MSL Technical Guide 26

Size-of-Source Effect in Infrared Thermometers

Introduction

The past few years have seen the widespread adoption in many industries of low-cost handheld infrared (IR) thermometers. This adoption has been accompanied by an increasing demand for absolute accuracy in the temperatures measured by these instruments. However, the accuracy of many IR thermometers is severely limited by a phenomenon known as the size-of-source effect (SSE), which arises from scattering and diffraction of radiation within the optical system of the device.

Despite the importance of this effect, the SSE is rarely mentioned in manufacturers' specifications, so users are generally unaware of the problem. The accuracies quoted in the specifications typically only apply for specific target conditions known only to the manufacturer. The general user has no means of determining these conditions nor any idea of the resulting errors when these conditions are not satisfied.

The SSE also poses a problem for recalibration, because the measured corrections depend on the size of the aperture of the calibration source and the measurement distance chosen by the calibration laboratory. The error caused by the SSE can be many times larger than the specified accuracy if the 'wrong' angular target size is chosen. Nevertheless, unlike the user, the calibration laboratory is in a position to fully characterise the SSE.

This technical guide discusses how the SSE can be evaluated in a relatively simple manner, and suggests a format for presentation of the SSE data on a calibration certificate. The guide is aimed at second-tier calibration laboratories in particular, and so the methods are designed to be neither time-consuming nor require any additional equipment over that already used for IR thermometer calibration. The required calculations are easily performed using a spreadsheet application, and Table 2 below can be used to check the accuracy of such calculations. This guide is an extension to MSL Technical Guide 22 [1] on the calibration of IR thermometers, which did not consider this important issue of the SSE. Technical Guide 22 should be read in conjunction with this one.

What is the Size-of-Source Effect?

IR thermometers determine the temperature of an object by measuring the amount of IR radiation emitted from a given area on the object. The size of this area is determined by the optical system of the thermometer and depends on the distance from the object to the thermometer. Roughly speaking, the thermometer measures over a constant angular field of view, often referred to as the distance-to-spot-size ratio (D:S). This means that doubling the distance to the object will double the spot size or field of view (see Figure 1). Some instruments project a laser beam onto the target in the form of a ring of dots in order to indicate to the user the location of the field of view. For these instruments, the change of field of view with measurement distance is readily observed. The angular field of view is given by

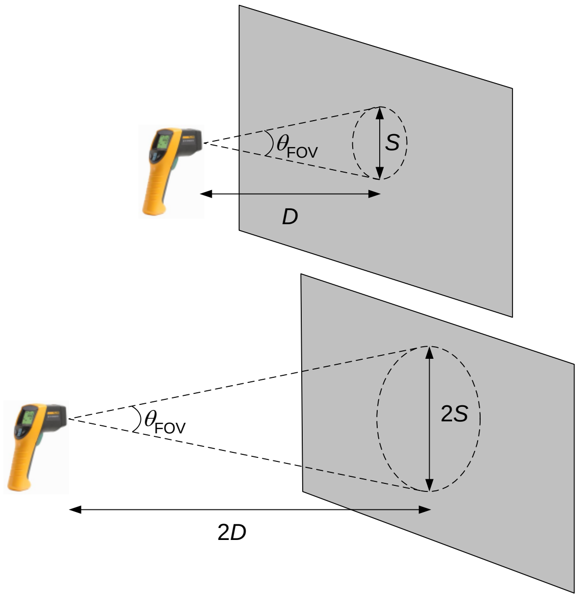

Figure 1. Ideally, doubling the measurement distance, D, doubles the spot size, S, of the nominal field of view, keeping the angular field of view, D:S or θ_{FOV}, constant.

$$\theta_{FOV} = 2\tan^{-1}\left(\frac{S}{2D}\right). \quad (1)$$

Ideally, the object to be measured should completely fill this field of view, and when this is the case, the reading should be independent of how far beyond the field of view the object extends. In practice, however, the field of view indicated by the D:S ratio or the ring of laser dots (the "nominal" field of view) is only approximate. Worse than this, the actual field of view does not have a sharp boundary, but instead blurs and tapers off towards the edge. The reason for this is that small imperfections in the optical system, as well as dirt, grease, or dust on the lens, cause radiation to be scattered out of the path that it would ideally take on its way to the thermometer's detector. This scattering has the consequence that some radiation from outside the nominal field of view falls onto the detector and some radiation from within the nominal field of view misses the detector. Hence, the actual field of view is not well defined.

