

# Radiance Calibration of Target Projectors for Infrared Testing

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## ABSTRACT

This paper provides a procedure for radiometric calibration of infrared target projectors using the RAD-9000 MWIR/LWIR spectral radiometer – a high-performance instrument supporting extremely accurate absolute and relative radiometric calibration of EO test systems. We describe the rationale for radiometric calibration, an analysis of error sources typically encountered by investigators during calibration of infrared imaging cameras when using target projectors, and a strategy for performing an absolute system end-to-end radiometric calibration with emphasis on high accuracy and ease of use.

**Keywords:** Absolute radiometry, detector, calibration, blackbody, reference source, RAD9000, spectral radiometer.

## 1. INTRODUCTION

Target Projectors are key instruments used in the test, evaluation, and calibration of infrared imaging sensors and cameras. In its most basic form, a target projector produces a radiance contrast between an infrared blackbody source and a background, via a target projected at infinity, ref. Fig. 1. Targets can be emissive and/or reflective which affects the configuration of the projector and defines required assets such as blackbodies or optics.

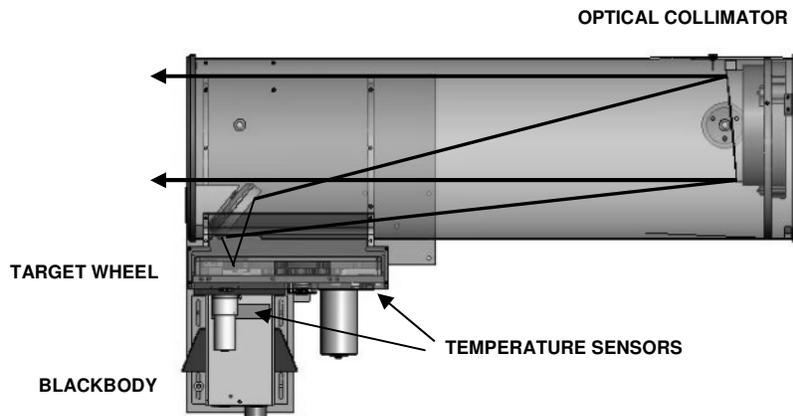


Figure 1 – Generic Infrared Target Projector

Radiance calibration of an infrared target projector is essential to properly determine the projector's radiance output as a function of temperature set point. An accurate radiance calibration curve is required to set target contrast and perform high-resolution infrared imaging system tests such as Minimum Resolvable Temperature Difference (MRTD), Signal Transfer Function (SiTF), and Noise Equivalent Temperature Difference (NETD). As infrared sensors inherently measure radiance rather than temperature, it makes sense to calibrate the test system radiometrically, provided an appropriate instrument is available. Given a well-behaved SiTF characteristics for a given UUT, the thermal imager's output signal is linear as a function of scene radiance. However, as radiance is inherently nonlinear as a function of temperature, sensor output is also nonlinear as a function of temperature.

Object radiance may be converted to apparent temperature using the following relationship

$$L_o(T_o) = \int_{\lambda_1}^{\lambda_2} [\epsilon_{o,\lambda} W_\lambda(T_o) + (1 - \epsilon_{o,\lambda}) W_\lambda(T_{amb})] d\lambda \quad [1]$$

Where  $L_o(T_o)$  is the integrated object radiance,  $W_\lambda(T_o)$  is the spectral object radiance determined using the Planck equation,  $W_\lambda(T_{amb})$  is the spectral background radiance, and  $\epsilon_{o,\lambda}$  is the spectral emissivity of the object. Equation [1] produces a non-linear radiance vs. temperature curve as would be measured by a high quality spectral radiometer such as the RAD9000, observing a reference blackbody.

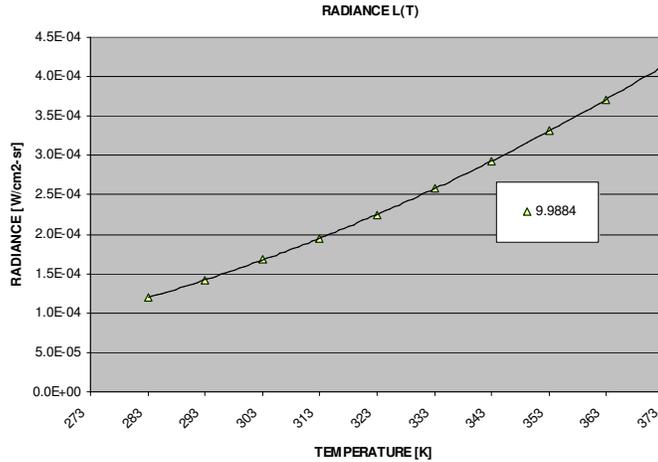


Figure 2 – Radiance to Temperature Calibration Curve ( $T_{amb} = 293$  K,  $\epsilon_o = 0.998$ ,  $\lambda_{CWL} = 9.988$   $\mu\text{m}$ )

