

# Uncertainty Budgets for IR Temperature Measurement – An Overview

## Abstract

In the field of infrared (IR) temperature measurement, accuracy of temperature measurements has not been as good as it is in contact temperature measurement. This is true for measurements made with thermal imagers as well as measurements made with handheld IR thermometers. In fact, many thermographers are not as interested in the measured temperature of an object as they are in the differences in temperature in the imager's field of view. However for various reasons such as regulation and accreditation, knowledge of the accuracy of measurements may be necessary.

To determine the accuracy of measurements, it is necessary to do a calibration on the measuring instrument. Just as important is creating an uncertainty budget for that instrument. The calibration gives the instrument an agreement to an established standard. The uncertainty budget tells the user how close to that agreement the user can expect his instrument to be on a repeated basis.

This paper discusses the elements needed for an IR thermometry uncertainty budget, especially as it relates to thermal imagers. It introduces a measurement equation and discusses how to apply that equation to measurements made with imagers. It discusses how to structure an uncertainty budget so it can be understood by other thermographers and assessors.

## Introduction

Although many applications using IR thermography or IR thermometry do not require knowledge of temperature measurement accuracy, there are some applications that do. For applications that do, a standardized method should be used to determine accuracy. An accepted method of determining the accuracy of a measurement is to prepare an uncertainty budget. This paper is intended as an overview of the information necessary to put together an uncertainty budget that will be acceptable to describe the accuracy of IR measurements.

## 1. Background

The information in this paper is based in a large part on the experience of constructing uncertainty budgets for IR thermometry at Fluke Corporation Hart Scientific Division.

The purpose of doing an uncertainty budget for any type of measurement is to determine the accuracy of that measurement. A properly calculated uncertainty budget reveals the accuracy of measurements and gives a means of communicating this understanding.

In IR thermometry, accuracy is often not a large concern to the users of this technology. This is the case with the users of IR thermometers. This is the case with the users of thermal imagers as well. However, there are occasions where knowledge of these instruments' accuracy is needed. There are a number of reasons to perform an uncertainty budget. Some industries require calibration on all pieces of measurement equipment. Sometimes that requirement can be of a legal nature. Some may be just to determine the accuracy of a measurement.

To begin this discussion, there are a few concepts that should be understood.

For temperature measurements, accuracy is the "closeness of agreement between the result of a temperature measurement and a true value of the temperature" [ASTM E 344-02]. In the case of temperatures up to about 960C, these standards (or true values) are defined by a set of fixed points (usually pure metals or pure water). In the US, these standards can be calibrated by NIST. Points between these fixed points are often defined by the ITS-90 temperature scale. In fact, the ITS-90 is considered as a standard temperature scale for calibration of PRTs [Nicholas & White].

Not to be confused with accuracy is repeatability. Repeatability is the ability to get the same results for a measurement during repeated measurements. In temperature measurement, it is "closeness of agreement between the results of successive measurements of the same temperature carried out under the same conditions of measurement" [ASTM E 344-02]. This is not the same as accuracy. A set of measurements may have a repeatability of 0.2°C. However, if all of these measurements are 1.0°C from what standards traceable to national laboratories indicate they should be, then they are actually less accurate than they are repeatable.

Traceability fixes an instrument's measurement to a standard [Nicholas & White]. If its calibration is traceable, it will have

been compared or calibrated to a standard. This standard may have been calibrated at a national laboratory, or it may be traceable to a national lab.

The uncertainty budget guideline that is followed in this paper is the Guide to U. S. Guide to the Expression of Uncertainty in Measurement commonly referred to as the GUM. It is recommended that anybody calculating uncertainty budgets have this guideline and follow it.

## 2. IR Uncertainty Budget Elements

In order to properly define the accuracy of a calibration or a measurement, an uncertainty budget should be performed. To do a proper uncertainty budget, any item that would influence a measurement should be considered [GUM].

A basic list of uncertainties for IR temperature measurement is listed in Table 1. These uncertainties can be used for uncertainty budgets for IR thermometer and imager calibration as well as IR thermometer and imager use. Some of these uncertainties do not apply in all cases.

