Influence of ambient temperature on the radiation of IR reference sources: effect on the calibration of IR sensors and method of compensation

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Influence of ambient temperature on the radiation of IR reference sources: effect on the calibration of IR sensors and method of compensation

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ABSTRACT

Blackbodies are the appropriate tools for IR sensors calibration and test. A well-known property of these object is their emissivity factor equals 1 while their transmission and reflection factors equal 0. Though some high emissive coatings with emissivity higher than 0.99 are now available on the market, a residual reflectivity factor always remains. The first part of this paper demonstrates the influence of the reflectivity factor on the radiated energy of a blackbody especially for blackbodies radiating at temperatures close to or below the ambient temperature. It happens that the difference between this radiated temperature, or apparent temperature, and the measured temperature maybe of several tenths of degrees! Such a difference leads to great uncertainty in the calibration procedure of thermal sensors. The case of sensors tested and calibrated into climatic chambers for outdoor applications is particularly critical.

The usual method to compensate this difference is to take emissivity and consequently reflectivity factor into the calculation of the theoretical irradiance received by the sensor. This calculation requires to have a live knowledge of the ambient temperature. While this may not always be the case, calculating the true irradiance i.e. the apparent temperature radiated by the reference source remains a complex calculation for major users of blackbodies. Indeed, they expect their blackbody source to be reliable and an actual reference source whatever the conditions of use. The second part of this paper presents a reminder about this calibration method of the absolute temperature of IR reference source and the correction method when ambient temperature doesn't change. The third part describes the integrated compensation method of the ambient temperature into the new controller of HGH's blackbody sources making these sources actual IR reference sources whatever the operating conditions.

Keywords: Infrared Reference source, blackbody, IR Systems calibration procedure, calibration uncertainty, IR radiation measurement, Temperature measurement.

1. DEFINITION OF THE TRUE TEMPERATURE OF A BLACKBODY

1.1 Differences between measured temperature, displayed temperature and radiated temperature

A perfect blackbody with emissivity equal 1 does not exist and calibrating and measuring specifications of IR sensors require the use of infrared reference sources, named blackbodies, with emissivity as high as possible.

As all objects, these "blackbodies" partially absorb a fraction $A(\lambda)$ of the incident radiation, they reflect a fraction $R(\lambda)$ of this incident radiation and transmit a fraction $T(\lambda)$..

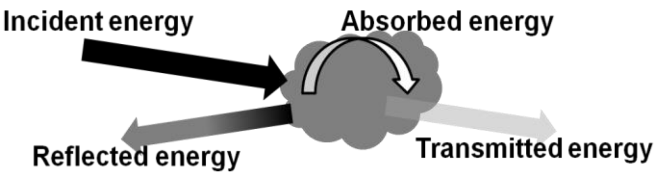

Figure 1: distribution of incident energy on usual objects

Since the fraction $A(\lambda)$ is re-emitted through radiation, an emission factor $\varepsilon(\lambda)$, called emissivity, is defined to quantify the ability of a body to re-emit this radiation.

$$\varepsilon(\lambda) + R(\lambda) + T(\lambda) = 1 \quad (1)$$

Manufacturing blackbodies thus consists in creating sources with emissivity value as high and as constant as possible over the widest spectral range. While transmission factor is easily 0, a reflection factor remains, reflecting the temperature of the environment.

$$R(\lambda) = 1 - \varepsilon(\lambda) \quad (2)$$

Three different temperatures should be considered into a blackbody: the measured temperature given by the contact sensor inserted into the emissive plate, the displayed temperature on the controller panel and the apparent temperature, i.e. the temperature of a perfect blackbody radiating the same energy as the given blackbody source.

