RAD9000: A High-Performance Spectral Radiometer for EO Calibration Applications

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ABSTRACT

This paper provides an update on the RAD9000 MWIR/LWIR spectral radiometer – a high-performance instrument supporting extremely accurate absolute and relative radiometric calibration of EO test systems. The system features an all-reflective optical system, internal and external thermal reference sources, a visible camera-based sighting/alignment capability, modular MWIR and LWIR detector/filter subassemblies, flexible control/display software, and a sophisticated graphical user interface (GUI). We present prototype performance data describing the instrument’s thermal sensitivity, radiometric accuracy, spectral resolution, calibration, and other key parameters.

Keywords: Absolute radiometry, detector, EO calibration, radiometry, reference source, spectral separation, thermal sensitivity.

1. INTRODUCTION

In order to provide infrared test and calibration scientists and engineers a highly accurate absolute spectral radiometer, Santa Barbara Infrared has developed the RAD9000[1]. The modular structure of the system provides for transportability and ease of system configuration (see Figure 1).

Figure 1 – RAD9000 Spectral Radiometer System – Front and Side Views

The RAD9000 design covers the 3-5 μm and 8-12 μm spectral bands, provides thermal sensitivity of better than 40 mK, supports object temperatures from 278-373 K, and delivers better than 2% spectral resolution ($\Delta\lambda/\lambda$). The RAD9000 optical system is an 8-inch, f/3, all-reflective design. Optical field-of-view (FOV) is 1 degree (17 mrad) to accommodate a visible CCD sighting camera FOV ten times the 1.67 mrad angular subtence of the IR detectors. This detector IFOV offers a good combination of sensitivity and spatial resolution in the infrared regions. The instrument may be configured with different field stops to provide other combinations of radiometric performance and angular resolution, as required.

In addition to high-performance relative radiometry, the RAD-9000 offers a high degree of absolute radiometric accuracy by utilizing a dedicated radiometric reference module. The reference module incorporates two 8-inch, variable temperature, high-emissivity extended sources to provide a stable, accurate absolute radiometric reference external to the main optics.

The RAD-9000 features computer-controlled operation, an intuitive graphical user interface (GUI), motorized focus adjustment from 3 m to Infinity, computer aided sighting/alignment capability, and an internal ambient reference for background subtraction and enhanced stability.

2. SYSTEM DESIGN

The complete RAD9000 system consists of the Electro-Optics Module (EOM), the Detector Radiometry Module (DRM), and the Radiometric Reference Module (RRM). Control of EOM and RRM modules is achieved via their associated CSE and RRM controller subsystems. The RAD9000 block diagram is shown in Figure 2.

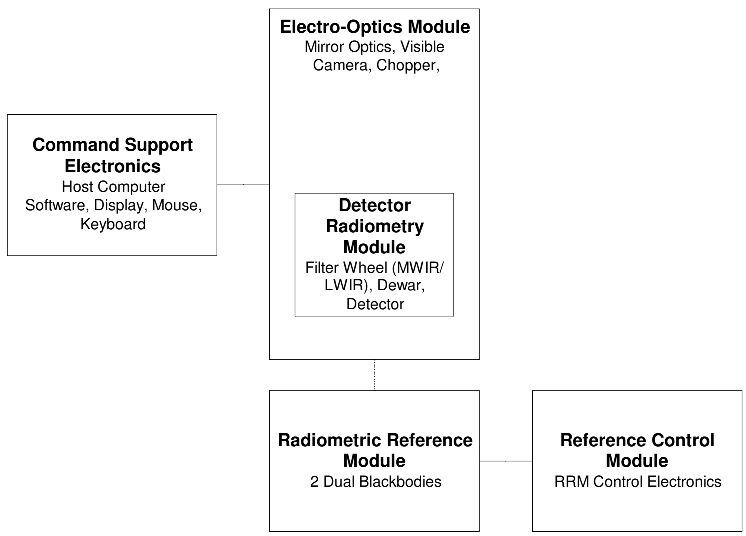

Figure 2 – RAD9000 System Block Diagram

2.1. Detector Modularity

Each Detector/Radiometry Module (DRM) contains a 30 position and optional 8 position filter wheel, an LN_2 pour fill dewar with integral infrared detector and temperature sensor, and low-noise pre-amplification electronics – all housed in a single easy to handle container (Figure 3).

