A Spectro-Radiometric Calibration Station for Blackbody Sources

Joseph D. LaVeigne*[a], Sean Strickland[a], Charles Petkovich[a], Len Kamlet[a]
[a]Santa Barbara Infrared, 30 S Calle Cesar Chavez, Santa Barbara, CA, USA 93103

ABSTRACT

Accurate radiometric calibration of IR sources can be challenging, but is required for advanced sensors being used today. Santa Barbara Infrared has developed a new test facility to provide spectro-radiometric calibration of extended area sources. The station comprises a Bruker Invenio Fourier transform infrared spectrometer or FTIR, a NIST-traceable, high-emissivity DB-04 blackbody reference and an automated stage for switching between the reference source and unit under test. The system uses a series of differential measurements to perform the radiometric calibration. The first output of the calibration is a spectral emissivity that can be used to calculate output radiance based on the temperature as measured in the well of the blackbody source. The second output of the calibration is a derived gradient term allowing the calculation of the temperature of the surface of the source based on the temperature of the thermometric measurement well and the temperature of the ambient environment. The additional gradient term allows for improved radiometric accuracy when operating at source and environment temperatures different from those at which the source was calibrated.

Keywords: Radiometric calibration, blackbody, infrared testing, emissivity

1. INTRODUCTION

Radiometric calibration and testing are becoming more common in infrared sensor testing. As detector sensitivity increases, the radiometric accuracy required for test and validation becomes more challenging. While absolute thermometric calibrations with mK scale accuracy are readily available, radiometric calibration with accuracy on the order of 1% or better remains difficult. To address this need, SBIR developed a new test capability to provide spectro-radiometric calibration over the wavelength range of 3-14um, covering the bands of interest for most thermal imaging sensors. The system is similar to the one described in Reference [1], and is described in detail below.

2. EXPERIMENTAL SETUP

2.1 Test Station Components

Figure 1 shows a schematic view of the test station. The NIST-traceable reference and the unit under test are mounted to a linear stage that switches between the two positions. Located between the FTIR and the blackbody being measured is a flexible shroud used to purge that volume with dry, gaseous nitrogen to reduce atmospheric absorption from CO2 and water vapor. The FTIR also uses a nitrogen purge for the same purpose. The Invenio has multiple detector options including an uncooled lanthanum-doped deuterium triglycine sulphate (La-DTGS) detector and a liquid nitrogen (LN2) cooled photoconductive mercury cadmium telluride (MCT) detector. The uncooled DTGS detector was used for these calibrations. While the DTGS detector is less sensitive than the cooled MCT, the fact that it is uncooled makes long-period measurements much more practical, as the detector does not need periodic refills of LN2. That type of photoconductive MCT also has known issues with nonlinear behavior when used in an FTIR application that can introduce spectral artifacts into the measurements. There have been efforts to compensate for these nonlinearities (see for example [2], [3]). However, the simplicity of the more linear DTGS along with its ease of use, particularly the fact that it does not require a cryogen, makes it the preferred detector.

*jlaveigne@sbir.com; phone 1 805 965 3669; www.sbir.com

Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXXIV, edited by
Gerald C. Holst, David P. Haefner, Proc. of SPIE Vol. 12533, 125330Y

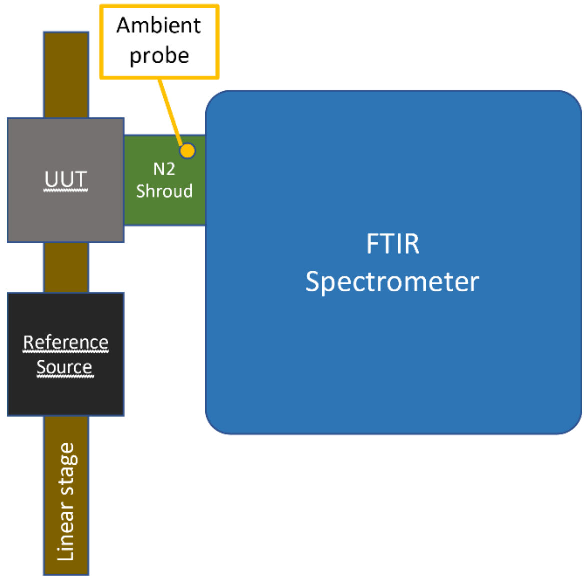

Figure 1 Block diagram of the radiometric calibration station.

