Evaluating uniformity of IR reference sources

Infrared reference sources such as blackbodies are used to calibrate and test IR sensors and cameras. Applications requiring a high thermal uniformity over the emissive surface become more and more frequent compared to the past applications. Among these applications are non uniformity correction of infrared cameras focused at short distance and simultaneous calibration of a set of sensor facing a large area blackbody. Facing these demanding applications requires to accurately measuring the thermal radiation of each point of the emissive surface of the reference source. The use of an infrared camera for this purpose turns out to be absolutely inefficient since the uniformity of response of this camera is usually worse than the uniformity of the source to be measured. Consequently, HGH has developed a testing bench for accurate measurement of uniformity of infrared sources based on a low noise radiometer mounted of translating stages and using an exclusive drift correction method. This bench delivers a reliable thermal map of any kind of infrared reference source.

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1. APPLICATIONS OF INFRARED REFERENCE SOURCES

In usual applications of blackbodies, the emissive surface is neither located at the focus of the collimating optics nor focused on the detector plane of the tested sensor. The emissive surface is usually at least slightly unfocused. For example, considering the case of the test of IR sensors with targets, the target plane is located at the focus of the optics or collimator whereas the emissive surface of the blackbody is located a few centimeters behind the target.

Blackbody surface

Targets on focal plane

Collimator

Figure 1 Usual location of blackbodies

Non uniformity correction test is made by placing an extended area infrared reference source in front of the sensor to be tested: the emissive surface must entirely cover the aperture of the sensor and the field of view. In this configuration, the source is usually placed a few centimeters in front of the front lens of the sensor, as close as possible to simultaneously cover the aperture and the field of view of the sensor, but not too close to avoid heating the mechanical mount and the first lens of the sensor.

In both above cases, the image of the emissive surface is not focused on the detector of the detector under test and no demanding specification is required on the uniformity of the emissive surface of this reference source. Though the manufacturing process of the infrared reference sources such as blackbodies leads to theoretically good uniformity, these applications doesn't require any proof of this uniformity value or an approximate measurement is sufficient.

However, new applications recently appeared requiring both an accurate knowledge on uniformity and the improvement of the uniformity of extended area infrared reference sources.

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.

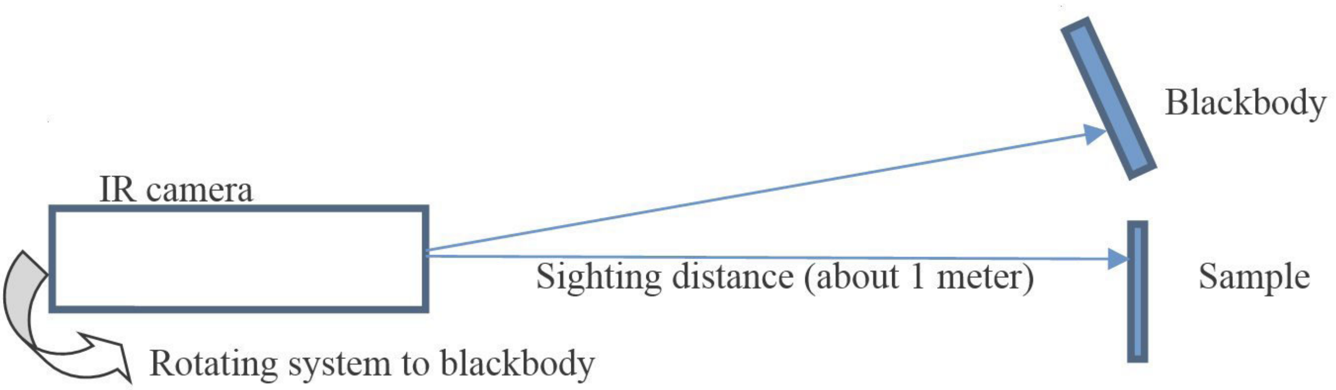


Figure 2 New non uniformity correction procedure

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.

