Chapter 2
Measurement of Surface Temperature Using Different Devices

2.1 Aim

As reported by several authors (Chew 1998; Hart 2001; Avdelidis and Moropoulou 2003; Barreira and Freitas 2007), there are several parameters that can influence significantly the measurement of surface temperatures using IRT. For that reason, this issue is deeply discussed in this chapter, including a comparison between the values obtained using three different devices (infrared camera, infrared thermometer and type T thermocouples).

The chapter describes the methodology and the results attained in two experimental campaigns, one in situ (IS) and the other one in laboratory (L). In the in situ case studies, the surface temperature of various finishing materials on the façades of a building was measured in different periods of the day and at different distances. This campaign included four case studies. The second campaign (laboratory) consisted in selecting materials with different emissivity, and exposing them to external environmental conditions, while measuring their surface temperature.

2.2 Materials and Techniques

During the test campaigns, an infrared camera, an infrared thermometer and type T thermocouples connected to a data logger were used. Before the measurements were carried out, calibration procedures were performed according to the operation manual of each device.

The main technical specifications of the thermographic camera used during the experimental campaigns (Fig. 2.1a) are presented in Table 2.1. An adequate tripod (Fig. 2.1b) guaranteed the stabilization of the camera during the tests. Reflection calibration and ambient and background compensation were assessed before each

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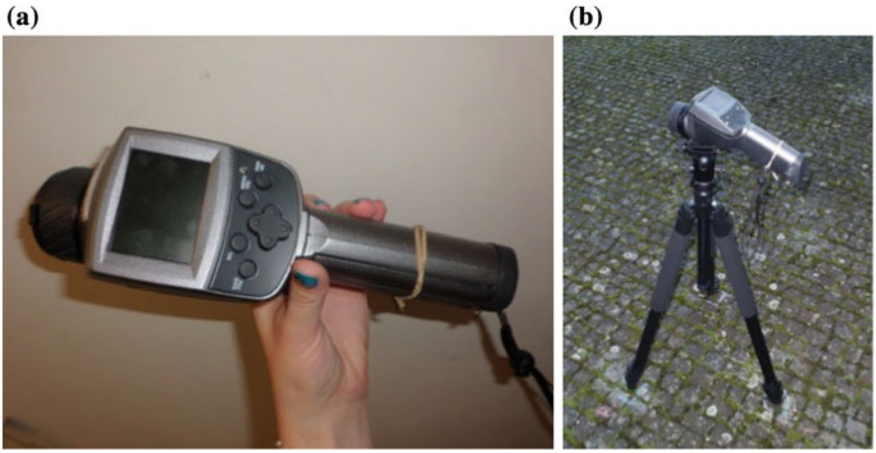

Fig. 2.1 **a** Infrared camera; **b** position of the camera during the measurements

Table 2.1 Specifications of the infrared camera

	Infrared camera
Measuring range	−20 to 250 °C
Resolution	0.1 °C
Accuracy	±2 °C or ±2% of reading
Detector	Uncooled focal plane array (microbolometer)
Spectral range	7.5–13 μm
Thermal image pixels	320 (H) × 240 (V) pixels
Focusing range	50 cm to infinite
IFOV	1.5 mrad

Table 2.2 Specifications of the infrared thermometer

	Infrared thermometer
Measuring range	−40–550 °C
Resolution	0.1 °C
Accuracy	±1 °C or ±1% of reading
Spectral range	8–4 μm
Distance to spot size (D:S)	12:1

measurement. The thermograms were treated using specific software, allowing the analysis, digital processing and archiving of the images captured by the camera.

The infrared thermometer is also a non-contact and non-destructive tool, which allows the measurement of the surface temperature of a single point on a material. The technical specifications of the device (Fig. 2.2a, b) can be found in Table 2.2.

A thermocouple is an electrical device that produces a temperature-dependent voltage as a result of the thermoelectric effect. The voltage can be converted into

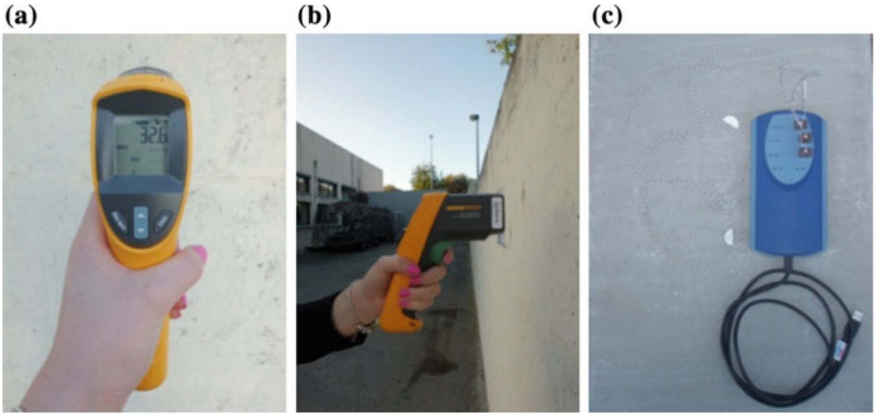

Fig. 2.2 **a** Infrared thermometer; **b** Position of the infrared thermometer during the measurements; **c** Data logger and type T thermocouples

temperature. Among the several models available on the market, the type T was selected for this work as it is a very stable thermocouple with a wide range of measurement (−200 to 350 °C).

The thermocouples were fixed to the surface of the materials with aluminium tape. In order to register and acquire the data from the thermocouples, a data logger was used (Fig. 2.2c). This device can be connected to a computer, and data is analysed using the data logger software. A 1 s interval was defined for the recording.

Two experimental campaigns, one in situ (IS) and the other in the laboratory (L), were implemented in order to compare the values measured by the different devices. The ambient conditions were varied throughout the tests as the measurements were made at different distances to the target (3, 9 and 15 m for IS and 3, 6 and 9 m for L) and in periods of the day with different luminosity, namely: (i)—direct solar radiation; (ii)—after sunset and (iii)—during night-time.

The first step of the procedure was defining the distances at which the thermograms were to be taken and marking the exact spot on the pavement. The thermocouples were then fixed to the surface and connected to the computer to begin data acquisition. Afterwards, the thermograms were taken at the desired distances, and finally, the infrared thermometer was used to measure the temperatures at different points.