The differential radiance seen by a UUT looking at an ideal target projector system may be expressed as the difference between target blackbody source and target background radiance:

$$\Delta L = L_o - L_{bkg} \quad [2]$$

For real-world blackbody and target surfaces with non-unity emissivity (i.e.,  $\epsilon < 1.0$ ), the reflected ambient components of the radiance must be included. The differential radiance can then be expressed as a sum of the Planck terms for each emitted and reflected radiance source:

$$\Delta L = \int_{\lambda_1}^{\lambda_2} [ \epsilon_{o,\lambda} W_\lambda(T_o) + (1 - \epsilon_{o,\lambda}) W_\lambda(T_{amb}) ] - [ \epsilon_{bkg,\lambda} W_\lambda(T_{bkg}) + (1 - \epsilon_{bkg,\lambda}) W_\lambda(T_{amb}) ] d\lambda \quad [3]$$

The non-linearity of the Planck function gives rise to a variation in differential radiance with ambient temperature change - even when thermometric  $\Delta T$  is maintained. This variation is known as a “radiometric  $\Delta T$ ” error. Table 1 illustrates the magnitude of the radiance difference as a function of ambient temperature change when observing a target blackbody source at a  $\Delta T$  of 1 K.

$T_{amb}$ [K]	$T_o$ [K]	Delta Radiance, $\Delta L$ [ $\mu\text{W}/\text{cm}^2$ ]	
		MWIR (3-5 $\mu\text{m}$ )	LWIR (8-12 $\mu\text{m}$ )
288	289	14.3	169.4
296	297	18.4	184.5
298	299	19.5	188.3
300	301	20.8	192.1
308	309	26.2	207.6

Table 1 – MWIR and LWIR Delta Radiance,  $\Delta L$  vs.  $\Delta T_{o-amb} = 1$  [K], change

## 2. CALIBRATION ACCURACY

### 2.1 Error Sources

Sources of error during calibration include uncertainties in emissivity of the target source and background, emittance and/or reflectance of the projection optics and baffling, thermometric to radiometric temperature difference, temporal instability of the target or background source radiance, temperature drift, view angle of the sensor or projector, and radiance uniformity of the sources. Typical target projectors can maintain differential temperatures of  $\pm 0.001^\circ\text{C}$ , but as ambient temperature varies, the target temperature can drift, resulting in an unstable image – thus affecting consistency of the test results<sup>3</sup>. The magnitude of these errors is dependent on the rate of change of the ambient temperature, and aforementioned system-specific factors such as target and background emissivity, optical emittance and baffling, and target edge characteristics. The measurement most sensitive to radiometric calibration error is that of MRTD.

The following analysis assesses the degree of MRTD accuracy achievable with the current state-of-the-art in radiometric calibration instrumentation and measurement techniques.

### 2.2. Radiometric Error Analysis

The radiometric output of a target projection system during MRTD testing is affected primarily by the error terms; radiometric calibration uncertainty and ambient temperature drift effects.

State-of-the-art IR calibration transfer standards such as SBIR's RAD9000 provide thermal sensitivity of approximately  $0.010^\circ\text{C}$  and absolute radiometric accuracy of  $\pm 0.25\%$  per single-ended radiance measurement. Thermal sensitivity is limited by detector noise, and absolute accuracy limited by NIST radiometric calibration of the transfer standard's thermal references.

Ambient temperature drift is a factor to be considered in the accurate measurement of MRTD for high-performance sensors. We consider the implications of ambient drift on projected MWIR and LWIR differential radiance, assuming a controlled ambient temperature of  $25 \pm 1^\circ\text{C}$  and  $\pm 3^\circ\text{C}$ , projected  $\Delta T$  set points of  $5.0$  and  $0.1^\circ\text{C}$ , and a reflected background target projector configuration utilizing a controlled source and passive background.