What effect does this have on the thermometer reading? Imagine a hot target object exactly the size of the nominal field of view, in cool ambient surroundings. Some of the radiation from the target itself will be lost, causing the detector signal to be lower than it would otherwise be. At the same time, some of the radiation from the ambient surroundings will be detected. However, because the ambient temperature is lower than the target temperature, the radiation gained from the surroundings will not match that lost from the target, and the net effect is that the thermometer reads a temperature that is too low.

Now imagine a slightly larger target object. The same amount of radiation as above is lost from within the nominal field of view, but now the amount gained from the surroundings is slightly increased due to the small amount of hot target outside the nominal field of view. The thermometer reading will still be too low, but it will be higher than in the case when the target is exactly the same size as the nominal field of view. As the target increases in size, the reading will correspondingly increase, until the target is of such a size that the radiation scattered from outside the nominal field of view exactly compensates for that lost from within the nominal field of view. This change in reading with change in target size is the origin of the name “size-of-source effect”.

Measuring the SSE during Calibration

All IR thermometers suffer to some degree from the SSE. For long-wavelength thermometers and thermal imagers, operating at 8–14 μm (or similar), the errors tend to be particularly large and require correcting in order to obtain meaningful measurements.

Ideally, the corrections for the SSE would be made so that the corrected temperature would correspond to the reading for an infinite size uniform-temperature target (or sufficiently large target). In this case, the radiation lost from within the nominal field of view would exactly match that gained from outside, and so this reading would give the correct target temperature.

However, empirical evidence suggests that when the manufacturers initially calibrate IR thermometers and put the temperature scale onto the devices, they do not themselves apply any corrections for the SSE. Thus, the reading will be correct, not for an infinite target, but when the target size that the calibration laboratory uses is the same as that used by the manufacturer. In fact, it is the angular size that is important. The manufacturer may, for example, have used a blackbody target of diameter $d = 100$ mm to carry out the initial calibration, and made measurements at a distance of $D = 600$ mm (these dimensions would be unknown to the calibration laboratory). This corresponds to an angular target size of $\theta_{tar} = 9.5°$:

$$\theta_{tar} = 2\tan^{-1}\left(\frac{d}{2D}\right). \qquad (2)$$

If the calibration laboratory has a 50 mm diameter blackbody, then they should find that the readings should be approximately correct when measurements are carried out at a distance of 300 mm (same value of θ_{tar}). When the blackbody is set to a temperature above ambient, measurements over shorter distances than 300 mm would produce readings that are too high (the angular size of the target would be larger), and measurements over longer distances would give low readings.

This suggests a simple means to characterise the SSE: simply measure a blackbody (or flat-plate calibrator) with a fixed aperture, maintained at a fixed temperature, over a range of distances, and record the change in reading with change in angular size of the target (see Figure 2). It is best to set the blackbody to the highest calibration temperature, as this gives the maximum resolution for the results. An example of such measurements is shown in Figure 3, where the reading changes by 8 °C for a blackbody at 250 °C. In Figure 4, the same data is plotted as a function of angular target size, rather than measurement distance, so that it is now independent of the actual blackbody aperture that was used. In this figure, it can be seen how the readings level off at a maximum value as the target gets bigger and bigger.

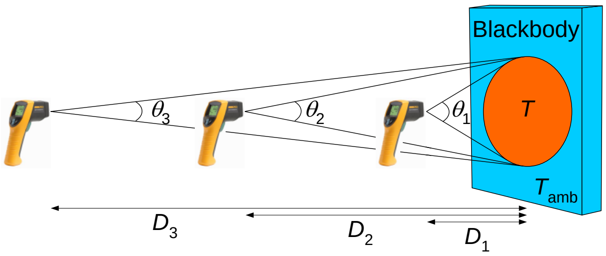

Figure 2. Characterising the SSE by measuring the same blackbody, at temperature T, over different distances D_1, D_2, $D_{3...}$. Each measurement corresponds to a different angular target size θ_1, θ_2, $\theta_{3...}$. The ambient temperature is T_{amb}.