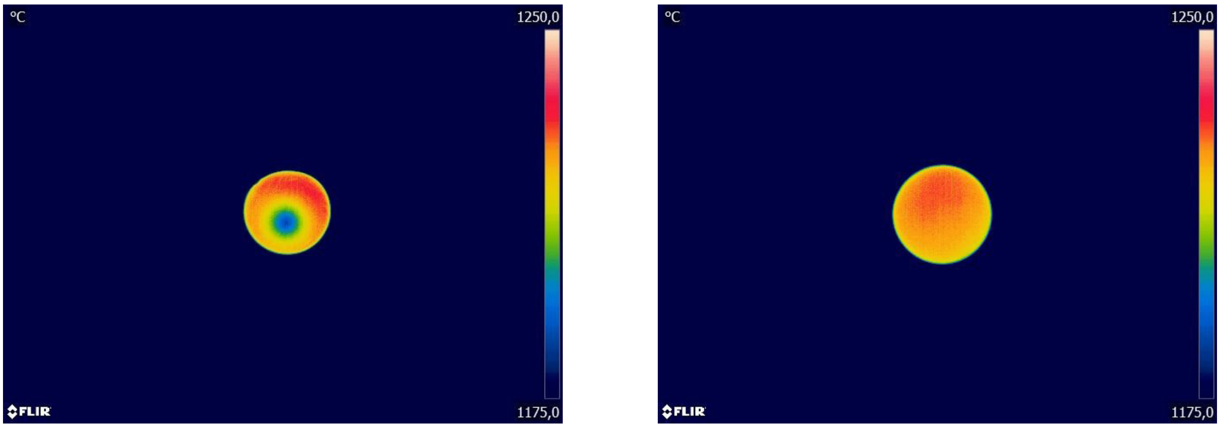


Figure 3 Example of unacceptable (left) and acceptable (right) cavity uniformity

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 180x180mm^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.

2. DEFINING THE BLACKBODY UNIFORMITY MEASUREMENT ISSUE

The first idea when measuring the uniformity of an infrared source is to use a thermal imager. The recent advances in technology over the past 10 years bring confidence in the performances of these imagers for quantitative applications. However, considering the results of [2], the use of IR cameras for uniformity measurement of IR reference source must be strictly limited to an approach of the non-uniformity value, for example for the diagnostic of heater failure. This is mainly due to two factors:

- The intrinsic non-uniformity of the camera. [2] shows that the thermal imagers delivers thermal maps with a intrinsic non uniformity of about 1% to 1.5% of the temperature of the measured source.

This level of error is at least the same as the non-uniformity level requirement for high end application blackbodies. So using thermal imagers as testing tools for infrared reference sources uniformity must be limited to resistance failure diagnostic. A more accurate method must be used to measure the residual non-uniformity of extended area blackbodies.

One may think that it may be possible to “scan” the emissive area of the source under test using always the same measurement point, for example the central point of the field of view. However, a second usual defect of thermal imagers keeps us from using this method.

- The size of source effect (SSE): the SSE is the ratio between the signal delivered by a camera aiming at a small centered source and the signal delivered by the camera over the same centered point but aiming at an extended area source at the same temperature. The difference between the two measurements is usually due to parasitic radiation entering the aperture of the camera and creating diffractions, scatters and reflections into internal optics.