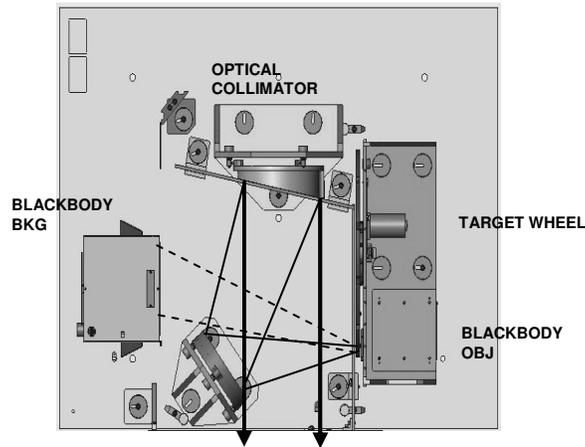


Figure 3 – Generic Reflective Background Target Projector System

Target and background radiance at the collimator aperture are given by:

$$L_{target} = L_{bb2}R_fR_p + L_fR_p + L_p \quad [4]$$

$$L_{background} = L_{bb1}R_tR_fR_p + L_tR_fR_p + L_fR_p + L_p \quad [5]$$

Where L and R denote radiance and reflectance, and the subscripts *bb*, *t*, *f*, and *p* indicate blackbody, target, fold, and primary surfaces.

Differential radiance ( $\Delta L$ ) is computed as in equation [2] by subtracting equation [5] from [4]:

$$\begin{aligned} \Delta L &= L_{t_{target}} - L_{background} \\ &= L_{bb2}R_fR_p + L_fR_p + L_p - [L_{bb1}R_tR_fR_p + L_tR_fR_p + L_fR_p + L_p] \\ &= R_fR_p [L_{bb2} - R_tL_{bb1} - L_t] \end{aligned} \tag{6}$$

Expanding the target and background blackbody radiance terms to include reflected ambient contributions yields:

$$\Delta L = R_fR_p \left[ \begin{aligned} &\epsilon_{bb2}W(\lambda, T_{bb2}) + (1 - \epsilon_{bb2})W(\lambda, T_{amb}) - R_t\epsilon_{bb1}W(\lambda, T_{bb1}) \\ &- R_t(1 - \epsilon_{bb1})W(\lambda, T_{amb}) - (1 - R_t)W(\lambda, T_{amb}) \end{aligned} \right] \tag{7}$$

Where  $\epsilon$  is the surface emissivity and  $W(\lambda, T)$  is the Planck function. Evaluating this expression for 0.98 target and mirror reflectance, 0.985 blackbody emissivity, and different combinations of ambient temperature,  $\Delta T$  set point, and spectral band yields the following tables for MWIR and LWIR testing:

$\Delta T_{bb}$ (K)	$\Delta T_{amb}$ (K)	MWIR (3-5 $\mu$ m)		LWIR (8-12 $\mu$ m)	
		$\Delta T_{app}$ (K)	$\Delta L$ (W/cm2/sr)	$\Delta T_{app}$ (K)	$\Delta L$ (W/cm2/sr)
5.0	1.0 (298-299 K)	$\Delta = 0.018$ <i>err</i> = 0.4%	$\Delta = 1.23E-7$ <i>err</i> = 0.4%	$\Delta = 0.018$ <i>err</i> = 0.4%	$\Delta = 1.2E-6$ <i>err</i> = 0.4%
	3.0 (298-301 K)	$\Delta = 0.054$ <i>err</i> = 1.1%	$\Delta = 3.82E-7$ <i>err</i> = 1.2%	$\Delta = 0.054$ <i>err</i> = 1.1%	$\Delta = 3.56E-6$ <i>err</i> = 1.2%
0.1	1.0 (298-299 K)	$\Delta = 0.016$ <i>err</i> = 18%	$\Delta = 1.23E-7$ <i>err</i> = 19%	$\Delta = 0.019$ <i>err</i> = 20%	$\Delta = 1.17E-6$ <i>err</i> = 20%
	3.0 (298-301 K)	$\Delta = 0.055$ <i>err</i> = 63%	$\Delta = 3.80E-7$ <i>err</i> = 57%	$\Delta = 0.057$ <i>err</i> = 60%	$\Delta = 3.56E-06$ <i>err</i> = 61%

Table 2. Ambient Drift-Related  $\Delta T$  Error

MRTD errors can become significant for large ambient temperature deviations ( $\Delta T_{amb}$ ). This illustrates the potential for compensation or correction methodologies for minimizing the influence of ambient temperature drift during IR testing.