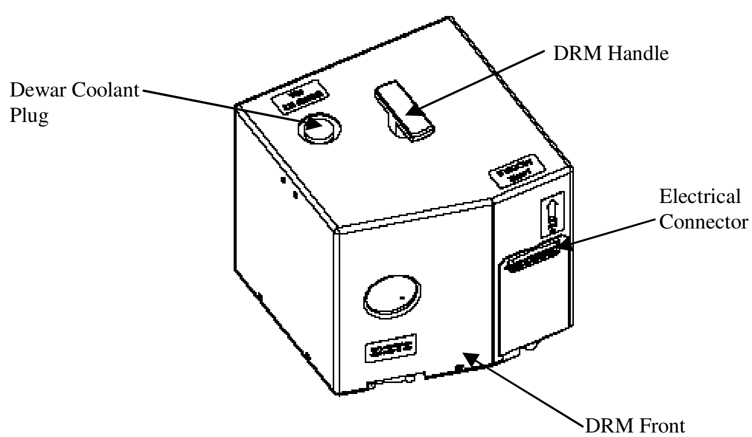

Figure 3 – Detector/Radiometry Module (DRM)

The DRM module is installed into the EOM during measurements, secured in place using a single locking handle, and is easily interchangeable.

2.2. Specifications

Key system development specifications for the RAD9000 are listed in Table 1.

PARAMETER	VALUE
Optical System	200 mm aperture, f/3 On-Axis Gregorian
Spectral Resolution	1.8% effective
Thermal Sensitivity (NEΔT)	< 40 mK [1]
Detector Types	InSb (MWIR) HgCdTe (LWIR)
Angular Resolution (IFOV)	1.7 mrad (variable)
Alignment Mode	CCD Camera (standard)
Radiometric References (absolute)	Dual External Sources (5-100°C)
Background Reference (relative)	Internal
Radiometric Accuracy	1 %
Focus Adjustment	3 m – infinity (Computer Controlled)
Detector Cooling	LN_2
Filter-Detector Modularity	Single Integrated Units
Attenuation Filters	Optional
Operational Temperature	+15°C to +40°C
Storage Temperature	-20 °C to +85°C
Shock	10 g

1 – IFOV = 1.7 mrad, λ = 4 μm (MWIR)/10 μm (LWIR), T_{object} = 25°C

Table 1 – RAD9000 Development Specifications

3. SYSTEM PERFORMANCE

3.1. Thermal Sensitivity

Noise Equivalent Differential Temperature (NEΔT) is a key metric often quoted for infrared instruments and is a measure of SNR. Typical broadband MWIR and LWIR UUT specs require NEΔT to be less than 25 mK and 100 mK, respectively. In order to support UUT test set calibration requirements, the RAD9000 has been designed to provide the highest possible Test Accuracy Ratio (TAR). The TAR of a spectral radiometer is driven by its thermal sensitivity and absolute radiometric accuracy. The RAD9000 has been tested under a variety of environmental conditions and object temperatures. Sensitivity was determined using the following relationship:

$$NE\Delta T = \Delta T / SNR$$

RAD9000 performance versus waveband and differential temperature is given in the Tables 2 and 3 respectively.

λ_c (μm)	NEΔT (K)	T_{Object} (K)	ΔT_{O-A} (K)
3.0	0.011	297	3
	0.010	309	15
4.0	0.018	297	3
	0.016	309	15
5.0	0.035	297	3
	0.032	309	15

Table 2 – Measured MWIR Thermal Sensitivity

λ_c (μm)	NEΔT (K)	T_{Object} (K)	ΔT_{O-A} (K)
8.0	0.042	297	3
	0.034	309	15
10.0	0.034	297	3
	0.022	309	15
11.7	0.028	297	3
	0.025	309	15

Table 3 – Measured LWIR Thermal Sensitivity

The values shown in Tables 2 and 3 meet the RAD9000's development specifications with margin.

