An Extended Area Blackbody for Radiometric Calibration

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ABSTRACT

SBIR is developing an enhanced blackbody for improved radiometric testing. The main feature of the blackbody is an improved coating with higher emissivity than the standard coating used. Comparative measurements of the standard and improved coatings are reported, including reflectance. The coatings were also tested with infrared imagers and a broadband emissivity estimate derived from the imagery data. In addition, a control algorithm for constant slew rate has been implemented, primarily for use in minimum resolvable temperature measurements. The system was tested over a range of slew rates from 0.05 K/min to 10 K/min and its performance reported.

Keywords: Blackbody, Radiometric calibration, Infrared, high emissivity, EO-IR Testing

1. INTRODUCTION

Extended area blackbodies are commonly used for testing infrared cameras and other thermal detection devices. Blackbodies are used as thermal sources to provide a desired radiance or apparent temperature to a device under test or to illuminate a target with a known radiance or apparent temperature or to provide a desired temperature difference between the features in a target.

For an ideal blackbody with an emissivity of 1, the only parameter required to calculate the radiance of the source is the temperature of the blackbody. For a system with non-unit emissivity, other factors must be considered in order to produce a desired radiance, including the emissivity and the radiance of the environment onto the surface of the source. Another factor to be considered is that the temperature of the surface of the source is needed, but the temperature may not be measured on the blackbody surface. Also, for extended area blackbodies, the temperature is typically measured in only one place so the uniformity of the surface temperature must also be considered. An ideal blackbody would have a unity emissivity, and the same temperature across the entire surface as that of the point where the temperature is measured.

Real blackbodies do not have unity emissivity, or perfectly uniform, accurately known surface temperatures. While cavity blackbodies can have effective emissivities approaching unity, they are typically large, slow to respond, and may not be practical if an application requires a large area source. In such cases, an extended area blackbody is required, and the effects of its deviation from ideal characteristics must somehow be compensated for in some fashion.

In addition to the enhanced coating in development, SBIR has also implemented a constant slew rate capability in its Infinity line of extended area blackbodies. Performance data over a range of slew rates is presented as well.

2. RADIOMETRY WITH A NON-IDEAL REFERENCE

2.1 Radiometric Theory

For calibration purposes, the desired output of a radiometric reference is a known absolute radiance. Thermal radiation from an ideal source is governed by Planck's Equation[1]:

$$L_{ideal}(\lambda, T) = \frac{2hc^2}{\lambda^5\left(e^{hc/\lambda kT}-1\right)},$$

Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXIV, edited by
Gerald C. Holst, Keith A. Krapels, Proc. of SPIE Vol. 8706, 870609 · © 2013 SPIE
CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2016251

Where h is Planck's constant, k is the Boltzman constant, c the speed of light, T the absolute temperature and l the wavelength. For a given body, the total radiation from the surface is the sum of the emitted, reflected and transmitted radiation:

$$L_{total} = L_{emitted} + L_{transmitted} + L_{reflected}$$

For a non-ideal surface, the emitted portion is scaled by its emissivity at a given wavelength:

$$L_{real}(\lambda, T) = \frac{\varepsilon(\lambda) 2hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)}$$

Assuming transmission is zero, the spectral reflectance of a surface can be written as $(1 - \varepsilon(\lambda))$ and the reflected radiance then becomes:

$$L_{reflected}(\lambda) = L_{ambient}(\lambda)(1 - \varepsilon(\lambda))$$

2.2 Radiometry using a non-ideal reference

Accuracy of a reference is an important part of any precise measurement. When performing radiometric measurements, the radiance of the calibration surface must be well known. An extended area blackbody may be used as a radiometric reference, with proper management[2,3]. The focus of this management is the reduced radiance due to an emissivity less than unity and the reflected radiance due to the same root cause. The reduced emitted radiance is easily to compensate by scaling the radiance by the emissivity of the source. For instance, if relative radiance is the key goal of a measurement, a calibration with two points collected close enough in time that the ambient conditions have not changed appreciably can serve to produce acceptable results. For the relative measurement, the reflected portion of the radiance of the reference does not matter. However, for absolute radiance measurements, or in cases where the ambient conditions change appreciably between measurements, the reflected radiance must be considered and doing so can be complicated. The basic problem with ambient compensation is the limited knowledge of the ambient environment. A probe can be used to measure the ambient temperature, which may be adequate in very controlled conditions, but often this is not the case and there is some error in the estimate of the effective ambient temperature. If a correction based on ambient temperature is being used, the error in the estimate of the ambient temperature can lead to errors in apparent temperature. Figure 1 shows the calculated error in apparent temperature if a one degree error is made in an ambient of 25C. At the real ambient of 25C, the error is about 30mK. In most cases this error is small, but it can be significant at low temperatures and may be significant relative to the ambient correction in cases where small variations from ambient are being measured. A surface emissivity of 0.995 would reduce this effect by a factor of 6, making measurements much more tolerable of imperfect knowledge of the ambient environment and its variations.