2.2 Test Methodology

The lower sensitivity of the DTGS does make achieving a high signal to noise measurement more challenging. This is overcome by taking a large number of measurements and averaging them to improve the accuracy. FTIR systems routinely collect and average multiple scans of an interferogram to improve SNR. A large number of measurements also takes a significant amount of time and can lead to the possibility of long-term instrument drift, limiting its overall accuracy. In order to minimize the effects of drift, measurements of the reference source and the unit under test are interlaced with scans at ambient temperature collected before and after each measurement at the calibration temperature.

Figure 2 shows an illustration of how a typical measurement cycle is performed. Each source changes temperature to the next setting while the opposite source is being measured to minimize the time between measurements. A typical calibration run performs this cycle 16 times and takes 4-5 hours. Longer runs with more cycles may be used when calibrating at lower temperatures.

After the radiance difference between the two sources is measured, the emissivity is calculated by comparing the UUT to the NIST-traceable reference.

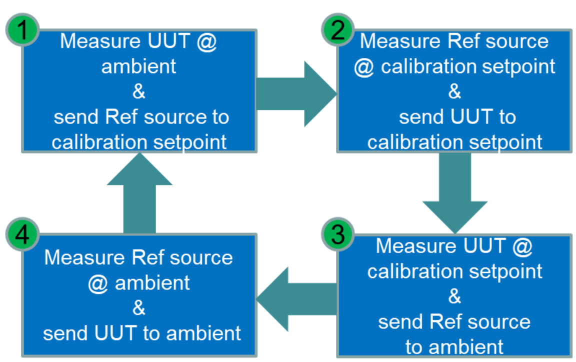

Figure 2 Interlaced measurement flow used to reduce the effects of long-term drift in the FTIR.

2.3 Temperature gradient

One challenge when using extended area blackbodies is that the temperature is usually measured with a probe in a well in the middle of the source, but the emitted radiance is determined by the temperature of the surface. Temperature gradients between the well and the surface are typically on the order of 1% of the temperature difference between the well and the outside environment. If the surface temperature is taken to be the well temperature, a radiance error can be introduced. One way to estimate the gradient is to make multiple measurements over a range of temperatures, however, this method can be time consuming and difficult as it relies on excellent long-term stability of the instrument being used in the calibration. Another method is to use the spectral variation of the Planck function to derive the well-to-surface gradient. If an initial estimate of the emissivity of the unit under test (UUT) is known, for instance from total hemispherical reflectance measurements of a test coupon with the same coating, then that initial measurement can be used as a starting point for the gradient derivation. The algorithm used in this research takes this approach and derives the gradient by performing a least-squares fit of the spectral radiance with two parameters: the thermal gradient of the blackbody and a linear scale factor of the initial spectral reflectance of the surface:

Equation (1) $$Error = \sum_{\lambda}\left([1 - A \cdot R(\lambda)] - \varepsilon(\lambda)\right)^2$$

Where

Equation (2) $$\varepsilon(\lambda) = \frac{L_S(\lambda, T_{Set}) - L_A(\lambda, T_{Ambient})}{L_{Planck}(\lambda, T_{Surface}) - L_{Planck}(\lambda, T_{Ambient})}$$

Where L_S and L_A are the measured spectral radiance at the calibration set point and ambient temperatures and L_{Planck} is the ideal spectral radiance at the given temperature (***surface*** or ambient) [4]:

Equation (3) $$L_{Planck}(\lambda, T) = \frac{2hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)}$$ [4]

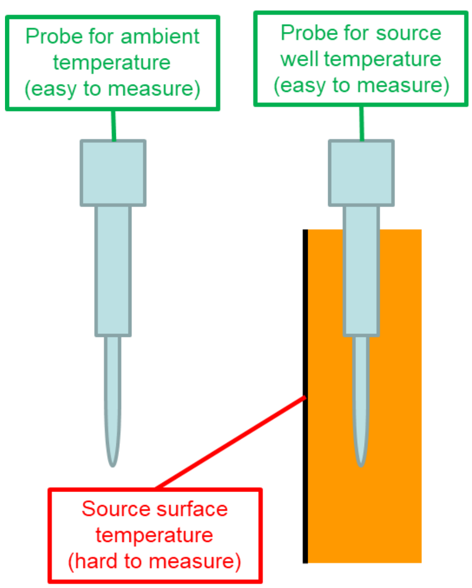

Figure 3 Diagram of the gradient between the source surface and the source temperature measurement well.

