TEMPERATURE CALIBRATION OF AN INFRARED THERMOGRAPHIC CAMERA AND ITS UNCERTAINTY OF MEASUREMENT

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Abstract. *A methodology was developed to calibrate the temperature output from a thermographic camera, used for maintenance planning purposes. Initially, a device was designed to calibrate the thermographic camera in PUC-Rio, starting from the knowledge of the emissivity of a black surface, as part of the upper base of a brass cylindrical block, and located 3 mm above the liquid surface of a temperature controlled calibration bath. Its temperature was measured by three calibrated thermocouples, inserted in radial holes bellow the black surface. Thus, the indicated temperatures of the thermographic camera was compared to the measured temperature. Then, the camera was calibrated against a blackbody in INMETRO, with its uncertainty estimated in the 0,54 °C to 0,62 °C range. Joining the two pieces of information, the emissivity of the black surface could be determined from ambient up to 150 ^{o}C. Its uncertainty was estimated in ± 0,02. When the thermographic camera measures the temperature of a target, the uncertainty of measurement was estimated in the 0,9 °C to 2,7 °C range, including the uncertainty of emissivity measurement and of surface temperature uniformity, matching the manufacturer's specification.*

Keywords: Thermographic camera, calibration, black body, maintenance, emissivity

1. INTRODUCTION

Temperature monitoring of electricity production equipments in hydroelectric power plants is a tool to be used for maintenance planning purposes. When the temperature gets higher than the manufacturer's specification value, or even the designer's one, it is assumed that a shift in its performance has occurred, and, therefore, a maintenance procedure must be used to recover its original operating characteristics. The sooner the problem is observed, the smallest will be the consequences of the interruption of the electric energy supply, and the smallest the maintenance costs will be. Therefore, a continuous temperature monitoring is an important follow up tool.

Traditionally, thermocouples and platinum resistance thermometers have been used for the job. However, they require many times that the equipment be de-energized, so that the sensors can be installed. Lately, the remote temperature measurement technology has been developed to a point to become an important tool for operation diagnosis.

The thermographic camera analyzes the infrared radiation emitted from the target, and interprets its signal, relating it to temperature, according to the laws of heat transfer by radiation. The existing equipment measures temperature with a reasonable accuracy if the surface emissivity of the target is known, and if the temperature is uniform. Therefore, the accuracy of temperature measurement by the thermographic camera depends on its calibration and on the signal interpretation at different operating conditions.

In this work, an infrastructure was developed to calibrate a thermographic camera, and to adequately interpret the infrared signal at different operating conditions. A methodology was developed to calibrate it at ideal conditions (known emissivity and uniform temperature) and, then , to measure the target emissivity.

Tipically, electricity production equipments operate in the 0 °C to 150 °C temperature range. The measurement tolerance is usually admitted as 2%. The thermographic camera that was used in this experiment has an accuracy of ± 2°C or 2%, whichever is greater, according to the manufacturer. Therefore, in this work, it was decided to calibrate the camera in the 0 °C to 150 °C temperature range.

The methodology consists in calibrating the camera against a blackbody in INMETRO (Instituto Nacional de Metrologia, Normalização e Qualidade Industrial, Brazil)), which is traceable to NIST (National Institute for Standards and Technology, USA). Then, the camera is calibrated in PUC-Rio against a black surface of a cylindrical brass block placed in a temperature controlled calibration bath. Using the radiation heat transfer relationships, the emissivity of the surface can be determined. The contribution of this work is to develop a methodology to measure the emissivity of a surface as a function of temperature with the thermographic camera, and then to measure the temperature of a target, having the same surface emissivity, at different operating conditions.

2. CALIBRATION OF THE THERMOGRAPHIC CAMERA AGAINST A BLACK BODY AT INMETRO

The calibration equipment consists of a temperature controlled blackbody, with known radiative properties. The camera views the blackbody surface at a measured temperature, and compares with the indicated value, thus performing a calibration by the comparison method. A MIKRON M315X8 blackbody, traceable to NIST, was used to calibrate the thermographic camera at INMETRO. The spectral emissivity of the blackbody, as a function of the wavelength, was measured by NIST and shown in Fig.1.