3. BLACKBODY PERFORMANCE

SBIR has developed a high emissivity coating process which has been applied to several blackbodies in order to test its radiometric performance. The coating and blackbodies have undergone a series of tests including reflectance measurements, and tests with Long Wave Infrared (LWIR) and Mid-Wave Infrared (MWIR) imagers. Separately, a constant slew rate control algorithm was developed for minimum resolvable temperature (MRT) testing and other applications that require a controlled rate change of temperature. Results and discussion of both are presented below.

3.1 Spectral measurements

Spectral reflectance measurements were made of two high emissivity coating samples as well as samples of the standard coating. Hemispherical reflectance was measured using a Surface Optics Coporation Hemispherical Reflectometer based on a Nicolet Fourier transform infrared spectrometer (FTIR) and specular reflectance measurements were conducted using a Bruker 113 FTIR. The hemispherical measurements used a calibrated diffuse gold reference and produced reflectance with an estimated absolute accuracy of 1%. The Bruker measurements used a specular reflectance stage with a diffuse aluminum reference. The Bruker measurements were initially conducted to investigate the relative performance at longer wavelengths and do not have an absolute reference. The reflectance spectra for both instruments are shown in Figure 2. The reflectance measurements of the two instruments are in good agreement for the standard coating. The Bruker spectra show the same features near 5.75 and 8.5 microns. However, the Bruker and hemispherical measurements of the high emissivity samples did not agree at wavelengths over 8 microns. The hemispherical data shows a significant rise in reflectance at from 9 to 13 microns, which is not reflected in the Bruker measurements. This disagreement will be discussed further after the imagery data is presented.

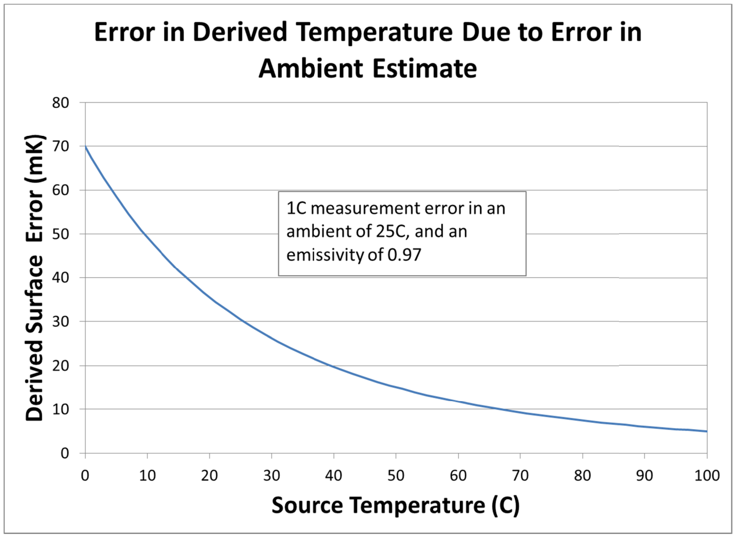

Figure 1. Error in derived apparent temperature.

