High performance spectroradiometer for very accurate radiometric calibrations and testing of blackbody sources and EO test equipment

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ABSTRACT

In the late eighties CI Systems pioneered the radiometric calibration and testing of electro-optical infrared test equipment[1,2] by using its advanced in-house developed infrared spectroradiometer (the SR 5000), applied to measurements of signatures of military objects and long path atmospheric spectral transmission. Technological advances of frame rates, temperature resolution, spatial resolution, widened spectral ranges and other performance parameters of Forward Looking Infrared imaging systems (FLIR's) and other electro-optical (EO) devices require more advanced test and calibration equipment. The projected infrared radiation of such equipment must be controlled with better radiance resolution and accuracy.

CI has carried out a number of optical modifications of the SR 5000, together with especially dedicated calibration algorithms, to significantly improve the blackbody radiance measurements at temperatures close to room temperature, resulting in: i) a factor of 5 improvement in sensitivity, measured by Noise Equivalent Temperature Difference (NEΔT), and ii) a factor of 5 to 10 improvement in accuracy (in the 3-5 micron and 8-12 microns spectral regions respectively). The most important modifications are the use of a higher D* and smaller detector, a different detector alignment procedure in which the signal to noise ratio is traded off with field of view uniformity of response, and a calibration procedure based on the division of the blackbody temperature range into several independent sub-ranges.

As a result, the new spectroradiometer (the SR 5000WNV) has advanced infrared spectroradiometry so that it now allows the EO device manufacturers to characterize the most modern and future test equipment, and insure its being suitable to test the new advanced infrared imaging systems.

Keywords: Infrared, spectroradiometry, radiometry, radiometric calibrations, blackbody, radiometric temperature

1. INTRODUCTION

The most advanced blackbody sources are used in test equipment, to emit very stable and accurately known IR radiation, to test the most modern FLIR's in production. Like a domino effect, as the FLIR's performance advances, the requirements of these blackbody sources and test equipment become more severe. Traditionally[1,2], these sources have been tested radiometrically, but the absolute radiance accuracy has always been of the order of 5%. In the new situation there is a need for routine radiometric calibration and testing of the IR sources, and, as a domino effect, to more stringent requirements of the radiometric equipment used for this job. An example is a new need for an advanced IR spectroradiometer, with the following specifications:

- NEΔT ≤ 40 millidegrees when measuring a blackbody in the following conditions:
  - Blackbody temperature = 25 C,
  - FOV = 1.7 milliradians,
  - Wavelength $\lambda = 4\ \mu$,
  - Spectral full width half maximum bandpass of 2% = 0.08 μ,
  - Electronic bandwidth = 1 Hz.
- Measurement of integral blackbody radiance in the spectral ranges of 3-5μ and 8-12 μ, with accuracy better than 1% of radiance, for blackbody temperatures between 5 and 100 C, when measured at a stable room temperature near 22 or 23 C.

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CI has taken up this challenge and set itself as a goal to develop an IR spectroradiometer with such performance characteristics. For a definition of IR spectroradiometer, see reference 3.

The final result, as shown in this paper in the next sections, is the construction of a very highly sensitive and accurate infrared spectroradiometer, the SR 5000WNV: it measures the absolute radiance and radiometric temperature of a blackbody near room temperature, with excellent sensitivity (40 mK) and accuracy (1% of radiance). The system is based on the standard SR 5000, on well proven technology and user friendly operation, developed by CI over the years, with NIST traceable blackbody for calibration, and software controlled, automatic algorithms for fast, fool proof system calibration.

Figure 1 shows the SR 5000WNV system: the optical head is tripod mounted for remote sensing measurements but it can be used also on an optical table, and the laptop PC controls the system through the dedicated SR 5000 Windows based Data Management (SRDM) software.

The optics is a 5" diameter on-axis Newtonian system with up to 10 milliradians field of view.