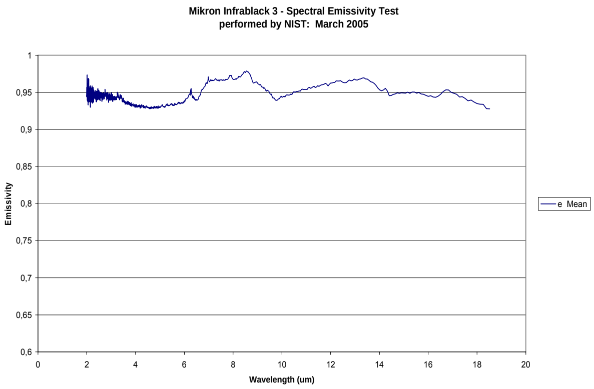

Figure 1 : Spectral emissivity of the MIKRON M315X8 blackbody, as measured by NIST

In the 2μm < λ < 18μm wavelength range the spectral emissivity (ε_λ) varies in the 0,94 ± 0,02 range with a confidence level of 95,45%, resulting in a total emissivity along the whole spectrum of ε = 0,96. The indicated temperature (T_c) is obtained by setting an emissivity value of 0,96 in the camera, which can be related to the blackbody temperature (T_b) by the least square fit method (Orlando et allii,1985), (Orlando et alli, 2003), (Holman, 1971) and (Benedict, 1977), resulting in a root mean square deviation (u_{fit}) :

$$T_b = A + B.T_c \qquad (1)$$

$$u_{fit} = \sqrt{\frac{1}{N-2}.\sum_{i=1}^{N}\left(A + B.T_{c,i} - T_{b,i}\right)^2} \qquad (2)$$

The camera also displays the root mean square of the measured temperature (u_d) , which can be interpreted as the temperature uniformity of the target surface measured by the camera. The stability of the blackbody temperature is very good. It is estimated that its expanded uncertainty (95,45 %) of measurement is U_b = ± 0,01 °C, or u_b = 0,005 °C for its standard uncertainty. In order to check the repeatibility of temperature measurement by the camera, each blackbody temperature (12) was measured ten (10) times. The fitting coefficients A and B, together with the root mean square deviation (u_{fit}), were calculated using all measured values (120). Then, the standard uncertainty of temperature calibration along the operating range of the camera (u_c), including the curve fit, if only one measurement is allowed, following (ISOGUM, 1995), can be estimated as :

$$u_c = \sqrt{u_{fit}^2 + (B.u_d)^2 + u_b^2} \qquad (3)$$

$$U_c = 2.u_c \qquad (4)$$

3. EMISSIVITY MEASUREMENT AT PUC-Rio

When the thermographic camera views a non black surface with emissivity ε at a measured temperature (T_b), an indicated camera temperature (T_c) is read, adjusting the emissivity for ε=1. Then, an effective temperature (T_{effect}) is calculated from the calibration curve, following Eq. (1) :

$$T_{effect} = A + B.\ T_c \tag{5}$$

The surface emissivity can thus be calculated from Eq. (6) :

$$\varepsilon = \left(\frac{T_{effect}}{T_b} \right)^4 \tag{6}$$

A device was designed to measure the emissivity at PUC-Rio. Alternatively, it can be used to calibrate the thermographic camera, provide that the surface emissivity is known.

It consists of a cylindrical brass block with 75 mm diameter and 110 mm height, inside a temperature controlled calibration bath, having its upper surface painted black and placed about 3 mm above the liquid surface of the bath. The bath temperature was measured six (6) times for each set temperature with a Rosemount 1925 standard platinum resistance thermometer (SPRT) to test repeatability. An HP34420A multimeter was used to measure the thermometer resistance with an equivalent uncertainty of ± 0,05 °C. The black surface temperature was measured by three type T thermocouples, gauge 24, using an HP34401A multimeter to measure its emf, with a maximum equivalent uncertainty of ± 0,3 °C. They were placed inside three radially drilled holes, immediately below the black surface. The device is shown in Fig. 2.