The temperature difference between the surface and the well of the blackbody is assumed to be proportional to the temperature difference between the well and the ambient environment. The gradient term is the constant that defines that proportion:

Equation (4) $$T_{surface} = T_{well} - grad * (T_{well} - T_{surface})$$

The gradient derivation can be combined to use multiple temperatures if the initial emissivity estimate does not show significant temperature dependence. This leads to a consistent gradient and emissivity that is valid over a range of temperatures.

2.4 Temperature gradient vs. effective emissivity

One question that may be raised is: "Why bother with the gradient instead of just treating everything as an effective emissivity?" The answer is that while the emitted radiance difference due to a temperature gradient for small temperature differences near ambient does behave much like emissivity, the reflected portion does not and the nonlinear Planck relationship to temperature can lead to errors as the source temperature starts to deviate significantly from that of the ambient environment. Consider the following example where an idealized source is modeled with spectrally flat emissivity of 99.5% and a 1% gradient between the well temperature and the ambient temperature. In such an instance, a source set to 125C in a 25C environment would have a surface temperature 1% of the source-ambient difference, or 124C. Using Equation Equation (2)

Equation (4), we can derive the following relationship for the effective emissivity.

Equation (5) $$\varepsilon_{eff}(\lambda) = \frac{\varepsilon_{phys} \cdot [L_{Planck}(\lambda, T_{Surface}) - L_{Planck}(\lambda, T_{Ambient})]}{[L_{Planck}(\lambda, T_{Well}) - L_{Planck}(\lambda, T_{Ambient})]}$$

Figure 4 shows effective emissivity calculations for the system described above for temperatures ranging from 26C to 175C. At 26C, the effective emissivity is close to 98.5% across the MWIR and LWIR bands, making it a reasonable assumption for small temperature differences near ambient. As the temperature difference gets larger, the effective emissivity at shorter wavelengths starts to change significantly. At 175C, the MWIR (3-5um) effective emissivity is approximately 2% different than that at 26C. Many calibrations are performed at high temperatures in order to improve SNR. If such a procedure were used in the case above, and the unit were calibrated at 175C, then a 2% error would be expected for measurements near ambient temperatures. Furthermore, if the system were used at an ambient temperature significantly different from that at which it was calibrated, then errors would be introduced there as well. Deriving the gradient more closely follows the actual physical behavior of the system and provides a more flexible calibration that allows a blackbody to be used over a wide range of source and ambient temperatures with a high degree of confidence in the radiometry.

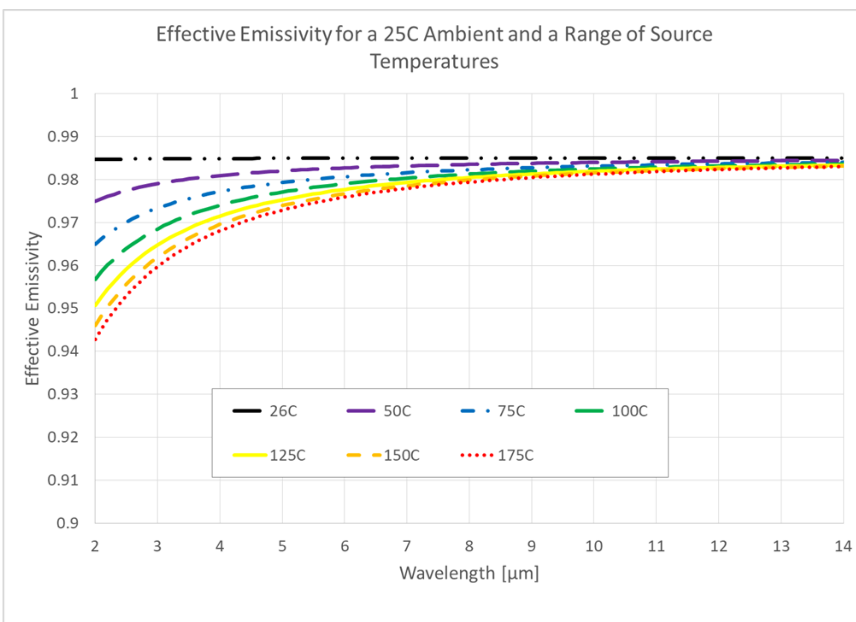

Figure 4 Modeled effective emissivity of a source with a 1% gradient between the thermometric control probe well and the radiating surface. The effective emissivity at shorter wavelengths at high temperatures deviates from that at lower temperatures. If a source is calibrated at higher temperatures and that effective emissivity is used at lower temperatures, the resulting errors could be significant, approaching 2% in the MWIR band for a source calibrated at 175C and then used 1C over an ambient of 25C.