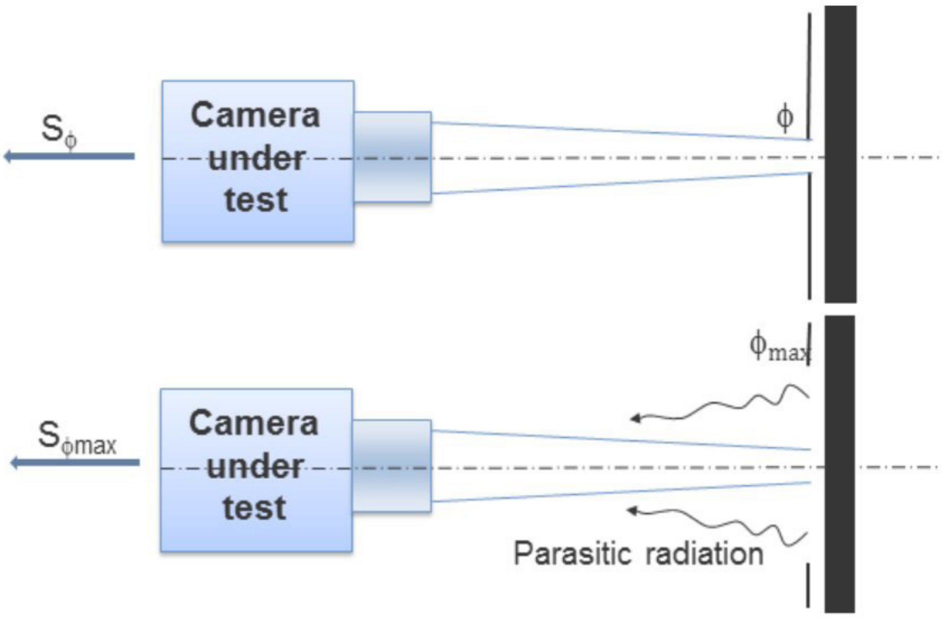


Figure 4 SSE measurement procedure

$$SSE = \frac{S_\phi}{S_{\phi max}} \tag{1}$$

[2] shows that this ratio may get up to 1.10 at low temperature (down to -10°C) for an extended source of 70mm compared to a small source of less than 10 mm. These conditions are equivalent to a temperature difference of 5°C. So, using a thermal imager to measure the non uniformity of a low temperature extended area source by reading only the central point measurement through the scanning method may lead to several degrees of fake non uniformity between the edges and the center of the source under test. Similar unsatisfying results are obtained for high temperatures (SSE lower than 0.9).

The specifications of the tool able to accurately measure the non uniformity of 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 uniformity testing 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.

3. IR SOURCES UNIFORMITY MEASUREMENT TOOL INTEGRATED INTO THE B3 BENCH

A uniformity measurement tool is the key element of the blackbody testing bench named B3 developed by HGH. This tool is made by the combination of a single element radiometer mounted on a motorized XY translation assembly.

Figure 5 Overview of the IR sources uniformity measurement bench

The uniformity measurement procedure is achieved by scanning the emissive surface of the IR reference 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.

3.1 Description of the radiometer

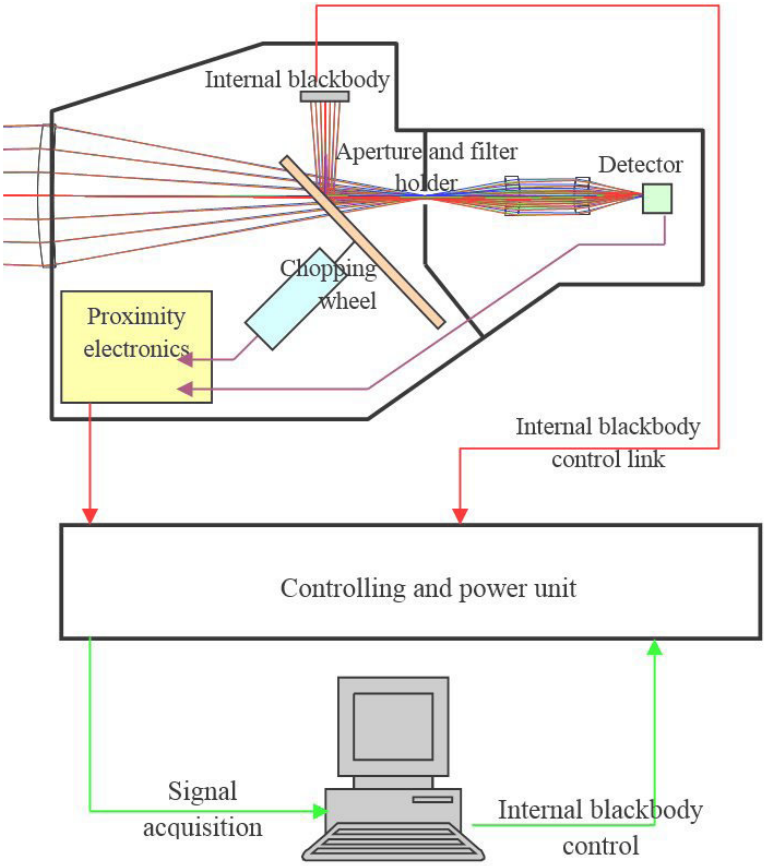


Figure 6 Operating sketch of the radiometer

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.

