A Study on the Effects of Bandwidth of IR Thermometry Measurements

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Abstract

In the world of low temperature, wide-band infrared (IR) thermometry, there are a number of uncertainties to consider when making measurements. Among these uncertainties are the effects of bandwidth variability for IR thermometers. This uncertainty becomes troublesome because emissivity does not necessarily have a constant value over the entire bandwidth of the IR thermometer being used for the measurement. With this knowledge there is an uncertainty in this measurement that can be determined. Determination of this uncertainty can be rather difficult due to the complexity of the mathematics involved.

This paper addresses this bandwidth related problem when making measurements in the long wave IR or the far IR region, especially the 8-14 µm band. This paper discusses the mathematical problem of calculating this uncertainty. It addresses the numerical theory involved in this calculation. It suggests a method of using simplified mathematics to perform a calculation of this uncertainty. It then discusses practical experimentation performed to verify this method. The reader of this paper will learn how to better calculate this uncertainty for IR thermometry.

1. Introduction

When calculating an uncertainty budget, every factor that can influence the measurement should be considered [1]. It has been suggested that uncertainty in bandwidth combined with emissivity variation as a function of wavelength should be considered in making wideband IR temperature measurements [2, 3]. It can be a complex problem to determine the effects of these phenomena on an IR temperature measurement. First, the actual bandwidth or spectral response of the IR thermometer may not be known. Second, if the uncertainty in bandwidth variation of the IR thermometer is known, it may be difficult to determine the effects of this bandwidth variation uncertainty due to the complexity of the mathematics.

2. Bandwidth in Wideband Instruments

Most handheld IR thermometers used to measure temperatures below 660°C are wideband instruments. These IR thermometers usually come with a bandwidth or spectral response specification. The most common bandwidth for handheld IR thermometers is the 8-14 µm band or some variation of this [4]. Even though these devices' bandwidth limits are published, uncertainty or variability in bandwidth limits is not generally published.

2.1. Testing for Bandwidth

It is possible to perform testing on the spectral response of a given IR thermometer. One facility where this can be done is SCIRCUS which is located on the NIST campus in Gaithersburg, MD [5, 6]. Such tests can be impractical for the user of an IR thermometer due to the cost involved.

2.2. Wideband IR Thermometers

Due to the factors discussed previously, a complete knowledge of an IR thermometer’s spectral response or even just bandwidth variability may not be practical to determine. However, the user of these instruments may be able to determine the effects of uncertainty in bandwidth by making a few assumptions. These assumptions include a measurement of the surface’s emissivity and assuming the bandwidth variation to be an arbitrary number. Testing for the validity of these assumptions will be discussed later in this paper.

3. Blackbody Emissivity

A blackbody describes an ideal thermal radiator [7]. A perfect blackbody would have an emissivity of unity. In actuality, there is no such thing as a perfect blackbody. There are certain geometric shapes which approximate a blackbody and have an emissivity close to unity. One of these is a cavity [7, 8]. However, outside of calibrations, cavities are not always practical for measurements.

3.1. Non Blackbody Surfaces

Flat surfaces do not act as blackbodies [8]. In other words, their emissivity is less than unity. The exact emissivity for a material is dependent on the material’s surface coating and finish.

A gray body is defined as a material having a constant emissivity response regardless of wavelength [7]. In other words, if a material has an emissivity of 0.950 at 2µm, it will have an emissivity of 0.950 at 3.9 µm, 5 µm, 8 µm and 14 µm, as well as any other wavelength in the electro-magnetic spectrum.

3.2. Emissivity’s Dependence on Wavelength

In reality a perfect gray body may not be obtainable. To illustrate this, Figure 1 shows the results of Fourier Transform Infrared (FTIR) testing [9, 10] on two paint samples. It is plain to see that the value for emissity is not constant with wavelength. This type of variance in spectral response of paints’ emissivity is very common [11].