It should be noted that with the infrared thermometer five temperature measurements were carried out and then the average value was calculated. Regarding the thermocouples, the data acquisition only ended when the measurement with the other two devices was completed, and at the end, the values were also averaged. The duration of the entire procedure was always less than 5 min.

In the in situ campaign, the surface temperature of three materials, with different emissivity, present on the façades of a building was measured. This campaign included four case studies (Fig. 2.3):

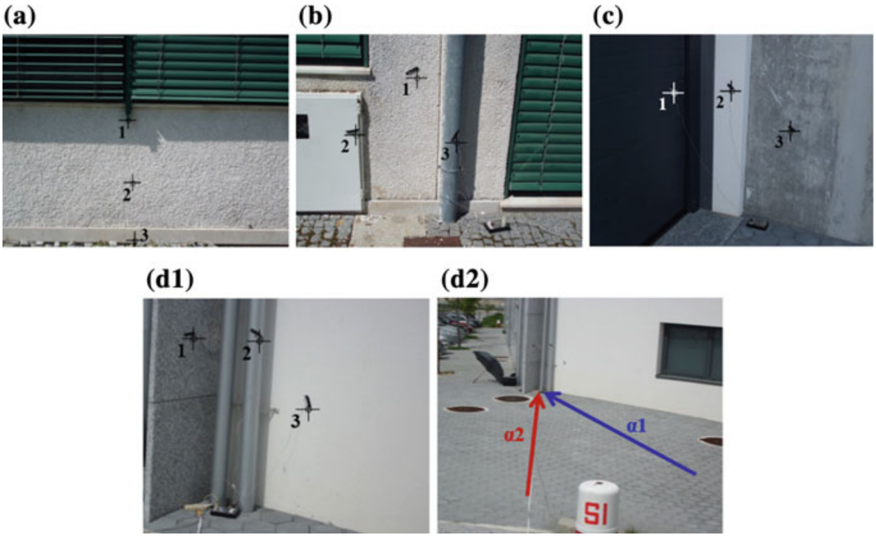

Fig. 2.3 Photograph of the case studies, including the location of the measuring points: **a** case study #01_IS; **b** case study #02_IS; **c** case study #03_IS; **d**1 case study #04_IS; **d**2 angles between the infrared camera and the target in case study #04_IS

- Case study #01_IS, where location "1" was on green lacquered aluminium, location "2" was on a projected coating mortar, and location "3" was on marble stone.
- Case study #02_IS, where location "1" was on a projected coating mortar, location "2" was on a metallic panel coated with white paint, and location "3" was on a galvanized steel downspout.
- Case study #03_IS, where location "1" was on a steel gate with rough surface, location "2" was on a white painted wall, and location "3" was on a concrete wall.
- Case study #04_IS was the last in situ example, and its geometry allowed including another parameter in the sensitivity analysis: the angle between the infrared camera and the target. The following three materials were evaluated in this case study: "1" for granite stone, "2" for a galvanized steel downspout and "3" for a white painted wall. Regarding the angle between the camera and the target, two values were tested, α1 and α2, as presented in Fig. 2.3d2.

Table 2.3 shows the input parameters used in the analysis of the thermal images, including the materials emissivity, the reflected temperature and the air temperature and relative humidity.

The laboratory campaign (L) consisted in selecting a group a commonly used construction materials, with different emissivity values, and exposing them to external environment conditions, while measuring their surface temperature. The specimens were placed against a wall ensuring that the incident solar radiation was identical and there were no reflections from nearby obstacles. The materials were grouped according to the following criteria:

Table 2.3 Emissivity, reflected temperature, air temperature and relative humidity for all in situ case studies

		ε	Reflected temperature (°C)			Air temperature (°C)			Relative humidity (%)		
			(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
#01_IS	1	0.92	21.7	14.8	13.1	16.8	20.2	17.1	44.1	32.5	42.9
	2	0.87									
	3	0.93									
#02_IS	1	0.87	23.0	5.8	4.5	19.4	22.1	16.8	52.2	35.3	71.0
	2	0.92									
	3	0.28									
#03_IS	1	0.96	25.0	16.9	13.4	22.1	21.0	16.8	35.9	41.6	69.9
	2	0.92									
	3	0.93									
#04_IS	1	0.85	34.2* 32.9#	19.2* 14.5#	15.8* 12.8#	22.9* 22.7#	23.6* 23.6#	19.5* 19.4#	40.1* 39.8#	35.5* 35.4#	46.1* 45.9#
	2	0.28									
	3	0.92									

ε—Emissivity
(i)—Direct solar radiation; (ii)—after sunset; (iii)—during night-time
*—Case study #04_IS (Fig. 2.3d2): α1
#—Case study #04_IS (Fig. 2.3d2): α2

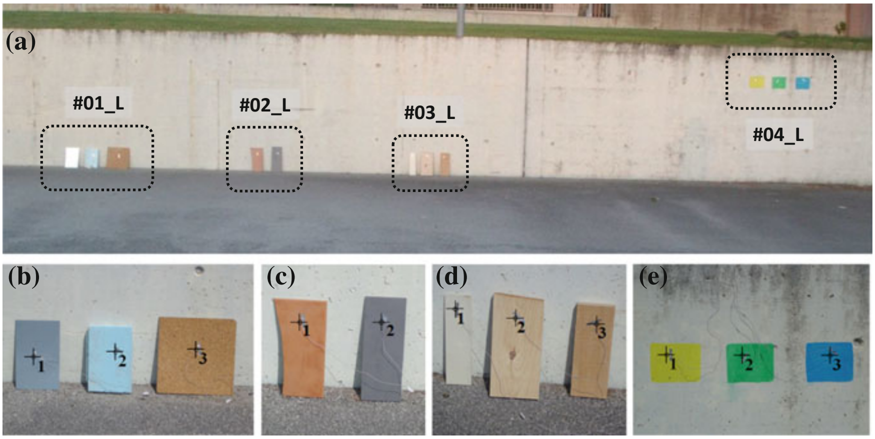

Fig. 2.4 Layout of the laboratory case study and location of the measuring points: **a** general view; **b** case study #01_L; **c** case study #02_L; **d** case study #03_L; **e** case study #04_L

- Case study #01_L consisted of three materials with low emissivity, "1" for a zinc plate, "2" for extruded polystyrene (XPS) and "3" for cork.
- Case study #02_L consisted of two ceramic tiles with different colours, "1" for an orange tile and "2" for a grey tile.
- Case study #03_L consisted of three types of wood, "1" for plywood, "2" for pine and "3" for beech.
- Case study #04_L: Three colours of a plastic paint were evaluated: "1" corresponding to yellow, "2" to green and "3" to blue.