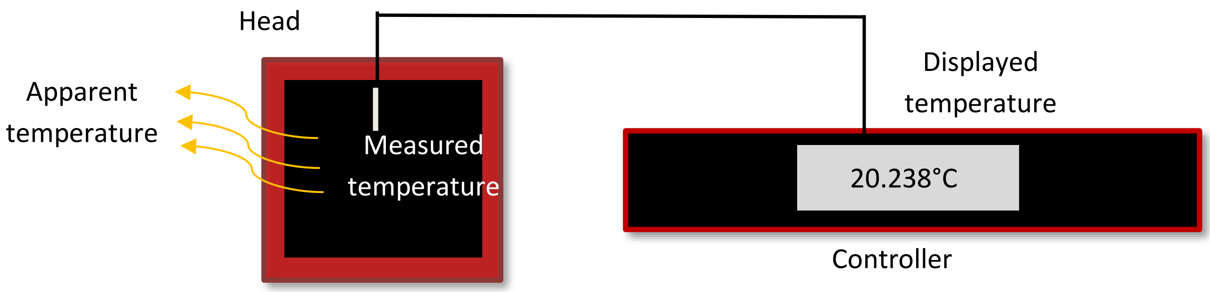

Figure 2: presentation of involved temperatures into a blackbody

The apparent temperature is the useful temperature for the test of IR sensors. The measured temperature is well-known thanks to calibrated contact sensor. Indeed, this contact sensor measures the actual temperature of the emissive plate and is directly involved into the regulation loop of the blackbody. The displayed temperature is the only value available for the operator. Thanks to accurate AD converters and electronics, displayed temperature equals measured temperature with a rather good uncertainty (about 10 mK). However, one would rather expect to have displayed temperature equals apparent temperature.

1.2 Calculation of radiated temperature – Influence of room temperature

The apparent temperature is calculated from the energy emitted and reflected by the blackbody source. The energy unit considered in infrared technology is the luminance i.e. density of flux per unit of surface and solid angle. Based on equation (2), the spectral density of luminance of a blackbody is calculated from:

$$\frac{dL_{BB}}{d\lambda}\left(T_{app}\right) = \varepsilon(\lambda) \times \frac{dL_{BB}}{d\lambda}(T_{meas}) + (1 - \varepsilon(\lambda)) \times \frac{dL_{BB}}{d\lambda}(T_{amb}) \tag{3}$$

Where $\frac{dL_{BB}}{d\lambda}$ is the spectral density of luminance given by the Planck's law and T_{amb} is the temperature reflected by the emissive surface i.e. frequently the ambient temperature. The total luminance is calculated through the integration of equation (3) over the spectral range of the tested IR sensor. The apparent temperature is then computed as the temperature providing the same luminance over the considered spectral range.

The apparent temperature value cannot be easily deducted from the measured temperature and obviously depends on the spectral range of operation. Table 1 shows various results of calculated apparent temperature in the case of emissivity equals 0.97 and 0.99 and assuming the room temperature is 23°C.

Emissivity	0.97		0.99	
Measured temperature	15°C	35°C	15°C	35°C
Apparent temperature	15.3°C	34.7°C	15.1°C	34.9°C

Table 1 : calculation of apparent temperatures in MWIR range for 23°C ambient temperature

The interest of a high emissivity is obvious. It leads to a low reflectivity and thus reduces the difference between the apparent temperature and the measured temperature. Table 2 shows the same calculations with 50°C ambient temperature. This case becomes more and more frequent for the test of IR sensors in climatic chambers for outdoor applications.

Emissivity	0.97		0.99	
Measured temperature	15°C	35°C	15°C	35°C
Apparent temperature	16.8°C	35.55°C	15.6°C	35.2°C

Table 2 : calculation of apparent temperatures in MWIR range for 50°C ambient temperature

Even using a high emissivity coating, the difference between the apparent temperature and the measured temperature is several tenth of degrees. The above calculations also assume the emissivity and the ambient temperature are well-known. Practically, a radiometric calibration by comparison with a reference blackbody and a live measurement of the ambient temperature are necessary to have a better knowledge of the radiation received by the sensor under test and reduce the uncertainty of calibration of this sensor.