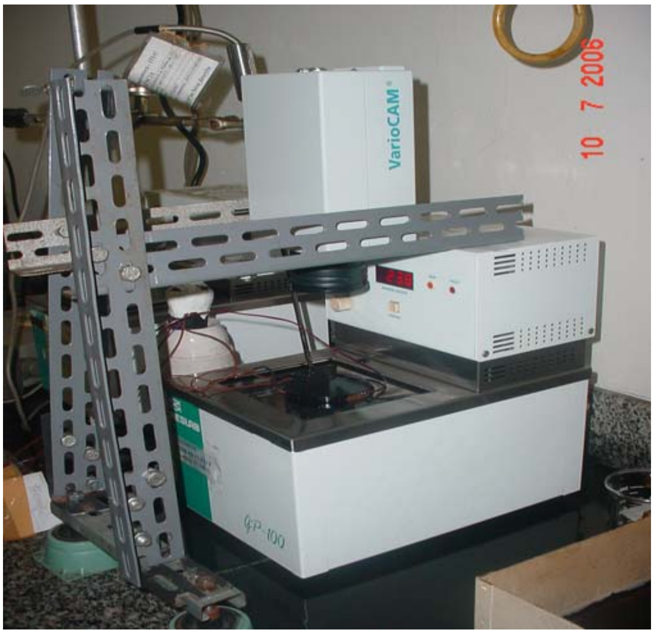

Figure 2 : Device for calibrating the thermographic camera at PUC-Rio

The thermocouple calibration was made by comparison with the output from the standard platinum resistance thermometer (SPRT) in the Pressure and Temperature Laboratory of PUC-Rio, which is accredited by the National Calibration Network (RBC) of Brazil, in a temperature controlled bath. Six (6) measurements were made, each one at every a 5 minute time interval, to check the repeatibility of results. The reference junction of each thermocouple was kept in an ice bath. The output from the thermocouples, in mV, was converted to °C (I_{ITS}), using the equations from ITS-90 (International Temperature Scale), and compared to the output from the SPRT (T_b) . A third degree polynomial, chosen by the least square fit method , minimized the root mean square deviation of the fit, among other polynomials. The uncertainty of measurement was estimated taking into account the standard thermometer uncertainty, the uncertainty of the fit (root mean square deviation) and the uniformity of the calibration bath. Table 1 shows the fit coefficients (C_1, C_2, C_3, C_4, C_5), together with the uncertainty of temperature measurement (U) at 95,45 % confidence level.

$$T_b = C_1 + C_2.T_{ITS} + C_3.T_{ITS}^2 + C_4.T_{ITS}^3 + C_5.T_{ITS}^4 \tag{7}$$

Table 1 : Curve fitting coefficients and uncertainty of measurement for type T thermocouples

	Thermocouples		
	1	2	3
C_1	0,26082	0,29289	-0,69686
C_2	0,99374	0,98043	1,05520
C_3	2,6977E-5	2,1821E-4	-1,4954E-3
C_4	0	-7,6167E-7	1,4452E-5
C_5	0	0	-4,5206E-8
U (°C)	0,25	0,15	0,30

The average temperature of the black surface (T_b) was estimated as an arithmetic mean of the three thermocouple readings (T_1, T_2, T_3), as indicated by Eq. (6) Uncertainty of average surface temperature (U_b) was calculated by Eq. (8), using the indicated value of the expanded uncertainty of each thermocouple in Table 1, respectively, U_1= ± 0,25 °C, U_2= ± 0,15 °C and, U_3= ± 0,30 °C.

$$T_b = \frac{T_1 + T_2 + T_3}{3} \tag{8}$$

$$U_b = \frac{\sqrt{U_1^2 + U_2^2 + U_3^2}}{3} = 0{,}14\ °\text{C} \tag{9}$$

$$u_b = \frac{U_b}{2} = 0{,}07\ °\text{C} \tag{10}$$

However, due to the non uniformity of the surface temperature, a type B expanded uncertainty U_b can be chosen to represent the maximum difference between any of the three measurement thermocouples (T_1, T_2, T_3) and the average value, if it is larger than the value in Eq. (9). The standard uncertainty (u_b) can be calculate as $u_b = U_b / \sqrt{3}$.

The black surface indicated temperature measurement by the thermographic camera (T_c) is made by setting an emissivity value of ε=1. The camera also displays the root mean square of the measured temperature (u_d) , which can be interpreted as the temperature uniformity of the target surface measured by the camera.

The effective temperature (T_{effect}) can be calculated using the calibration curve, Eq. (5)

$$T_{effect} = A + B.\ T_c \tag{5}$$

The value to be used for the standard uncertainty of the effective temperature (u_{effect}) is the same as u_c, obtained during the calibration against a blackbody at INMETRO, Eq. (3). For interpolation purposes, Eq. (11) can be used.

$$u_{effect} = \sqrt{u_{fit}^2 + (B.u_d)^2 + u_b^2} \tag{11}$$

where u_{fit} is taken from Eq. (2), and u_b = 0,005 °C , for INMETRO's blackbody temperature standard uncertainty. The camera displays the root mean square of the measured temperature (u_d).