Figure 2.4 shows the photographs of the four case studies of the laboratory campaign, including the exact location of the measuring points. Table 2.4 shows the environmental parameters used in the analysis of the thermal images and the emissivity values adopted for the materials.

The thermal images presented in this chapter were all obtained assuming a constant value of emissivity ($\varepsilon = 0.90$), for homogeneity purposes and to facilitate their comparison. Afterwards, in the image processing and analysis required to the determination of the surface temperature, the emissivity of each material was introduced as input. The values of emissivity were obtained in the literature, such as Gaussorgues (1999), Hart (2001) and Omega (2002).

Table 2.4 Emissivity, reflected temperature, air temperature and relative humidity for all laboratory case studies

		ε	Reflected temperature (°C)			Air temperature (°C)			Relative humidity (%)		
			(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
#01_L	1	0.20	4.8	10.8	16.0	19.1	13.0	11.8	52.0	78.3	92.0
	2	0.60									
	3	0.70									
#02_L	1	0.93									
	2	0.93									
#03_L	1	0.83									
	2	0.90									
	3	0.94									
#04_L	1	0.93									
	2	0.92									
	3	0.94									

ε—Emissivity
(i)—Direct solar radiation; (ii)—after sunset; (iii)—during night-time

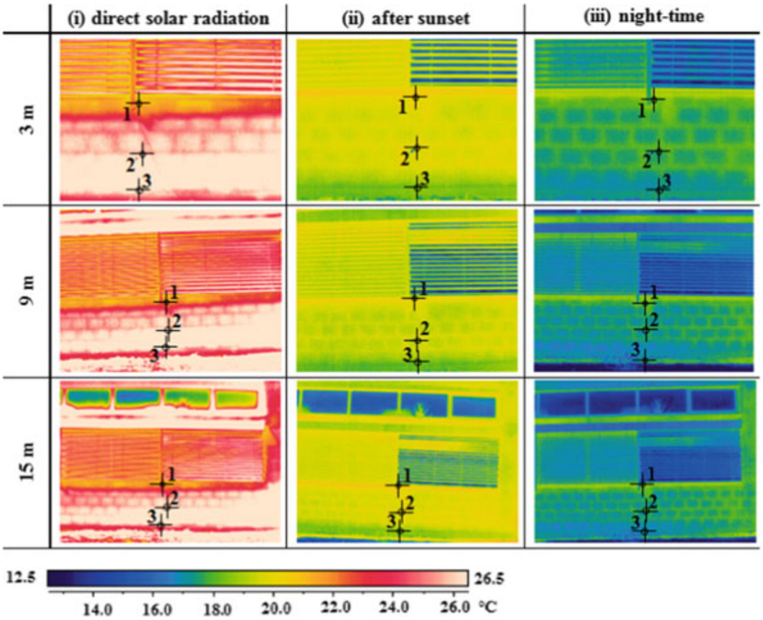

Fig. 2.5 Thermograms for case study #01_IS in the three periods of the day

2.3 Results of the In Situ Case Study

2.3.1 Case Study #01_IS

In Fig. 2.5, it is possible to observe the sequence of thermograms obtained throughout the test. In order to facilitate the interpretation and comparison of the thermal images, the same temperature scale was adopted for the entire data set.

Table 2.5 shows the results of the measurements carried out with the three devices, in the three periods of the day. The relative differences to the value measured by the thermocouple, assumed as the reference temperature, are also included in the table. To facilitate the interpretation of the differences, a colour scale (gradation) was included: blue for negative differences, white for null and red for positive differences.

Generally, the results show that there is no great difference between measurements made by the three devices. Even the effect of solar radiation did not prove to be very important, although the measurements made at 1:00 pm, with direct solar radiation, pointed out to slightly larger differences. The distance to the target was not an important factor as no clear relation was identified between this parameter and the relative differences between devices.

Table 2.5 Temperature results in case study #01_IS

Device	1			2			3		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Thermocouple [°C]	22.7	20.1	17.2	27.8	20.3	18.1	25.3	18.7	17.7
Infrared thermometer [°C]	23.3	20.0	17.3	27.3	19.6	17.1	26.3	18.5	16.9
Thermogram at 3 m [°C]	22.2	19.9	17.7	26.7	19.8	17.8	24.1	18.3	17.1
Thermogram at 9 m [°C]	22.5	19.5	17.9	27.3	19.6	17.3	24.6	18.1	17.3
Thermogram at 15 m [°C]	22.3	20.0	17.9	27.3	19.6	17.2	24.2	18.4	17.3
Differences									
Infrared thermometer vs. thermocouple [°C]									
	0.6	-0.1	0.1	-0.5	-0.7	-1.0	1.0	-0.2	-0.8
Thermogram vs.thermocouple [°C]									
3 m	0.5	0.2	-0.5	1.1	0.5	0.3	1.2	0.4	0.6
9 m	0.2	0.6	-0.7	0.5	0.7	0.8	0.7	0.6	0.4
15m	0.4	0.1	-0.7	0.5	0.7	0.9	1.1	0.3	0.4
Infrared thermometer vs. thermogram [°C]									
3 m	1.1	0.1	-0.4	0.6	-0.2	-0.7	2.2	0.2	-0.2
9 m	0.8	0.5	-0.6	0.0	0.0	-0.2	1.7	0.4	-0.4
15 m	1.0	0.0	-0.6	0.0	0.0	-0.1	2.1	0.1	-0.4

2.3.2 Case Study #02_IS

In Fig. 2.6, it is possible to observe the sequence of thermograms obtained throughout the test. Once again, in order to facilitate the interpretation and comparison of the thermal images, the same temperature scale was adopted for the entire data set.

Table 2.6 shows the results of the measurements carried out with the three devices, in the three periods of the day, including the relative differences. To facilitate the interpretation of the results, the same colour scale used in case study #01_IS is applied once again.

