Use of New Standards for Hand-Held Infrared Thermometer Calibration

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Abstract

Historically, there has been a lack of standards for infrared (IR) thermometer calibration. This is true when it comes to determination of IR thermometry uncertainty budgets. However, recently there has been some progress in this area. The first standard to address this is from the International Bureau of Weights and Measures (BIPM). It is intended for high-end radiation thermometers using cavities as a calibration source. The second is a technical guide from Measurement Standards Laboratory in New Zealand. It covers hand-held IR thermometer calibration.

This paper combines ideas in these two documents to help the reader better calculate uncertainty for IR thermometer calibration. It gives the reader a standardized structure to present uncertainty for IR thermometer calibration. It discusses practical testing done to verify the uncertainty calculation discussed in these documents. The intended audience for this paper is any technician who calibrates IR thermometers.

1 Introduction

In the fields of IR thermometry calibration and radiation thermometry calibration, there have been a number of developments in standards and guidelines over the past three years. Many of these standards are geared toward the higher end radiation thermometer work done at national laboratories. While these standards may not be targeted toward the calibration of IR thermometers, with a little bit of knowledge, their principles can be applied to calibrations done with handheld IR thermometers.

2 Current Standards for IR Thermometry

There are several standards for IR and radiation thermometry. These standards come from both international and national standards bodies.

2.1 BIPM CCT-WG5

In 2008, the BIPM CCT-WG5 on Radiation Thermometry released "Uncertainty Budgets for Calibration of Radiation Thermometers below the Silver Point" [1]. There are two aspects of this document that preclude its use with calibration of IR thermometers. First, its scope precludes instruments whose readout is directly in temperature, which includes handheld IR thermometers. Second, it covers uncertainties for radiation thermometer calibrations using blackbody cavities. For the most part, handheld IR thermometers are calibrated using flat-plate calibrators as their radiation source. In spite of the differences in calibrating these two classes of instruments, analogs exist between the blackbody scheme discussed by WG5 and the flat-plate calibration scheme discussed in this paper. These similarities are summarized in Table 1.

Table 1. Analogs between blackbody and flat-plate uncertainties

CCT-WG5 Uncertainty	**Flat-plate Analog**
Blackbody	**Source**
Calibration temperature	Calibration temperature
Blackbody emissivity, isothermal	Source Emissivity, isothermal
Blackbody emissivity, non-isothermal	Source Emissivity, non-isothermal
Reflected ambient radiation	Reflected ambient radiation
Cavity bottom heat exchange	Source heat exchange
Convection	Convection
Cavity bottom uniformity	Source uniformity
Ambient conditions	Ambient conditions
Radiation Thermometer	**IR Thermometer**
Size-of-source effect	Size-of-source effect
Non-linearity	Non-linearity
Reference temperature	Reference temperature
Ambient temperature	Ambient temperature
Atmospheric absorption	Atmospheric absorption
Gain ratios	Gain ratios
Noise	Noise

2.2 MSL TG22

Measurement Standards Laboratory of New Zealand (MSL) has a technical guide available on their web site along with a spreadsheet to assist in the use of calculations using the Sakuma-Hattori Equation (1). The technical guide is written on a calibration technician level and is meant to address handheld IR thermometer calibrations including those done with flat-plate calibrators. It discuses a basic measurement equation (2) based on the Sakuma-Hattori Equation.

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

where:
A, B, C: Sakuma-Hattori parameters
c_2: Second Radiation Constant
T: temperature
S(T): signal (from radiated flux)

$$S(T_{meas}) = S(T_S) + \frac{(1-\varepsilon_{instr})}{\varepsilon_{instr}}\left[S(T_W) - S(T_d)\right] + \frac{(\varepsilon_S - \varepsilon_{instr})}{\varepsilon_{instr}}\left[S(T_S) - S(T_W)\right] \tag{2}$$

where:
S(T): implementation of the Sakuma-Hattori Equation
ε_S: emissivity of the measured surface
ε_{INST}: instrument emissivity setting
T_{MEAS}: IR thermometer readout temperature
T_S: measured surface temperature
T_W: reflected radiation temperature (walls)
T_d: detector temperature

2.3 VDI

The German standards organization, Verein Deutscher Ingenieure (VDI), has a series of IR standards available in both English and German [2]. These standards cover the topics including specifications, calibration and test methods.