The surface emissivity (ε) can be calculated from Eq. (6), using temperature values of Eq. (5) and (8). Uncertainty of emissivity measurement (u_ε) can be calculated from Eq. (12).

$$u_\varepsilon = 4.\varepsilon.\sqrt{\left(\frac{u_{effect}}{T_{effect}}\right)^2 + \left(\frac{u_b}{T_b}\right)^2} \tag{12}$$

The expanded uncertainty (U_ε) of emissivity measurement (95,45%) can be calculated from Eq. (13).

$$U_\varepsilon = 2.\ u_\varepsilon \tag{13}$$

4. TEMPERATURE MEASUREMENT WITH THE THERMOGRAPHIC CAMERA

The measurement of temperature by the thermographic camera can be made by pointing it to the target, after having set an emissivity value of ε=1, resulting in an indicated temperature (T_c). Then, the effective temperature (T_{effect}) can be calculated from the calibration curve, Eq. (5). The target temperature (T_b) can, therefore, be calculated from Eq. (14), using the same surface emissivity (ε) value measured in a similar surface at PUC-Rio.

$$T_b = \frac{T_{effect}}{\sqrt[4]{\varepsilon}} \quad * \tag{14}$$

The uncertainty of temperature measurement with the thermographic camera can be estimated from the knowledge of the surface emissivity and its uncertainty, determined as before. In many practical applications the target temperature can only be measured once. If a smaller uncertainty is desired, several measurements have to be made.

The value to be used for the standard uncertainty of the effective temperature (u_{effect}) is the same as u_c , obtained during the calibration against a blackbody at INMETRO, Eq. (3). For interpolation purposes, Eq. (11) can be used.

$$u_{effect} = \sqrt{u_{fit}^2 + (B.u_d)^2 + u_b^2} \tag{11}$$

where u_{fit} is taken from Eq. (2), and u_b = 0,005 °C , for INMETRO's blackbody temperature standard uncertainty. The camera displays the root mean square of the measured temperature (u_d).

The surface emissivity and its uncertainty were determined by Eq. (6) and (12).

The uncertainty of the target temperature (u_b) can be determined by Eq. (15)

$$u_b = T_b \cdot \sqrt{\left(\frac{u_\varepsilon}{4.\varepsilon}\right)^2 + \left(\frac{u_{effect}}{T_{effect}}\right)^2} \tag{15}$$

$$U_b = 2 \cdot u_b \tag{16}$$

5. RESULTS

5.1 Calibration of the thermographic camera against a blackbody at INMETRO

Table 2 : Calibration of the thermographic camera against a blackbody at INMETRO, for one measurement

	TEMPERATURE (°C)		UNCERTAINTY (°C)			
	Camera T_c	Blackbody T_b	Blackbody u_b	Fit u_{fit}	Camera u_d	Expanded U_{effect}
1	35,12	34,90	0,005	0,156	0,25	0,58
2	45,42	45,10	0,005	0,156	0,26	0,60
3	55,43	55,10	0,005	0,156	0,24	0,57
4	65,65	65,10	0,005	0,156	0,25	0,58
5	75,79	75,10	0,005	0,156	0,23	0,55
6	85,87	85,10	0,005	0,156	0,23	0,55
7	95,89	95,00	0,005	0,156	0,22	0,54
8	105,98	105,07	0,005	0,156	0,22	0,54
9	116,19	115,10	0,005	0,156	0,25	0,58
10	126,30	125,10	0,005	0,156	0,26	0,60
11	136,47	135,10	0,005	0,156	0,24	0,57
12	146,50	145,10	0,005	0,156	0,27	0,62

Ten measurements for each of the 12 blackbody temperatures in the 25 °C to 150 °C range were made to test the repeatability of the camera. Their averages are shown in Table 2. The blackbody has a temperature uncertainty (95,45%) of ± 0,01 °C. The fitting coefficients are in shown in Eq. (17), (18), (19).

$$A = 0{,}216392\ °C \quad (17)$$

$$B = 0{,}988795 \quad (18)$$

$$u_{fit} = 0{,}156\ °C \quad (19)$$

It can be seen that the uncertainty of temperature measurement (95,45%) is in the 0,54 °C to 0,62 °C range. Also, the most important contribution to it is the temperature uniformity of the target surface measured by the camera.

