DETERMINING SIZE OF SOURCE FOR HANDHELD INFRARED THERMOMETERS – THEORY AND PRACTICE

Frank Liebmann
Fluke Corporation Hart Scientific Division
799 Utah Valley Dr.
American Fork, Utah 84003
801-763-1600
Frank.Liebmann@hartscientific.com

Abstract - Infrared (IR) thermometry is a very useful form of temperature measurement. It has advantages over contact thermometry. These advantages typically include a quicker response time and not having to interfere with the system being measured. However, it is typically not as accurate as contact thermometry. Part of the difference in accuracy is due to the fact that IR thermometers themselves are not as accurate as contact thermometers. The other part of the difference can be due to the user not controlling factors which can cause greater uncertainty of measurement. Major uncertainties in IR thermometry can be a result of emissivity, repeatability and size of source effect (SSE). Size of source (sometimes referred to as spot size) can be especially difficult because information on size of source is difficult to find.

This paper discusses size of source as it applies to IR thermometers. It covers experimentation done on handheld IR thermometers to determine size of source using accepted practices. It also compares this data to manufacture's specifications given with the tested instruments. It demonstrates how to apply this knowledge to account for the uncertainty caused by not having a source of proper size and shows how to apply this data to an uncertainty budget.

SIZE OF SOURCE EFFECT AND SPOT SIZE

The purpose of the experimentation described in this paper is to put forth a method for an IR calibrator user to easily evaluate the uncertainty caused by surface non-uniformity combined with size of source effect issues. As a basis for discussion, a few terms and concepts must first be discussed.

Size of Source Effect

Size of source effect is the phenomenon "caused by lens aberrations and by light scattered from within the optical system" [1]. The same reference goes on to describe the effect as a "change in temperature indication when an automatic optical pyrometer… views a radiant target… being changed in diameter" [1]. In this paper, size of source effect (SSE) will refer to the ratio of the amount of energy contained within a given circle compared to the amount of energy contained within a circle of infinite diameter received by an IR thermometer. This ratio is specified by β throughout this paper. This ratio is used since it is more convenient for calculation of uncertainties at multiple temperatures.

The ramification of SSE is that the user of an IR thermometer must be concerned with how large of an area is needed to obtain an accurate measurement. When using an IR calibrator, the user must also be concerned with the uniformity of the calibrating surface.

Spot Size Diagrams

Many IR thermometers come with spot size diagrams. These tools are a good guideline to determine how much target size is needed for a measurement. However, they can be misleading for two reasons. First, their area only includes a percentage of the entire energy received by the IR thermometer. Second, the percentage of energy within the spot diagram is not necessarily specified by a standard. Thus 80%, 90%, 95% or 99% of the energy or power could be within the specified spot size. This can cause a great amount of confusion and uncertainty when measuring surfaces.

IR CALIBRATOR UNIFORMITY AND SIZE

When determining uncertainty, it is important to know the uniformity of the IR calibrator target as well as knowing the IR thermometer's SSE. This becomes more of a factor when the size of the surface being measured is less than what the IR thermometer is actually measuring. In other words, this must be considered when calibrating IR thermometers where 100% of SSE is larger than the calibration source or target size.

Hart's Definition of IR Calibrator Uniformity

418X uniformity for a diameter (d) is defined as the difference in average temperature in any circle with a diameter (D) less than or equal to a diameter (d). This average is shown mathematically in (1).

$$T_{AVG}(D) = \frac{1}{A}\int T dA = \frac{4}{\pi D}\int_0^{D/2}\int_0^{2\pi} T(r,\theta) r d\theta dr \qquad (1)$$

This can be calculated for a given diameter on a flat plate by applying a Riemann sum to samples within the given diameter D.