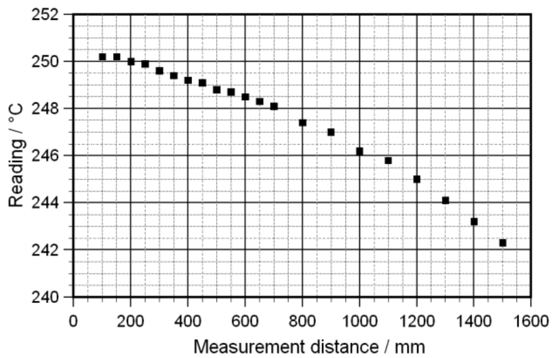

Figure 3. A set of readings as a function of measurement distance for a blackbody at $T = 249.7$ °C, with aperture diameter of $d = 120$ mm and effective emissivity of $\varepsilon_{bb} = 0.9910$. The ambient temperature was $T_{amb} = 23$ °C.

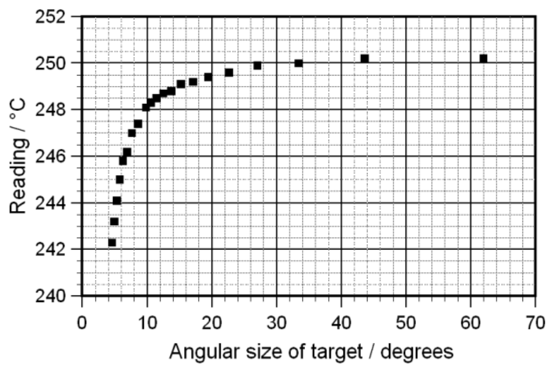

Figure 4. Same data as plotted in Figure 3, but as a function of angular target size instead of measurement distance.

Comparison Phase of the Calibration

The main phase of a calibration is comparison of the readings of the device under test with those of a reference thermometer, and a determination of any required corrections. However, it is clear from Figure 3 that because of the SSE, the corrections determined during this phase will depend on the distance from the blackbody at which the measurements are made. It seems obvious that the best choice of measurement distance is that for which the correction determined from the SSE data (such as that in Figure 3) is close to zero. At this distance, the angular size of the calibration source will be close to that used by the manufacturer, and so ideally, the corrections at all temperatures will be minimised.

As discussed in MSL Technical Guide 22 [1], the required correction is equal to the difference between the expected temperature reading and the actual reading. The expected reading is not necessarily equal to the true temperature of the blackbody as given by the reference thermometer, but depends on the blackbody emissivity and the instrumental emissivity, and may depend on the ambient temperature and the temperature of the detector inside the IR thermometer. Details of how to determine the expected reading can be found in [1]. For the example shown in Figure 3, the IR thermometer operated over a wavelength range of 8–14 μm and the instrumental emissivity was set to $\varepsilon_{instr} = 1$, so the expected temperature was $T_{exp} = 248.3$ °C. From the graph, it can be seen that this reading occurred when the measurement distance was 650 mm, and so this distance should be used to carry out the comparison phase of the calibration. Note that because the blackbody aperture was 120 mm in diameter, the angular target size is $\theta_{tar} = 10.5°$. This should correspond to the angular size of the target used by the manufacturer during the initial calibration.

Figure 5 shows a graph of the results from the comparison phase, where the correction is plotted as a function of the IR thermometer reading. The data is also tabulated in Table 1. Note that the comparison phase was carried out at a distance of 250 mm from a 50 mm diameter aperture. This represents a slightly larger angular target than the ideal size suggested by the SSE measurements above (11.4° instead of 10.5°). Hence, the correction near 250 °C is not zero, and in fact is negative because of the slightly larger target (in most cases the same aperture size would be used for both the SSE measurements and the comparison phase). The corrections plotted in Figure 5 (the last two columns of Table 1)

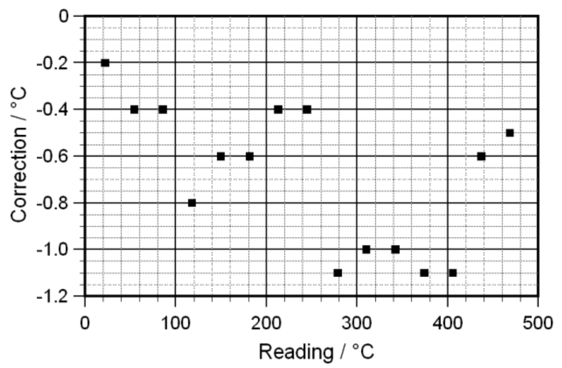

Figure 5. Corrections determined during the comparison phase of a calibration using a blackbody with an angular size of 11.4°. The correction is equal to the expected reading minus the actual reading.