5.2 Emissivity determination at PUC-Rio

Table 3 : Black surface temperature measured by thermocouples

Black Surface Temperature (°C)							
T_1	T_2	T_3	T_b	U_{max}	$U_{average}$	U_b	u_b
25,01	24,98	24,94	24,98	0,04	0,14	0,14	0,07
34,00	33,94	34,00	33,98	0,04	0,14	0,14	0,07
44,49	44,40	44,56	44,48	0,08	0,14	0,14	0,07
54,11	53,96	54,16	54,08	0,12	0,14	0,14	0,07
63,70	63,69	64,02	63,81	0,21	0,14	0,21	0,12
73,69	73,49	73,93	73,70	0,23	0,14	0,23	0,13
83,06	83,20	83,85	83,37	0,48	0,14	0,48	0,28
92,92	92,67	93,67	93,08	0,58	0,14	0,58	0,34
82,77	82,67	82,88	82,77	0,10	0,14	0,14	0,07
92,18	92,13	92,56	92,29	0,27	0,14	0,27	0,15
101,05	100,97	101,84	101,29	0,55	0,14	0,55	0,32
110,12	110,17	111,35	110,55	0,80	0,14	0,80	0,46
120,40	120,31	121,66	120,79	0,87	0,14	0,87	0,50
120,52	120,50	121,87	120,96	0,91	0,14	0,91	0,52
130,04	129,86	131,35	130,42	0,93	0,14	0,93	0,54
139,91	139,70	140,81	140,14	0,67	0,14	0,67	0,39

Table 4 : Emissivity determination as a function of temperature

Black Surface (Table 2)		Thermographic Camera				Emissivity		
		Indicated		Effective (ε=1)				
T_b	u_b	T_c	u_d	T_{effect}	u_{effect}	ε	u_ε	U_ε
°C	°C	°C	°C	°C	°C			
24,98	0,07	24,72	0,40	24,66	0,43	0,996	0,006	0,012
33,98	0,07	33,51	0,35	33,35	0,38	0,992	0,005	0,010
44,48	0,07	43,79	0,31	43,52	0,34	0,988	0,004	0,009
54,08	0,07	52,58	0,33	52,21	0,36	0,977	0,004	0,009
63,81	0,12	62,15	0,34	61,67	0,37	0,975	0,005	0,009
73,70	0,13	71,62	0,37	71,03	0,40	0,970	0,005	0,009
83,37	0,28	80,84	0,29	80,15	0,33	0,964	0,005	0,009
93,08	0,34	89,62	0,32	88,84	0,35	0,954	0,005	0,010
101,29	0,07	98,97	0,59	98,07	0,60	0,966	0,006	0,013
110,55	0,15	108,09	0,71	107,09	0,72	0,964	0,007	0,015
120,79	0,32	117,88	0,80	116,77	0,81	0,960	0,009	0,017
130,42	0,46	127,23	0,90	126,02	0,90	0,957	0,010	0,019
140,14	0,50	137,46	0,85	136,14	0,85	0,962	0,009	0,019

It can be seen that the emissivity has an approximately constant value of ε = 0,96 for temperature values higher than 70 °C, with an uncertainty of ± 0,02.

5.4 Temperature measurement with the thermographic camera

A simulation was carried on for three sets of temperature measurement, to check repeatibility. Tables 5, 6 and 7 shows the results.

It can be seen from Tables 5, 6 and 7, that the uncertainty of temperature measurement (95,45%) by the thermographic camera is in the 0,9 °C to 2,7 °C range, matching the manufacturer's declaration, that is ± 2 °C, or 2%, whichever is greater.

The uncertainty of temperature measurement with the thermographic camera is estimated in Tables 5, 6 and 7 for situations where only one measurement is allowed. If smaller uncertainty values are required, several measurement (n) must be made. Then, the average of the measured values represents the true temperature. Its uncertainty can be calculated by dividing the expanded uncertainty, estimated for only one measurement, by $\sqrt{n}$.

Finally, the non uniformity of target surface temperature has the greatest contribution to its measurement.

Table 5 : Uncertainty of temperature measurement with the thermographic camera. Data Set 1.