This list does not include aperture related uncertainties which will not be discussed in this paper. Apertures are often used in high end IR thermometry to reduce the effects of scatter on measurements.

Related Usage	Uncertainty	Brief Description
Calibrator	Calibration Uncertainty	Uncertainty of the Calibrator's Calibration
Calibrator	Stability (long term)	Long term drift of the IR calibrator during its calibration interval
Calibrator, Surface	Uniformity	Temperature uncertainty due to uniformity within the area being measured
Calibrator, Surface	Noise	Based on the surface's temperature stability
Calibrator	Display Resolution	Based on the display resolution of the calibrator
IR Thermometer	Readout Resolution	Based on the display resolution of the IR thermometer
IR Thermometer, IR Imager	Ambient Temperature	The effects of ambient temperature on the IR thermometer's measurement
IR Thermometer, IR Imager	Noise	Based on the IR thermometer's temperature stability
IR Thermometer, IR Imager	Atmospheric Losses	Based on the difference between the IR thermometer's atmospheric losses between its calibration and use
IR Thermometer, IR Imager	Angular Displacement	Based on the change in emissivity of an object when a measurement is not being taken at a normal angle from that object
IR Thermometer, IR Imager	Background Temperature	The effects of background temperature on the IR thermometer's measurement
IR Thermometer, IR Imager	Spectral Variation	The effects of the IR thermometer not measuring within its specified bandwidth
IR Imager	Display Uniformity	The effect of measurement variation in the area of interest on the imager's display

Table 1: List of IR Thermometry Related Uncertainties

## 3. IR Uncertainty Budget Structure

Having the correct uncertainty budget structure allows communication of uncertainties to people outside one's organization. The following section gives basic information on necessary elements to an uncertainty budget.

### 3.1. Type 'A' Uncertainties and Type 'B' Uncertainties

Uncertainties are divided into two categories, Type 'A' and Type 'B'. Type 'A' uncertainties are those determined by statistical methods. Type 'B' uncertainties are those not determined by statistical methods.

An example of an uncertainty determined using statistical methods is the following. Repeatability needs to be determined for an uncertainty budget. A number of measurements is taken from a known temperature source. These measurements are compared to each other. The uncertainty for repeatability is based on this comparison.

A couple of examples of uncertainties not determined by statistical methods are the following. One example would be an accuracy specification provided by a manufacturer. Another example is an uncertainty determined entirely by modeling such as using Planck's Law to model the effects of uncertainty in emissivity.

### 3.2. Distributions

The two major distributions we will talk about here are rectangular and normal. There are other distributions listed in the GUM.

A rectangular distribution is one where uncertainty is distributed equally within a set of limits. An example is an IR thermometer with an accuracy specification of  $\pm 1.0^{\circ}\text{C}$  at  $100^{\circ}\text{C}$ . The uncertainty would be  $1.0^{\circ}\text{C}$  with a rectangular distribution. Standard deviation for a rectangular distribution can be determined by dividing the rectangular distribution by the square root of 3 ( $\sim 1.7$ ).

A normal distribution is often known as a bell curve or a Gaussian distribution. It predicts roughly 68% of measurements will fall within one standard deviation, and roughly 95% of measurements will fall within two standard deviations. The following is an example of a normal distribution. 20 measurements are taken to determine repeatability. 19 of the measurements (95%) fall within  $\pm 0.4^{\circ}\text{C}$ . This means if the samples have a normal distribution, they have two standard deviations of  $0.4^{\circ}\text{C}$ .

Standard deviation can easily be determined by the use of a spread sheet program such as MS Excel. In Excel, this is accomplished by the STDEV() function. This will give you one standard deviation. To get a number for 2 standard deviations, simply multiply this number by 2 ( $2 * \text{STDEV}()$ ).

A brief note about the term 'k' of coverage factor in uncertainty budgets, a  $k=1$  uncertainty means it has a normal distribution and has been stated as 1 standard deviation. Likewise, a  $k=2$  uncertainty means the uncertainty has been stated as 2 standard deviations [Nicholas & White].