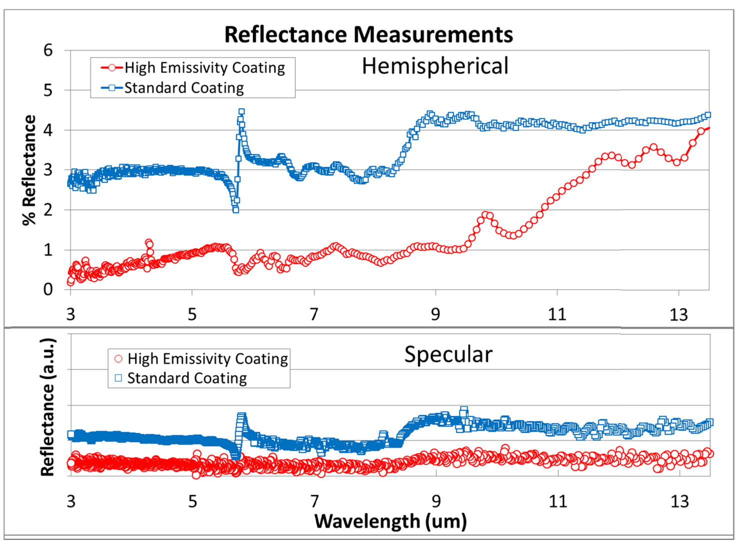

Figure 2. Spectral Measurements from two different spectrometers. The in the upper pane were collected with a Surface Optics Hemispherical Reflectometer. The spectra in the lower pane were collected with a Bruker 113 FTIR spectrometer. The standard coating measurements are in good agreement, but the high emissivity coating spectra do not show similar spectra, especially at wavelengths longer than 8 microns.

3.2 Imagery Tests

Two blackbodies were coated with the standard coating on one side of the blackbody and the high emissivity coating on the other. This allowed simultaneous collection of imagery from both coatings removing effects from temporal changes in the ambient environment or variations in camera response. In addition, a blackbody with standard coatings was measured as well. This blackbody was modified to have several holes placed in the surface to produce a set of small cavities with near unity emissivity as reference points. The blackbodies were then tested using two infrared cameras: An IRCameras IRC800 MWIR imager and a FLIR Photon 640 microbolometer. Both tests involved measuring the two blackbodies over a range of temperatures, averaging several hundred frames to reduce temporal noise and average out slight variations due to air currents near the blackbody surface. The cameras were calibrated using a blackbody with a standard coating placed close enough to the imager to be out of focus and to fully fill the sensors field of view with the center portion of the blackbody. Figure 3 shows an image of both blackbodies collected at a set point of 60C. They are very representative of all of the images collected with both cameras. The two blackbodies were measured in the same position and were therefore not measured simultaneously. The standard coating average was used as a reference point between the data sets. The line through the two images is the position of the temperature profile shown in Figure 4. The profile measurement in particular gives a good indication of how close the radiance of the high emissivity coating is to that of the cavities.

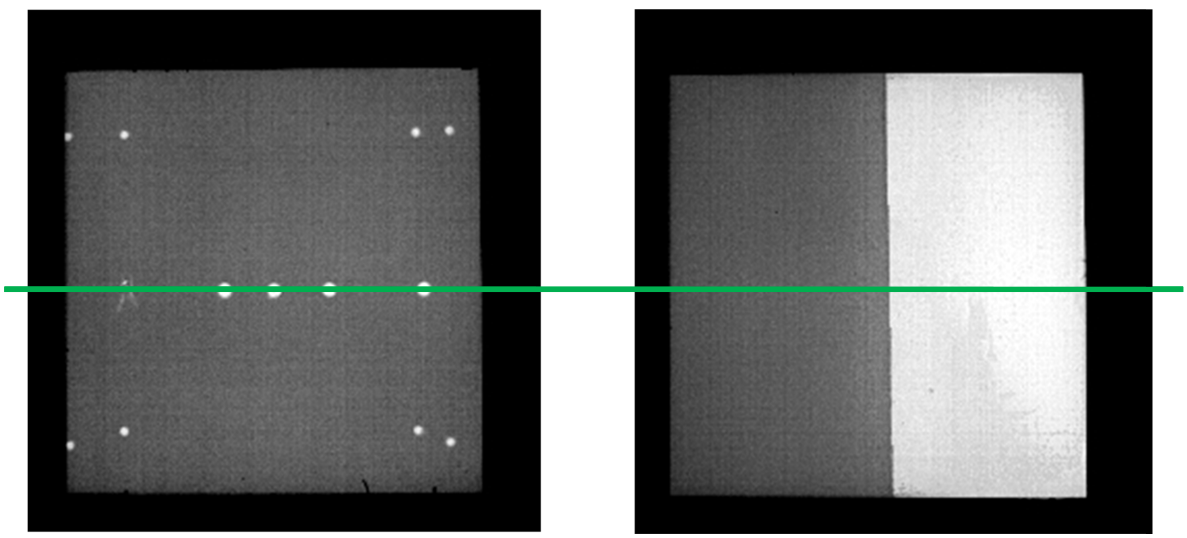

Figure 3. Imagery of blackbodies used in testing the high emissivity coating. The left image is a blackbody with standard coatings and several holes placed in the surface to create small cavities with near unity emissivity. The right image is a blackbody with the standard coating on the left and the high emissivity coating on the right. The green line is the location of the temperature profile shown in Figure 4.