T_c °C Camera	u_d °C Camera	T_{effect} °C Eq. (3)	u_{effect} °C Eq. (11)	ε Table 3	$u_ε$ Table 3	T_b °C Eq. (16)	u_b °C Eq.(17)	U_b °C Eq. (18)
24,75	0,37	24,69	0,40	0,996	0,006	25,00	0,59	1,2
33,49	0,35	33,33	0,38	0,992	0,005	33,96	0,54	1,1
43,64	0,31	43,37	0,34	0,988	0,004	44,33	0,49	1,0
52,34	0,33	51,97	0,36	0,977	0,004	53,83	0,52	1,0
62,02	0,23	61,54	0,28	0,975	0,005	63,68	0,48	1,0
71,50	0,28	70,92	0,32	0,970	0,005	73,59	0,53	1,1
81,04	0,28	80,35	0,32	0,964	0,005	83,57	0,54	1,1
90,03	0,31	89,24	0,34	0,954	0,005	93,49	0,60	1,2
99,14	0,54	98,25	0,56	0,966	0,006	101,46	0,83	1,7
108,14	0,71	107,14	0,72	0,964	0,007	110,60	1,04	2,1
117,86	0,78	116,76	0,79	0,960	0,009	120,77	1,18	2,4
127,31	0,90	126,10	0,90	0,957	0,010	130,50	1,37	2,7
137,63	0,76	136,30	0,77	0,962	0,009	140,31	1,27	2,5

Table 6 : Uncertainty of temperature measurement with the thermographic camera. Data Set 2.

T_c °C Camera	u_d °C Camera	T_{effect} °C Eq. (3)	u_{effect} °C Eq. (11)	ε Table 3	$u_ε$ Table 3	T_b °C Eq. (16)	u_b °C Eq.(17)	U_b °C Eq. (18)
24,88	0,34	24,82	0,37	0,996	0,006	25,13	0,57	1,1
33,49	0,35	33,33	0,38	0,992	0,005	33,96	0,54	1,1
43,86	0,26	43,58	0,30	0,988	0,004	44,55	0,46	0,9
52,93	0,31	52,55	0,34	0,977	0,004	54,42	0,51	1,0
62,22	0,31	61,74	0,34	0,975	0,005	63,88	0,52	1,0
71,65	0,37	71,06	0,40	0,970	0,005	73,74	0,58	1,2
80,78	0,29	80,09	0,33	0,964	0,005	83,31	0,54	1,1
90,23	0,28	89,44	0,32	0,954	0,005	93,69	0,59	1,2
98,89	0,59	98,00	0,60	0,966	0,006	101,21	0,86	1,7
108,06	0,61	107,07	0,62	0,964	0,007	110,52	0,97	1,9
117,89	0,80	116,79	0,81	0,960	0,009	120,80	1,20	2,4
127,07	0,77	125,86	0,78	0,957	0,010	130,26	1,29	2,6
137,65	0,85	136,32	0,85	0,962	0,009	140,33	1,32	2,6

Table 7 : Uncertainty of temperature measurement with the thermographic camera. Data Set 3.

T_c °C Camera	u_d °C Camera	T_{effect} °C Eq. (3)	u_{effect} °C Eq. (11)	ε Table 3	u_ε Table 3	T_b °C Eq. (16)	u_b °C Eq.(17)	U_b °C Eq. (18)
24,54	0,38	24,48	0,41	0,996	0,006	24,79	0,59	1,2
33,55	0,29	33,39	0,33	0,992	0,005	34,02	0,51	1,0
43,88	0,25	43,60	0,29	0,988	0,004	44,57	0,46	0,9
52,48	0,29	52,11	0,33	0,977	0,004	53,97	0,49	1,0
62,20	0,34	61,72	0,37	0,975	0,005	63,86	0,54	1,1
71,70	0,25	71,11	0,29	0,970	0,005	73,79	0,51	1,0
80,71	0,29	80,02	0,33	0,964	0,005	83,24	0,54	1,1
88,61	0,32	87,83	0,35	0,954	0,005	92,07	0,61	1,2
98,87	0,58	97,98	0,59	0,966	0,006	101,19	0,86	1,7
108,06	0,61	107,07	0,62	0,964	0,007	110,52	0,97	1,9
117,88	0,67	116,78	0,68	0,960	0,009	120,79	1,11	2,2
127,30	0,86	126,09	0,86	0,957	0,010	130,49	1,35	2,7
137,11	0,85	135,79	0,85	0,962	0,009	139,79	1,32	2,6

6. CONCLUSIONS

An experimental methodology was developed to calibrate thermographic cameras for remote temperature measurement. The calculated uncertainties match the manufacturers' specification, that is, ± 2 °C, or 2%, whichever is greater, for situations where only one measurement is allowed. Furthermore, the methodology allows the determination of the surface emissivity to within ± 0,02. The methodology is simple and allows a temperature calibration laboratory to follow it with just a small investment. Finally, if a smaller uncertainty is required, several measurements should be made.

7. AKNOWLEDGEMENTS

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