To define the total uniformity for a diameter d, all average temperature values must be computed between 0 and d. The difference of the maximum and minimum average temperature ($T_{AVG-MAX}$ - $T_{AVG-MIN}$) between D=0 and d is the uniformity for diameter d as shown in (2).

$$\begin{aligned} &T_{UNIF}(d) = T_{AVG}(D_{MAX}) - T_{AVG}(D_{MIN}) \\ &where \\ &D_{MIN} < d \\ &D_{MAX} < d \end{aligned} \qquad (2)$$

D_{MAX} is the diameter of largest average temperature
D_{MIN} is the diameter of smallest average temperature

To measure this distribution (T(r,θ)), an IR thermometer measures a number of points on the target's surface. These measurements demonstrate the surface's temperature gradient.

Uniformity Testing at Hart

Uniformity testing done at Hart Scientific has found that uniformity as tested on the 418X IR Calibrators has been well within the published specification limits. These specifications are shown in Table 1. This testing means that a user of these instruments can feel comfortable using the specifications to calculate uncertainty due to SSE combined with target uniformity.

Table 1: 418X IR Calibrator Uniformity Specifications

Model	Temperature	Uniformity at 50mm	Uniformity at 125mm
4180	-15°C	±0.10°C	±0.15°C
4180	0°C	±0.10°C	±0.10°C
4180	120°C	±0.20°C	±0.25°C
4181	35°C	±0.10°C	±0.10°C
4181	250°C	±0.25°C	±0.50°C
4181	500°C	±0.50°C	±1.00°C

SIZE OF SOURCE EFFECT TESTING

The purpose of this SSE testing was two-fold. First, knowledge of how manufacture's spot size diagrams relate to SSE within a circle was desired. Second, a practical method was needed to test SSE for handheld IR thermometers. This method needed to be inexpensive and non-time-consuming, but still have good repeatability.

Practical Size of Source Testing at Hart

To test SSE for handheld devices, a simple method was devised based on a "Target Size Test Method" [2] outlined by ASTM.

A set of apertures was constructed at increasing diameters from 0mm to 150mm at 12.5mm increments. They were constructed out of an inexpensive material. The aperture holes were placed so that they would be centered on the center of the source. A fixture to hold the apertures was constructed.

The source used for this test was a Hart Scientific 4181 IR Calibrator. For most of the tests, the target was controlled at 250°C. The one exception was IR Thermometer 2 which has a measurement limit of 200°C. The ASTM standard states the "temperature source is stabilized at a value near the top of the calibration range of the radiation thermometer" [2]. For this test, 250°C was chosen due to safety concerns with the use of the apertures at higher temperatures.

The apertures were placed in front of the target at a distance of 100mm. The handheld thermometer was mounted on a tripod. It was centered on the aperture at a specified distance from the aperture. For smaller apertures, the IR thermometer was moved in the horizontal and vertical position until the signal was maximized. For the larger apertures, the center was found by finding where a 1% drop off in energy was located on either side, then going to the center of these two points. This was done in both the horizontal and vertical directions.

The temperature reading of the measurements through the apertures was recorded. The test was done three times to ensure repeatability.

The temperatures were used to compute percent of signal at each temperature. ASTM suggests an equation for a narrowband instrument based on Planck's Law [2]. However, since all the handhelds tested were wideband instruments, Planck's Law was numerically evaluated for the instruments' bandwidth. This equation is shown in (3). The emissivity setting of the IR thermometer was taken into account. Some of the instruments do not have an adjustable emissivity setting. In all cases except for IT Thermometer 2, the emissivity setting is 0.95. For IR Thermometer 2, the emissivity setting is 0.97.

$$S_{IRT} = \varepsilon \int_{\lambda_1}^{\lambda_2} \frac{c_1}{\lambda^5 \left[\exp\left(\frac{c_2}{\lambda T_{MEAS}} \right) - 1 \right]} d\lambda + (1-\varepsilon) \int_{\lambda_1}^{\lambda_2} \frac{c_1}{\lambda^5 \left[\exp\left(\frac{c_2}{\lambda T_{BG}} \right) - 1 \right]} d\lambda$$

$$\beta(D) = \frac{S_{IRT}(D) - S_{IRT}(0)}{S_{IRT-MAX} - S_{IRT}(0)} \qquad (3)$$