For small thermal contrast settings (*i.e.* – low angular frequency MRTD testing), RDT accuracy is limited by the transfer standard’s thermal sensitivity and ambient drift effects. Calibration accuracy near zero  $\Delta T$  is twice the transfer standard’s thermal sensitivity, or  $\pm 0.020^\circ\text{C}$ . Ambient drift-related error due primarily to the target emittance; and less so the passive background source, is approximately  $\pm 0.020^\circ\text{C}$  for a  $\Delta T$  of  $1^\circ\text{C}$ . The worst-case error is an RSS of these terms, or  $\pm 0.028^\circ\text{C}$  for a  $\Delta T$  of  $1^\circ\text{C}$ . For ambient temperature drift  $> 3^\circ\text{C}$  the error increases significantly.

	$\Delta T_{\text{amb}} = 1\text{ }^{\circ}\text{C}$	$\Delta T_{\text{amb}} = 3\text{ }^{\circ}\text{C}$
System Calibration Accuracy	$\pm 0.020\text{ }^{\circ}\text{C}$	$\pm 0.020\text{ }^{\circ}\text{C}$
Ambient Drift Error	$\pm 0.020\text{ }^{\circ}\text{C}$	$> 0.060\text{ }^{\circ}\text{C}$
MRTD Accuracy ( $\Delta T_{\text{O-BKG}} = 0.100\text{ }^{\circ}\text{C}$ )	$\pm 0.028\text{ }^{\circ}\text{C}$	$> 0.065\text{ }^{\circ}\text{C}$

Table 3. Tolerance Allocation for MRTD ( $\Delta T = 0.100^{\circ}\text{C}$ )

For large thermal contrast settings, RDT accuracy is limited by the transfer standard’s absolute radiometric accuracy at both the high and low set points, and ambient drift for large DT settings. Two times the worst-case transfer standard accuracy is  $\pm 0.5\%$ . Ambient drift effects at or above the specified crossover point of  $\pm 5^{\circ}\text{C}$  are 0.4% for a  $\Delta T$  of  $1^{\circ}\text{C}$ . The worst-case error is the sum of these two terms, or  $\pm 0.9\%$  and  $\pm 1.7\%$  for a  $\Delta T$  of  $1^{\circ}\text{C}$  and  $3^{\circ}\text{C}$  respectively.

	$\Delta T_{\text{amb}} = 1\text{ }^{\circ}\text{C}$	$\Delta T_{\text{amb}} = 3\text{ }^{\circ}\text{C}$
Radiometric Accuracy	$\pm 0.5\%$	$\pm 0.5\%$
Ambient Drift Error	$\pm 0.4\%$	$\pm 1.2\%$
MRTD $\Delta L$ Accuracy ( $\Delta T_{\text{O-BKG}} = 5.0\text{ }^{\circ}\text{C}$ )	$\pm 0.9\%$	$\pm 1.7\%$

Table 4. Tolerance Allocation for MRTD ( $\Delta T = 5.0^{\circ}\text{C}$ )

It should be noted that the standardized MRTD procedure actually produces a result more accurate than the hardware-related  $\Delta T$  errors listed above. Averaging the positive and negative contrast settings at the two resolution limits cancels the systematic calibration error associated with each measurement, and thus improves accuracy of the MRTD test result. As such, these error analyses are intended to be conservative.

A straightforward, end-to-end radiometric target projector calibration procedure utilizing SBIR’s RAD9000 spectral radiometer system is discussed in the next section. Once calibrated, the target projector serves as a measurement standard for full characterization of IR sensor performance.

### 3. CALIBRATION METHODOLOGY

In order to characterize spectral radiance as a function of wavelength, a spectral radiometer is employed. SBIR has developed and currently utilizes an extremely accurate absolute spectral radiometer system called the RAD9000<sup>1,2</sup>. The RAD9000 provides spectral resolution of 1.8% in the 3-5 micron and 8-12 micron bands, thermal sensitivity better than 0.010 K in each IR channel, and absolute radiometric accuracy of  $\pm 0.25\%$  over an operating temperature range of 10-100°C.