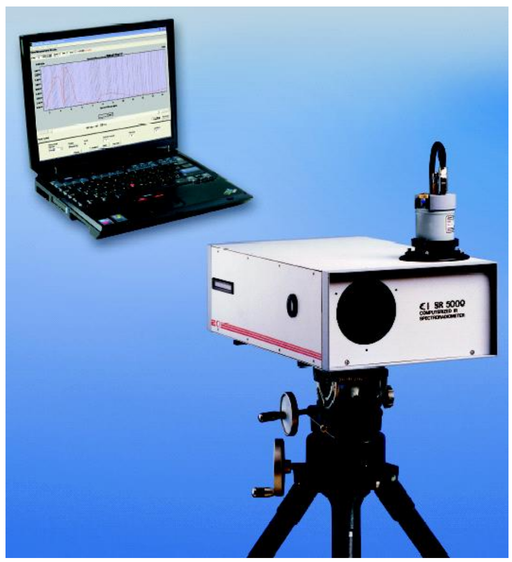

Figure 1. The tripod mounted SR 5000 WNV state-of-the-art infrared spectroradiometer, with the laptop PC for system control.

Besides high sensitivity and accuracy achieved with liquid nitrogen cooled InSb and HgCdTe detectors, the SR 5000[3] offers:

1. Continuous spectral measurement by an infrared Circular Variable Filter (CVF) with 2% spectral resolution,
2. Side viewing for convenient pointing and alignment on the target without parallax, through CCD imaging with large field of view,
3. Internal floating room temperature blackbody referencing for reduction of environment noise,
4. Motorized focusing from 1.5 meters (SR 5000WNV) to infinity by computer control, with one automatic memory setting for infinity,
5. Many modular options, such as higher field of view CCD for monitoring the scene being measured, 3-decades neutral density attenuator, visible and near infrared coverage by special CVF's and detectors, motorized variable field of view, boresight telescope, and others,
6. Standard spectral mathematical algorithm for data analysis and display,
7. Data storing and retrieval capability.

A three-dimensional solid drawing of the optical system, with the optics and its various components is shown in figure 2.