Three regions of interest were selected to be averaged: One in the area where the standard coatings of the two blackbodies overlapped, a second that comprised the center of the cavities in the modified blackbody with standard coatings and a third in a neighboring area where the high emissivity coating was applied. Some long period drift is known to occur, especially in the microbolometer, as the cameras and optics change with the ambient environment. In order reduce these effects, the difference between the standard coating and high emissivity area (cavities in the one black body and new coating in the other) was taken and used for further analysis.

When investigating small temperature differences, such as those shown in the profile from Figure 4, it is important to keep in mind that the thermometric temperature of the surface of the blackbody may not be the same as that in the center of the source plate, where the thermometric probe is located. The blackbody with the small cavities provides a way to estimate the gradient between the surface and the blackbody center. The holes placed in the standard coating blackbody were drilled to the same depth as the thermometric probe. The change in radiance due to emissivity will follow a different curve than that due to a difference between the measured and actual surface temperature. The effect is more pronounced in the MWIR region for the ambient temperatures near 25C in the data collected. The emissivity of the standard coating has been measured numerous times and is fairly well known to be 0.97 in the MWIR region of the spectrum. Assuming this value for the emissivity, a temperature gradient can be extracted from the data collected based on the difference between the surface and cavity radiance. Figure 5 shows the measured differences of the standard coating and the cavity and high emissivity coating extracted from the regions of interest in the MWIR data. The dotted line gives a fit to the data assuming a cavity emissivity of 1 and a standard coating of 0.97. The solid line is a fit with the same emissivity and a gradient of 0.0025 times the difference between the ambient and thermometric well temperature. This value is reasonably consistent with the thickness and thermal conductivity of the standard coating. The high emissivity coating has not had its conductivity measured, but is thinner than the standard coating and a priori value of 0.001 was assumed for its thermal gradient. The fit to the MWIR high emissivity coating, shown by the dashed line in Figure 5 gives an emissivity of 0.999.

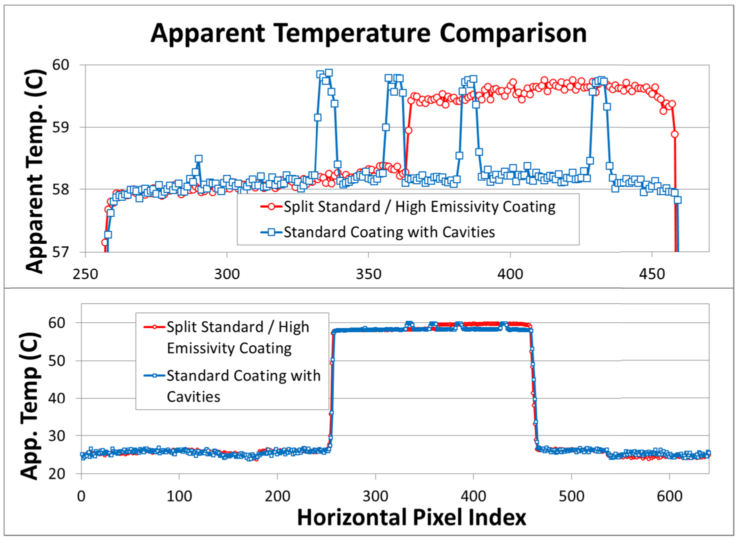

Figure 4. Temperature profile of blackbodies used for testing. The location of the profiles is shown in Figure 3. Note that the high emissivity coating has an apparent temperature very close to that of the cavities placed in the blackbody with a complete standard coating.