Observing the results, the discrepancy of values obtained for point "3" is the most relevant finding. In fact, the measurements made with the IR camera are not very accurate. The high reflectance of this material, meaning that it is highly influenced by reflections, is the most likely reason to explain these results. The differences between the thermocouple and the infrared thermometer are relatively small, whichever the period of measurement. Once again, the distance to the target was not a relevant factor to explain the differences.

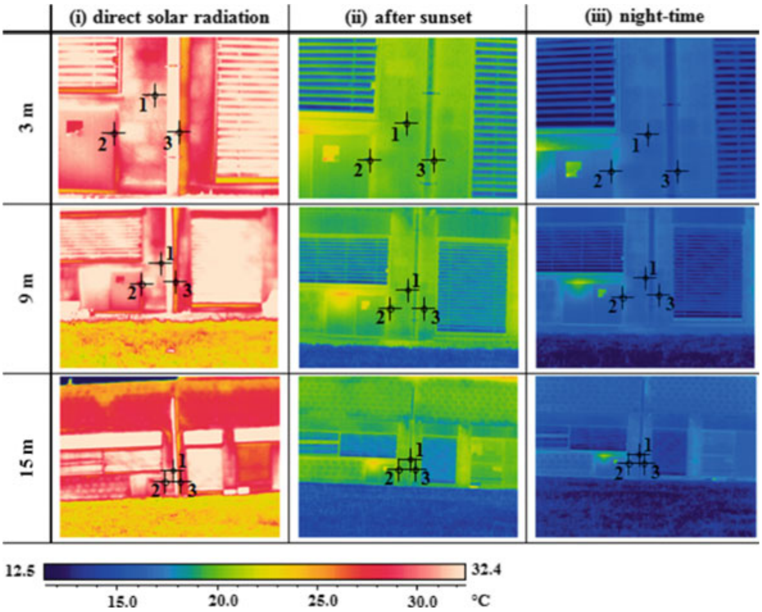

Fig. 2.6 Thermograms for case study #02_IS in the three periods of the day

2.3.3 *Case Study #03_IS*

Figure 2.7 shows the sequence of thermograms obtained throughout the test. In this case study, it was impossible to use the same temperature scale due to the high surface temperatures recorded in situation (i)—direct solar radiation. A different scale was thus used only for this period. The results of the measurements carried out with the three test devices, for the three periods of the day, as well as the relative differences between them, are displayed in Table 2.7.

The largest differences occur when the points are under direct solar radiation—scenario (i)—while in the other two periods the relative difference between devices is always below 2 °C. These results point out to the importance of, when quantitative thermography is intended, avoiding situations where radiation can be an important factor and thus bias the results. One should also stress the very good agreement between the infrared thermometer and thermograms after the sunset and at the night-time. As in the previous case studies, the distance to the target did not affect the accuracy of the measurements with the infrared camera.

Table 2.6 Temperature results in case study #02_IS

Device	1			2			3		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Thermocouple [°C]	31.3	21.7	18.6	30.7	20.9	17.9	36.8	21.1	17.1
Infrared thermometer [°C]	32.9	20.7	17.5	32.5	20.6	17.7	35.5	20.6	16.7
Thermogram at 3 m [°C]	32.6	22.3	18.2	30.5	21.3	17.7	59.2	50.8	40.8
Thermogram at 9 m [°C]	32.5	22.3	18.0	30.3	21.3	17.6	57.8	50.5	40.8
Thermogram at 15 m [°C]	32.6	22.1	18.0	29.9	21.2	17.8	56.6	50.3	41.3
Differences									
Infrared thermometer vs. thermocouple [°C]									
	1.6	-1.0	-1.1	1.8	-0.3	-0.2	-1.3	-0.5	-0.4
Thermogram vs.thermocouple [°C]									
3 m	-1.3	-0.6	0.4	0.2	-0.4	0.2	-22.4	-29.7	-23.7
9 m	-1.2	-0.6	0.6	0.4	-0.4	0.3	-21.0	-29.4	-23.7
15 m	-1.3	-0.4	0.6	0.8	-0.3	0.1	-19.8	-29.2	-24.2
Infrared thermometer vs. thermogram [°C]									
3 m	0.3	-1.6	-0.7	2.0	-0.7	0.0	-23.7	-30.2	-24.1
9 m	0.4	-1.6	-0.5	2.2	-0.7	0.1	-22.3	-29.9	-24.1
15 m	0.3	-1.4	-0.5	2.6	-0.6	-0.1	-21.1	-29.7	-24.6

2.3.4 Case Study #04_IS

Figures 2.8 and 2.9 depict the sequence of thermograms obtained throughout the test. The sequence of thermograms presented for both test angles is on the same temperature scale. Table 2.8 shows the results of the measurements carried out with the three devices, in the three periods of the day and for the two angles between the IR camera and the target, including the relative differences.

The inaccuracy in the measurement of the surface temperature of metallic elements with the IR camera is once again evident as the relative differences in point "2" are always higher than 6 °C, reaching 18 °C under direct solar radiation and for α1. Regarding the angle between the IR camera and the target, the first angle, α1, presented a better performance after the sunset and during night-time, while the opposite situation occurred when the specimen was under direct solar radiation. This situation confirms, once more, the importance of solar radiation in quantitative thermography. As in the previous examples, no clear trend was identified concerning the distance to the target.

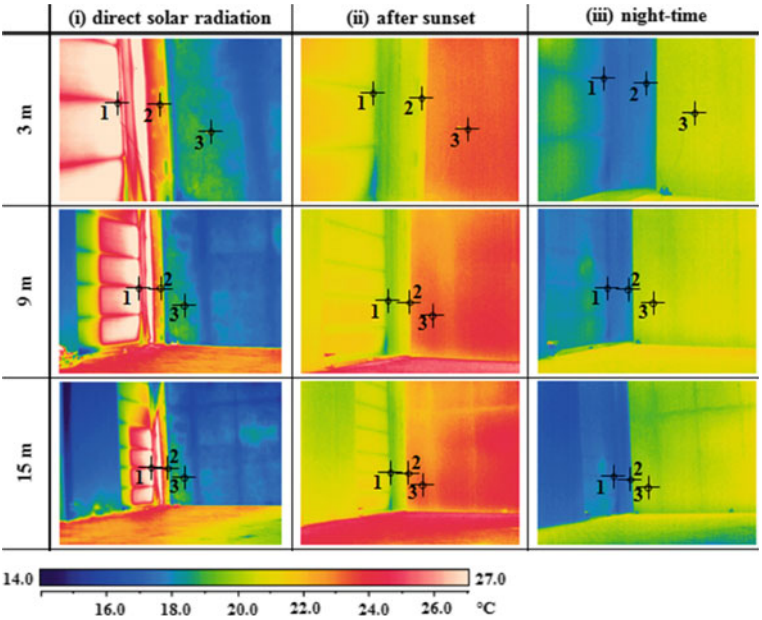

Fig. 2.7 Thermograms for case study #03_IS in the three periods of the day (temperature scale only for (ii) and (iii))