In addition to this calibration, a correction is required on the measured temperature before display to make it equal to the radiated temperature. For example, in the case of 0.97 emissivity and for a 15°C required apparent and displayed temperature:

- At 23°C ambient temperature, the blackbody must be regulated at 14.7°C (measured temperature)
- At 50°C ambient temperature, the blackbody must be regulated at 13.2°C (measured temperature)

2. PRINCIPLE OF RADIOMETRIC CALIBRATION OF BLACKBODIES AND CORRECTION OF DISPLAY

2.1 Radiometric calibration by comparison with a reference blackbody

The calibration procedure is made by the repeated, successive and automatic comparison of the radiation of the blackbody source under test with the radiation of a reference blackbody previously calibrated by a National Metrology Institute (NMI) to guarantee the traceability of results. The spectral range of the comparison tool (radiometer, pyrometer, IR thermographic camera) defines the spectral range of calibration. The blackbody under test and the reference blackbody are both set and stabilized at the same temperature while the room temperature remains stabilized at 23°C ± 2°C. 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 below example is given for a blackbody, serial number 597, calibrated over the MWIR range. The approximate emissivity of this blackbody is 0.97.

Aimed source	Temperature set (°C)	Measurement number	Measured value (°C)
Reference	20	1	20,29843428
BBUT sn 597		2	20,23516779
Reference		3	20,28975016
BBUT sn 597		4	20,234
Reference		5	20,27066474
BBUT sn 597		6	20,226
Reference		7	20,29985767
BBUT sn 597		8	20,217
Reference		9	20,26995236
BBUT sn 597		10	20,206
Reference		11	20,29117396
BBUT sn 597		12	20,203
Reference		13	20,28134837
BBUT sn 597		14	20,201
Reference		15	20,29829194
BBUT sn 597		16	20,193
Reference		17	20,3321504
BBUT sn 597		18	20,194
Reference		19	20,34124868
BBUT sn 597		20	20,227

Table 3 : Example of raw measurements at 20°C for the reference blackbody and the BBUT serial number 597

The difference between two 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.

Difference between measurement number	Temperature set point (°C)				
	0	20	50	80	150
2 and 1	-0,157	-0,063	0,202	0,454	0,580
4 and 3	-0,228	-0,056	0,221	0,454	0,384
6 and 5	-0,201	-0,045	0,219	0,371	0,514
8 and 7	-0,136	-0,083	0,221	0,387	0,452
10 and 9	-0,151	-0,064	0,237	0,413	0,452
12 and 11	-0,176	-0,088	0,198	0,349	0,308
14 and 13	-0,114	-0,080	0,200	0,385	0,337
16 and 15	-0,072	-0,105	0,247	0,332	0,476
18 and 17	-0,100	-0,138	0,203	0,402	0,387
20 and 19	-0,116	-0,115	0,205	0,392	0,467
Average difference (°C)	**-0,15**	**-0,08**	**0,22**	**0,39**	**0,44**
Standard deviation	**0,05**	**0,03**	**0,02**	**0,04**	**0,08**

Table 4 : Example of apparent temperature difference measurements for the reference blackbody and the BBUT serial number 597

Since the absolute apparent temperature of the reference blackbody is known from the certificate of calibration delivered by the NMI accredited laboratory, the absolute apparent temperature of the BBUT is calculated consequently from Equation (4).

$$Apparent\ Temp_{BBUT} = Apparent\ Temp_{refBB} + difference \tag{4}$$

	Temperature set point				
	0	20	50	80	50
Reference BB apparent temperature (°C)	1,1	20,3	49,4	78,9	148
Difference (°C)	-0,15	-0,08	0,22	0,39	0,44
BBUT apparent temperature (°C)	**0,95**	**20,22**	**49,62**	**79,29**	**148,44**

Table 5 : Example of final apparent temperature calibration results for the BBUT serial number 597 at 23°C ambient temperature

Table 5 means the blackbody sn 597 behaves like a perfect blackbody at 49.62°C when the controller display shows 50°C i.e. when the blackbody is stabilized at 50°C measured temperature and when the ambient temperature is 23°C ± 2°C. Indeed, the above values are consistent with the apparent temperatures calculated in Table 1.