Table 1. Calibration data, the last two columns of which are plotted in Figure 5. The column labelled T / °C is the true temperature of the blackbody, as measured by a reference thermometer. The column labelled T_{exp} / °C is the expected IR thermometer reading as determined using the methods in [1] based on a blackbody emissivity of $\varepsilon_{bb} = 0.9984$, an instrumental emissivity of $\varepsilon_{instr} = 1$, and an ambient temperature of $T_{amb} = 23$ °C.

T / °C	T_{exp} / °C	Reading / °C	Correction/ °C
22.05	22.05	22.2	–0.2
54.09	54.05	54.4	–0.4
85.48	85.40	85.8	–0.4
117.35	117.23	118.0	–0.8
149.15	149.00	149.6	–0.6
181.00	180.82	181.4	–0.6
212.78	212.57	213.0	–0.4
244.60	244.35	244.7	–0.4
277.67	277.39	278.5	–1.1
309.24	308.92	309.9	–1.0
341.56	341.21	342.2	–1.0
373.32	372.93	374.0	–1.1
404.92	404.50	405.6	–1.1
436.71	436.25	436.8	–0.6
468.33	467.83	468.3	–0.5

should be tabulated on a calibration certificate with the proviso that they only apply when measuring targets with angular size of 11.4°. Additional corrections must be applied for smaller or larger targets, as determined from the SSE data. The next section describes how these additional corrections are calculated.

Determining the SSE as a Function of Temperature

The SSE data plotted in Figure 4 allows the calibration laboratory to determine the additional corrections as a function of angular target size, but only, in this case, for targets at 250 °C. This is of limited use, because the user of the IR thermometer will require corrections at whatever temperature is being measured.

Fortunately, the data in Figure 4 can be used to determine corrections at all temperatures. A detailed derivation of how this is done can be found in [2], but just the key equation is given here:

$$\frac{S(T_{2,meas}) - S(T_{2,exp})}{S(T_{1,meas}) - S(T_{1,exp})} = \frac{S(T_2) - S(T_{amb})}{S(T_1) - S(T_{amb})} . \qquad (3)$$

In this equation, the function $S(T)$ is the ideal response function of the IR thermometer's detector for a given temperature T. As given in [1], this function is well approximated by the equation

$$S(T) = \frac{C}{\exp\left(\frac{c_2}{AT + B}\right) - 1} , \qquad (4)$$

where A, B, and C are constants related to the properties of the IR thermometer, c_2 is a universal constant with the value 14388 μm.K, and T has the units of kelvin. The values of A and B can be determined from the wavelength specifications of the IR thermometer:

$$A = \lambda_0 \left(1 - \frac{\Delta\lambda^2}{2\lambda_0^2}\right) \qquad (5)$$

and

$$B = \frac{c_2 \Delta\lambda^2}{24\lambda_0^2}, \qquad (6)$$

where λ_0 is the centre wavelength of specified range and $\Delta\lambda$ is the width of this range. The value of C cancels throughout equation (3), so setting $C = 1$ is sufficient to solve this equation.

Equation (3) is useful because it allows a single set of SSE measurements for a given blackbody temperature, T_1, to be used to predict the measurements that would occur at any other temperature, T_2. For example, suppose we want to know what the measured temperature would be for a measurement distance of 1000 mm if the blackbody in Figure 3 was at 400 °C instead of 249.7 °C. That is, we want to determine, using equation (3), the value of $T_{2,\mathrm{meas}}$ given $T_1 = 249.7$ °C, $T_{1,\mathrm{exp}} = 248.3$ °C, $T_{1,\mathrm{meas}} = 246.2$ °C, $T_2 = 400$ °C, and $T_{\mathrm{amb}} = 23$ °C. Substituting these values into equation (4), with $A = 9.36$ μm and $B = 178$ μm.K (for an 8–14 μm IR thermometer), gives:

$$S(T_1) = 0.06226$$

$$S(T_{1,\mathrm{exp}}) = 0.06177$$

$$S(T_{1,\mathrm{meas}}) = 0.06105$$

$$S(T_2) = 0.12173$$

$$S(T_{\mathrm{amb}}) = 0.00768.$$

In addition, the value of $T_{2,\mathrm{exp}}$, calculated from [1], is 397.7 °C, giving $S(T_{2,\mathrm{exp}}) = 0.12070$. Substituting all of these values into equation (3) gives:

$$S(T_{2,\mathrm{meas}}) = \frac{(0.12173 - 0.00768)}{(0.06226 - 0.00768)}(0.06105 - 0.06177) + 0.12070 = 0.11920.$$

This signal value can then be converted to a temperature value using the inverse of equation (4):

$$T = \frac{c_2}{A \ln(C/S + 1)} - \frac{B}{A}, \qquad (7)$$

which gives $T_{2,\mathrm{meas}} = 394.2$ °C.