2.4 Results of the Laboratory Case Study

2.4.1 Case Study #01_L

In Fig. 2.10, it is possible to observe the sequence of thermograms obtained throughout the test. All the thermograms are presented with the same temperature scale. Table 2.9 shows the results of the measurements carried out with the three devices, in the three periods of the day, including the relative differences. To facilitate the interpretation of the results, a colour scale used is applied once again: blue for negative differences, white for null and red for positive differences.

The results show that the surface temperature measured by the infrared thermometer and the infrared camera is not accurate for the zinc plate, regardless of the time of the day and the distance. This is related to reflections, as metallic surfaces have very high reflectance, which considerably influences the results. Overall, the smallest differences occurred in the measurements made during night-time. However, the results reveal that the surface temperature measured under direct solar radiation can be quite different, even if measured with the same equipment, which was expected as the materials have different thermal properties.

Table 2.7 Temperature results in case study #03_IS

Device	1			2			3		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Thermocouple [°C]	50.5	20.6	17.9	46.2	20.8	17.9	35.8	23.8	21.1
Infrared thermometer [°C]	52.1	21.3	18.4	46.9	21.2	18.0	36.9	24.1	21.0
Thermogram at 3 m [°C]	53.0	20.6	17.8	45.4	21.2	18.1	36.9	23.9	21.2
Thermogram at 9 m [°C]	53.0	20.4	17.7	45.4	21.2	18.1	36.9	23.9	21.1
Thermogram at 15 m [°C]	53.1	20.5	17.6	45.3	21.2	18.0	37.0	23.6	20.7
Differences									
Infrared thermometer vs. thermocouple [°C]									
	1.6	0.7	0.5	0.7	0.4	0.1	1.1	0.3	-0.1
Thermogram vs.thermocouple [°C]									
3 m	-2.5	0.0	0.1	0.8	-0.4	-0.2	-1.1	-0.1	-0.1
9 m	-2.5	0.2	0.2	0.8	-0.4	-0.2	-1.1	-0.1	0.0
15 m	-2.6	0.1	0.3	0.9	-0.4	-0.1	-1.2	0.2	0.4
Infrared thermometer vs. thermogram [°C]									
3 m	-0.9	0.7	0.6	1.5	0.0	-0.1	0.0	0.2	-0.2
9 m	-0.9	0.9	0.7	1.5	0.0	-0.1	0.0	0.2	-0.1
15 m	-1.0	0.8	0.8	1.6	0.0	0.0	-0.1	0.5	0.3

The distance from the camera to the target also seems to influence the results, generally decreasing surface temperature. As the distance is less than 10 m, differences between the measurements were not expected (Chew 1998). One possible reason derives from the samples being on the ground in a position with a slight bias from perpendicular.

2.4.2 Case Study #02_L

In Fig. 2.11, it is possible to observe the sequence of thermograms obtained throughout the test. All the thermograms are presented with the same temperature scale. Table 2.10 shows the results of the measurements carried out with the three devices, in the three periods of the day, including the relative differences.

The most accurate results were, once again, obtained during night-time, while the largest differences occurred in period (i)—direct solar radiation. In this case study, it was also possible to identify a direct relationship between the relative differences and the distance to the target, regardless of the period of the day. As expected, no significant differences were attained between the orange and the grey tile. However, when the measurements are carried out with direct solar radiation, the grey tile

Table 2.8 Temperature results in case study #04_IS

Device	1			2			3		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Thermocouple [°C]	36.7	24.2	20.6	35.7	23.6	20.1	37.5	22.9	19.5
Infrared thermometer [°C]	30.2	25.3	21.1	32.8	23.7	20.4	33.4	23.1	19.4
Thermograms for α1 [°C]									
Thermogram at 3 m [°C]	32.9	25.4	21.4	17.4	30.3	28.6	36.8	22.9	19.5
Thermogram at 9 m [°C]	33.0	25.0	21.5	18.2	30.9	28.3	37.0	22.6	19.2
Thermogram at 15 m [°C]	32.9	24.9	21.1	18.3	30.9	30.0	37.1	22.7	19.2
Thermograms for α2 [°C]									
Thermogram at 3 m [°C]	33.1	26.1	21.1	23.6	42.4	33.5	35.4	23.3	18.8
Thermogram at 9 m [°C]	33.2	26.0	22.2	24.0	42.3	36.1	35.6	23.0	19.7
Thermogram at 15 m [°C]	33.1	26.0	22.2	23.2	42.5	36.1	36.2	22.8	19.8
Differences									
Infrared thermometer vs. thermocouple [°C]									
	-6.5	1.1	0.5	-2.9	0.1	0.3	-4.1	0.2	-0.1
Thermogram vs.thermocouple for α1 [°C]									
3 m	3.8	-1.2	-0.8	18.3	-6.7	-8.5	0.7	0.0	0.0
9 m	3.7	-0.8	-0.9	17.5	-7.3	-8.2	0.5	0.3	0.3
15 m	3.8	-0.7	-0.5	17.4	-7.1	-9.9	0.4	0.2	0.3
Thermogram vs.thermocouple for α2 [°C]									
3 m	3.6	-1.9	-0.5	12.1	-18.8	-13.4	2.1	-0.4	0.7
9 m	3.5	-1.8	-1.6	11.7	-18.7	-16.0	1.9	-0.1	-0.2
15 m	3.6	-1.8	-1.6	12.5	-18.9	-16.0	1.3	0.1	-0.3
Infrared thermometer vs. thermogram for α1 [°C]									
3 m	-2.7	-0.1	-0.3	15.4	-6.6	-8.2	-3.4	0.2	-0.1
9 m	-2.8	0.3	-0.4	14.6	-7.2	-7.9	-3.6	0.5	0.2
15 m	-2.7	0.4	0.0	14.5	-7.0	-9.6	-3.7	0.4	0.2
Infrared thermometer vs. thermogram for α2 [°C]									
3 m	-2.9	-0.8	0.0	9.2	-18.7	-13.1	-2.0	-0.2	0.6
9 m	-3.0	-0.7	-1.1	8.8	-18.6	-15.7	-2.2	0.1	-0.3
15 m	-2.9	-0.7	-1.1	9.6	-18.8	-15.7	-2.8	0.3	-0.4