2.2 Correction applied on measured temperature before display

The curve showing Apparent temperature vs. measured temperature is shown below for the above example of Table 5.

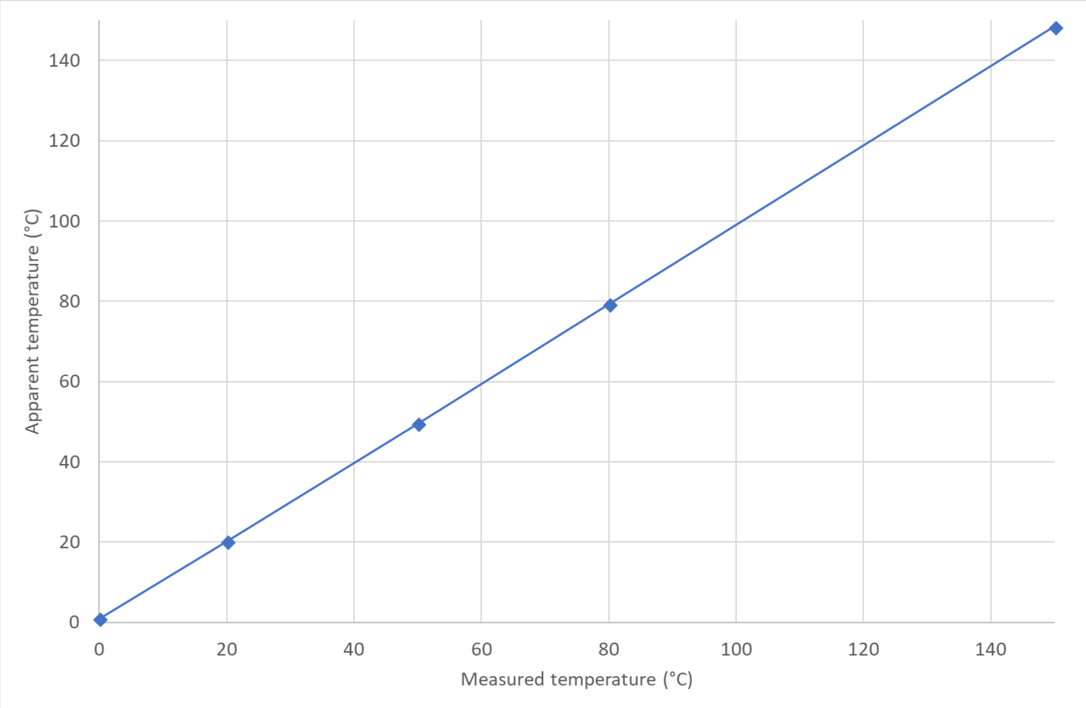

Figure 3: apparent temperature vs. measured temperature

A linear conversion is applied to each segment of the curve to convert measured temperature into displayed temperature and have Displayed temperature = Apparent temperature. Considering the above example and the segment [20 ;50], the conversion equation is

$$Displayed\ temperature = 0.98\ \times Measured\ temperature + 0.62 \tag{5}$$

When the contact sensor measures 20°C, the displayed temperature on the controller screen is 20.22°C i.e. equals the apparent temperature. Of course, if the operator requires a 20°C apparent temperature setpoint on the display, the reverse correction is automatically applied to the contact sensor setpoint:

$$Measured\ setpoint = 1.0204\ \times Displayed\ setpoint - 0.6327 \tag{6}$$

From equation (6), a 20°C apparent setpoint on the display requires a 19.775°C contact setpoint, i.e. about 0.2°C correction. Consequently, this correction is unfortunately valid over a restricted range of ambient temperature. For a 50°C ambient temperature and based on apparent temperature calculations of Table 2 the expected correction at 20°C is rather about 1.5°C.