3. RESULTS

Results for two blackbodies that have been calibrated using this method are provided below. The first is a SBIR, high-emissivity blackbody with a VANTABLACK S-IR coating. The second is an SBIR blackbody with a standard coating. For both blackbodies, calibration data was collected at 175C, 150C, 125C, 100C, and 75C. As described above, data from all of the temperatures was analyzed together using the same scale factor for the initial reflectance to derive a single gradient term that applied to all temperatures. Once this gradient was derived, it was used to calculate the surface temperature for each calibration set point. This surface temperature was then used to calculate emissivity at each calibration temperature. Figure 5 through Figure 8 show the results of the calibrations over the range of temperatures for the high-emissivity and standard sources. The features around 4.3 um and between 5um and 8um are due to CO2 and H2O absorption in those respective bands. The dry nitrogen source available for this testing did not provide a consistent flow for the duration of the tests, resulting in the artifacts mentioned above. Facility improvements were being implemented at the time of this paper which are expected to reduce the absorption artifacts.

3.1 Calibration of a high-emissivity source

The first practical implementation of the system at SBIR was to perform a transfer to a secondary source for day-to-day use within the SBIR facility. This secondary source (a VANTABLACK S-IR-coated SBIR Infinity DB-04 blackbody) provides a traceable radiometric reference for frequent use that can be moved from station to station without the risk of accidental damage to the primary. The blackbody calibration was performed at 175C, 150C, 125C and 100C. Multiple temperatures were measured to test the estimation of the gradient. Unless the source has a significant temperature-dependent change in emissivity, only a single measurement would typically be needed. This would usually be performed at a high temperature to maximize the radiance thus improving overall SNR, particularly for shorter wavelengths between 3 and 4 um.

Figure 5 shows the results of the 175C calibration. The plots include the initial emissivity from total hemispherical reflectance (THR) measurements and the derived gradient is noted on the plot as well. Figure 6 shows a demonstration of the sensitivity of using spectral measurements to derive the gradient. In this figure, emissivity plots of the optimal gradient along with plots for gradients 0.1% higher and lower than the derived value are shown, along with a plot for a gradient of zero. The latter demonstrates why the gradient must be understood in order to achieve accurate, convenient radiometry using an extended area source. Without the gradient, errors can be introduced when a blackbody is used at a different set point and/or different environmental temperature. Proper use of the gradient can improve overall accuracy of radiometry using extended area sources.

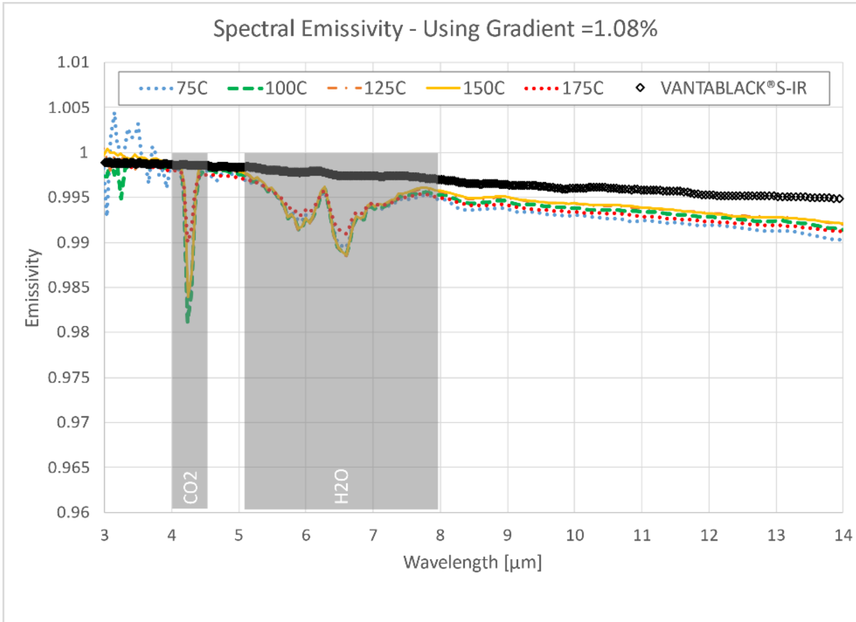

Figure 5 Calibration results for SBIR high-emissivity blackbody.