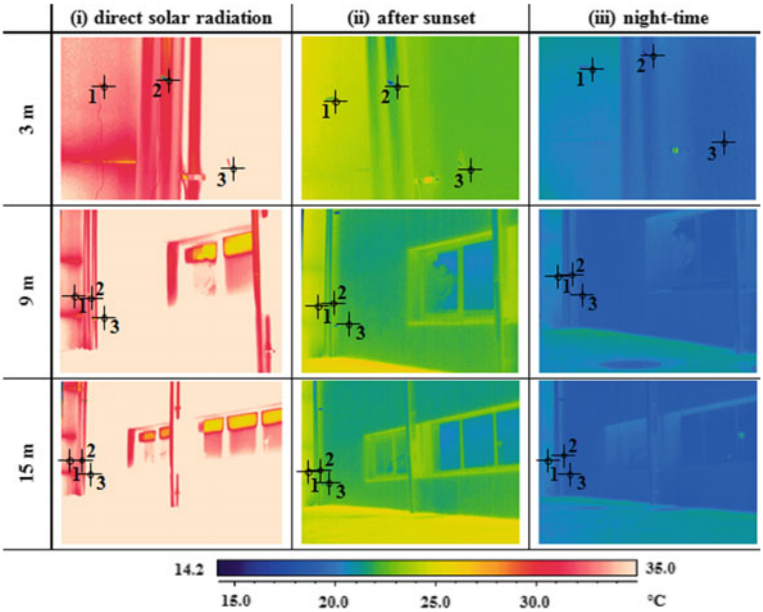

Fig. 2.8 Thermograms for case study #04_IS and for α1 in the three periods of the day

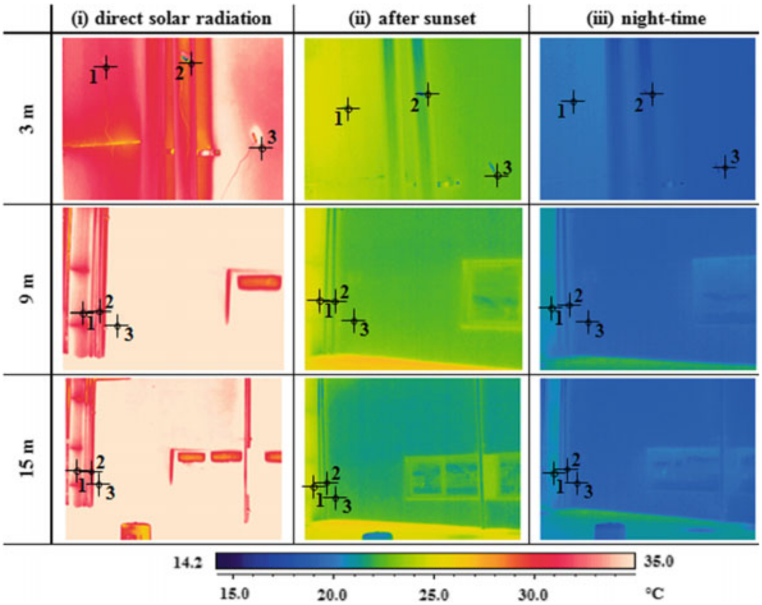

Fig. 2.9 Thermograms for case study #04_IS and for α2 in the three periods of the day