The two paints shown in Figure 1 will be used for analysis later in this paper.

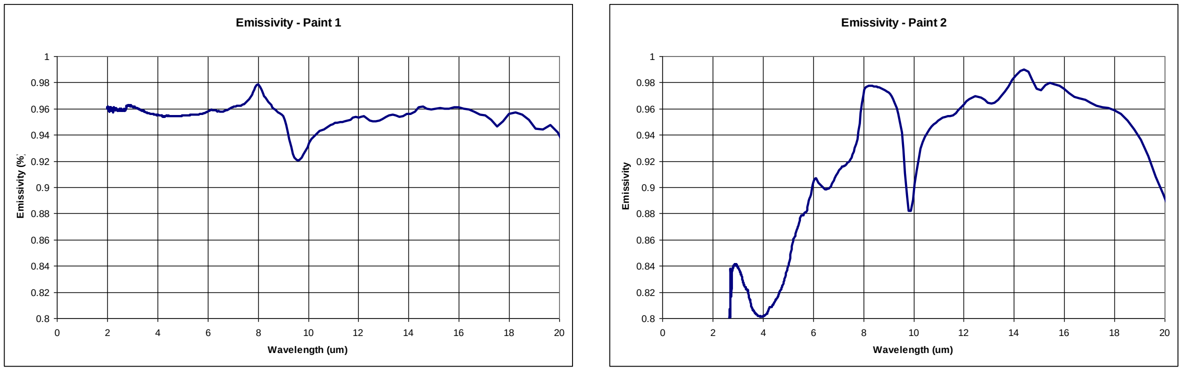

Figure 1. Spectral Response of Emissivity

4. The Mathematical Challenge

With the information discussed in Section 3, it can be seen that emissivity is not necessarily constant with wavelength. This is the first challenge in investigating the effects of bandwidth variability. The second challenge is calculating the effects of bandwidth uncertainty using mathematics related to infrared temperature measurement. To evaluate these effects, the total power density emitted over the IR thermometer’s bandwidth must be known along with the spectral response of the emissivity ($\varepsilon(\lambda)$).

4.1. Planckian Model

The physical equation describing blackbody emissions is Planck’s Law (1) [7]. The result for this equation gives power density emitted per unit wavelength over a spherical angle. For non-blackbodies, the power density emitted per unit wavelength is given by multiplying the emissivity $\varepsilon(\lambda)$ by Planck’s Law.

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

4.2. Challenges Faced with Integrating Planck’s Law

To obtain the total blackbody power density over the bandwidth of an IR thermometer, Planck’s Law must be evaluated over the bandwidth of an IR thermometer as shown in (2). The surface’s exitance $E(\lambda,T)$ must be compared to that of a perfect blackbody $E_{BB}(\lambda,T)$ (where $\varepsilon(\lambda) = 1.0$) as shown in (3). This model gives total exitance within the bandwidth of the IR thermometer. Note that this model assumes a flat band spectral response for the IR thermometer.

$$E(\lambda,T)=\int_{\lambda_1}^{\lambda_2}\frac{\varepsilon(\lambda)c_1}{\lambda^5\left[\exp\left(\frac{c_2}{\lambda T}\right)-1\right]}d\lambda \tag{2}$$

$$\varepsilon_{EFF} = \frac{E(T)}{E_{BB}(T)} \tag{3}$$

To evaluate the effects of bandwidth variability, the emittance of the surface must be evaluated against that of a perfect blackbody. This must be done over the entire bandwidth of the IR thermometer used for measurement as shown in (2).

The problem with evaluating these equations is that it cannot be done analytically. It must be approximated numerically. Besides being time consuming, this may be challenging to laboratory personnel or end users of the IR thermometer. The following sections will discuss a method to make a reasonable calculation possible.