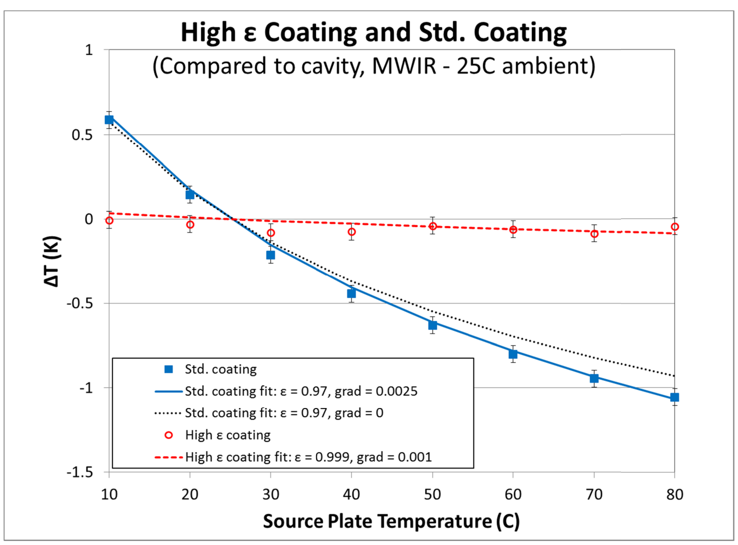

Figure 5. MWIR apparent temperature differences between the standard and high emissivity coatings relative to the center of the cavities in the standard coating source plate, along with fits to that data. The dotted line is a theoretical curve for the standard coating using the measured value of 0.97 as the emissivity.

The LWIR imagery was processed in a fashion similar to that of the MWIR. The LWIR data was more variable than the MWIR. That coupled with the reduced separation between gradient and emissivity in the LWIR and the lower LWIR emissivity of the standard coating, made an independent derivation of the gradient impractical. For consistency, the gradient term extracted from the MWIR data was used in both coatings and an emissivity fit for each. The data and fits are shown in Figure 6. The fit to the standard coating data produced an emissivity of 0.958, in good agreement with that of the hemispherical data. The fit to the high emissivity coating produced an emissivity estimate of 0.995. This value is not in agreement with the hemispherical data which would produce an average emissivity of 0.98 over the spectral response range of the microbolometer. However, this value is consistent with the small rise in reflectance shown in the reflectance data collected with the Bruker FTIR.

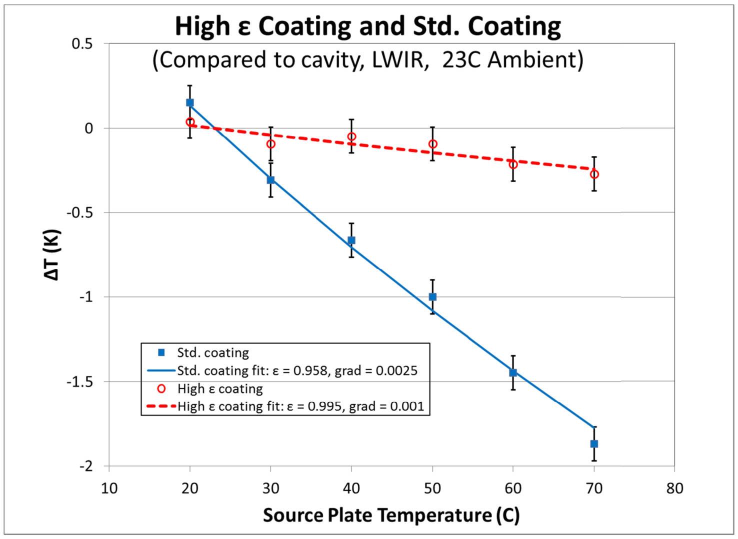

Figure 6. LWIR apparent temperature differences between the standard and high emissivity coatings relative to the center of the cavities in the standard coating source plate, along with fits to that data.

3.3 Emissivity Discussion

The emissivity estimates extracted for the high emissivity coating are rather remarkable, especially those from the MWIR data. The hemispherical reflectance data yields values that are within the estimated accuracy of zero in that band. The cavities provide an approximation of an ideal source, but without a known reference with an emissivity accurate to .001, an emissivity of 0.999 cannot be claimed in good faith. That said, the differences between the standard coating and cavity radiance are very close to their expected values, giving weight to the near unity estimate of the cavity emissivity. The LWIR data shows more variation than the MWIR. This is attributed to both the lower sensitivity of the camera and its greater preclusion toward drift with the environment. The LWIR imagery data is not consistent with the measured hemispherical reflectance data. The data collected with the Bruker FTIR does not show a similar feature as seen in the LWIR hemispherical reflectance. This may be due to an unknown variation in the samples. Unfortunately, the physical differences between the two samples make it impractical for one to be measured in the other spectrometer and neither spectrometer can be easily used to measure one of the full sized source plates. The two different samples were prepared at different times so the variation may be due to an unknown process variation. The discrepancy with be further investigated as the coating development progresses. Given the relative agreement between the Bruker and imagery data, the broadband emissivity estimates from the imagery data are assumed to be correct. Given the incomplete knowledge of the cavity emissivity, it is prudent to limit the emissivity claim for the new coating to >0.99 until further measurements can be made with a traceable reference.

