table 2 Example of apparent temperature difference measurement between the reference blackbody and the low temperature BBUT serial number 431*

Since the absolute apparent temperature of the reference blackbody is known from the certificate of calibration delivered by the BIPM accredited laboratory with its registered CMC, the absolute apparent temperature of the BBUT is calculated consequently from Eq. 3:

$$Apparent\ Temp._{BBUT} = Apparent\ Temp._{refBB} + difference \tag{3}$$

| | Temperature set point (°C) | | | | |
|---|---|---|---|---|---|
| | 0 | 20 | 50 | 80 | 150 |
| Reference BB apparent Temp. (°C) | 0,80 | 20,20 | 49,50 | 79,10 | 148,30 |
| Difference (°C) | -0,33 | -0,10 | 0,17 | 0,36 | 0,77 |
| **BBUT apparent Temp. (°C)** | 0,47 | 20,10 | 49,67 | 79,46 | 149,07 |

*Table 3 Example of absolute apparent temperature calculation for the low temperature BBUT serial number 431*

Table 3 example means that when the blackbody is stabilized at 80°C, it radiates the same energy as a perfect blackbody at 79.46°C over the 3-5µm spectral band.

# 4. PERFORMANCES AND TEST RESULTS

## 4.1 Evaluation of the bench measurement system performances

The noise level of the radiometer must have a limited contribution to the uniformity and calibration measurement error. Consequently the NETD of the radiometer has been measured especially at low temperatures. The noise level is measured over 100 samples i.e. 1 second signal acquisition considering the modulation frequency of the chopping wheel. This averaging condition is applied to all further measurements, especially to the temperature measurement of each spot during the uniformity test and to the calibration error calculation. The measured NETD level of the radiometer is 10 mK at 50°C.

The global error of uniformity measurement is evaluated at 50°C over a 50 x 50 mm$^2$ low temperature blackbody. This source is assumed to be uniform: it is equipped with only one heating/cooling device wider than the emissive surface area and consequently has no edge effect; the air convection effect is evaluated at 15 mK over such a small height (50 mm). A thermal map of this source is acquired using the B3 bench and the standard deviation of the uniformity is calculated. This procedure shows that the standard deviation error of the uniformity measurement system of the B3 bench is 30 mK at 50°C. This level of error is acceptable considering the residual non-uniformity requirement on low temperature extended area blackbodies.

## 4.2 Example of uniformity measurements and analysis of results on various IR sources

The uniformity measurement is conducted on a low temperature IR reference source with a 180 x 180 mm$^2$ emissive surface at 50°C. The uniformity thermal map is shown on fig.7. A smoothing algorithm is applied to the image to get a real rendering.

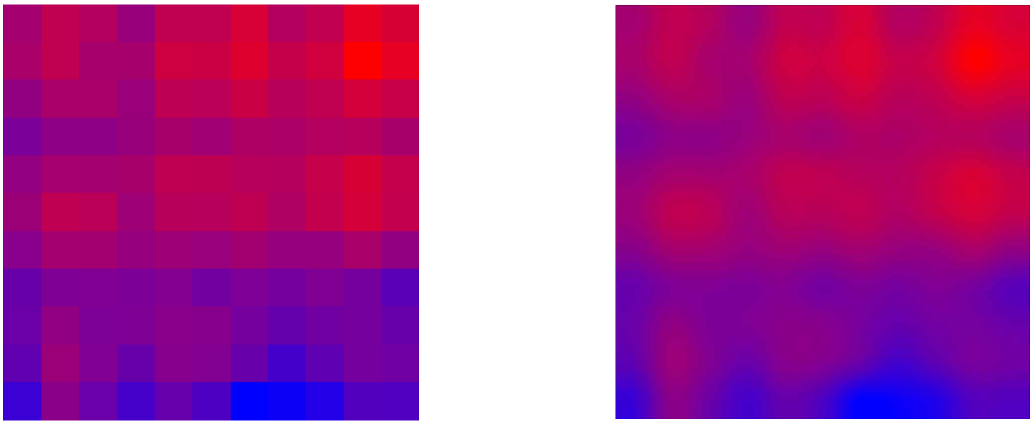
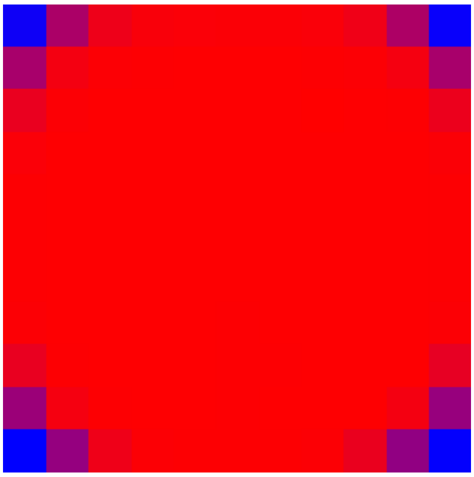