In (3), the measured temperature for each aperture diameter is T_{MEAS}. T_{BG} is what the IR thermometer uses for the background temperature in its temperature calculation. This number is measured and calculated internal to IR thermometers. For this test, 23°C was used for calculation. The values λ_1 and λ_2 are the spectral band limits of the IR thermometer. For instance, if the IR thermometer is an 8 – 14 µm instrument, λ_1 and λ_2 will be 8 and 14 µm respectively.

$S_{IRT}(0)$ is the signal of the measurement made with the 0mm diameter aperture. The $S_{IRT-MAX}$ is the maximum signal measured in a set of measurements. $S_{IRT}(D)$ is the signal for a given diameter aperture. $\beta(D)$ is a calculation of the ratio of the energy received from the target at a given aperture diameter compared to the maximum signal received.

Using (3) accounts for the energy from background radiation and the emissivity setting of the IR thermometer. This is predicted by Kirchoff's Law [1]. It also accounts for signal from the aperture, accounted for by $S_{IRT}(0)$.

The results of these tests are shown in Table 2. A curve fit was performed on the SSE data for the purpose of analysis. The target equation for the curve fit is a variant of the Weibull Cumulative Distribution Function [3] shown in (4).

Table 2. Comparison of SSE Testing Results

IRT	**Distance**	**Spot Size**	**Ratio of Maximum Power**			
(#)	**(mm)**	**(mm)**	**1xSS**	**2xSS**	**3xSS**	**4xSS**
1	380	38	0.884	0.970	0.997	1.000
2	100	40	0.882	0.996	1.000	1.000
3	300	38	0.940	0.993	0.999	1.000
4	300	25	0.816	0.972	0.992	0.997
5	300	24	0.971	0.998	1.000	1.000
6a	300	19	0.982	0.998	1.000	1.000
6b	600	19	0.980	0.993	0.997	0.999
7	1150	19	0.898	0.955	0.963	0.975

$$\beta = 1 - \frac{a}{\exp\left[\left(\frac{D}{b}\right)^{c}\right]} - \frac{1-a}{\exp\left[\left(\frac{D}{d}\right)^{e}\right]} \qquad (4)$$

Table 3 gives the typical repeatability of the tests. The repeatability at smaller aperture sizes tended to be worse. This is most likely due to lack of signal coupled with alignment difficulty using smaller apertures.

Table 3. Generalized Repeatability of Measurements

Ratio of Max Power (β)	**Typical Repeatability**
0.000 to 0.800	0.008
0.800 to 0.900	0.008
0.900 to 0.950	0.003
0.950 to 0.980	0.002
0.980 to 0.990	0.002
0.990 to 0.999	0.001
1.000	0.000

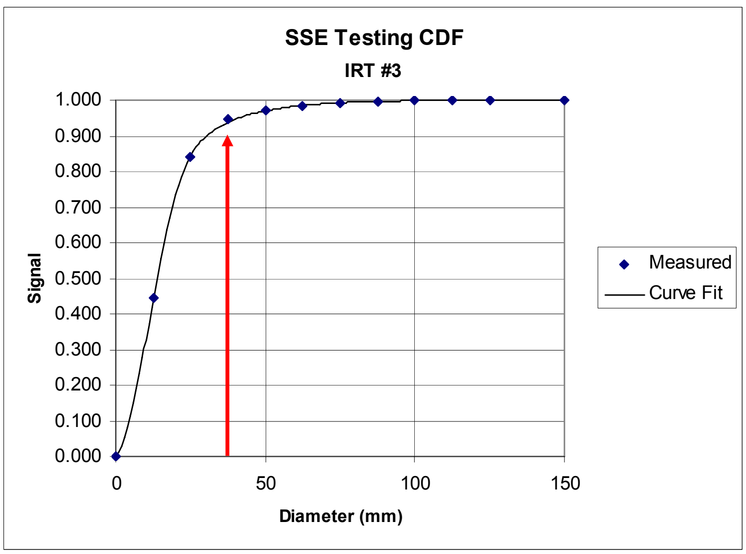
Comparison to Manufactures Spot Size Diagrams