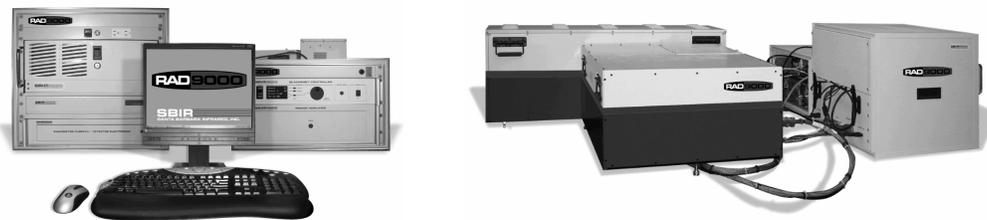


Figure 4 – RAD9000 Spectral Radiometer System – Front and Side Views

Radiometric calibration of the instrument involves characterization of the relationship between the signal response of each channel and incident radiation per spectral interval. The key to accurate calibration is the use of high-performance reference radiation sources with accuracy and stability comparable to (or better than) the RAD9000 system itself. To address this need, the RAD9000 radiometric reference module (RRM) was developed for use as an integral part of the RAD9000 system. The RRM includes two adjustable reference blackbodies to overfill the RAD9000 aperture. Each blackbody is calibrated radiometrically at NIST, and thus represents the most accurate extended thermal reference source currently available.

When integrated with the RAD9000, the RRM provides automated bracketing of object radiance via automatic translation of the two RRM sources into (and out of) the RAD9000 aperture. This allows the user to accurately determine radiometric qualities such as emissivity, spectral radiance, apparent temperature, and other parameters.

The dual-extended source blackbodies have an 8” diameter, with variable temperature control from 5°C to 100°C, exhibit high effective emissivity (> 0.999 from 2-14 μm), and operate under automated PID control. Due to their location external to the RAD9000 optical path, the RRM reference blackbodies provide better than 1% absolute radiometric calibration accuracy of the entire signal path, from the entrance aperture to the detector. As the RRM is designed to serve as an integral part of the RAD9000, calibration may be performed prior to each data collection, thereby delivering the most accurate MWIR and LWIR spectral radiance measurement capability available.

### 3.1 Spectral Radiometer Calibration

The RAD9000 detectors and electronics are designed to produce a linear output as a function of input irradiance, for all wavelengths in the MWIR/LWIR channels. First, the two NIST traceable extended source blackbody reference sources are presented to the radiometer to determine slope and offset coefficients that fully characterize the instrument’s spectral response function. The radiometer alternately views the two RRM reference blackbodies and collects signals from the high and low thermal reference points. The RAD9000 averages measured data over a number of measurements selected for the calibration period. Let the radiance levels from reference source 1 and 2 be defined as  $L_1$  and  $L_2$ , respectively, and the corresponding signal counts measured by the radiometer as  $S_1$  and  $S_2$ . Gain ( $G_\lambda$ ) and radiance offset ( $O_{offset,\lambda}$ ) may be determined using the following relationships:

$$1/G_\lambda = (L_2 - L_1)/(S_2 - S_1) \quad [8]$$

and

$$L_{0_{offset,\lambda}} = (L_1 S_2 - L_2 S_1)/(S_2 - S_1) \quad [9]$$

Rearranging terms, object radiance may be expressed as a linear relationship to the collected signal:

$$L_\lambda(T) = A_\lambda \cdot S_\lambda(T) + L_{0_{offset,\lambda}} \quad \text{where } A_\lambda = 1/G_\lambda \quad [10]$$

Radiometer response (signal, in mV) may alternately be expressed in terms of responsivity and irradiance:

$$S_\lambda(T) \equiv R(\lambda) \cdot L_\lambda(T) \quad [11]$$

Where  $R(\lambda)$  is the absolute instrument response [typically expressed in V/W/cm<sup>2</sup>/sr] and  $L_\lambda(T)$  in the integrated in-band radiance [in W/cm<sup>2</sup>/sr].

Calibration of the MWIR and LWIR infrared channels is initially performed using data collected at any two points within the range of potential object radiance using the RRM’s reference blackbodies. Calculating gain and offset for each spectral band and storing the results in convenient software-based look-up tables (LUTs) allows easy conversion from radiance to apparent temperature using equations [1] and [11].

### 3.2 Infrared Target Projector Calibration

The basic approach for determining absolute radiance from a target projector is the same as that used for calibrating the spectral radiometer, as described above. Both target projector and the RRM reference blackbody sources are placed close to the same plane when viewed by the RAD9000. In this arrangement, the difference in optical path length between the target and background sources and the RRM reference sources is kept small (< 2 m) to limit atmospheric attenuation at the shorter wavelengths. The RAD9000 is positioned on-axis with respect to the target projector, to limit the angular rotation in azimuth or elevation needed to view the background radiance. The angular resolution (IFOV) of the RAD9000 is 1.7 mrad in its basic configuration, thereby providing adequate sampling capability for high-resolution IR targets. A typical target used for both projector calibration and UUT evaluation is the half-moon target shown in Fig. 5. The RRM reference blackbody sources overfill the IFOV of the RAD9000 detectors, and are used as flood sources.