### 3.3. UC budget Explanations

An uncertainty budget should come with an explanation for each uncertainty. This makes understanding the uncertainty budget easier for auditors and customers. Table 1 gives some basic uncertainty budget explanations, although, more elaboration may be given for an explanation.

## 4. IR Math

One of the biggest challenges of calculating uncertainties for IR thermometry is dealing with the math. This is due to the complex mathematical and physical nature of the IR measurement system.

### 4.1. Measurement Equation

An uncertainty budget should be based on a measurement equation [GUM]. The way an IR thermometer or imager calculates temperature is based on detector signal. This is true whether the instrument under test is being calibrated or being used for temperature measurement. A basic measurement equation for IR temperature measurement is shown in Equation 1. This is a simplified equation. It should be noted that each of these terms is influenced by the factors shown in Table 1. For example, the signal for any measurement depends on both the background temperature ( $T_{BG}$ ) and the temperature of the object being measured ( $T_{SURF}$ ).

$$S(T) = \varepsilon S(T_{SURF}) + (1 - \varepsilon) S(T_{BG})$$

Equation 1. Basic Measurement Equation for IR Thermometry

### 4.2. Planck's Law

Radiation is what an IR thermometer measures. Radiance is modeled using Planck's Law [DeWitt & Nutter]. Although not

much explanation will be given on how to mathematically apply this equation in all situations, knowledge of how the different elements of Planck's Law can influence uncertainty is important. For example, the term  $\lambda$  refers to wavelength. This indicates that spectral variation or the bandwidth limit variation of the optical system should be considered.

It should be noted that the L (spectral radiance) in Equation 2 is related to and is proportional to the S (signal) in Equation 1.

$$L(\lambda, T) = \frac{c_{1L}}{\lambda^5 \left[ \exp\left(\frac{c_2}{\lambda T}\right) - 1 \right]}$$

Equation 2. Planck's Law

### 4.3. SH Equation

One alternative to using Planck's Equation that has been suggested is the Sakuma-Hattori Equation [Saunders et al] shown in Equation 3. It is problematic for the user of handheld industrial type instruments in that the A, B and C constants are most likely not provided for these instruments.

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

Equation 3. Sakuma-Hattori Equation

### 4.4. IR Math Made Simple

Planck's Law is rather complicated. If the 8 to 14  $\mu\text{m}$  band is being used for measurements, the equation must be evaluated over the instrument's bandwidth. This is not a trivial task, since the equation turns into an integral that must be solved numerically. For many uncertainties not determined by statistical methods, a mathematical calculation must be made. Instead of mathematically calculating the effects of uncertainty in items such as emissivity uncertainty, background temperature and the effects of scatter, there are sources which provide charts and graphs to simplify these calculations [ASTM E 1256-95, Fluke, Mikron]. Two examples of graphs which can be used are shown in Figures 1 and 2. They are based on numerical modeling of Planck's Equation done at Hart Scientific and show the effects of uncertainty in emissivity and background temperature.