3. DYNAMIC COMPENSATION OF THE ROOM TEMPERATURE INFLUENCE

3.1 Dynamic compensation method

The luminance corresponding to the contact sensor setpoint temperature is deducted from Equation (3) and integrated over the considered spectral range:

$$L_{BB}(T_{meas}) = \frac{L_{BB}(T_{app}) - (1-\varepsilon) \times L_{BB}(T_{amb})}{\varepsilon} \tag{7}$$

T_{app} is the required apparent temperature of the blackbody surface, T_{amb} is the ambient temperature and maybe strongly different from the ambient temperature during the calibration process. The blackbody head is equipped with an external sensor so T_{amb} value is known in real time, leading to an autonomous operation of the dynamic compensation procedure.

The considered emissivity value in Equation (7) is the apparent emissivity calculated over the considered spectral range:

$$\varepsilon = \frac{L_{BB}(T_{app\_cal}) - L_{BB}(T_{amb\_cal})}{L_{BB}(T_{meas\_cal}) - L_{BB}(T_{amb\_cal})} \tag{8}$$

The temperature of regulation is then computed from the calculation of $L_{BB}(T_{meas})$ in Equation (7). This compensation method allows to have Displayed temperature equals Apparent temperature whatever the Ambient temperature.

3.2 Practical application and results

A 0.97 emissivity blackbody head is integrated into a climatic chamber. The dynamic compensation procedure is set ON for this blackbody. Another similar blackbody is installed outside the climatic chamber. Both blackbodies are stabilized at 50°C with a residual instability lower than 0.002°C i.e. negligible compared to other sources of uncertainty: this information is controlled in real time on the display of both blackbodies. The temperature outside the climatic chamber remains constant (23°C ± 2°C) during the test while the temperature of the chamber varies from 25.7°C to 45°C. A radiometer, operating over the 8-14 µm spectral range and located outside the chamber, aims successively at the blackbody in the chamber through an aperture and at the blackbody outside the chamber. The blackbody located outside the chamber is consequently used as a reference for the radiometer, to compensate its possible drift. The apparent temperature difference between the 2 blackbodies is then calculated for different temperatures of the chamber.

Important note: during our tests, the external blackbody temperature was not corrected. Consequently, a non-zero constant value was expected on the difference of radiation between the 2 blackbodies.

Climatic chamber temperature (°C)	Blackbody external sensor temperature (°C)	Temperature difference between internal and external blackbody (°C)
25.7	26	0.2
28.7	28.4	0.15
29.2	29	0.2
32.1	31.5	0.2
36	34.85	0.15
45	41.7	0.13

Table 6 : Dynamic compensation: apparent temperature difference between a blackbody inside a climatic chamber and a reference blackbody

The expected offset between the 2 blackbodies is obviously 0.2°C. Using the dynamic compensation method, the maximum error in the above example is 0.07°C for a 20°C ambient temperature difference. This result has to be compared with the theoretical temperature difference between these two blackbodies if no dynamic compensation is applied: the error is then 0.5°C for a 20°C difference as shown in Table **7**.

Climatic chamber temperature (°C)	Reference blackbody apparent temperature (°C)	Climatic chamber blackbody theoretical apparent temperature (°C)	Theoretical temperature difference between internal and external blackbody (°C)
25.7	50	49,34	0,66
28.7		49,42	0,58
29.2		49,43	0,57
32.1		49,49	0,51
36		49,6	0,4
45		49,85	0,15

Table 7 : Theoretical apparent temperature difference between a blackbody inside a climatic chamber and a reference blackbody

3.3 Selection of radiometric correction and compensation mode

The controller of HGH's blackbodies allows an easy selection of different modes of display.