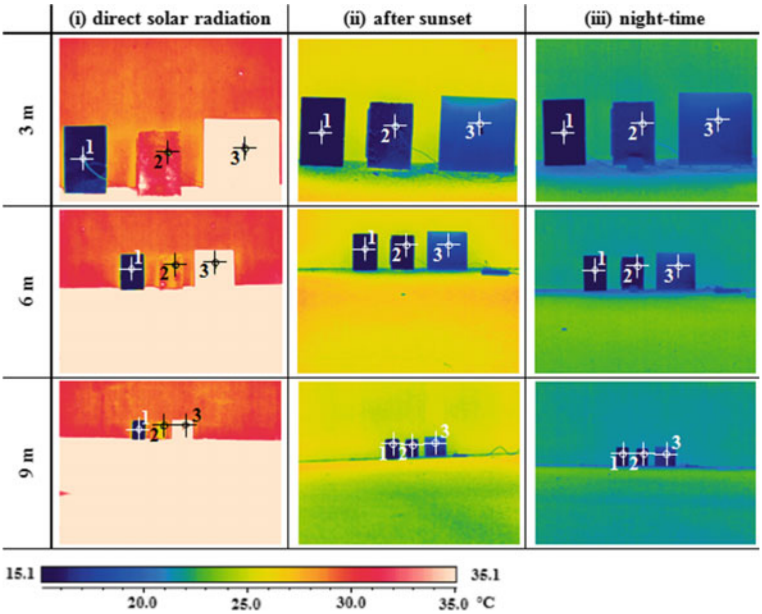

Fig. 2.10 Thermograms for case study #01_L in the three periods of the day

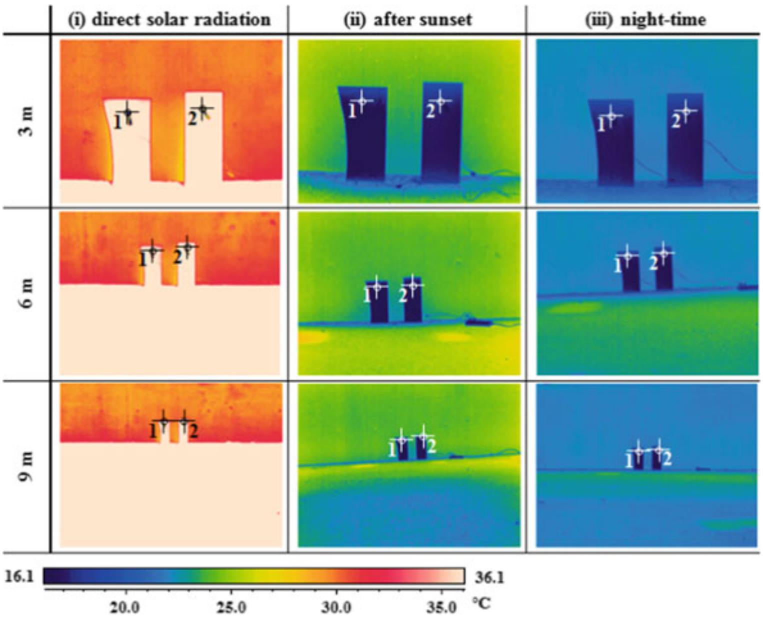

Fig. 2.11 Thermograms for case study #02_L in the three periods of the day

Table 2.9 Temperature results in case study #01_L

Device	1			2			3		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Thermocouple [°C]	47.1	18.4	17.3	40.3	17.6	16.2	44.1	18.2	18.4
Infrared thermometer [°C]	37.2	15.3	16.7	35.7	14.6	16.9	46.4	16.4	17.8
Thermogram at 3 m [°C]	52.2	-39.1	-4.8	42.2	17.9	16.9	45.8	21.7	18.2
Thermogram at 6 m [°C]	15.2	-40.1	-9.6	40.1	15.9	15.9	46.6	20.8	17.7
Thermogram at 9 m [°C]	-40.1	-40.1	-13.5	38.3	14.5	14.8	44.7	19.6	17.3
Differences									
Infrared thermometer vs. thermocouple [°C]									
	-9.9	-3.1	-0.6	-4.6	-3.0	0.7	2.3	-1.8	-0.6
Thermogram vs.thermocouple [°C]									
3 m	-5.1	57.5	22.1	-1.9	-0.3	-0.7	-1.7	-3.5	0.2
6 m	31.9	58.5	26.9	0.2	1.7	0.3	-2.5	-2.6	0.7
9 m	87.2	58.5	30.8	2.0	3.1	1.4	-0.6	-1.4	1.1
Infrared thermometer vs. thermogram [°C]									
3 m	-15.0	54.4	21.5	-6.5	-3.3	0.0	0.6	-5.3	-0.4
6 m	22.0	55.4	26.3	4.4	1.3	1.0	-0.2	-4.4	0.1
9 m	77.3	55.4	30.2	-2.6	0.1	2.1	1.7	-3.2	0.5

presents slightly higher temperatures, while when measurements are performed after sunset and during night-time, the surface temperature is very similar in the two specimens.

2.4.3 *Case Study #03_L*

In Fig. 2.12, it is possible to observe the sequence of thermograms obtained throughout the test. All the thermograms are presented with the same temperature scale. Table 2.11 shows the results of the measurements carried out with the three devices, in the three periods of the day, including the relative differences.

The results confirm the negative effect of direct solar radiation, as the relative differences were always higher in this period, regardless of the material. The highest relative differences occurred between the thermocouple and thermograms. However ,

Table 2.10 Temperature results in case study #02_L

Device	1			2		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Thermocouple [°C]	43.9	19.1	17.8	46.9	19.0	17.6
Infrared thermometer [°C]	42.2	17.9	17.4	43.3	17.9	17.4
Thermogram at 3 m [°C]	40.4	17.8	17.6	41.2	17.8	17.5
Thermogram at 6 m [°C]	39.5	16.0	17.3	41.0	16.1	17.2
Thermogram at 9 m [°C]	37.8	15.7	17.1	39.5	15.7	16.8
Differences						
Infrared thermometer vs. thermocouple [°C]						
	-1.7	-1.2	-0.4	-3.6	-1.1	-0.2
Thermogram vs.thermocouple [°C]						
3 m	3.5	1.3	0.2	5.7	1.2	0.1
6 m	4.4	3.1	0.5	5.9	2.9	0.4
9 m	6.1	3.4	0.7	7.4	3.3	0.8
Infrared thermometer vs. thermogram [°C]						
3 m	1.8	0.1	-0.2	2.1	0.1	-0.1
6 m	2.7	1.9	0.1	2.3	1.8	0.2
9 m	4.4	2.2	0.3	3.8	2.2	0.6

generally, the differences are smaller when compared with the ones obtained in the case studies #01_L and #02_L. Besides, by contrast with these two cases, the distance from the camera to the target is not so relevant, possibly due to the thermal/optical properties of the wood.

2.4.4 *Case Study #04_L*

In Fig. 2.13, it is possible to observe the sequence of thermograms obtained throughout the test. All the thermograms are presented with the same temperature scale. Table 2.12 shows the results of the measurements carried out with the three devices, in the three periods of the day, including the relative differences. The measurements performed by the different devices are very similar. The largest differences occurred in colour blue under direct solar radiation.