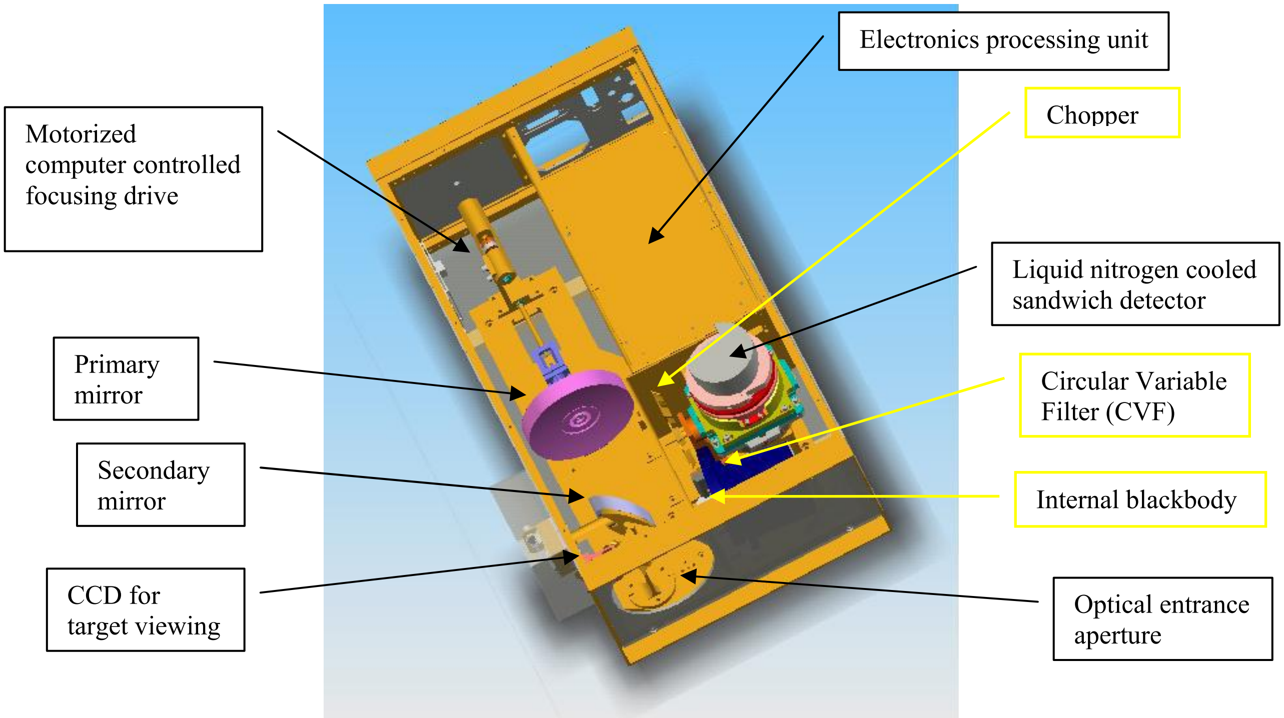

Figure 2. Three-dimensional diagram of the SR 5000WNV system.

2. THEORETICAL NEΔT PREDICTIONS

We start by checking whether the CI standard SR 5000 spectroradiometer[3] fulfills the application requirements defined in section 1 above. Direct blackbody NEΔT measurements made with the standard SR 5000 using the values of the parameters of section 1 showed that the standard SR 5000 as is, is not satisfactory: the noise equivalent temperature difference NEΔT is worse than required by a factor of between 3 and 4.

In order to improve this result, first we build a spectroradiometric performance model to translate the known SR 5000 performance in its standard conditions, into a performance prediction for the conditions of section 1. In a second stage, a comparison of this prediction with the actual measured SR 5000 performance is used to validate the model. Then, in the third stage, as it is shown later, the same model shows us the way to design the SR 5000 modifications needed to fulfill the requirements of section 1.

It is known[4] that the NEΔT performance of a well designed IR radiometer or spectroradiometer (such as one similar to the SR 5000) can be predicted, once the optical parameters and the detector spectral figure of merit D_λ* are known, as follows:

$$NE\Delta T = \frac{F\#^2 \sqrt{\frac{\pi}{4}} \times d \times \sqrt{BW}}{D_\lambda^* \times \Delta\lambda \times \left.\frac{\partial L}{\partial T}\right|_{T=T_m,\lambda} \times (\frac{\pi}{4})^2 \times s^2 \times \tau_\lambda} = \frac{\sqrt{\frac{\pi}{4}} \times d \times \sqrt{BW}}{D_\lambda^* \times \Delta\lambda \times \left.\frac{\partial L}{\partial T}\right|_{T=T_m,\lambda} \times \Omega \times A_o \times \tau_\lambda} \quad (1)$$

In this equation:

NEΔT is the Noise Equivalent temperature difference of the spectroradiometer, when measuring a blackbody at temperature T_m,

F# is the f number of the spectroradiometer collection optics,

d is the detector diameter,

D^*_λ is the spectral detectivity of the detector in units of cm√Hz/Watt (reference 4, equation 1.25, page20), normalized to detector area and electronic bandwidth: this is usually measured and given by the detector manufacturer,

λ is the wavelength at which the measurement is done,

$\Delta\lambda$ is the wavelength full width half maximum bandpass of the spectroradiometer monochromator (in this case a CVF or Circular Variable Filter), at the measurement wavelength,

L is the blackbody spectral radiance at temperature T_m and wavelength λ,

$\partial L/\partial T$ is the partial derivative of L with respect to temperature,

s is the diameter of the field stop defining the field of view of the spectroradiometer,

Ω is the solid angle field of view of the spectroradiometer,

A_o is the area of the collection optics,

τ_λ is the monochromator transmittance at wavelength λ,

BW is the electronic bandwidth of the measurement.

The factors $\sqrt{(\pi/4)}$ in the numerator and $(\pi/4)^2$ in the denominator of equation (1) result from assuming circular optics, circular detector and circular field of view (FOV).

Further assumptions in equation (1) are:

1. The electronics noise contribution is negligible,
2. Equation (1) here is more general than Equation 1.42 of reference 4, because here the field stop area $\pi/4s^2$ is not necessarily equal to the detector area $\pi/4d^2$, but the detector is large enough to receive all radiation entering the field of view of the instrument through the field stop.
3. The NEΔT measurement will be done with an electronic bandwidth BW of 1 Hz.