*Figure 7 Uniformity thermal map of a 180x180 mm² blackbody (dark blue=48.927°C; hot red = 49.311°C)*

The standard deviation of the measured uniformity is 70 mK. Though the source is stabilized (2 mK stability), the residual edges effect of the thermoelectric devices appears clearly on the smoothed image.

The air convection effect is also particularly visible on both images. The air convection effect can be removed by calculating the average of the fig.7 map and the thermal uniformity map of the same source turned upside down, taking care to rotate this latter image before the calculation of the average. This method allows getting the thermal map of any IR source when it is used horizontally.

The uniformity of a 25 mm diameter cavity blackbody at 1200°C is also measured using the B3 bench. The thermal map and the list of corresponding temperature measurements are shown fig.8.



| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 528,352 | 949,802 | 1148,423 | 1183,490 | 1188,959 | 1190,577 | 1189,326 | 1184,867 | 1153,875 | 955,841 | 515,266 |
| 938,817 | 1168,150 | 1192,211 | 1196,335 | 1198,285 | 1198,649 | 1198,583 | 1197,352 | 1193,099 | 1172,149 | 937,677 |
| 1135,907 | 1193,678 | 1198,642 | 1199,699 | 1199,854 | 1199,515 | 1200,100 | 1200,275 | 1199,146 | 1194,871 | 1143,538 |
| 1189,089 | 1198,092 | 1199,845 | 1199,188 | 1199,298 | 1198,737 | 1199,290 | 1199,526 | 1200,027 | 1198,894 | 1190,790 |
| 1195,442 | 1199,147 | 1199,370 | 1198,822 | 1199,109 | 1198,244 | 1198,855 | 1199,182 | 1199,402 | 1199,760 | 1196,312 |
| 1196,677 | 1198,891 | 1199,068 | 1198,444 | 1198,349 | 1197,725 | 1198,383 | 1198,677 | 1199,176 | 1199,679 | 1197,472 |
| 1196,372 | 1198,655 | 1198,584 | 1198,089 | 1198,023 | 1197,544 | 1198,041 | 1198,234 | 1198,805 | 1199,252 | 1197,177 |
| 1193,146 | 1198,502 | 1198,405 | 1197,880 | 1197,933 | 1197,274 | 1197,555 | 1198,119 | 1198,419 | 1199,048 | 1194,540 |
| 1134,194 | 1197,027 | 1198,313 | 1198,181 | 1197,858 | 1197,051 | 1197,497 | 1197,645 | 1198,107 | 1198,050 | 1126,151 |
| 901,928 | 1172,614 | 1197,322 | 1197,930 | 1197,654 | 1196,936 | 1197,616 | 1197,530 | 1197,769 | 1168,197 | 888,088 |
| 499,988 | 881,940 | 1150,994 | 1193,084 | 1196,549 | 1196,644 | 1196,617 | 1193,211 | 1137,783 | 871,613 | 506,750 |

*Figure 8 Thermal uniformity map of a cavity blackbody and table of temperature measurements (°C)*

The list of the considered measurements used for the uniformity calculation are highlighted in blue or red in the table in fig.8, all the other measurements being at least partially outside the cavity aperture.