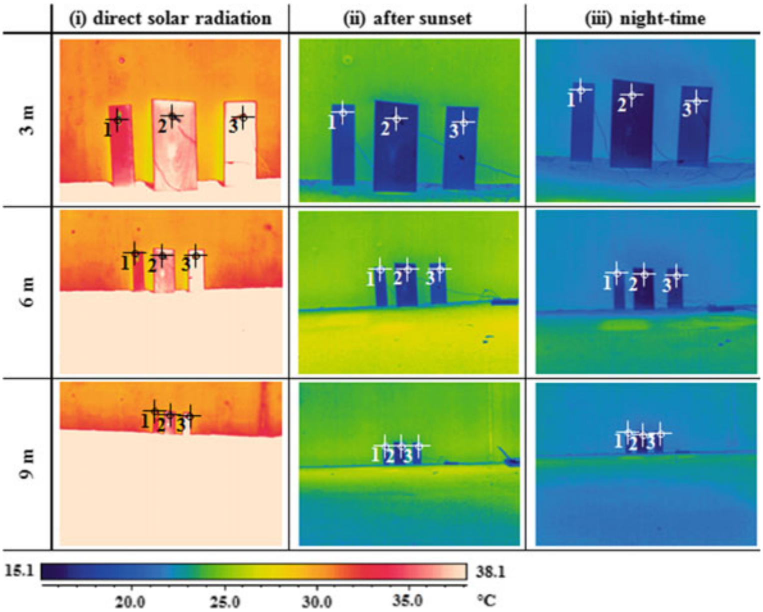

Fig. 2.12 Thermograms for case study #03_L in the three periods of the day

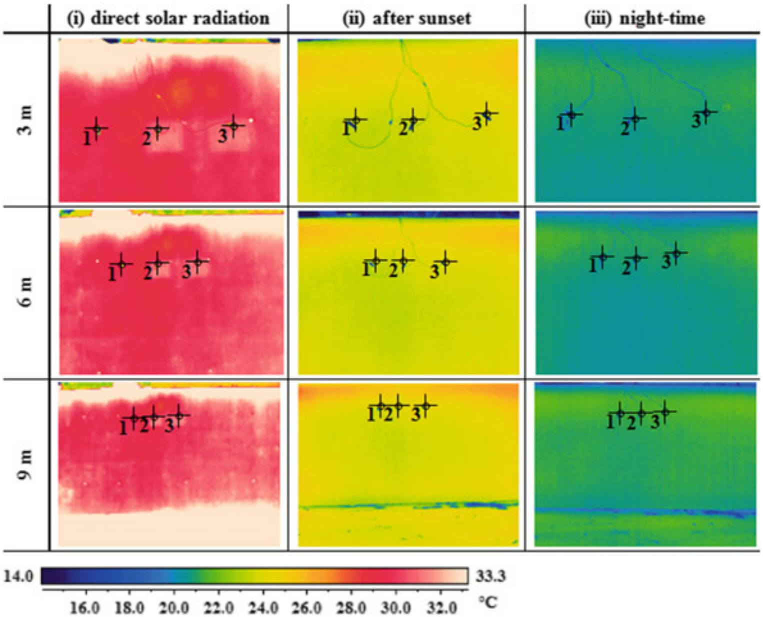

Fig. 2.13 Thermograms for case study #04_L in the three periods of the day

Table 2.11 Temperature results in case study #03_L

Device	1			2			3		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Thermocouple [°C]]	37.7	18.7	18.0	41.7	18.1	16.6	43.3	18.9	18.8
Infrared thermometer [°C]	36.6	17.9	18.1	39.4	17.6	16.9	41.7	18.4	17.4
Thermogram at 3 m [°C]	38.2	18.0	18.7	39.7	17.7	16.8	41.1	18.9	17.4
Thermogram at 6 m [°C]	37.3	17.9	18.3	39.3	17.8	16.6	41.3	19.2	17.3
Thermogram at 9 m [°C]	36.9	17.3	18.4	38.9	17.7	16.7	39.4	19.0	17.5
Differences									
Infrared thermometer vs. thermocouple [°C]									
	-1.1	-0.8	0.1	-2.3	-0.5	0.3	-1.6	-0.5	-1.4
Thermogram vs.thermocouple [°C]									
3 m	-0.5	0.7	-0.7	2.0	0.4	-0.2	2.2	0.0	1.4
6 m	0.4	0.8	-0.3	2.4	0.3	0.0	2.0	-0.3	1.5
9 m	0.8	1.4	-0.4	2.8	0.4	-0.1	3.9	-0.1	1.3
Infrared thermometer vs. thermogram [°C]									
3 m	-1.6	-0.1	-0.6	-0.3	-0.1	0.1	0.6	-0.5	0.0
6 m	-0.7	0.0	-0.2	0.1	-0.2	0.3	0.4	-0.8	0.1
9 m	-0.3	0.6	-0.3	0.5	-0.1	0.2	2.3	-0.6	-0.1

2.5 Discussion of the Results

In the experimental campaign described in this chapter, several set-ups and boundary conditions were created to compare the performance of IRT with other surface temperature measurement techniques such as infrared thermometer and thermocouples. The main objective was to understand the ideal conditions for accurate measurements with the infrared camera.

The most evident finding of the tests was the fact that the surface temperature measured under direct solar radiation can be very tricky. In fact, the results show different surface temperatures even when measured with the same device. After sunset and at night-time, the differences are lower as the sun is not influencing the measurements.

The results also show that the surface temperature measured by the infrared thermometer and the infrared camera is not accurate for metallic materials with low emissivity, regardless of the time of the day and the distance to the target. The most probable reason for this is the effect of reflections, as metallic surfaces have very high reflectance, which considerably influences the results.

Table 2.12 Temperature results in case study #04_L

Device	1			2			3		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Thermocouple [°C]]	30.9	24.3	21.8	32.6	24.5	21.4	33.6	24.7	21.5
Infrared thermometer [°C]	31.6	24.1	20.7	33.2	24.2	21.1	32.8	24.5	21.3
Thermogram at 3 m [°C]	31.4	24.3	21.0	32.6	24.7	21.2	32.2	24.8	21.1
Thermogram at 6 m [°C]	31.4	24.1	21.1	32.7	24.6	21.2	32.2	24.7	20.9
Thermogram at 9 m [°C]	31.2	24.4	21.4	32.7	25.0	21.2	31.8	24.9	21.6
Differences									
Infrared thermometer vs. thermocouple [°C]									
	0.7	-0.2	-1.1	0.6	-0.3	-0.3	-0.8	-0.2	-0.2
Thermogram vs.thermocouple [°C]									
3 m	-0.5	0.0	0.8	0.0	-0.2	0.2	1.4	-0.1	0.4
6 m	-0.5	0.2	0.7	-0.1	-0.1	0.2	1.4	0.0	0.6
9 m	-0.3	-0.1	0.4	-0.1	-0.5	0.2	1.8	-0.2	-0.1
Infrared thermometer vs. thermogram [°C]									
3 m	0.2	-0.2	-0.3	0.6	-0.5	-0.1	0.6	-0.3	0.2
6 m	0.2	0.0	-0.4	0.5	-0.4	-0.1	0.6	-0.2	0.4
9 m	0.4	-0.3	-0.7	0.5	-0.8	-0.1	1.0	-0.4	-0.3

Concerning the laboratory case studies, the average absolute error (excluding the zinc plate) was 5.6%. The measurements performed during the night are the most accurate ones, as the values obtained by the infrared devices are quite similar to the ones measured by the thermocouples (an error of 2.7% on average). The more accurate set-up was the infrared camera with a distance to the target of 3.0 m. The distance to the target also influences the results, generally decreasing surface temperature and increasing the error up to 7.2%. That may be related not only with the distance to the target but also because the samples were on the ground in a position with a slight bias from perpendicular.

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