2.4 ASTM

The current ASTM standard relating to IR thermometry covers a number of test methods [3]. In addition to this, there are currently work items covering temperature measurement for IR thermometry [4] and calibration of IR thermometers [5]. The temperature measurement work item includes a section to help make calculation of IR temperature measurement uncertainties easier. This section includes mathematical examples of calculation.

3 Applying the Standards

The uncertainty budget structure shown in this paper is based on the CCT-WG5 standard [1]. The WG5 standard is meant for measurements using a blackbody cavity. Since handheld IR thermometers are often calibrated using a flat-plate IR calibrator, the word source is used in this paper instead of blackbody as was discussed previously. TG22 gives Equation (2) as a measurement equation to calculate uncertainty [6]. The following section gives a summary of the uncertainties listed in Table 1.

3.1 Calibration Source Uncertainties

The calibration temperature of the source is the temperature of the source as indicated by the source's read-out.

Isothermal emissivity is the effective spectral emissivity, at ambient temperature. This emissivity is specific to the spectral band of the IR thermometer being calibrated. Non-isothermal emissivity is any emissivity variations that occur when a surface is at a temperature other than ambient. It should be noted that there are two methods to determine the calibration temperature of the source [6]. First, this temperature can be determined by contact thermometry. In this case, the emissivity of the surface is determined by some other method such as Fourier-transform infrared [7] or radiometric comparison [4]. Since emissivity for a specific surface coating can vary widely, this can cause a large amount of uncertainty in the emissivity prediction. The second method is to calibrate the surface is by radiation thermometry. The emissivity may still vary over time or be dependent on spectral bandwidth, but these two uncertainties are reduced by quite a bit. An example summary of these two methods is shown in Table 2. The uncertainty in emissivity is considered to be 0.01 in this comparison.

Table 2. Differences in emissivity related uncertainty between contact and radiometric calibrated surfaces

	Radiometric			**Contact**		
T (°C)	**U_{CAL-T} (°C)**	**U_{EMIS} (°C)**	**U_{COMB} (°C)**	**U_{CAL-T} (°C)**	**U_{EMIS} (°C)**	**U_{COMB} (°C)**
-15	0.4	0.0	0.4	0.4	0.5	0.6
0	0.4	0.0	0.4	0.4	0.2	0.4
50	0.5	0.0	0.5	0.4	0.3	0.5
100	0.5	0.0	0.5	0.5	0.6	0.8
200	0.7	0.0	0.7	0.6	1.2	1.3
350	1.2	0.0	1.2	0.7	2.4	2.5
500	1.6	0.0	1.6	0.8	3.5	3.6

Reflected radiation is defined as "the thermal radiation incident upon and reflected from the measurement surface of the specimen" [4]. This phenomenon is sometimes referred to as background radiation, and the cause of its effect is sometimes referred to as background temperature. This uncertainty is much more of a concern when calibrating instruments with a flat-plate than it is with a blackbody cavity. It is especially a concern when measuring objects at temperature below ambient.

Source heat exchange is the uncertainty of the difference between the source's control sensor and the source's surface due to heat flow between the sensor location and the source's surface. If the flat-plate is calibrated with a radiometric calibration, this uncertainty is minimized. However, there still is some uncertainty since the heat flow may be different from time to time. Figure 1 shows an example of temperature difference between the control sensor and the calibrator surface for a specific flat-plate. In this example, the control sensor is located 6 mm behind the calibrator surface.