As shown in Table 2, the SSE data does not always correlate to the spot size shown in the manufacture's documentation. This is because scatter is not always considered as part of the spot size in these devices. For most of the IR thermometers tested, 99.9% of the energy was with in 4 times the spot size. At diameters less than 4 times the spot size, the results varied.

For most of the IR thermometers tested, their specifications state that typically 90% of the energy is within the specified spot size. The two exceptions to this are IR Thermometer 1 (specified at 80%) and IR Thermometer 7 (not specified). In the case of IR Thermometer 7, the test showed 90% of the energy being within 1 spot size.

For the rest of this paper, examples will be based on IR Thermometer 3's test results. Figure 1 shows the Cumulative Distribution of Power versus diameter with a curve fit for IR Thermometer 3. The curve fit is based on a Weibull Distribution as shown in (4). The vertical line and arrow represent the spot size specification in the IR thermometer's manual. Note the decaying effects of scatter beyond the arrow.

Figure 1. IR Thermometer 3: Spot Size and Cumulative Distribution of Power



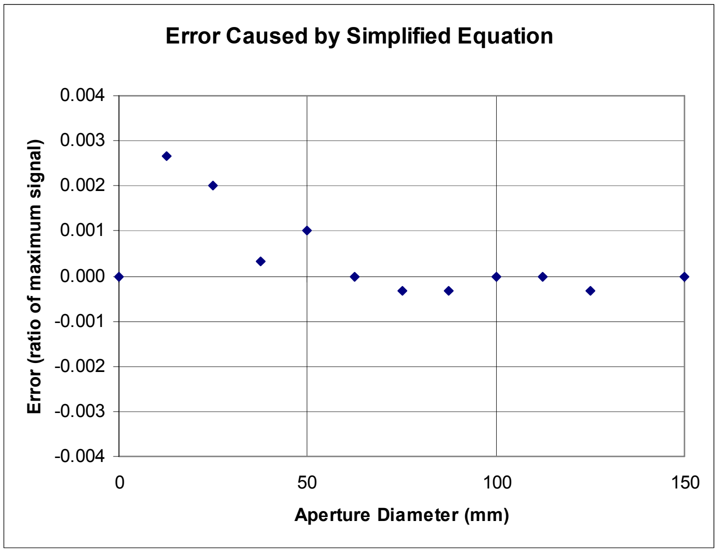
Simplified Mathematics

Since (3) may be difficult to evaluate, consideration was given to using Planck's Law for a single wavelength shown in (5). IR Thermometer 3 is an 8 – 14 µm instrument. For λ, a value of 10 µm was used. This is because at 250°C, the radiated energy tends to be closer to the lower wavelengths.

$$S_{IRT} = \varepsilon \frac{c_1}{\lambda^5\left[\exp\left(\frac{c_2}{\lambda T_{MEAS}}\right)-1\right]}\Delta\lambda + (1-\varepsilon)\frac{c_1}{\lambda^5\left[\exp\left(\frac{c_2}{\lambda T_{BG}}\right)-1\right]}\Delta\lambda \qquad (5)$$

The difference between calculation using the simplified method shown in (5) and the integrated method from (3) is shown in Figure 2. Most of the error occurs at the smaller aperture diameters.