During the detector alignment process in the factory, a trade-off is made between the best NEΔT value that can be reached and the so called field of view flatness (or uniformity of response), so that a point source give a signal as independent as possible of its position within the field of view. The price paid to achieve a typical uniformity of ±10%, is a loss of signal of approximately a factor of 2. To take this into account in our NEΔT model, we note that in practice this phenomenon is equivalent to a decrease of the measured D^*_λ by a factor of 2.

We now calculate the NEΔT value predicted by equation (1) for the SR 5000 standard conditions, knowing its optical parameters:

T = 100 C,
FOV = 6 milliradians,
F# = 4,
d = 0.2 cm.,
D^*_λ = 7.5E+10 cm.√Hz/Watt; this value of InSb detector D* is artificially decreased by a factor of 2 from a typical value, in order to take into account the FOV flatness trade-off explained above,
BW = 1Hz,
$\lambda = 5\ \mu$,
$\Delta\lambda = 0.7\%\ 5\ \mu = 0.035\ \mu$,
s = 0.3 cm.,
$\tau_\lambda = 0.36$.

Equation (1) with these parameter values yields:

$$NE\Delta T_{s\tan dardSR5000} = \frac{16\sqrt{\frac{\pi}{4}} \times 0.2}{7.5E+10 \times 0.035 \times 3.6E-05 \times (\frac{\pi}{4})^2 \times 0.09 \times 0.36} \approx 1.5m\deg C. \quad (2)$$

This theoretical estimate agrees well with the standard SR 5000 measured NEΔT values in the above conditions. This model does not take into account electronic noise contributions from the synchronous detection circuitry and analog to digital conversion. Because of these additional noise contributions and the variability in production among individual instruments, CI commits itself, in its commercial literature, to an NEΔT of a few millidegrees, usually 5, when measured under these stated conditions. This good agreement between the result of equation (2) and experimental results shows that this theoretical approach for NEΔT assessment is justified: constant contributions to the noise by the electronic processing are not significant or at most are of the same order of magnitude of 1 millidegree.

In practice, NEΔT is measured[4] by recording the two signals S_1 and S_2 corresponding to two different blackbody temperatures in the vicinity of the temperature range of most measurements (filling the field of view of the instrument), recording the peak to peak noise n_{pp}, and calculating:

$$NE\Delta T_{measured} = \frac{1}{2\pi}\frac{n_{pp}}{S_2 - S_1}\Delta T \tag{3}$$

ΔT in (3) is the difference between the two measured temperatures (in units of degrees C). The factor 1/2π is needed to properly take into account the fact that n_{pp} is random noise, while NEΔT is defined in this field as root mean square noise.

If we were now to use the conditions of section 1 with the standard SR 5000 without any design modifications, the predicted NEΔT would change as follows. The new parameter values are:

T = 25 C,
FOV = 1.7 milliradians,
F# = 4,
d = 0.2 cm.,
D^*_λ = 6E+10 cm.√Hz/Watt,
BW = 1Hz,
λ = 4 μ,
Δλ = 2% 4 μ = 0.08 μ,
s = 0.085 cm.,
τ_λ = 0.36.

The predicted new NEΔT value is given by:

$$NE\Delta T_{SR5000new} = \frac{16\sqrt{\frac{\pi}{4}}\times 0.2}{6E+10\times 0.08\times 2.8E-06\times(\frac{\pi}{4})^2\times 0.0072\times 0.36} = 130m\deg C. \tag{4}$$

This value is 88 times worse than the SR 5000 NEΔT measured in the standard conditions, and is also outside the requirement of 40 mdeg. of section 1.

The actual SR 5000 NEΔT measurements in the conditions of equation (4) agree with the prediction of equation (4). This fact shows us that:

1) The model of equation (1) is correct,
2) The contribution of the effects mentioned above (such electronic noise, A/D conversion, etc.) to the total noise is negligible in this case too.