3.2. Spectral Response

RAD9000 spectral response is shown in Figures 4 and 5. In both cases, optics, window, and spectral filter characteristics have been tightly specified, such that the relative spectral curves observed is due primarily to detector response characteristics.

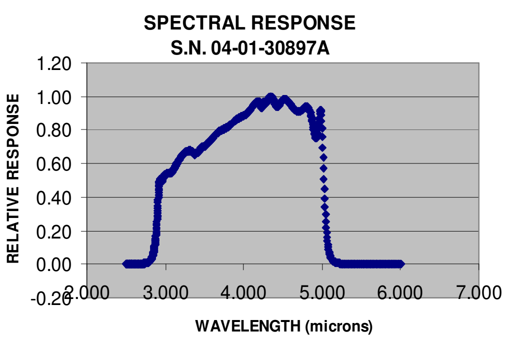

Figure 4 – MWIR Detector Spectral Response

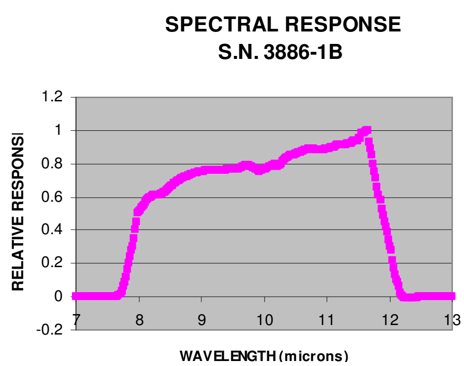

Figure 5 – LWIR Detector Spectral Response

3.3. Absolute Radiometric Accuracy

Absolute accuracy of an instrument is a measure of its systematic error; the non-random deviation of a measurement from the true value. Accuracy is independent from noise expressed as sensitivity or SNR. Accuracy is determined by testing the measurement against a known or calibrated standard. The RAD9000 includes two 8-inch diameter external reference blackbodies whose radiant output is calibrated by NIST. The absolute radiometric accuracy was measured and is better than 0.5% over the full operating temperature range.

Both MWIR and LWIR channels exhibited low deviation with respect to apparent temperature set-point from 288 – 373 K. MWIR is characterized by gaseous absorption bands which affect accuracy of measurement in those regions. These bands are not an issue for the LWIR which has high atmospheric transmission from 8 –

12 µm. SNR also affects accuracy within the band as more available radiance is able to be integrated at higher apparent temperatures. MWIR absolute accuracy at 308 K is shown in Figures 6 and 7.

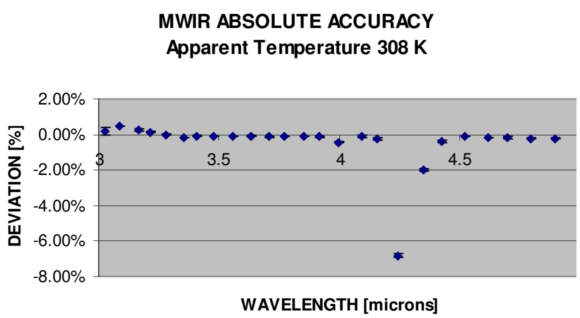

Figure 6 – MWIR Radiance Deviation

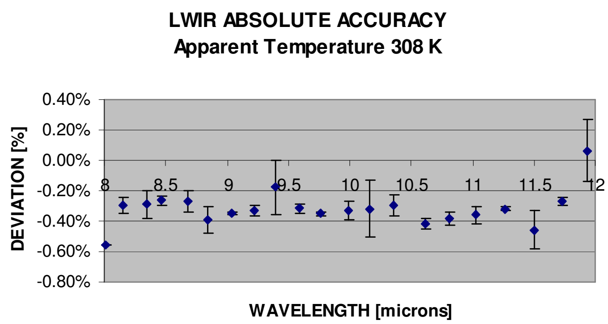

Figure 7 – LWIR Radiance Deviation

Average MWIR and LWIR radiometric accuracy was computed by averaging the absolute value of the deviation for all filter bands within each infrared channel. The results are listed in Table 4.