Figure 2: Error Caused by Simplified Equation

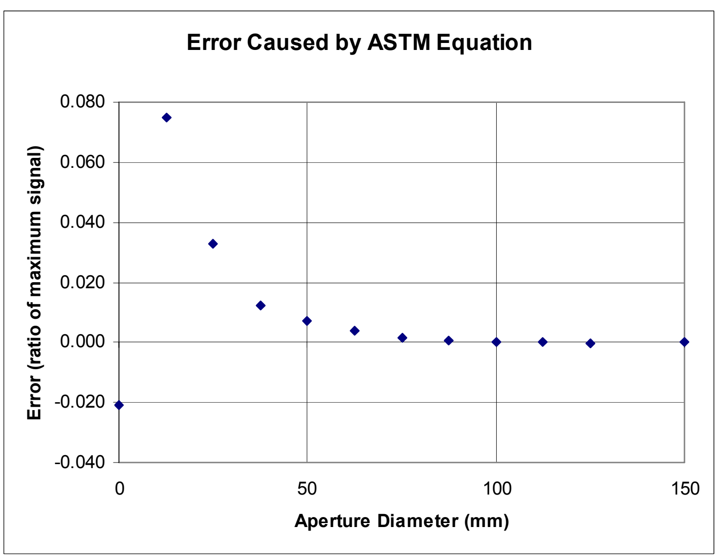


A second equation that was considered is included in the ASTM standard [2]. This equation is modified to calculate β and is shown in (6). It is meant to calculate the SSE at levels of 99% and above and may not be suited for calculating lesser SSE. The ASTM standard is for radiation thermometers with emissivity settings of 1.00 used to measure blackbodies. This type of measurement is not always possible with handheld instruments.

$$\beta = 1 - \frac{\Delta T}{\left[1 - \exp\left(\frac{-c_2}{\lambda T}\right)\right]} \frac{c_2}{\lambda T^2} \tag{6}$$

The difference between calculation using the ASTM equation shown in (6) and the integrated method from (3) is shown in Figure 3. Most of the error occurs at the smaller aperture diameters.

Figure 3. Error Caused by ASTM Equation



ACCOUNTING FOR UNCERTAINTY

Once the SSE is characterized, this data can be used to calculate uncertainty caused by SSE and IR calibrator uniformity issues.

Using Test Data and Uniformity Data

If 100% of the signal is contained within the target size, the target's uniformity specification can be used completely for evaluation. For this example, the 4181's uniformity specification is used. At 250°C, the uniformity is specified as ±0.25°C at a 50mm diameter and as ±0.50°C at a 125mm diameter. This means that 100% of the signal will have an uncertainty of ±0.25°C. Referring to the graph in Figure 1, 3% of the signal comes between the diameters of 50mm and 125mm. This will cause an additional uncertainty of 3% of ±0.50°C or ±0.02°C. Since these uncertainties are correlated, they should be summed giving an uncertainty of ±0.27°C.

Having Less Source then SSE

A different problem occurs if the source is smaller than the SSE needed to get an accurate measurement from an IR thermometer.

To illustrate this problem, a 62.5mm diameter target at 250°C will be considered. For simplicity, it is assumed the target has complete temperature uniformity on its surface. From the SSE testing illustrated in Figure 1, it has been demonstrated IR Thermometer 3 has 98.3% of its detected signal within this diameter. This means that when the IR thermometer is properly centered on the target, 1.7% of its signal will come from areas not on the target. By applying the inverse of (3), it can be calculated that this can cause up to 2.7°C of error in the calibration.

Inclusion in an Uncertainty Budget

Using the testing method described in Section 3 with the analysis from this section, type 'B' uncertainties can be calculated as shown above. These uncertainties can be quite large and should be considered for any IR thermometer calibration.

CONCLUSION

Knowledge of size of source is important for the calibration and use of IR thermometers. To determine size of source, a simple test can be done as outlined in this paper. This helps the user of these instruments to determine uncertainty caused by the uncertainty of surface uniformity of an IR calibrator. Even more important, uncertainty can be calculated for the case when the IR calibrator source is smaller than 100% of the IR thermometer's SSE. This uncertainty calculation will lead to better knowledge of the accuracy of IR thermometer calibrations and measurements.

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