The measured NEΔT result according to equation (3) is:

$$NE\Delta T_{measured} = \frac{1}{2\pi}\frac{n_{pp}}{S_2 - S_1}\Delta T \approx 130m\deg. \tag{5}$$

3. THE CHALLENGE

The gap between the value shown in equation (5) and the sought value of 40 mdeg. is more than a factor of 3, and it seems at first that this is quite difficult to overcome. It is now clear that some modifications to the standard SR 5000 must be introduced, if an NEΔT value better than 40 mdeg. is to be reached in the conditions of section 1. The challenge is then to find which design modifications let us comfortably achieve this purpose, implement them and test the new instrument performance.

Let us first make a list of possible modifications that may result in NEΔT improvements, and then assess which ones are feasible in order of priority, from the point of view of technical effectiveness (e.g. amount of improvement versus engineering effort). The guiding model is equation (1).

DESIGN MODIFICATION	NEW PARAMETER VALUE	FACTOR OF NEΔT IMPROVEMENT	IMPLEMENTATION DECISION
a. Increase the throughput ΩA_o	Since the field of view is specified, A_o must be increased	Proportional to A_o	No
b. Use higher D* detector (by special selection of manufacturer)	2.4E+11 cm√Hz/W	2	Yes
c. Decrease detector size: by decreasing the focal length, the field stop and detector size can be decreased, with the same field of view	0.5 mm.	4	Yes
d. Don't optimize response uniformity in the FOV	Modified detector alignment procedure	2	Yes
e. Increase τ_λ	Dependent on CVF manufacturer	Proportional to τ_λ	No
TOTAL IMPROVEMENT FACTOR BY IMPLEMENTED MODIFICATIONS		**16**	

Table 1 List of modifications of the SR 5000 implemented to achieve the required value of NEΔT=40 mdeg. when measuring a 25 C blackbody.

Dividing the value in equation (5) by the total factor of Table 1, we get an estimated improvement to:

$$NE\Delta T = 8 \text{ mdeg.,} \qquad (6)$$

if all the modifications of Table 1 marked "Yes" in the rightmost column are actually implemented. This result is well within the required value of 40 mdeg. Even with the addition of approximately 4 mdeg. from electronic and A/D noise, and a factor of 3 for instrument variability, we are still within this specification.

The modifications of Table 1 marked "Yes" were implemented on several instruments, and the measured NEΔT results were all between 20 and 25 mdeg., in good agreement with these predictions. The so modified SR 5000 is now called SR 5000WNV.

4. BLACKBODY RADIANCE MEASUREMENT ACCURACY WITH THE SR 5000WNV

The goal is to measure the integral radiance of a blackbody of unknown temperature, in the spectral ranges of 3-5μ and 8-12 μ with accuracy better than 1%, for blackbody temperatures between 5 and 100 C. The hope is that it can be achieved with the same SR 5000WNV model according to the modifications of Table 1, without further modifications. Figure 3 shows the blackbody temperature error corresponding to 1% of blackbody radiance error, in the two integral ranges above, as function of temperature.