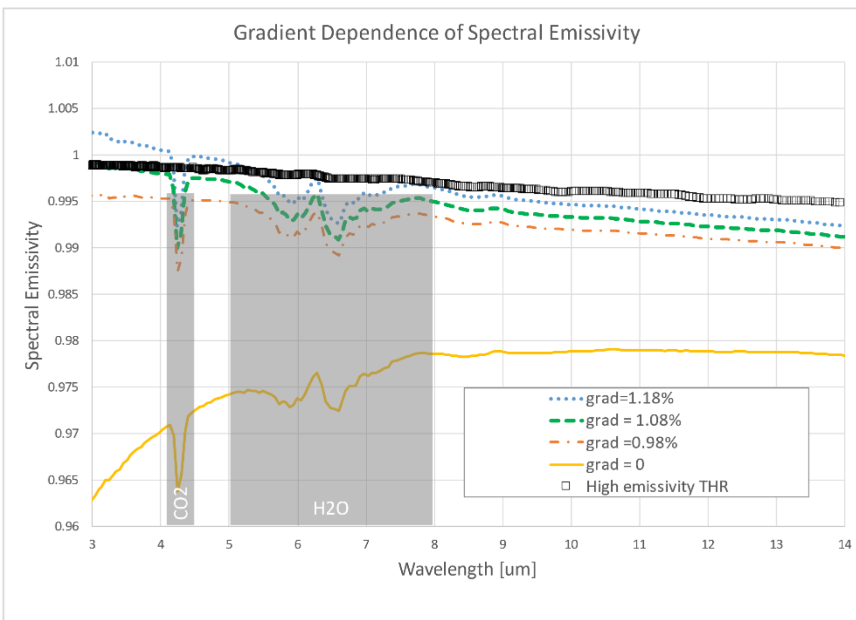

Figure 6 Plots of 175C emissivity derived with a range of gradients. The shorter wavelengths are quite sensitive to the gradient, showing a significant change in emissivity with just a 0.1% change in gradient.

3.2 Calibration of a standard source

The same test performed in Section 3.1 was repeated on a source with a more standard painted surface using the same interlaced measurements of the sources with interspersed measurements of an ambient temperature surface. Figure 7 shows the resulting spectral emissivity of the standard blackbody compared to that derived from a THR measurement of the same coating. The measured emissivity is higher than that of the THR measurement, which is not necessarily inconsistent because the FTIR measurement is directional while the THR is an average of the total hemispherical reflectance. For the purposes of radiometry, the former is considered to be more representative of how the blackbody source is likely to be used and thus considered the more useful quantity under most use cases.

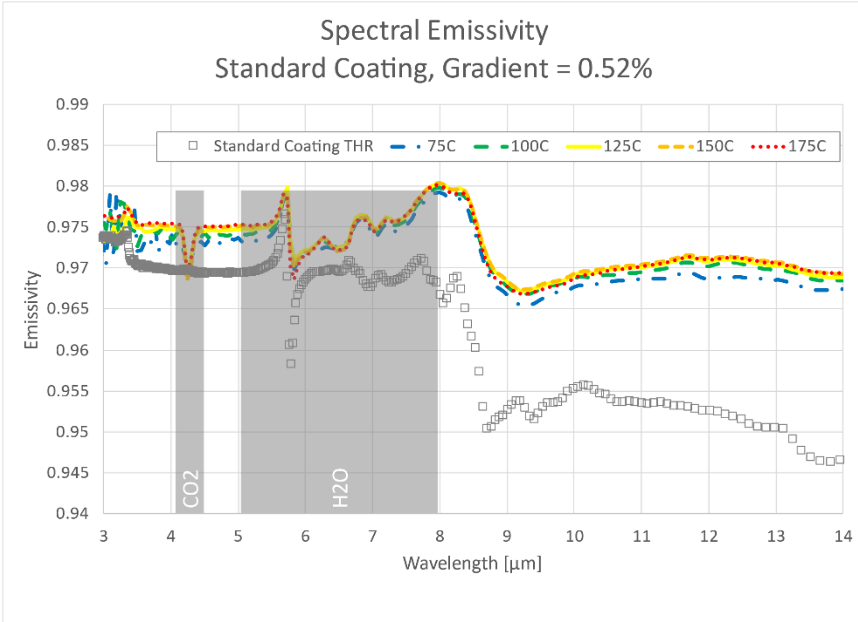

Figure 7 Calibrated spectral emissivity for a source with a standard coating.