Apparent Temperature Accuracy (Band Average)		
Absolute Deviation		
T_{obj} (K)	MWIR (3-5 µm)	LWIR (8-12 µm)
288	0.04/0.014*	0.013
297	0.006	0.008
308	0.004	0.004
328	0.003	0.006
373	0.005	0.013

*Average for 3.5-5.0 µm

Table 4 – Average MWIR and LWIR Radiometric Accuracy

3.4. Spectral Resolution

Radiometric calibration of test sets frequently requires determination of spectral radiant output. Broadband IR cameras can determine integrated responsivity, but cannot provide information about spectral variation. A spectral radiometer must have sufficient resolution for accurately determining the spectral content of radiation incident upon its aperture. To meet its development specification for spectral resolution, the RAD9000 includes spectral filters featuring high slope accuracy for spectral purity and reduced spectral overlap. The instrument's spectral resolution ($\Delta\lambda/\lambda$) as a function of wavelength is shown in Figures 8 and 9.

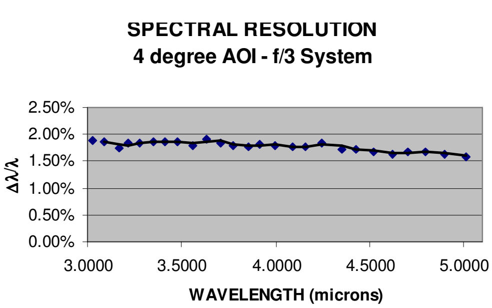

Figure 8 – MWIR Spectral Resolution

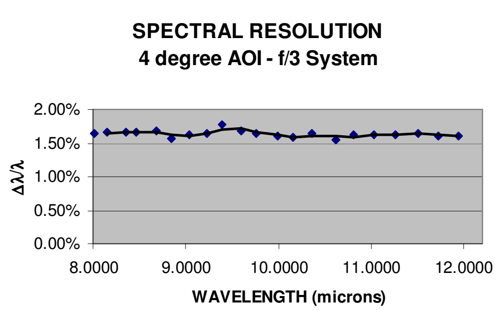

Figure 9 – LWIR Spectral Resolution

4. SYSTEM CALIBRATION

The calibration of the infrared channels aims to characterize, for each channel, the relationship between the radiation incident on the detector and the detector output. The signal in counts from a radiometer channel whose spectral pass band is $\Delta\lambda$ observing a blackbody target at temperature T_{bb} is

$$S(T_{bb}) = G \cdot L(T_{bb}) + S_o$$

where G is the radiometric gain, $L(T_{bb})$ is the radiance from a target, and S_o is the radiometric offset of the channel. Radiometric calibration of the instrument consists of determining the relationship between the radiance and detector counts from each channel. This is accomplished by exposing the radiometer to two different external radiation targets of known radiance whose calibration is traceable to NIST.

4.1. Instrument Response Function

One of these targets operates at a temperature lower than the expected object and the other warmer than the object, typically ± 5-10 K. With this arrangement, the calibration is most precise over the normal range of observed temperatures and the effects of any non-linearity in the system are minimized. Figures 10 and 11 show typical RAD9000 transfer functions.