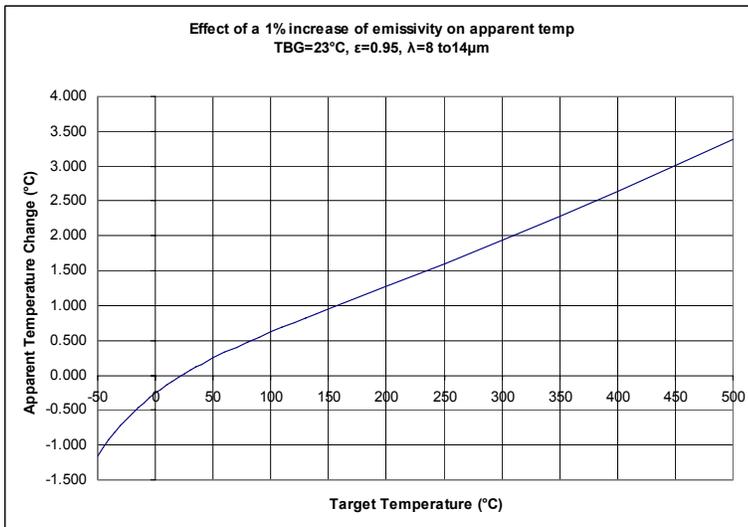


Figure 1. Effect of a 1% Change in Emissivity

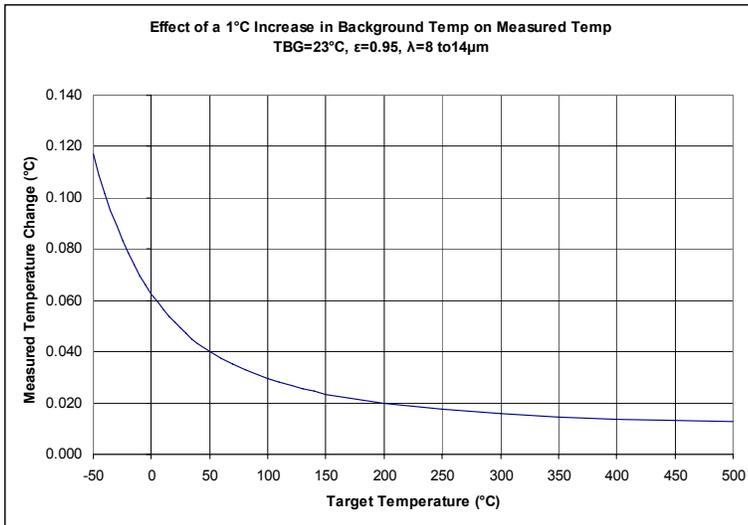


Figure 2. Effect of a 1°C Change in Background Temperature

## 5. IR Uncertainty Budget Calculation

With the knowledge described here, it is possible to calculate an uncertainty budget.

For any independent or uncorrelated uncertainties a sum of squares can be used [GUM]. If any of the factors are correlated, they must be calculated by summing the components. An example of a simple uncertainty budget calculation is shown in Equation 4. In this example, all uncertainty budget items are uncorrelated, so a sum of squares is used. Note that  $u_1$  and  $u_3$  follow a normal distribution, so they are divided by 2 since they are  $k=2$  uncertainties. The term  $u_2$  is divided by the square root of 3 since it follows a rectangular distribution.

$$U = 2\sqrt{\left(\frac{u_1}{2}\right)^2 + \left(\frac{u_2}{\sqrt{3}}\right)^2 + \left(\frac{u_3}{2}\right)^2}$$

Equation 4. Example of Uncertainty Budget Calculation Equation

The sum of squares gives the  $k=1$  or combined standard uncertainty represented by a lowercase 'uc'. Multiplying this number by 2 gives the  $k=2$  uncertainty or the combined expanded uncertainty represented by an uppercase 'U' [GUM].

### 5.1. Emissivity – How Bad Can It Be

One component that should always get special attention in an IR uncertainty budget is emissivity. In order to make accurate temperature measurements, the emissivity of the surface or cavity being measured should have a determined emissivity. This is true when using an IR thermometer to make measurements, and it is especially true when calibrating an IR instrument.

A relationship between emissivity change and measured temperature change can be mathematically modeled. The results of one such exercise is shown in Figure 1. Note that at ambient background temperature, emissivity has no effect. The graph in Figure 1 shows the effects of a 1% change in emissivity. It is not a stretch to see how much worse the effect is when there is an uncertainty of several percent in emissivity.

Another thing to keep in mind when considering emissivity is that surfaces do not exhibit a constant value for emissivity over all wavelengths. In other words, these surfaces are not gray [DeWitt & Nutter]. This becomes a problem when using two instruments with different spectral responses. An example of a non-gray surface is shown in Figure 3. This emissive spectral response is typical of paints. The graph in Figure 3 was measured by Fourier transform infrared (FTIR) testing [Hannsen et al].