5. The Mathematical Solution

Considering the difficulties of evaluating Planck's Law, the question arises if it is practical to evaluate emissivity in this manner. The integral shown in (2) is not easily calculated. The following sections discuss a method to easily make an estimate of this effect.

5.1. Averaging Emissivity

To find the effective emissivity in the bandwidth under consideration, one must take a Planck's Law weighted average of the emissivity within the bandwidth as shown in (2) and (3). To estimate the emissivity, a simple average of the emissivity as shown in (4) is considered.

$$\varepsilon_{AVG} = \int_{\lambda_1}^{\lambda_2} \varepsilon(\lambda) d\lambda \tag{4}$$

A second method that is considered is more like the weighted average shown in (2) and (3). This method is shown in (5). This method breaks the bandwidth of the IR thermometer into two half-bands. The Planckian blackbody exitance (E) for each half-band is considered against the total exitance in both half-bands. This number is then multiplied by the average emissivity in each of the half-bands. The percentages used for these calculations are shown in Table 1.

$$\varepsilon_{HB} = \varepsilon_{LOW} \frac{E_{LOW}}{E_{BAND}} + \varepsilon_{HI} \frac{E_{HI}}{E_{BAND}} \tag{5}$$

Table 1. Half-band Percentages

	8-14 µm		7-14 µm		5-20 µm	
	$\frac{E_{LOW}}{E_{BAND}}$	$\frac{E_{HI}}{E_{BAND}}$	$\frac{E_{LOW}}{E_{BAND}}$	$\frac{E_{HI}}{E_{BAND}}$	$\frac{E_{LOW}}{E_{BAND}}$	$\frac{E_{HI}}{E_{BAND}}$
100°C	58.8%	41.2%	59.0%	41.0%	68.9%	31.1%
200°C	63.3%	36.7%	64.9%	35.1%	77.7%	22.3%
350°C	67.1%	32.9%	69.8%	30.2%	84.2%	15.8%
500°C	69.1%	30.9%	72.4%	27.6%	87.5%	12.5%

5.2. Theoretical Comparison of Laws

Figure 2 shows a theoretical comparison of these two methods at four different temperatures using both Paint 1 and Paint 2. The values in the graph represent the differences in effective emissivity between the two paints over two bandwidths as shown in equation (6). Equation (6) was used to calculate the differences shown in the graph in the upper left hand corner of Figure 2. Table 2 shows the effect of temperature measurements on surfaces having differences in emissivity. The numbers in Table 2 are based on numerical modeling of Planck's Equation and are similar to numbers found in published texts [12, 13] and an upcoming standard [14].