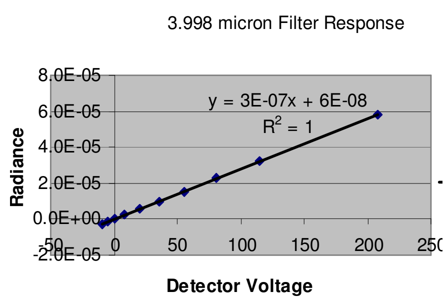

Figure 10 – MWIR Detector Response

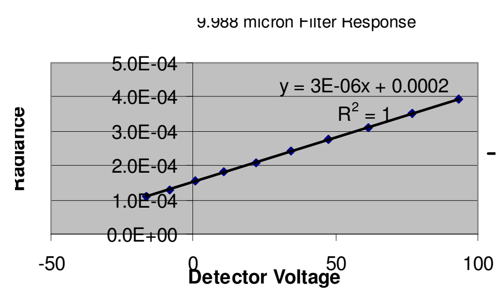

Figure 11 – LWIR Detector Response

In addition to using a 2-point calibration, offset and drift, directly related to radiance emitted from the instrument and it surroundings, can be determined and removed by using an internal ambient reference, $L(T_{Inst})$ which is viewed every integration cycle. Thus, by using a two blackbody calibration approach we can determine the radiometric gain and offset of each of the infrared channels, in a way that allows us to achieve the highest accuracy with minimal correction for any signal channel non-linearity.

The blackbodies used for calibration do not have unity emissivity, and thus reflect a radiation component which must be included in the calibration. For a given infrared band-pass and ideal blackbody, the integral:

$$L_\lambda(T) = \int R_\lambda(\lambda) \cdot B(\lambda, T) d\lambda$$

is a function of the object's apparent temperature only. $R_\lambda(\lambda)$ is the spectral response of the detector for the bandpass and $B(\lambda,T)$ is the Planck function. For non-ideal blackbodies the radiance can be evaluated using the following relationship. If the emissivity of the black body (i = 1, 2) in the channel of wavelength λ is, $\varepsilon_{i,\lambda}$ assumed constant across the bandwidth of the channel, then the corresponding calibration signal is

$$L_i = \varepsilon_{i,\lambda} L_\lambda(T_j) + (1 - \varepsilon_{i,\lambda}) L_\lambda(T_{inst})$$

where T_i and T_{inst} represent the temperatures of the specific black body and the instrument environment respectively. The RAD9000 blackbodies were specially constructed to produce a near unity emissivity broadband across both infrared channels. Hemispherical directional reflectance measurements of the blackbody surfaces indicated that the effective reflectance was less than 0.3% from 3-12 μm, and almost completely insensitive to temperature, as shown in Figure 12. This outstanding reference source performance is one of the keys to achieving the absolute radiometric accuracy discussed in section 3.3.

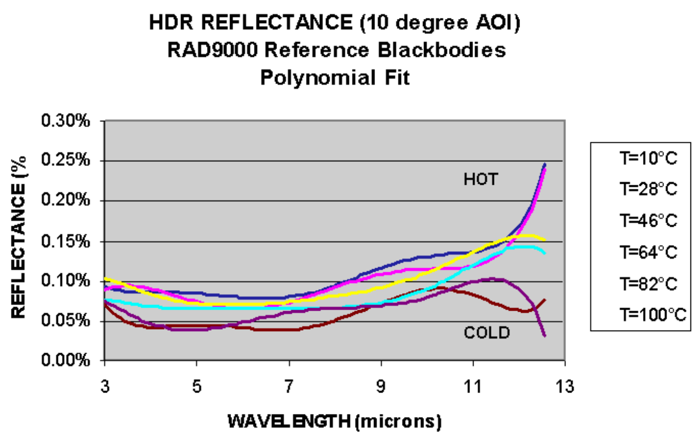

Figure 12 – Reflectance of RAD9000 Blackbody Emitting Surface

4.2. NIST Calibration

Radiometric calibration of the two blackbodies used in the RAD9000 was performed at the NIST, using the NIST Water Bath Blackbody (WBBB) as a reference source, and the NIST TXR and FTXR radiometers as transfer standards. Details of the WBBB[2] and TXR[3,4] have been published elsewhere and will not be elaborated on in this paper. A schematic of the test is given in Figure 13.