In order to accurately determine the radiance of an unknown object (target or background) the RAD9000 automatically brackets the object radiance at multiple apparent temperature set points within the linear response range of the IR sensor or camera UUT. Similar to calibration of the RAD9000, this is achieved via the use of two calibrated, variable temperature reference blackbodies, typically set to bracket the expected object temperature by ± 5-10 K.

This two-point calibration approach is most precise over the normal range of observed temperatures, and the effect of target projector non-linearity is minimized by the small differential temperature range observed. Each RRM reference source radiance and emissivity characteristic is known as a function of temperature. Absolute radiance accuracy has been characterized well below 0.5%, as discussed previously.

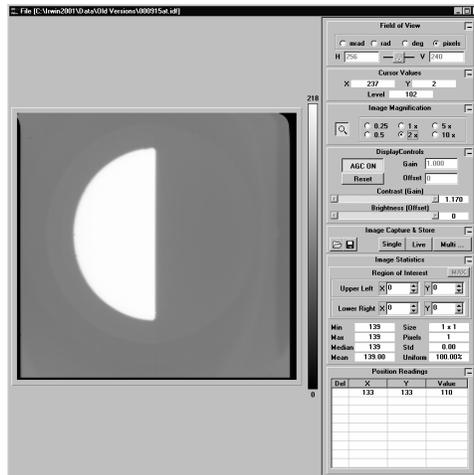


Figure 5 - Half-Moon Calibration Target

A plot of measured vs. ideal radiance may be constructed over the object temperature range of 5- 100°C. Linear regression is used to determine correction coefficients (a,b) for target radiance. A second-order polynomial is used with the following form to determine the radiance difference. Correction coefficients may be stored in software to provide a dynamic correction of radiance as a function of temperature set point.

$$\Delta L_o(T_o) = a[L_o(T_o) - L(T_{amb})] + b[L_o(T_o) - L(T_{amb})]^2 \quad [12]$$

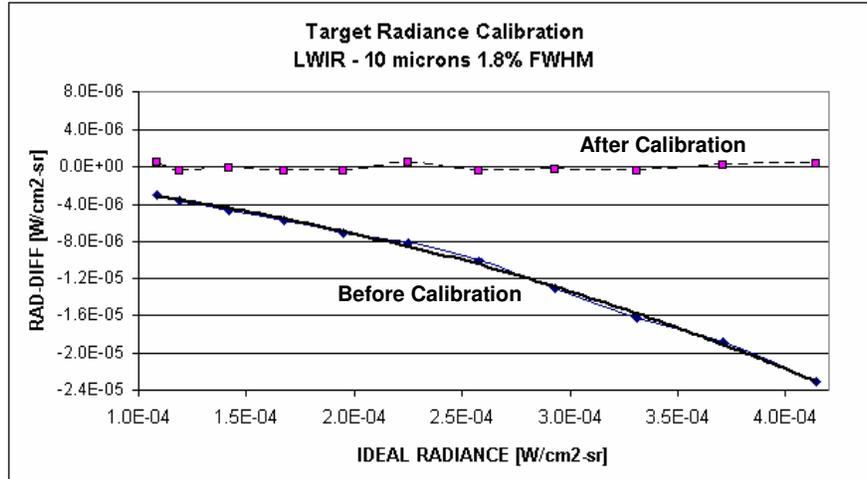


Figure 6 - Target Projector Source Radiance Calibration at 10  $\mu\text{m}$

RAD [W/cm <sup>2</sup> /sr]	T <sub>app</sub> [K]	$\Delta\text{RAD}_{\text{CORR}}$ [W/cm <sup>2</sup> /sr]	ABS ERR [%]	$\Delta\text{T}_{\text{app}}$ [K]
1.088E-04	278	5.00E-07	0.46 %	0.244
1.193E-04	283	-5.00E-07	0.42 %	0.214
1.422E-04	293	-2.00E-07	0.14 %	0.066
1.674E-04	303	-5.00E-07	0.30 %	0.176
1.952E-04	313	-5.00E-07	0.26 %	0.16
2.250E-04	323	4.00E-07	0.18 %	0.14
2.580E-04	333	-5.00E-07	0.19 %	0.142
2.930E-04	343	-3.00E-07	0.10 %	0.089
3.310E-04	353	-5.00E-07	0.15 %	0.133
3.710E-04	363	2.00E-07	0.05 %	0.015
4.140E-04	373	3.00E-07	0.07 %	0.078