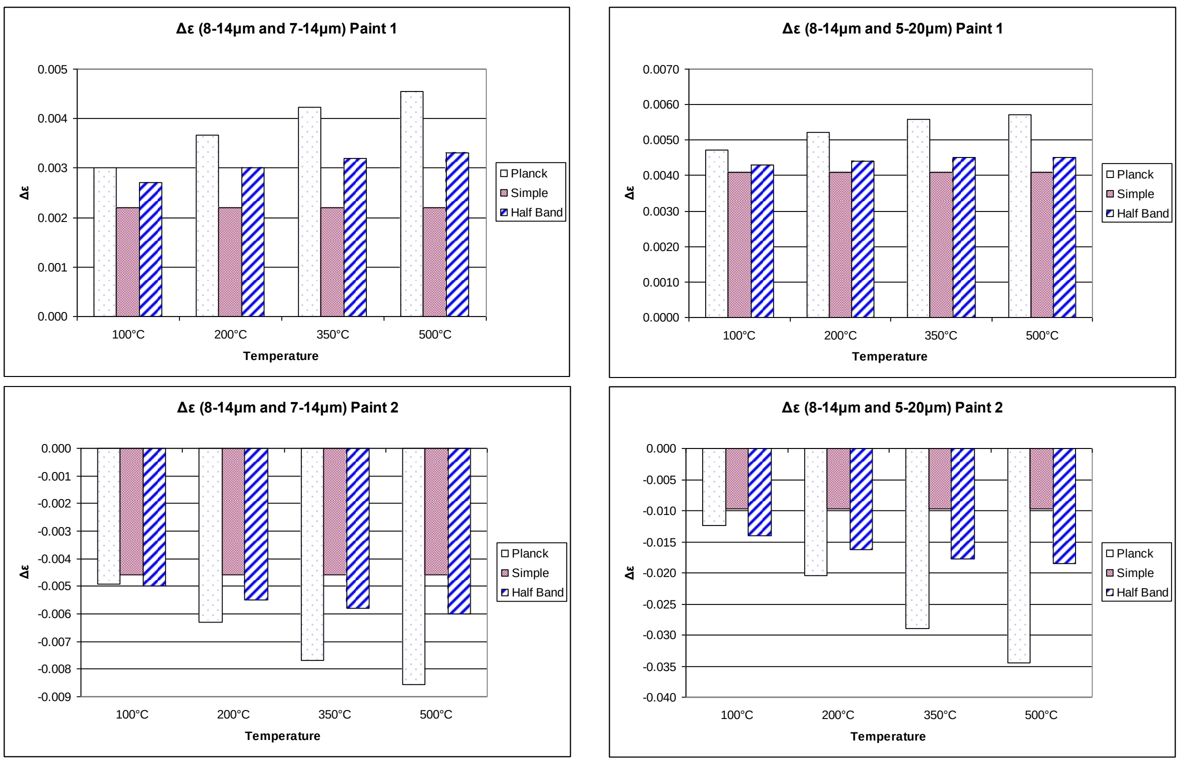

Figure 2. Difference between Planckian and Simple Average and Half Band Weighted Average

$$\Delta\varepsilon = \varepsilon_{PAINT1}(7-14\mu m) - \varepsilon_{PAINT1}(8-14\mu m) \qquad (6)$$

Table 2. Temperature Difference for 1% change in Emissivity (from ε=0.95)

T (°C)	8-14 µm ΔT/Δε (°C/%)	5-20 µm ΔT/Δε (°C/%)
100	0.64	0.60
200	1.32	1.16
350	2.36	1.98
500	3.51	2.90

Using the data from Figure 2 and Table 2, consider a measurement made at 350°C using an 8-14 µm instrument. If two different paints have an emissivity difference (Δε) of 0.004, this would translate into a measured temperature difference of about 0.94°C.

Considering the data in Figure 2 and Table 2, the half power method estimates effective emissivity better than the simple average. Both methods did well estimating emissivity differences between the 8-14 µm band and the 7-14 µm band. However, neither method did well when considering larger bandwidth differences such as was shown between the 8-14 µm band and the 5-20 µm band. This was especially true at higher temperatures.

6. Practical Experimentation

To verify this theory, practical experimentation was done. This experimentation involved the use of IR thermometers with the same specified bandwidth (8-14 µm) measuring both Paint 1 and Paint 2. It also involved measuring with an IR thermometer with a different specified bandwidth (5-20 µm). These instruments were used to measure two different surfaces.

6.1. Setup

For a validation of the theory discussed above, several flat plate IR calibrators painted with the two paints in Figure 1 were measured. A high-end 8-14µm IR thermometer was used to take a baseline measurement at four different temperatures. Then a number of handheld IR thermometers were used to make measurements on these surfaces. The IR thermometers' differences in temperature readout from the high-end IR thermometer's measurement were noted.

6.2. Uncertainties

The experimental uncertainty budget structure is shown in Table 3. The 'IR Thermometer (IRT) Measurement' uncertainty is a typical IR Thermometer uncertainty budget [2, 3] based on the following uncertainties: target noise, target display resolution, IRT readout resolution, IRT ambient temperature, IRT noise, IRT atmospheric losses, IRT angular displacement and IRT background temperature. The 'Radiometric Measurement' uncertainty is based on Fluke-Hart Scientific's 4181 uncertainty budget [4]. The 'Target Drift' uncertainty is based on historical data from 4181 calibrations. The 'FTIR Data' uncertainty is based on information from the provider of this testing.