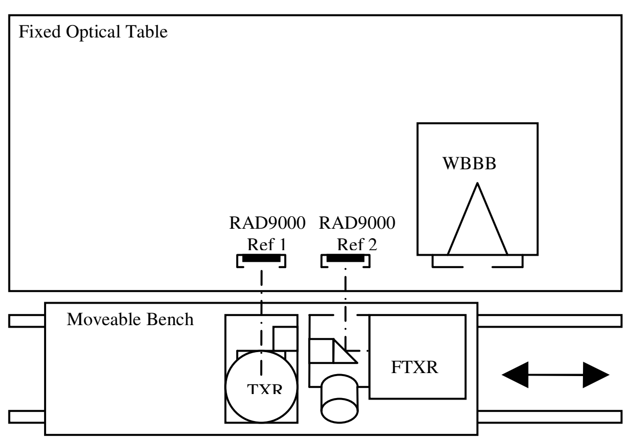

Figure 13 – RAD9000 Blackbody Calibration Test Schematic

Figure 14 shows the results from the TXR Channel 2 (band center near 10 μm). Data on the reference standard NIST WBBB is shown alongside data from the RAD9000 blackbodies (BB1 and BB2). The vertical axis shows the difference between an ideal blackbody's radiance and that produced by the RAD9000 reference sources. It is seen, for example for BB2, that the deviation at a radiance level of about 20 W/m^2sr (about 85°C) is about 0.1 $W/m^2/sr$, which equates to an error of approximately 0.5%.

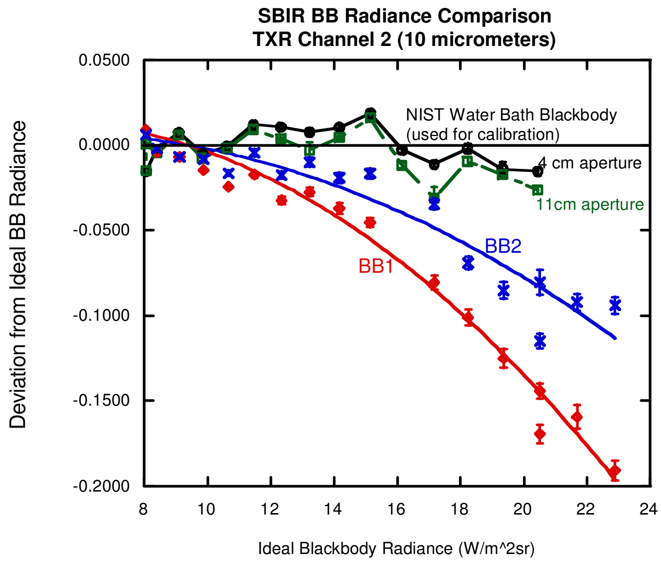

Figure 14 – RAD9000 Blackbody Calibration Comparison

Data from this calibration was then fit to an idealized radiometric response to determine the thermometric correction for the blackbodies. The thermometric correction was fit using a 4^{th} order polynomial. Results are shown in Figure 15.

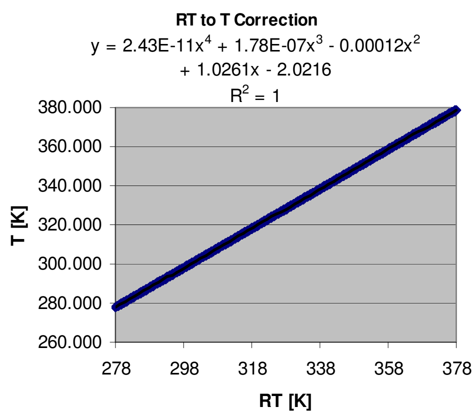

Figure 15 – RAD9000 Blackbody Radiometric-Thermometric Correction

This correction curve was then loaded into the controller firmware as an array, enabling the system to provide automatic compensation during operation.

5. SUMMARY

The RAD9000 spectral radiometer delivers outstanding thermal sensitivity for both 3-5µm and 8-12 µm channels, over a wide range of object temperatures, and with better than 2% relative spectral resolution. The incorporation of unique, high emissivity, integral reference sources has allowed the RAD9000 to demonstrate an extremely high degree of absolute radiometric accuracy, as required for calibration of current and emerging EO test stations.

ACKNOWLEDGEMENTS

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