Figure 6 shows the predicted temperature readings at 400 °C for the whole range of angular target sizes plotted in Figure 4, based on the SSE measurements at 250 °C. Figure 7 shows the corrections that are required in addition to the calibration corrections when the angular target size differs from that used during the comparison phase. These are simply the differences between the predicted reading at the calibration target size and the predicted reading for the target size indicated along the x-axis of the graph. These curves can be calculated for as many temperatures as required, and a graph like this with multiple curves could be presented on the calibration certificate.

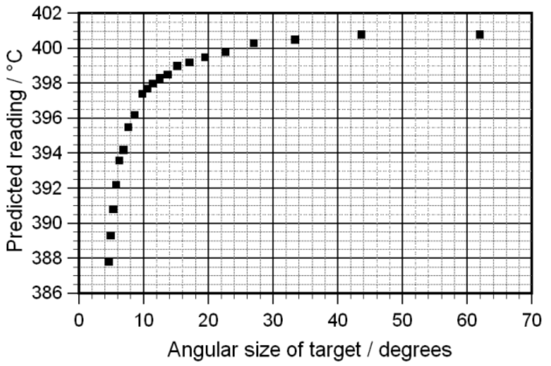

Figure 6. Predicted readings for the same conditions as in Figures 3 and 4, but for the blackbody at 400 °C. The points have been calculated using equation (3) from the measurements plotted in Figure 4.

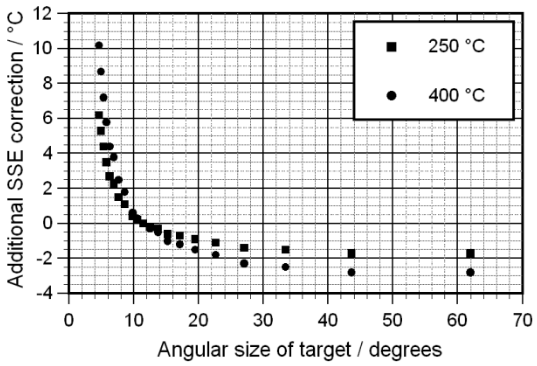

Figure 7. Corrections required to account for the SSE in addition to those found during the comparison phase of the calibration, for blackbody temperatures of 250 °C and 400 °C. These are the differences between the readings for an angular target size of 11.4° (which was the blackbody size during the comparison phase) in Figures 4 and 6, respectively, and the corresponding readings for the particular target size along the x-axis.

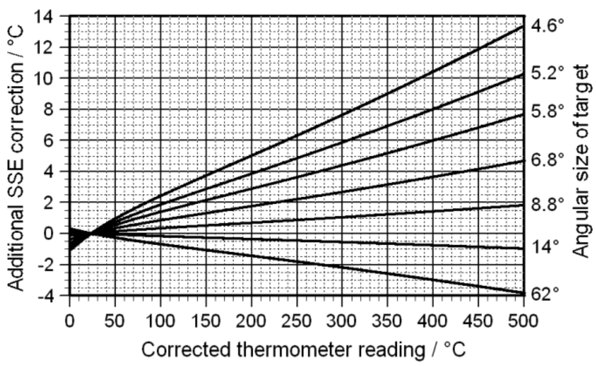

Figure 8. Alternative method for graphing the additional SSE corrections, as a function of temperature for a number of different angular target sizes. The points plotted in Figure 7 corresponds to points somewhere on this graph. The additional corrections for a target size of 11.4° are zero for all temperatures.

Table 2. Example calculation for the $\theta = 5.2°$ curve in Figure 8. For this, and all other curves in Figure 8, the following values from the conditions occurring during the SSE measurements in Figure 3 are used: $T_1 = 249.7$ °C, $\varepsilon_{bb} = 0.9910$, $T_{amb} = 23$ °C, $T_{1,exp} = 248.3$ °C (from [1]), and $T_{SSE,\theta_0} = 248.5$ °C (from Figure 4). For the specific $\theta = 5.2°$ curve, the value of $T_{SSE,\theta}$ is equal to 243.8 °C (again from Figure 4), giving $T_{1,meas} = 243.6$ °C. Values of T_2 have been chosen from 0 °C to 500 °C in 50 °C steps (first column of the table), and the remaining columns have been calculated from left to right using the equation or reference indicated.