3.4 Application to targets

Targets are also an area of concern in radiometric testing and can benefit from a high emissivity coating as well. The requirements for a target include the coating be compatible with the production of very fine features. The coating applied to the blackbodies as described above has also been shown to be compatible with target fabrication. Figure 7 shows a microscopic photograph of features on a target that was coated after the features were made in the target. The slit is 30 um wide and showed no measurable change in width. The slit corners as well as that of the square are well defined and show no rounding after the high emissivity coating was applied.

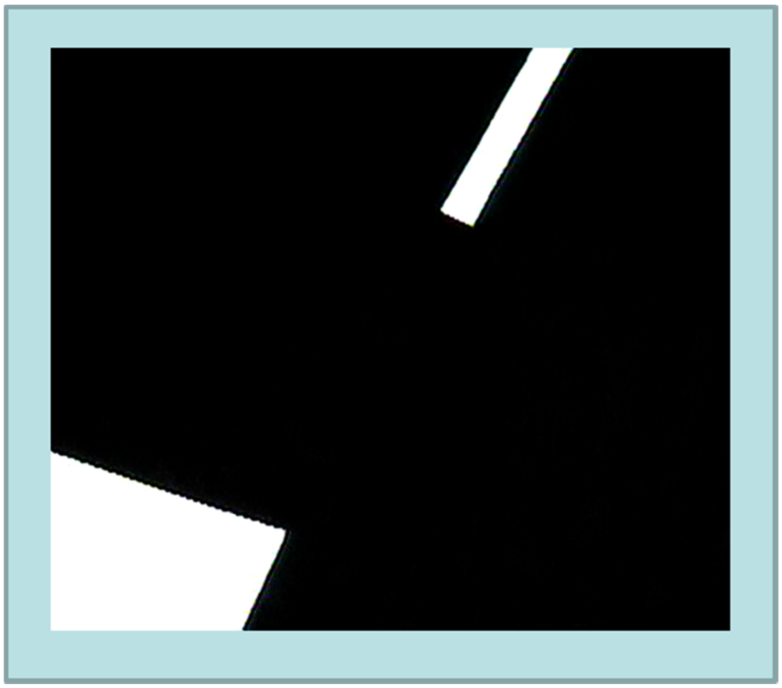

Figure 7: Microscope image of a target with small features and high emissivity coating. The coating was applied after the features were made in the target. The slit shown is 30 um wide and did not measurably change after the application of the high emissivity coating

3.5 Constant Slew Rate

Santa Barbara Infrared, Inc (SBIR) has also implemented a new constant slew rate control algorithm for its Infinity line of extended area blackbodies. This capability is primarily meant for minimum resolvable temperature (MRT) testing where the source for a backlit target is slowly changed until the target is just visible. However, the algorithm implemented can be used for any slew rate and is primarily limited by maximum slew rate of the blackbody at the current temperature. The control allows a user set slew rate and end temperature. Upon the command to start, a profile from the current temperature to the end temperature is established and the blackbody controlled to that profile until the end temperature is met, after which the blackbody will settle at the endpoint until another command is received.

The new algorithm was tested using a SBIR 4” Infinity extended area blackbody. The system was commanded to slew from a near ambient 25C, down to a reasonable delta temperature from ambient, then up to a similar delta temperature above ambient and then back to 25C. The algorithm was tested over a series of rates from 0.05K/min to 10K/min. The faster slews were set to stop before they exceeded the maximum delta T from ambient when going cold. Plots of the results from the 0.05K/min and 3.5 K/min tests are shown in Figures 8 and 9 respectively. Plots from the other rates are generally similar. Deviation from profile is measured during each pass through the control loop (approximately 3 times per second). The deviations recorded were based only on the individual measurement at that time, no averaging of measurements was performed. After the slew is started, the blackbody typically takes 30 seconds or so to stabilize on the profile, after which time the profile is generally held with sub-mK accuracy. Table 1 gives the average maximum deviations for each of the slew rates tested. The average deviation is the standard deviation from the profile beginning 30 seconds after the start of the slew. The maximum deviation is over the same time. For slews faster than 0.35K/min the maximum deviations larger than 1mK are due to the system taking slightly longer than 30 seconds to settle at the higher rates.