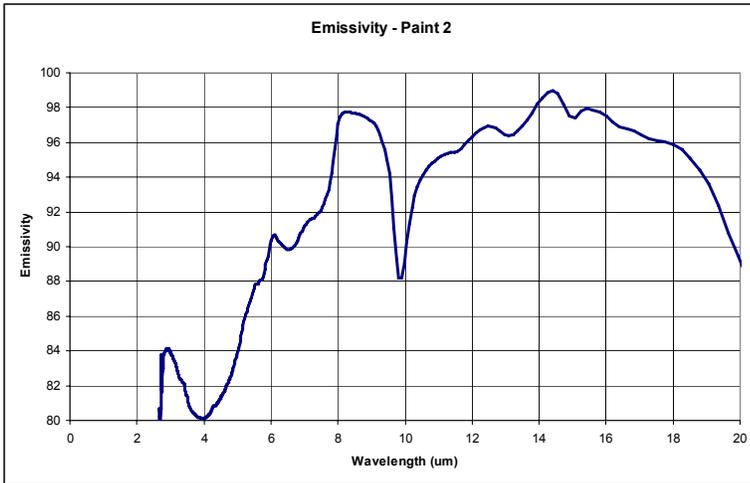


Figure 3. Emissivity of a Typical Paint

### 5.2. IR Thermometer Example Uncertainty Budgets

An example uncertainty budget for an IR thermometer calibration is shown in Table 2. Due to demonstrational purposes, it only considers 1 temperature. In a complete uncertainty budget, a number of temperatures reflecting the range of measurement should be evaluated. Note that these uncertainties correspond to those listed in Table 1. The equation used to sum the uncertainties is shown in Equation 5. The MS Excel formulas used to sum these uncertainties are shown in Equation 6. The MS Excel formula contents for rows correspond to the rows of Table 2. For example Row 4 is the ‘Uniformity’ row and Row 15 is the ‘Spectral Variation’ row. Column E is the ‘Divisor’ column, and Column F is the ‘100°C’ column.

Uncertainties	Denot.	Type	Dist	Divisor	100°C
<b>Target Uncertainties</b>					
Calibration Uncertainty	$u_1$	B	normal	2	0.284
Stability (long term)	$u_2$	A	normal	2	0.050
Uniformity	$u_3$	B	rectangular	$\sqrt{3}$	0.145
Noise	$u_4$	A	normal	2	0.109
Display Resolution	$u_5$	A	rectangular	$\sqrt{3}$	0.005
<b>IR Thermometer Uncertainties</b>					
Readout Resolution	$u_6$	A	rectangular	$\sqrt{3}$	0.050
Ambient Temperature	$u_7$	B	rectangular	$\sqrt{3}$	0.030
Noise	$u_8$	A	normal	2	1.000
Atmospheric Losses	$u_9$	B	normal	2	0.010
Angular Displacement	$u_{10}$	B	rectangular	$\sqrt{3}$	0.030
Background Temperature	$u_{11}$	B	rectangular	$\sqrt{3}$	0.116
Spectral Variation	$u_{12}$	B	normal	2	0.240
<b>Combined Standard Uncertainty</b>	$u_c$	$k=1$	normal		0.549
<b>Combined Expanded Uncertainty</b>	U	$k=2$	normal		1.097

Table 2. Example Uncertainty Budget

$$uc = \sqrt{\left(\frac{u_1}{2}\right)^2 + \left(\frac{u_2}{2}\right)^2 + \left(\frac{u_3}{\sqrt{3}}\right)^2 + \left(\frac{u_4}{2}\right)^2 + \left(\frac{u_5}{\sqrt{3}}\right)^2 + \left(\frac{u_6}{\sqrt{3}}\right)^2 + \left(\frac{u_7}{\sqrt{3}}\right)^2 + \left(\frac{u_8}{2}\right)^2 + \left(\frac{u_9}{2}\right)^2 + \left(\frac{u_{10}}{\sqrt{3}}\right)^2 + \left(\frac{u_{11}}{\sqrt{3}}\right)^2 + \left(\frac{u_{12}}{2}\right)^2}$$

$$U = 2uc$$

Equation 5: Combined Uncertainty for Example Uncertainty Budget

$$= 2 * \text{SQRT}(\text{SUM}((F3/E3)^2 + (F4/E4)^2 + (F5/E5)^2 + (F6/E6)^2 + (F7/E7)^2 + (F9/E9)^2 + (F10/E10)^2 + (F11/E11)^2 + (F12/E12)^2 + (F13/E13)^2 + (F14/E14)^2 + (F15/E15)^2))$$