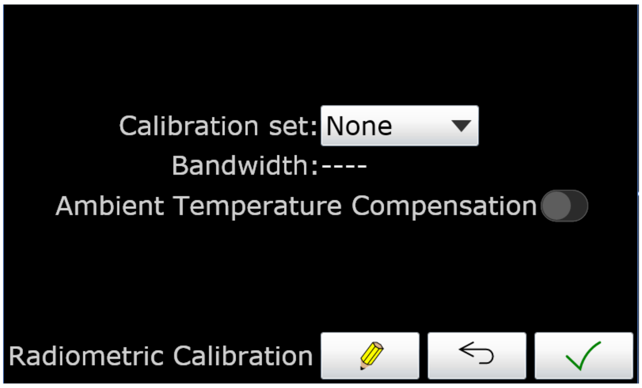

Figure 4: Displayed temperature selection: no correction

Figure 4 shows the selection page of the displayed temperature when no correction is applied. With the "None" selection, the displayed temperature equals the measured temperature i.e. the temperature measured by the thermal contact sensor inserted into the emissive plate. It is up to the operator to take the emissivity and room temperature into account to calculate the actual radiation of the blackbody using Equation (3).

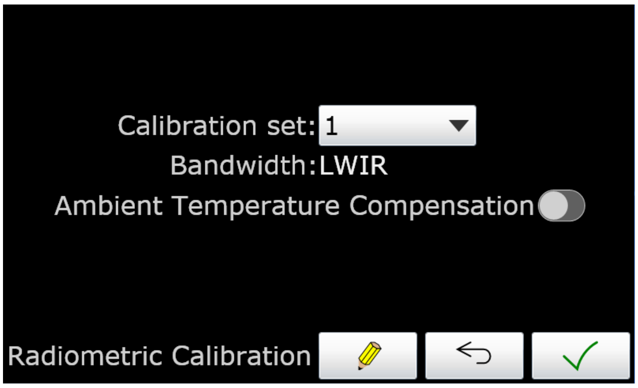

Figure 5: Displayed temperature selection: LWIR apparent temperature correction

Figure 5 shows the selection page of the displayed temperature when the LWIR correction is applied, the correction parameters being saved into calibration parameters set number 1, 4 correction parameters sets being available. With this selection, the displayed temperature equals the apparent temperature radiated by the blackbody over the LWIR spectral range. This correction is valid for ambient temperatures of 23°C ± 2°C.

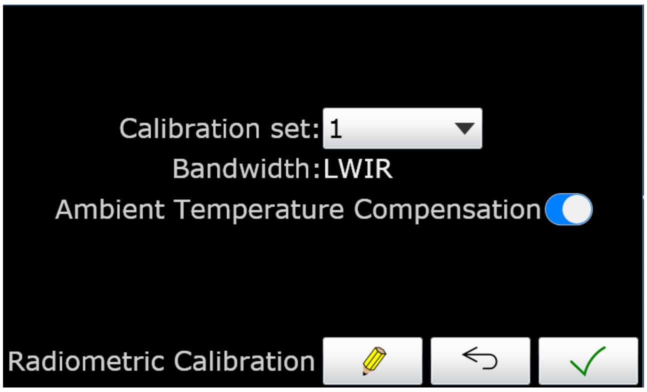

Figure 6: Displayed temperature selection: LWIR apparent temperature correction with dynamic compensation

Figure 6 shows the selection page of the displayed temperature when the LWIR correction is applied and the dynamic compensation procedure is valid. With this selection, the displayed temperature equals the apparent temperature radiated by the blackbody over the LWIR spectral range independently from the ambient temperature change, this ambient temperature being lively measured by a sensor connected to the blackbody.

4. CONCLUSION

Using a blackbody is apparently easy: the emissive surface gets quickly stabilized at the defined setpoint and the controller offers a live display of its temperature with a high resolution. However, the signification of this displayed temperature may be ambiguous especially if the operator is expecting this temperature to be what the tested sensor actually sees. The new generation of HGH's new controller removes this ambiguity by clearly displaying either the temperature measured by the sensor or the radiated temperature at usual laboratory temperature over the appropriate bandwidth or the radiated temperature over the appropriate bandwidth whatever the room temperature, compatible with demanding applications in climatic chambers. In addition to simplifying the calculation for the operator, it strongly reduces the sources of error which might be of several tenth of degrees.

5. REFERENCES

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