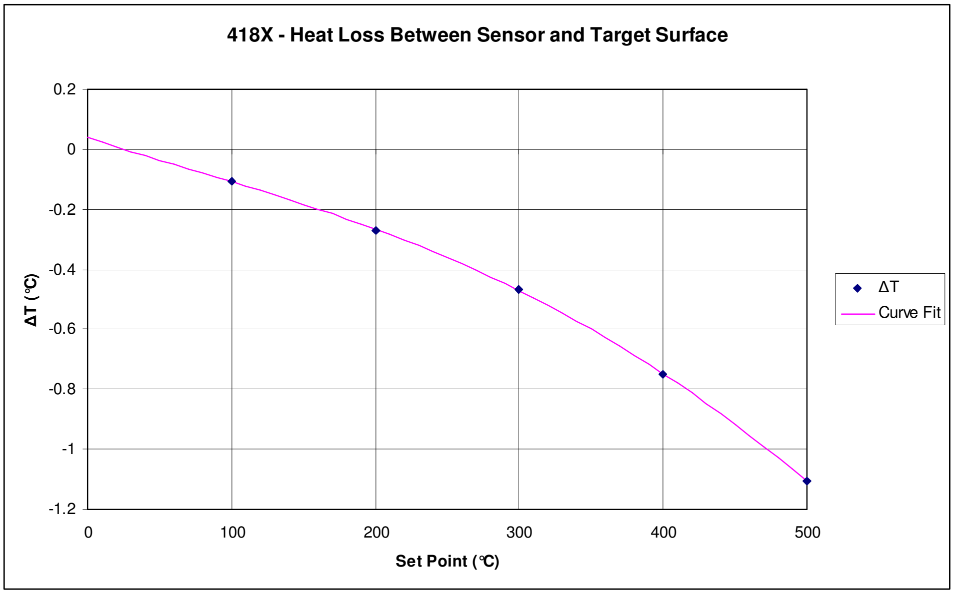

Figure 1. Temperature difference between control sensor and surface

For a flat-plate calibrator, the effects of convection are minimal. However, if a source of forced air is close to the calibrator surface, this uncertainty may be more of an issue. Essentially, when a forced air source is placed close to the surface, the uniformity pattern of the surface may be changed. This may be a very difficult uncertainty to test. The conditions of air flow may have to be exaggerated to get a true idea of the effect of this uncertainty.

Source uniformity is uncertainty due to temperature non-homogeneity on the calibrator surface. Since an IR thermometer averages the temperatures within its spot, this uncertainty will be how much the uniformity will cause a difference in measurement between a measurement of a small spot at the center of the source and a larger spot corresponding to the IR thermometer under test. The source uniformity uncertainty is closely related to the size-of-source effect uncertainty discussed in the IR thermometer uncertainties.

Ambient conditions relate to the ambient temperature of the room where the IR calibrator is located. Testing can be done to test for the effect of ambient conditions. However, the conditions may have to be exaggerated to determine this effect. In addition, in testing, it may be difficult to distinguish between the ambient conditions and the IR thermometer ambient temperature and reference temperature uncertainties.

3.2 IR Thermometer Uncertainties

Size-of-source effect is "the difference in the radiance- or temperature reading of the radiation thermometer when changing the size of the radiating area of the observed source" [8]. For calibration work using a flat-plate source, it is any temperature measured from the source or its surroundings that is not covered by the uniformity uncertainty in the calibration source uncertainties section. An illustration of this is shown in Figure 2. If the flat-plate could be large enough to include the entire signal received by the IR thermometer, this uncertainty would be zero. However, there is always a small amount of scatter at any diameter. This uncertainty will become larger if the source diameter is smaller than the field-of-view of the IR thermometer [9].