Table 3.: Uncertainty Budget Elements

Uncertainty	Type
IR Thermometer Measurement	A
Radiometer Measurement	A
Target Drift	A
FTIR Data	B

The total expanded uncertainties for the experiment are shown in Table 4.

Table 4. Experimental Uncertainty

	IRT 1&2	IRT 3&4	IRT 5, 6 &7	IRT 8
	U	U	U	U
	(°C)	(°C)	(°C)	(°C)
100°C	0.381	0.308	0.338	0.298
200°C	0.400	0.387	0.570	0.621
350°C	0.568	1.024	1.211	1.167
500°C	1.111	1.770	2.463	1.808

6.3 Theoretical Values

Table 5 shows the theoretical emissivity differences between Paint 2 and Paint 1. This calculation was done using the data shown in Figure 1 and the equations (2) and (3). To use this for a comparison between the two paints the following example is given.

Two IR thermometers are used to measure Paints 1 and 2. One IR thermometer is an 8-14µm instrument and the second is a 7-14µm instrument. These instruments would measure the differences in emissivity of 0.013. Looking at Table 2, this translates into a measured temperature difference of approximately 4.6°C.

Table 5. Differences in Emissivity between Paint 2 and Paint 1

T	8-14µm Δε	7-14µm Δε	5-20µm Δε
100°C	+0.006	-0.002	-0.011
200°C	+0.006	-0.004	-0.019
350°C	+0.006	-0.006	-0.022
500°C	+0.006	-0.007	-0.034

6.4 Results

The results of the tests for the 8-14µm instruments are shown in Figure 3. The y-axis represents the difference in emissivity between measurements on Paint 1 and Paint 2. These differences are calculated from the differences in temperature readout. The error bars represent the combined expanded uncertainty (k=2) of the experiment. The horizontal lines represent the theoretical difference between in 8-14 µm band emissivity and 7-14 µm band emissivity.

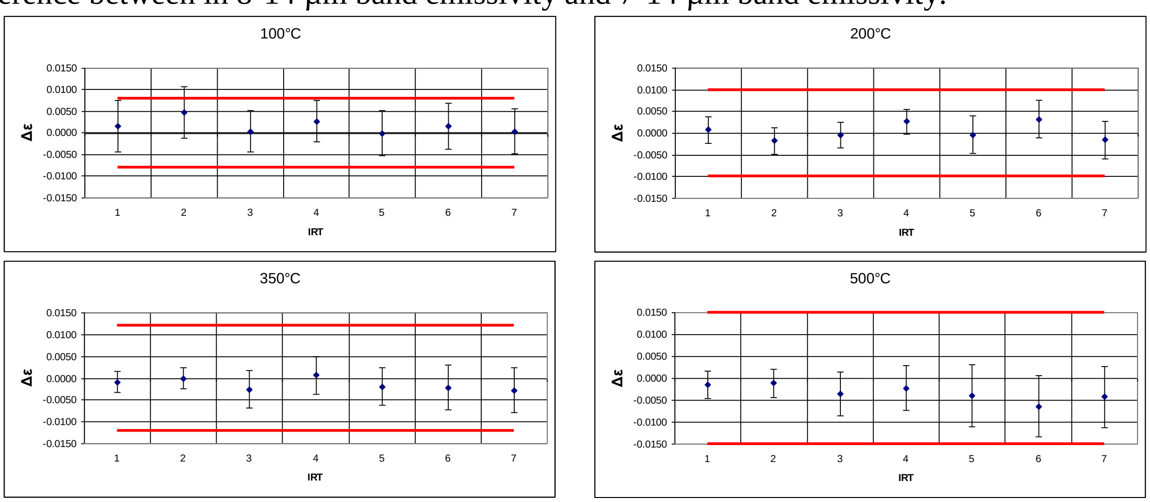

Figure 3. Results of 8-14µm testing

Figure 4 shows the results of the 5-20 µm tests. The solid lines represent the theoretical values described by (2) and (3) and the data from Figure 1. The dots represent measured data. The error bars represent the combined expanded uncertainty for this experiment.