The new algorithm provides excellent slew rate control with accuracy to the desired profile for rates below 5K/min comparable to the sub-mK accuracy of the blackbody in a steady state.

Table 1. Results from constant slew rate tests.

Slew Rate (C/min)	0.05	0.075	0.1	0.25	0.35	0.5	0.75	1	1.5	2	3.5	5	7.5	10
Std. dev. (mK)	0.1	0.1	0.1	0.2	0.2	0.4	0.5	0.7	0.2	0.4	0.7	1.2	1.2	1.3
Max dev. (mK)	0.6	0.3	0.4	0.9	1.3	1.5	2.3	3.1	1.7	2.5	5.7	9.2	9.2	5.8

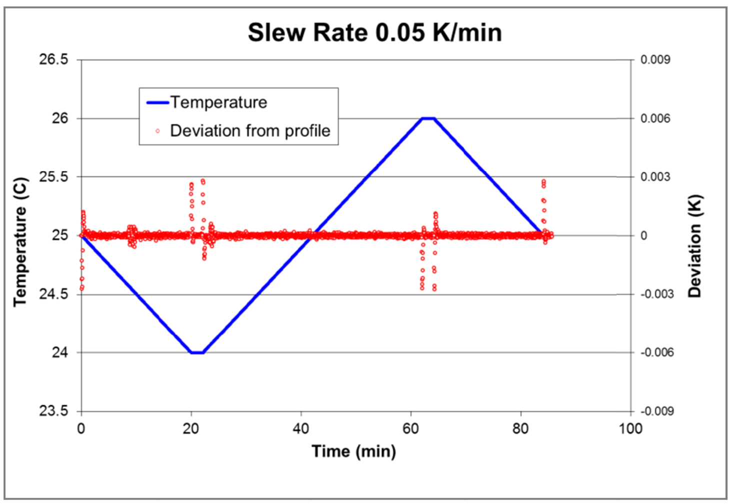

Figure 8. Constant slew rate results for 0.05K/min rate test.

4. SUMMARY

Santa Barbara Infrared, a HEICO company, has developed a high emissivity coating for improved radiometric accuracy. The coating has higher emissivity than the standard coating and approaches unity based on the reflectance and imagery data collected. Although the data indicates a MWIR average emissivity 0.999 and a LWIR emissivity of 0.995, both claims are limited to 0.99 until further testing with a traceable reference can be performed. On a separate system a constant slew rate algorithm was implemented and tested. The testing showed excellent tracking of the desired profile, to sub-mK accuracy for rates less than 5K/min.

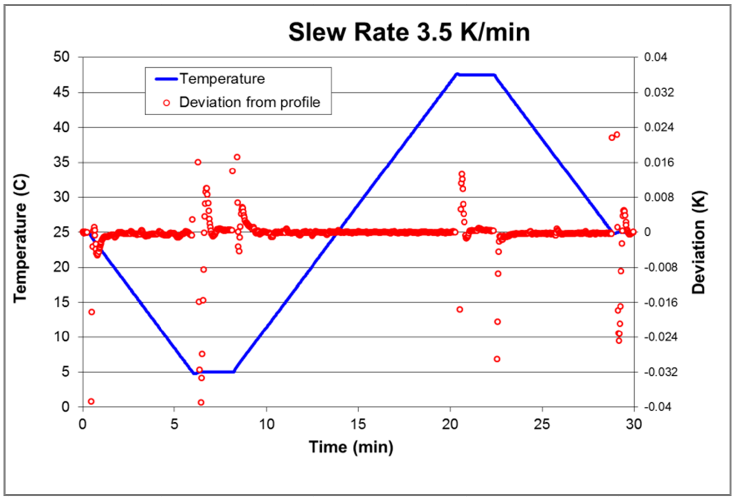

Figure 9. Constant slew rate results for 0.05K/min rate test.

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