T_2 / °C	$S(T_2)$ using eq. (7)	$S(T_{2,exp})$ from [1]	$T_{2,exp}$ / °C using eq. (7)	$S(T_{2,meas})$ using eq. (3)	$T_{2,meas}$ / °C using eq. (7)	$T_{2,exp} - T_{2,meas}$ / °C
0	0.00522	0.00524	0.2	0.00531	1.0	–0.8
50	0.01132	0.01129	49.8	0.01118	49.1	0.7
100	0.02025	0.02014	99.5	0.01976	97.6	1.9
150	0.03190	0.03168	149.2	0.03097	146.4	2.8
200	0.04604	0.04569	198.9	0.04456	195.1	3.8
250	0.06236	0.06187	248.6	0.06026	243.9	4.7
300	0.08059	0.07994	298.3	0.07778	292.6	5.7
350	0.10046	0.09962	348.0	0.09688	341.3	6.7
400	0.12173	0.12070	397.7	0.11733	389.9	7.8
450	0.14421	0.14298	447.3	0.13894	438.5	8.8
500	0.16773	0.16629	497.0	0.16156	487.1	9.9

Alternatively, it may be more useful to produce a graph with temperature reading along the *x*-axis and multiple curves for different angular target sizes. Such a graph is shown in Figure 8. These curves are easier to interpret than those in Figure 7. The curves in Figure 8 have been calculated using equation (3) based on the SSE measurements in Figure 4. The procedure for calculating these curves is as follows:

1. Choose a number of angular target sizes that span the range of angular sizes on the *x*-axis of Figure 4. Rather than choosing equally-spaced sizes, choose them in such a manner that the readings on the *y*-axis of Figure 4 are close to being equally-spaced. This will lead to the larger number of small sizes seen down the right-hand axis in Figure 8. For each angular size, θ, follow the steps 2–4 below.

2. Determine $T_{1,meas}$ from:

$$T_{1,meas} = T_{1,exp} + T_{SSE,\theta} - T_{SSE,\theta_0} ,$$

   where $T_{1,exp}$ is the expected reading for the blackbody used to carry out the SSE measurements in Figures 3 and 4, $T_{SSE,\theta}$ is the reading from the SSE data in Figure 4 corresponding to the angular target size θ, and T_{SSE,θ_0} is the reading in Figure 4 corresponding to the angular target size, θ_0, used for the comparison phase of the calibration. Note that these values may have to be interpolated between the particular measurements made in Figure 4. The values of $T_{1,exp}$ and T_{SSE,θ_0} will be the same for each value of θ.

3. Select values of T_2 to cover the range of calibration temperatures. For each value of T_2, calculate $T_{2,exp}$ with all other conditions the same as for the SSE measurements in Figures 3 and 4. Then determine $T_{2,meas}$ for each value of T_2 using equation (3).

4. Plot $T_{2,exp} - T_{2,meas}$ on the *y*-axis against $T_{2,meas}$ on the *x*-axis to produce one of the curves shown in Figure 8.

An example calculation for the $\theta = 5.2°$ curve in Figure 8 is given in Table 2. Once the T_2 values in the first column have been decided on, each of the remaining columns is calculated in sequence from left to right. The last two columns represent the $\theta = 5.2°$ curve plotted in Figure 8. The other curves can be calculated in a similar way, beginning at step 2 with a different value of $T_{SSE,\theta}$.

Conclusion

The majority of general purpose IR thermometers are so severely affected by the SSE that calibration of these instruments is pointless unless the SSE is accounted for in the calibration process. The methods given in this technical guide provide a relatively simple means for calibration laboratories to determine and report corrections for the SSE as function of the target size. These methods can be used with either blackbody calibration sources or flat-plate calibrators, and apply to all direct-reading IR thermometers or thermal imagers, even those with a fixed emissivity setting.

References

[1] MSL Technical Guide 22: "Calibration of Low-Temperature Infrared Thermometers", http://msl.irl.cri.nz.

[2] P Saunders, "Dealing with the size-of-source effect in the calibration of direct-reading radiation thermometers", submitted to *Temperature: Its Measurement and Control in Science and Industry*, Vol. 8.

Prepared by Peter Saunders, June 2012.

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