$$Signal = k \cdot \left(Radiance_{source}(\Delta\lambda) - \frac{dR_{BB}}{d\lambda}(T_{int\,BB}, \lambda) \cdot \Delta\lambda\right) \tag{2}$$

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:

$$Radiance_{source}(\Delta\lambda) = \frac{A}{e^{\frac{B}{T+273}+\frac{C}{(T+273)^2}}-D} \tag{3}$$

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

3.2 Scanning method

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:

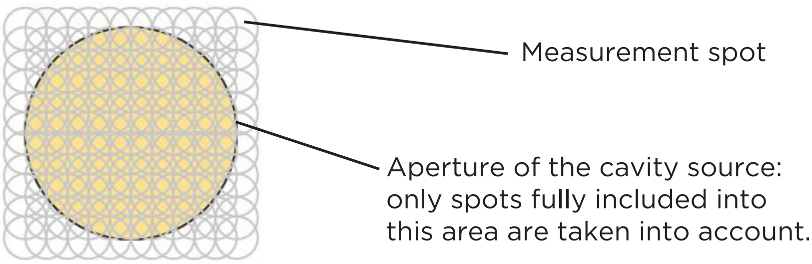


Figure 7 Spot network for a 25 mm diameter cavity blackbody

- For a 180 x 180 mm 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 Temporal drift correction

Two measurements of the same point of a source assumed to be stable over time, which is actually the case as shown in paragraph 2, allows evaluating the temporal drift of the radiometer. A maximum drift of 0.04°C at 85°C is measured over 2 minutes. This drift cannot be considered as negligible compared to the expected uniformity of extended area low temperature blackbodies (0.1°C at 50°C).

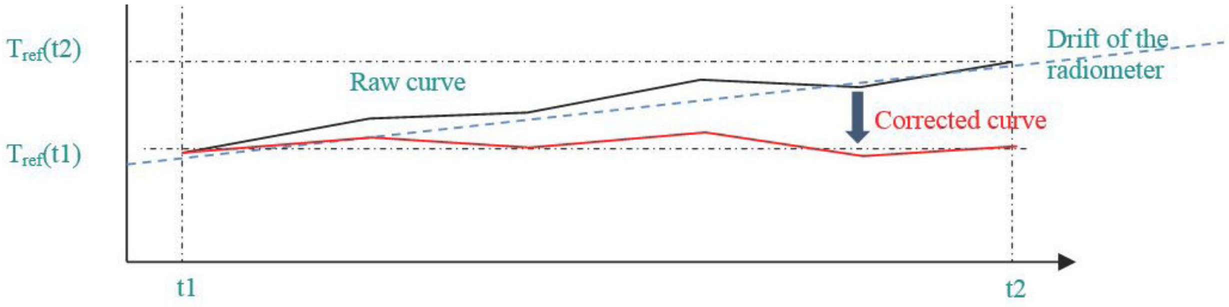


Figure 8 Correction procedure of the temporal drift of the radiometer

Consequently, the raw measurements are corrected by removing the drift of the radiometer. This drift is measured in real time. A point of the source is defined as the reference point for the drift measurement. The temperature $T_{ref}(t0)$ of the reference point is measured at the beginning of the scanning process. At the end of each complete measured column (c), the radiometer gets back to the reference point and measures the temperature of the reference point $T_{ref}(c)$. The drift for the column c is defined as:

$$drift(c) = T_{ref}(c) - T_{ref}(t0) \tag{4}$$

The drift of raw measurements of the spots of the column is removed in proportion of the time elapsed since t0:

$$T_{corrected}(c,l) = T_{raw}(c,l) - drift(c) \times \frac{t(c,l)-t0}{t0(c)-t0} \tag{5}$$

4. PERFORMANCES AND TEST RESULTS

4.1 Evaluation of the uniformity measurement system performances

Some key properties of the uniformity measurement bench have been evaluated.

The SSE of the radiometer has been measured according to the procedure shown in Figure 4 for different temperatures. Whatever the temperature, the measured SSE of the radiometer is about 0.999, i.e. much better than the SSE of any thermal imagers tested in [2]. This SSE level leads to an error of 30 mK at 50°C.

The noise level of the radiometer must have a limited contribution to the uniformity 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. The measured NETD level of the radiometer is then 10 mK at 50°C.

The global error of uniformity measurement is evaluated at 50°C over a 50x50 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 rms uniformity is calculated.