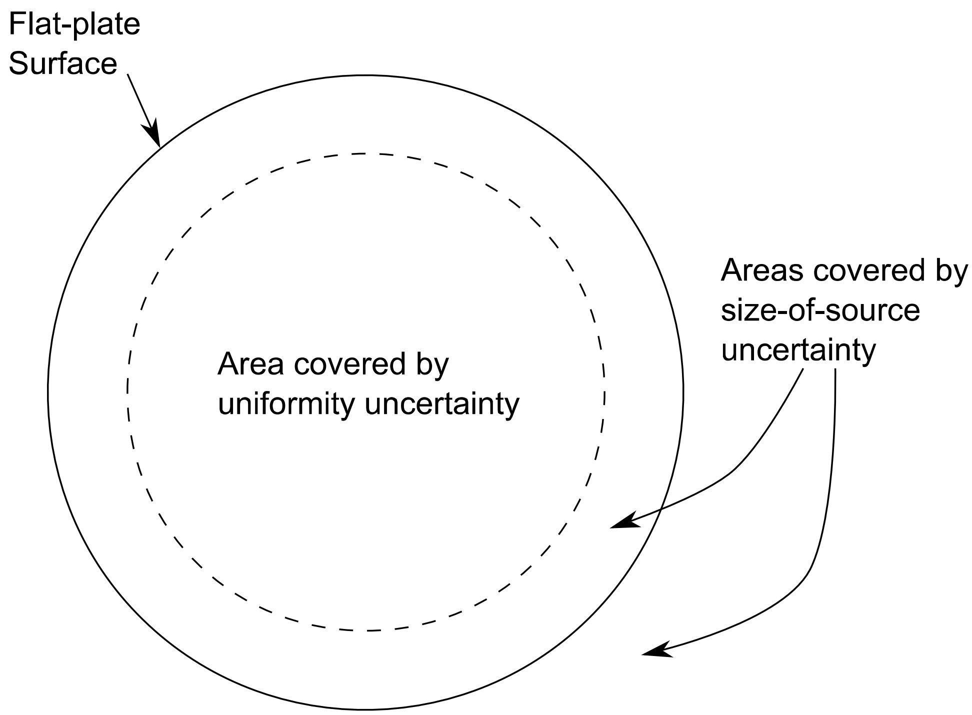

Figure 2. Uniformity and size-of-source uncertainty

Non-linearity and gain ratios relate to how well the IR thermometer optics, detector, and electronics measure radiometric flux. Since the signal or radiance readout of handheld IR thermometers will most likely not be available to the end-user, the expanded uncertainties (k = 2) of 400 ppm for non-linearity and 20 ppm for gain ratios can be used for the 10 µm wavelength [1].

Reference temperature and ambient temperature are two related uncertainties that have to do with transient detector temperature and steady-state detector temperature respectively. Detector temperature can be calculated using a method discussed later in this paper [6]. Testing should be done to determine how thermal transients effect the IR temperature measurements and how different steady-state temperatures effect the IR temperature measurement.

The ideal way to calculate an uncertainty for atmospheric absorption would be to consult a standard atmosphere and model its effect [10]. However, this is not practical for most technicians. Instead, for distances under 1 m, the expanded uncertainty (k = 2) is normally 200 ppm [1]. A summary of the non-linearity, gain ratios and atmospheric uncertainties, as discussed here, are shown in Table 3. The amount of temperature uncertainty in this table is calculated for the 8 – 14 µm spectral band. This calculation uses Equation (3).

$$U(T) = \frac{1}{\left(\frac{\partial S}{\partial T}\right)} \frac{U(S)}{S} S \tag{3}$$

where:
U(T): uncertainty in temperature
∂S / ∂T: first derivative of the
U(S) / S: ratio of uncertainty in signal to signal
S: radiometric signal

Table 3: Non-linearity, gain ratios and atmospheric uncertainties

Temp (°C)	**Atmospheric absorption**	**Non-Linearity**	**Gain Ratios**
U(S)/S	0.0002	0.0004	0.00002
-15	10 mK	20 mK	1 mK
0	11 mK	22 mK	1 mK
50	15 mK	30 mK	2 mK
100	20 mK	40 mK	2 mK
200	31 mK	61 mK	3 mK
350	49 mK	99 mK	5 mK
500	71 mK	141 mK	7 mK

Noise, sometimes referred to as noise equivalent temperature difference (NETD), is a phenomenon experienced by the IR thermometer's measurement system. This uncertainty can be taken from the IR thermometer's specifications or determined by experimentation.

4 Practical Testing

To verify many of the uncertainties discussed in the previous section, testing should be done. This section discusses the results of some practical testing related to these uncertainties.

4.1 Emissivity and Calibration Temperature

There are two approaches to IR source calibration [6]. The first involves using a contact thermometer as a reference for the flat-plate. When using this method, emissivity and heat-flow between the reference thermometer and the flat-plate surface are not accounted for [11]. If the emissivity is very tightly controlled during the coating process, this may cause an expanded uncertainty of 0.01 as shown by testing done at Fluke [12]. If the process is not tightly controlled, this expanded uncertainty is likely to be closer to 0.02. The second approach involves using a radiometric transfer standard to determine the radiometric temperature of the surface. This is how Fluke's flat-plates are calibrated. Through uncertainty analyses, it was found that the radiometric approach provided lower uncertainties at most temperatures. A summary of this analysis is shown back in Table 2.

4.2 Source Uniformity and Size-of-Source Effect

IEC 62492-1 defines size-of-source effect is as "the difference in the radiance- or temperature reading of the radiation thermometer when changing the size of the radiating area of the observed source" [8]. ASTM E 1256 gives a method to test 'target size' [3]. This method involves use of an aperture of variable size used with a radiation source to determine field-of-view for a radiation thermometer. This method was used to determine size-of-source effect for a number of IR thermometers at Fluke [9]. One such set of data is shown in Figure 3. This data were compared to the spot size specification provided by the IR thermometer manufacture. The specification is represented by the arrow. As dictated by IEC 62492-1, the 'field-of-view' is specified with a percentage, size and measuring distance [8]. In the case of the IR thermometer measured in Figure 3, the specification is 37.5 mm diameter (90%), measuring distance: 300mm. Note that the size-of-source testing showed that the IR thermometer tested better than this specification.