4. DISCUSSION

The goal of radiometric calibration is to provide accurate, traceable radiance from a source at any given temperature. As shown in the modeled response in Section 2.4, this can be challenging for infrared sources when the ambient environment contributes through reflected radiance or other losses, such as convection, which can alter the source's emitting surface temperature. The calibration data collected for the two examples above was processed to derive a gradient and spectral emissivity terms, with the goal of providing a single, consistent spectral emissivity for all temperatures and a gradient term that best accounts for the real thermal losses that occur at the surface of a source. The same data can also be processed to calculate the effective emissivity at each temperature assuming zero gradient between the probe well of the source and its surface. Figure 8 plots the effective emissivity of the 75C – 175C calibration data of the high-emissivity source. As expected, the effective emissivity varies with temperature in a similar fashion to the idealized model discussed in Section 2.4. While the gradient and spectral emissivity results may be more convenient and practical to use in most cases, it should be recognized that using an effective emissivity is a valid approach when the use case conditions closely match the calibration conditions. For this reason, we recommend providing both results and leaving the decision of which to use up the individual investigator, providing them with the flexibility to choose which path to follow to best suit their needs.

One clear advantage of this calibration technique is that it requires measurement only at a single [set point & ambient] temperature condition, which then can be applied to any combination of set point and ambient conditions with minimal error introduced. The set point for surface temperature can therefore be set to the maximum temperature of the blackbody in order to maximize signal to noise, reducing measurement uncertainty and measurement collection time. And the model provided can allow the end user to select their applicable wavelength range and operating conditions, based their test requirements.

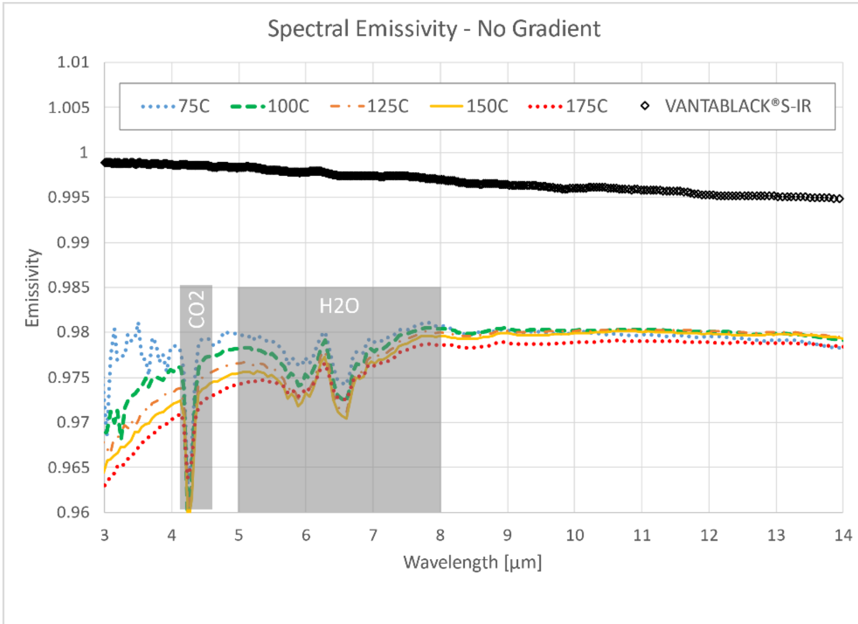

Figure 8 Calibration results from the high-emissivity blackbody using an effective emissivity assumption with zero gradient between the source well and source surface.

REFERENCES

[1] S. N. Mekhontsev, V. B. Khromchenko and L. M. Hanssen, "NIST radiance temperature and infrared spectral radiance scales at near-ambient temperatures.," *International Journal of Thermophysics*, pp. 1026-1040, 2008.

[2] L. Shao and P. R. Griffiths, "Correcting Nonlinear Response of Mercury Cadmium Telluride Detectors in Open Path Fourier Transform Infrared Spectrometry," *Analytical Chemistry*, vol. 80, pp. 5219-5224, 2008.

[3] R. Richardson, Y. H. and P. Griffiths, "Effects of Detector Nonlinearity on Spectra Measured on Three Commercial FT-IR Spectrometers," *Applied Spectroscopy*, pp. 572-578, 1998.

[4] G. Boreman and E. Dereniak, Infrared Detectors and Systems, New York: John Wiley & Sons, 1996, p. 66.