Table 5 - Delta Temperature Error: Target Projector Source Radiance Calibration at 10  $\mu\text{m}$

A plot of background radiance is typically constructed to monitor drift as a function of both target radiance and ambient temperature fluctuation. Typically, the time constant of environmental temperature instability is longer than the time required to perform a radiometric measurement, so as not to affect the end result. However, drift due to radiant coupling of the background to the target source blackbody (or the lack of test facility temperature control) can influence measurements if not subtracted out of the final radiance calculation. This error term is separate from any emissivity models as emissivity is typically a constant radiance offset over the measurement conditions. Drift offset is typically non-linear and is encountered in MRTD testing (as described in the above error analysis) where small differences in radiance between target and background must be maintained in order to provide repeatable radiance contrast to the observer. If drift is repeatable, then LUT or algorithmic-based correction such as the RDT correction may be employed as a function of ambient conditions and target radiance to maintain a constant difference in projected differential radiance between source and background. If drift effects are not well-behaved, the best option is to employ a controllable background source with reflective targets.

### 3.3 Factors Affecting Calibration

It should be noted that a spectral radiometer can often deliver more accurate target projector calibration than a broadband transfer standard, since the spectral variability of projector (and radiometer) response is inherently calibratable using spectral techniques. In particular, the effects of CO, CO<sub>2</sub>, and H<sub>2</sub>O in the optical path are more easily compensated with spectral measurement techniques. The RAD9000 allows the user to select filters to provide more accurate calibration in the MWIR than could be obtained with a broadband instrument.

The RAD9000 RRM's reference blackbody sources provide virtually flat spectral emissivity in the infrared. In most cases, RRM reference source emissivity varies less than 0.002 over the spectral range of each IR channel (MWIR and LWIR). Therefore, a constant correction term may be applied to the calibration accounting for emissivity.

In general, it is recommended that before applying broadband radiometric calibration to any IR target projector, system output should be characterized using a spectral radiometer such as the RAD9000, to validate the projector's spectral content and identify any potential limitations associated with a broadband calibration.

### 3.4 Determination of Projector/Source Radiometric Properties

In some cases, it may be desirable to use a spectral radiometer to measure the spectral emissivity of an IR source in either a stand-alone or target projector configuration. The integrated radiance of an unknown source is determined from equation 1. Three unknowns must be determined;  $T_o$ ,  $T_{amb}$ , and  $\epsilon_{o,\lambda}$

- Using a two-point measurement of references of known emissivity and radiance (such as those provided in the RAD9000 RRM), one may solve for object radiance  $L_o$ , as follows:

$$L_{Hot} = \int_{\lambda_1}^{\lambda_2} \epsilon_{Hot,\lambda} W_{\lambda}(T_{Hot}) + (1 - \epsilon_{Hot,\lambda}) W_{\lambda}(T_{amb}) d\lambda \quad [13]$$

and

$$L_{Cold} = \int_{\lambda_1}^{\lambda_2} \epsilon_{Cold,\lambda} W_{\lambda}(T_{Cold}) + (1 - \epsilon_{Cold,\lambda}) W_{\lambda}(T_{amb}) d\lambda \quad [14]$$

Measured object integrated radiance can now be obtained from the RAD9000 by using the form of equation [10]

$$L_o(T_o) = A_{\lambda} \cdot S_o(T_o) + L_{offset} \quad [15]$$

Before object temperature can be derived an accurate determination of object emissivity and ambient temperature must be made.

- Ambient temperature should be monitored via a NIST traceable high precision thermometer in the location of the test measurement; appropriately shielded from stray radiation sources, and recorded as a function of time during calibration. The RAD-9000 features an internal reference blackbody that is monitored via a calibrated smart thermometer and is polled alternately with the measured source to facilitate accurate determination of source radiance.  $T_{amb}$  is known to better than  $\pm 0.010$  °C.  $L_{amb}$  can be determined by integrating the Planck function over the spectral band at  $T_{amb}$ .