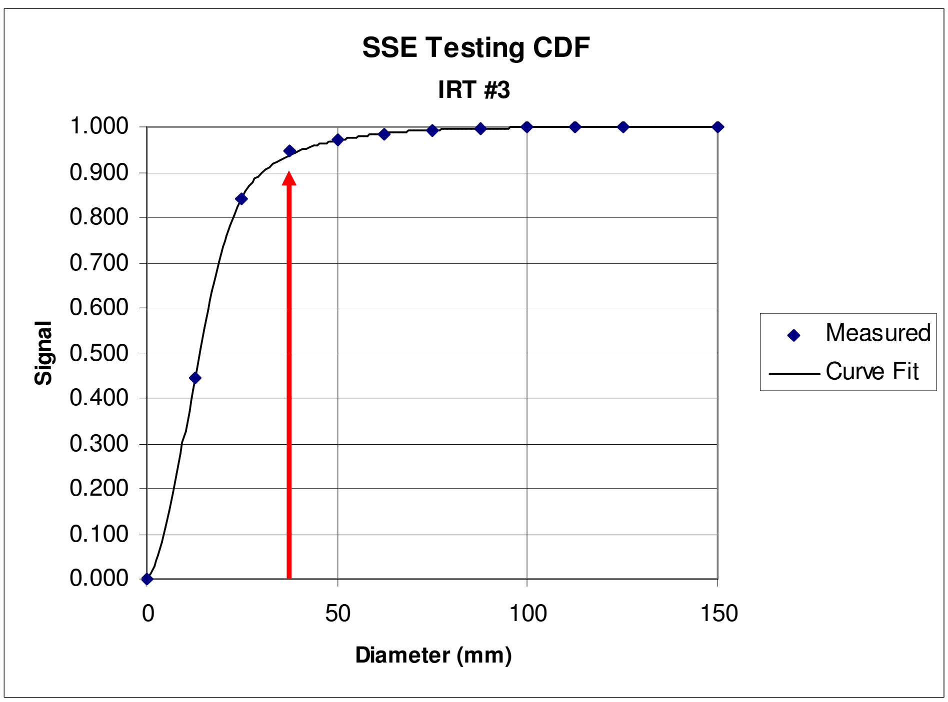

Figure 3. Size-of-source measurement

The flat-plate manufacturer can provide a specification for flat-plate uniformity. If needed, the calibration technician can perform his/her own uniformity testing which is likely to result in better uncertainty. One thing to keep in mind is that the IR thermometer being calibrated averages the temperatures inside its field-of-view, so the uncertainty due to flat-plate uniformity can be determined by an average of measurements at various places on the flat plate [13]. The instrument performing this testing must have a spot size smaller than that of the IR thermometer being calibrated. A thermal imager can also be used. However, the imager's non-uniformity correction (NUC) must be better than the flat-plate uniformity [14].

It would be best practice for laboratory personnel to do a size-of-source or field-of-view test for at least two diameters corresponding to either the flat-plate's uniformity specification or measured uniformity of the flat-plate. One such analysis is shown in Table 4. The uniformity uncertainty is calculated by taking the field-of-view inside a given region and multiplying it by the uniformity uncertainty for that region. Since the uncertainty in these regions is correlated, the uncertainties are summed. In this example, 97% of the field-of-view is within a 50 mm diameter. 2.97% of the field-of-view is between the diameters of 50 mm and 125 mm. The remaining 0.03% is accounted for by the size-of-source effect uncertainty.

Table 4. Analysis of uniformity data

Diameter	**Field-of-view**	**Uniformity Uncertainty (°C) (k=2)**	**SSE Uncertainty (°C) (k=2)**
50 mm	0.97	0.16	
125 mm	0.9997	0.26	
Total		0.163	0.030

4.3 Ambient and Reference Temperature

TG22 discusses how detector temperature can influence measurements. It also presents a method to measure detector temperature shown in Equation (4) [6]. It should be noted that detector temperature and reference temperature are likely to be close in value. This may not be the case if an IR thermometer has undergone 'thermal shock', which means "subjecting an IR thermometer to a rapid temperature change". [4]

$$S(T_d) = \frac{\varepsilon_{instr1} S(T_{meas1}) - \varepsilon_{instr2} S(T_{meas2})}{\varepsilon_{instr1} - \varepsilon_{instr2}} \quad (4)$$

where:

S(T): implementation of the Sakuma-Hattori Equation

ε_{INST1}, ε_{INST2}: instrument emissivity setting

T_{MEAS1}, T_{MEAS2}: IR thermometer readout temperature

T_d: detector temperature

Practical testing to verify the calculation using Equation (4) was done at Fluke. The tests showed a relationship between detector temperature and ambient temperature as shown in Figure 4. The solid lines represent the test difference average in temperature and the expanded uncertainty limits of the experiment. The two largest uncertainties were repeatability and the reference temperature calculation due to quantization or round-off error. Results from this type of testing can be used to show a relationship between measured temperature and ambient temperature.

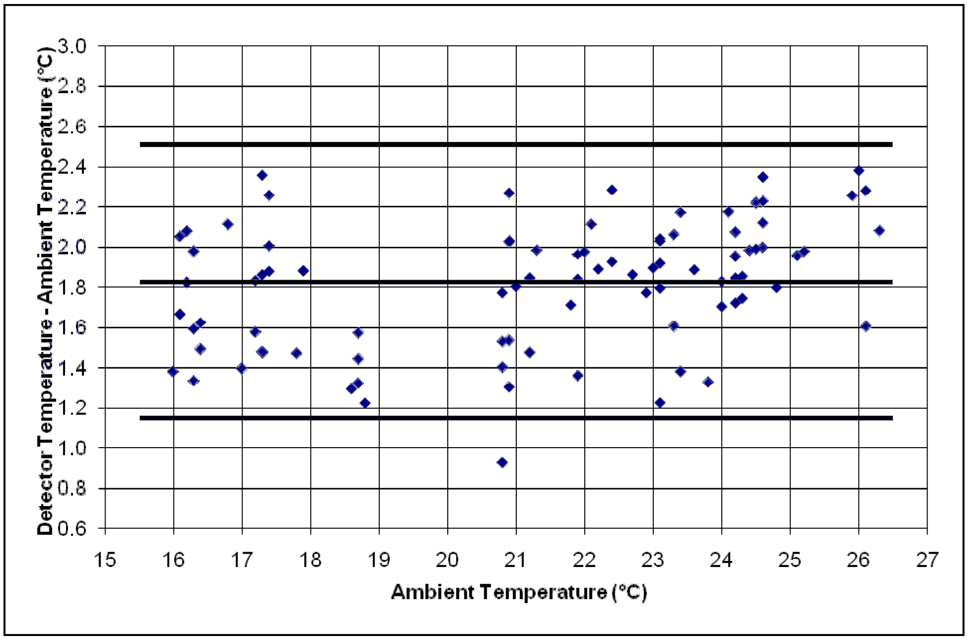

Figure 4. Detector temperature versus ambient temperature.

5 Sample Uncertainty Budget

A sample calculated uncertainty budget is shown in Table 5. The uncertainties shown in the uncertainty budget are based on those discussed previously in Table 1. The data shown in Table 5 is not representative of a specific uncertainty budget using a specific IR thermometer or a specific flat-plate calibrator but are given just as an example.

Table 5. Sample uncertainty budget.

Uncertainty	**Desig.**	**Value (°C)**
Source		
Calibration temperature	U_1	0.250
Source Emissivity, isothermal	U_4	0.300
Source Emissivity, non-isothermal	U_5	0.000
Reflected ambient radiation	U_6	0.030
Source heat exchange	U_7	0.012
Convection	U_8	0.012
Source uniformity	U_9	0.163
Ambient conditions	U_{10}	0.001
IR Thermometer		
Size-of-source effect	U_{11}	0.030
Non-linearity	U_{12}	0.040
Reference temperature	U_{13}	0.066
Ambient temperature	U_{14}	0.330
Atmospheric absorption	U_{15}	0.020
Gain ratios	U_{16}	0.002
Noise	U_{17}	0.250
Combined Expanded Uncertainty (k=2)		0.599

6 Conclusion

With the use of new standards intended for use with radiation thermometry, a standard infrared thermometry uncertainty budget format can be considered. The information presented in this paper is a starting point for knowledge of infrared thermometry uncertainty budget structure and uncertainty budget computational know-how for calibration laboratory personnel performing calibrations of infrared thermometers. In the future, this information should be implemented in a standard for calibration of infrared thermometers or uncertainty budget determination for calibration of infrared thermometers.

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