The uniformity of the fig.8 blackbody is consequently 3.94°C peak to peak at 1200°C, i.e. about 0.3% of the temperature. This result is compatible with the current requirement for high end thermal imager calibration.

## 4.3 Uncertainty of the calibration procedure and example of calibration uncertainty results

The uncertainty of calibration is the other major information required for a reliable certificate of calibration with the calibration value itself. The uncertainty of our calibration procedure is calculated by taking all potential sources of error into account:

- Reference blackbody calibration uncertainty given by the BIPM accredited laboratory,
- Reference blackbody stability during calibration process,
- Radiometer thermal resolution when aiming at the reference blackbody,
- Radiometer thermal resolution when aiming at the blackbody under test (BBUT),
- BBUT stability during calibration process,
- Measurement repeatability of the apparent temperature, calculated from the standard deviation of the difference measurement divided by the square root of the number of measurements (i.e. 10).

The quadratic average of the above uncertainties is computed to get the global uncertainty of calibration of blackbody under test. This error value is given over a 2-sigma range i.e. with 95% probability that the true radiated temperature is included within the range “nominal value ± 2-sigma error”.

| | Temperature set point (°C) | | | | |
|---|---|---|---|---|---|
| **Source of error** | **0** | **20** | **50** | **80** | **150** |
| Reference BB stability (°C) | 0,002 | 0,002 | 0,002 | 0,002 | 0,002 |
| Reference BB calibration uncertainty (°C) | 0,500 | 0,300 | 0,200 | 0,150 | 0,150 |
| Radiometer thermal resolution on reference BB (°C) | 0,010 | 0,010 | 0,010 | 0,010 | 0,010 |
| Radiometer thermal resolution on BB under test (°C) | 0,010 | 0,010 | 0,010 | 0,010 | 0,010 |
| Measurement repeatability of the apparent temperature (°C) | 0,013 | 0,004 | 0,008 | 0,009 | 0,026 |
| Stability of BB under test (°C) | 0,002 | 0,002 | 0,002 | 0,002 | 0,002 |
| **Standard deviation uncertainty ($\sigma$) (°C):** | 0,500 | 0,300 | 0,201 | 0,151 | 0,153 |
| **Enlarged uncertainty ($2\sigma$) (°C):** | **1,10** | **0,70** | **0,50** | **0,40** | **0,40** |

*Table 4 Example of calibration error calculation for the low temperature BBUT serial number 431*

Considering again the example at 80°C, the 2-sigma uncertainty on the absolute apparent temperature i.e. 79.46°C is 0.4°C and means that the true radiometric temperature is between 79.06°C and 79.86°C with 95% probability. It can be noticed that the main contribution of this global uncertainty is due to the reference blackbody calibration uncertainty. These results, nominal value and uncertainty, can be directly used by operators when using a blackbody for thermal imager calibration for example. They are reliable and linked to international primary standards through the reference blackbody calibration certificate.

## 5. CONCLUSION

Measuring the uniformity of IR reference sources such as blackbodies is a challenging operation since blackbodies are themselves used for correcting non uniformity of thermal imagers and infrared cameras. Simultaneously, blackbody users must have confidence on the optical properties of these infrared optical sources. Thanks to the B3 bench developed by HGH, a high accuracy measurement of the uniformity and a reliable measurement of the radiometric temperature are achieved. All the tested blackbodies are consequently delivered with a detailed test sheet showing its optical properties and bringing confidence in these infrared reference sources to the operators.

## 6. REFERENCES

[1] Gaussorgues, G., [Infrared Thermography], Chapman & Hall, London, chapter 3 (1994).

[2] A. Whittam, R. Simpson, H. McEvoy, [Performance tests of thermal imaging systems to assess their suitability for quantitative temperature], Quantitative InfraRed Thermography Journal QIRT-2014-202 (2014).

[3] C. Barrat, S. Violleau, [Evaluating uniformity on IR reference sources], SPIE 9649-6 (2014).