- If we assume that object emissivity does not vary significantly within the particular spectral band being measured, that the spectral band  $\Delta\lambda/\lambda$  is less than a few percent, object emissivity may be estimated using the following relation:

$$\epsilon_o = \int_{\lambda_1}^{\lambda_2} \epsilon(T_o) d\lambda = \epsilon_{bb} \frac{L_o - L_{amb}}{L_{bb} - L_{amb}} = \epsilon_{bb} \frac{\Delta L_{o-amb}}{\Delta L_{bb-amb}} \quad [16]$$

In this relation apparent temperatures of either “Cold” or “Hot” reference blackbodies is increased or decreased to match the thermometric temperature of the object. The  $\Delta L$  ratio will uniquely estimate the object emissivity at the mean apparent object temperature.

For the target projector case shown in Figure 1 the object apparent emissivity must be adjusted for the reflectance and self emittance of each of the mirrors. The object radiance expression given in equation [1] is re-written to account for the mirrors in the optical path

$$L_o(T_o) = \int_{\lambda_1}^{\lambda_2} R_f R_p [\epsilon_o W(T_o) + (1 - \epsilon_{o,\lambda}) W(T_{amb})] + R_p [\epsilon_f W(T_f)] + [\epsilon_p W(T_p)] d\lambda \quad [17]$$

To simplify the derivation of object emissivity we make the assumption that the temperatures of the mirrors equal ambient. This assumption may not be accurate in all cases particularly for measuring low radiance levels in the LWIR due to degraded reflectance optics, or coupled sources so the test professional is cautioned to fully characterize the test conditions and the target projector prior to applying an emissivity factor to the system. Having said this for most typical applications we apply equation [17] to equation [16] and solve for object emissivity -

Therefore

$$\epsilon_o = \frac{\int_{\lambda_1}^{\lambda_2} \epsilon(T_o) d\lambda}{R_f R_p} \frac{\Delta L_{o-amb}}{\Delta L_{bb-amb}} \quad [18]$$

- Now that object radiance, object emissivity and ambient temperature have been accurately determined the object apparent temperature,  $T_o$ , can now be derived by rearranging terms in the Planck function.

This approach is particularly useful for stand-alone IR sources and target projection systems previously calibrated thermometrically but requiring an accurate radiometric temperature calibration.

## 4. TRACEABILITY

### 4.1 NIST Calibration

Radiometric calibration of the two RAD9000 RRM reference sources was performed at NIST, using the NIST Water Bath Blackbody (WBBB) as a reference source, and the NIST TXR and FTXR radiometers as transfer standards. Details of RAD9000 RRM source calibration<sup>2</sup> have been published elsewhere and will thus not be repeated here. The calibration test setup is illustrated in Figure 7.

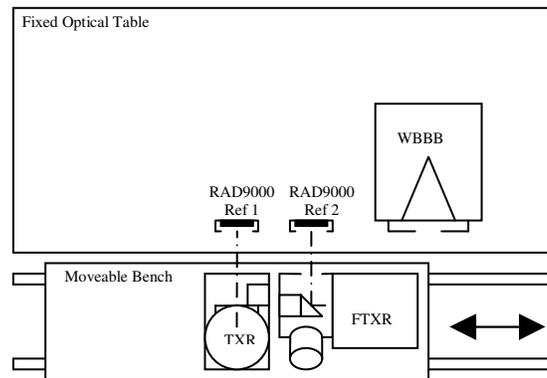


Figure 7 – RAD9000 Blackbody Calibration Test Schematic

The data set from this calibration was fit to an idealized radiometric response to determine thermometric correction terms for the blackbodies<sup>4</sup>. The thermometric correction was fit using a 4<sup>th</sup> order polynomial. This correction curve was then loaded into RAD9000 controller firmware as a LUT, enabling the system to provide automatic compensation during operation.

## SUMMARY

Accurate MWIR and LWIR calibration of IR target projectors represents a challenge to the test professional seeking to maintain a Test Accuracy Ratio (TAR) greater than 4:1 for test and evaluation high-performance thermal imagers. The RAD9000 spectral radiometer system produced by SBIR provides the test and metrology community with the capability to perform radiometric calibration accurate to better than  $\pm 0.5\%$ , with outstanding thermal sensitivity across both the MWIR and LWIR spectral regions. The system supports a wide range of object temperatures, provides better than 2% relative spectral resolution, and allows automated and remote operation through an advanced user interface.

A procedure for accurate radiometric calibration of target projectors has been described, and a radiometric error analysis for crucial MRTD measurement presented.

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