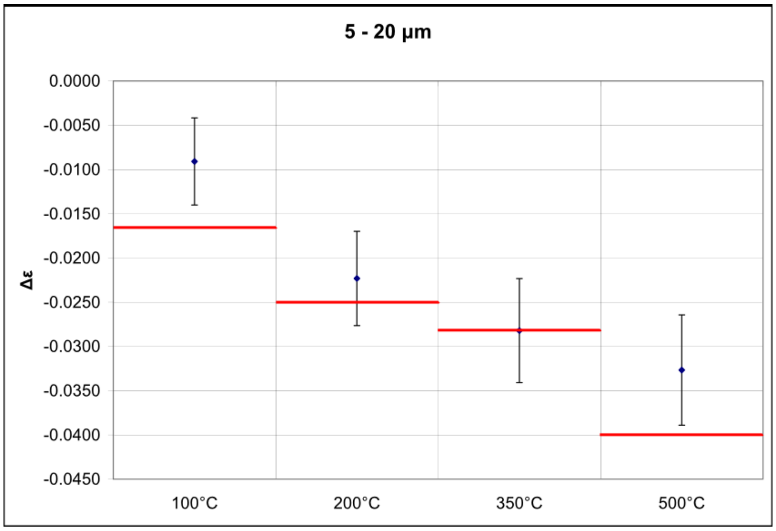

Figure 4. Results of 5-20 µm testing

6.5 Discussion

The differences from the transfer standard in the 8-14 µm data was for the most part within the experimental uncertainties. It is also within the theoretical differences between the emissivity of the 8-14µm band and the 7-14µm band. This suggests that when computing uncertainty for these handheld devices, assuming a bandwidth variance of 1 µm is valid. It also shows that this uncertainty is not significant when compared to the overall uncertainty budget of these devices.

The 5-20 µm data was close to theory. The 100 °C and 500 °C data were outside of the combined expanded uncertainty of the experiment. This suggests that there may be some additional bandwidth variance in the 5-20 µm instrument. It does show, however, that the trend predicted by the FTIR measurements is valid.

7. Conclusion

From the theoretical data discussed in this paper, taking a simple average of emissivity is a valid way to calculate emissivity differences when small differences in bandwidth or spectral response are considered, such as the differences shown between the 8-14 µm band and the 7-14 µm band. However, when considering large differences in spectral bandwidth such as shown between the 8-14µm band and the 5-20µm band, neither of the averaging techniques accurately estimate this difference.

The practical experimentation confirmed that the theoretical Planckian averaged emissivity (based on FTIR measurements) is valid for small differences in bandwidth. The practical data for the large difference (shown in Figure 4) shows some deviation from the experimental uncertainty. This is likely due to one of two factors. First, the modeling used in this paper considers only a flatband spectral response for the IR thermometer. In reality, the IR thermometer likely does not have a flatband spectral response. Second, the variability in bandwidth limits for the 5-20µm device may be larger than expected. This would be very apparent at the lower limit of this band on Paint 2 as shown in Figure 1.

The practical experimentation also showed that considering a bandwidth variance of 1 µm is sufficient for 8-14 µm devices. This data suggests that these two combined methods (FTIR data and using a small difference in IR thermometer bandwidth variability), is a valid method for calculating temperature uncertainty due to bandwidth differences. If the two measuring devices have a larger bandwidth difference, much more care must be taken to insure accurate emissivity is calculated.

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