Equation 6: MS Excel Implementation of Equation 6.5

Imager uncertainty budgets should be similar to the one shown in Table 2. However, an additional uncertainty should be considered. Most imagers undergo a non-uniformity correction (commonly called NUC). This helps to correct for temperature uniformity errors across the display of the imager. However, this correction does not completely solve non-uniformity problems. This problem has been documented in a previous paper [Thomas et al].

This uniformity uncertainty is rather easy to evaluate experimentally. An object of known temperature can be measured at different parts of the display that is used to measure temperature. The results of one such test is shown in Figure 4. In this test two objects of similar temperature were placed next to each other. A thermographic image was taken. Then the objects' positions were switched and a second thermographic image was taken. The uniformity is evaluated by taking the sum of the temperatures measured in a given position, then subtracting the sum of the temperatures in the center of the display. When this result is divided by two, the difference in measured temperature on the display is given, since the difference in the temperature of the two objects cancels. This method is similar to a uniformity test for dry-wells outlined in an accepted standard [EA 10/13]. An example of the math involved is shown in Equation 7.

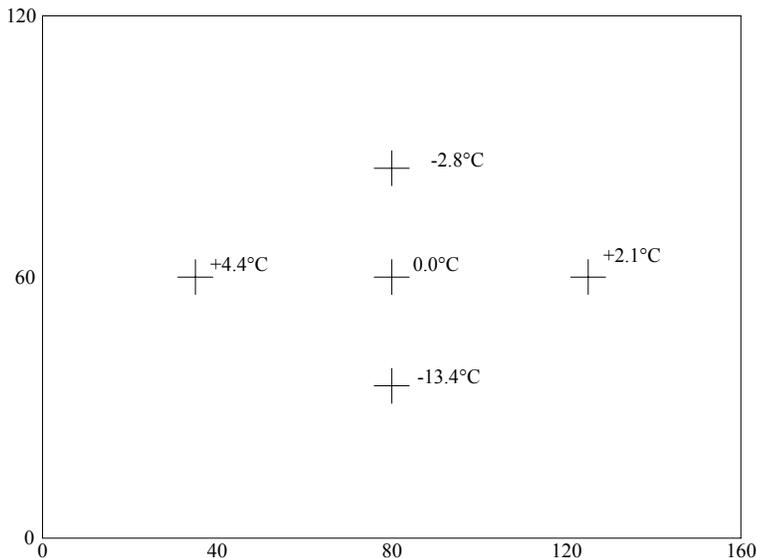


Figure 4. Imager Uniformity Example at 390°C

$$\Delta T = \frac{(T_{RIGHT1} + T_{RIGHT2}) - (T_{CENTER1} + T_{CENTER2})}{2}$$

Equation 7: Imager Uniformity Calculation

## Conclusion

Constructing an uncertainty budget for IR temperature measurement is not a trivial task. However, by paying attention to the uncertainties involved in a measurement an uncertainty budget is a powerful tool. A properly constructed uncertainty budget will give knowledge of the accuracy for a given measurement. It will also portray this accuracy to colleagues and auditors.

## Acknowledgments

The author greatly appreciates the help of many people in developing this technique in calculating IR thermometry uncertainties. Among the people who have helped are Tom Wiandt, Mike Hirst and Rick Walker of Fluke Corporation Hart Scientific Division; Ingrid Gooding of Fluke; Patrick Parker, Alex Nikittin, Steve King, Medwin Schreher, Thomas Heinke and Reno Gärtner of Raytek; Leonard Hanssen, Benjamin Tsai, Sergey Mekhontsev and Howard Yoon of NIST and Kendall Johnson of the Space Dynamics Laboratory at Utah State University.

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