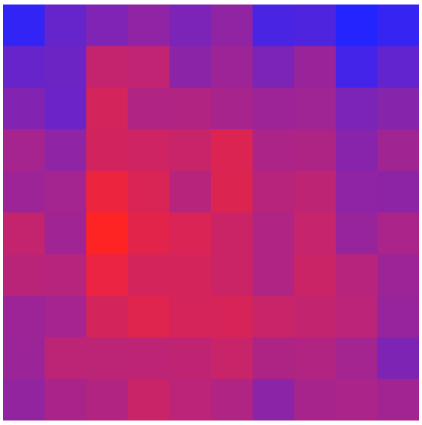
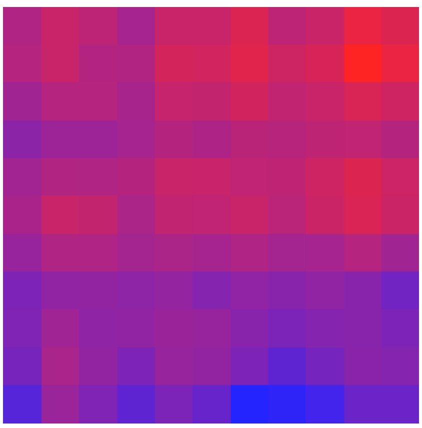


Figure 9 Uniformity thermal map of a 50x50 mm² blackbody (dark blue=49.255°C; hot red = 49.464°C)

The calculation of the rms uniformity from the above thermal map gives 40 mK. Taking the residual air convection effect into account, we can consider that the error of the uniformity measurement system of the B3 bench is 30 mK rms 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 180x180 mm^2 emissive surface at 50°C. The uniformity thermal map is shown below. A smoothing algorithm is applied to the image to get a real rendering.



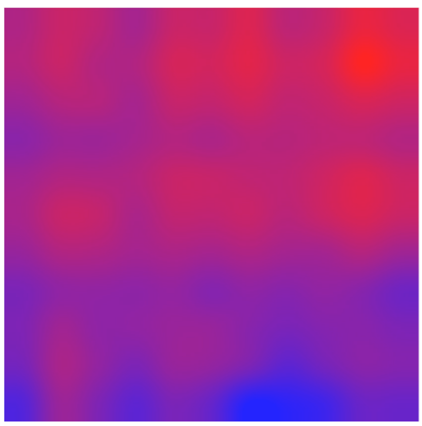
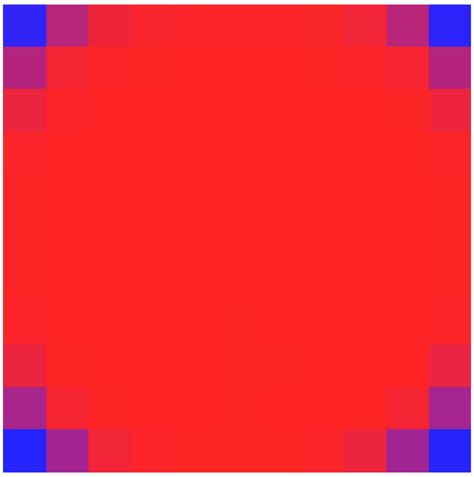


Figure 10 Uniformity thermal map of a 180x180 mm² blackbody (dark blue=48.927°C; hot red = 49.311°C)

The measured uniformity is 70 mK rms. 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 above 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 below.



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 10 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 above table, all the other measurements being at least partially outside the cavity aperture.

The uniformity of the above 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.

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. As the residual non uniformity level of thermal imagers is higher than the expected non uniformity on blackbodies, the use of thermal imagers for uniformity measurement must be limited to heaters/coolers failure diagnostic. A high accuracy measurement of the uniformity is achieved thanks to the B3 bench developed by HGH. With a maximum error of 30 mK rms at 50°C, this bench is able to provide the thermal uniformity map of low temperature extended area blackbodies and high temperature cavity blackbodies as well. This accurate measurement allows improving the manufacturing process of high end blackbodies in order to make them compatible with the increasing demanding uniformity specifications on these IR reference sources.

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, G. Chauvel, [Improving cooling of cavity blackbodies], SPIE 8896-20 (2013).

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