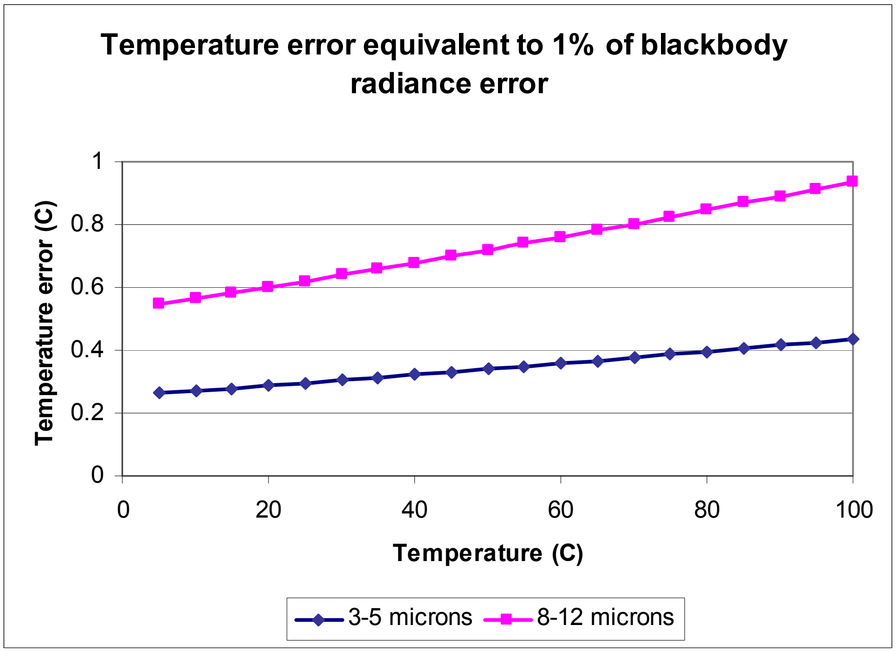

Figure 3. Temperature error equivalent to 1% of integrated blackbody radiance error.

According to our experience, the simple use of the fundamental equations of spectral IR radiance measurements (equations (1) and (2) of reference 3, reported here),

$$S(\lambda) = K(\lambda)\left[W(\lambda) - P(\lambda, T_{\text{int}})\right], \text{ and} \tag{7}$$

$$K(\lambda) = \frac{S_C(\lambda)}{P(\lambda, T) - P(\lambda, T_{\text{int}})} \tag{8}$$

with one single calibration temperature T covering the whole range of 5 to 100 C, does not yield better than a few percent accuracy, and therefore it does not fulfill the 1% requirement.

As explained in reference 3 Equation (7) expresses the linearity of the measured spectral signal $S(\lambda)$ of the instrument in volts, with respect to the difference between the blackbody radiance to be measured $W(\lambda)$ and the internal blackbody reference radiance $P(\lambda,T_{int})$. This is so because the SR 5000 design is based on: i) linearity of the detector, ii)chopping of the optical signal, iii) AC coupling of the detector electronic signal, iv) multiplication of the chopped signal by a suitable synchronous reference chopper signal, and v) low-pass filtering of the result. $P(\lambda,T_{int})$ is known because the internal blackbody temperature is monitored to 0.1 C resolution and accuracy. For clarity, we must remind the reader here that we are dealing only with radiance measurements of blackbodies. So, all of $W(\lambda)$, $P(\lambda,T_{int})$ and $P(\lambda,T)$ are Planck functions, each one at a specific temperature. Equation (8) exploits the same relation as equation (7) to measure the instrument spectral response function $K(\lambda)$, using a blackbody at known temperature T, emitting Planck radiance $P(\lambda,T)$ and giving a measured signal S_C. Once $K(\lambda)$ is known from equation (8), since T and T_{int} are known, it can be plugged into (7) to calculate the unknown $W(\lambda)$.
The $K(\lambda)$ function is in principle independent of temperature; if this were truly the case, once measured at a certain calibration temperature T, it should give accurate results when used to measure the blackbody radiance at different temperatures. However in fact, when measured at different calibration temperatures, $K(\lambda)$ is shown to be not constant enough as function of T, to yield the desired accuracy.

It is to be noted first that the noise contribution to the radiance measurement error is negligible, since the measured NEΔT values in the conditions of section 1 (20-25 mdeg.), are much lower than the temperature error values of figure 1 (a factor of 10 in the worst case). We therefore must look elsewhere for sources of error in the accuracy of radiance measurements.

Accuracy of infrared radiometric and spectroradiometric measurements is known from practical experience to be of the order of a few percent of radiance for a blackbody filling the field of view of the radiometer and using liquid nitrogen cooled InSb and HgCdTe detectors. The contributing phenomena to the errors are multiple and varied, and some of them are listed below:

- Emissivity error of the calibration source,
- Unknown and uncontrolled atmospheric self-emission and scattering of transient sources into the radiometer collection optics,
- Deviation from linearity of the detector and electronic amplification,
- Inaccuracy of calibration blackbody temperature monitoring,
- Inaccuracy of internal blackbody reference temperature monitoring,
- Uncontrolled scattered radiation from the room and the internal walls of the instrument into the detector.

Figure 4 shows as examples typical response functions K(λ) measured at 5 and 10 μ at different calibration temperatures. Except for the peak and dip around room temperature, which are spurious because they are due to the singularity of equation (8) for $T=T_{int}$, the general trend is of a K function which is constant as function of temperature.

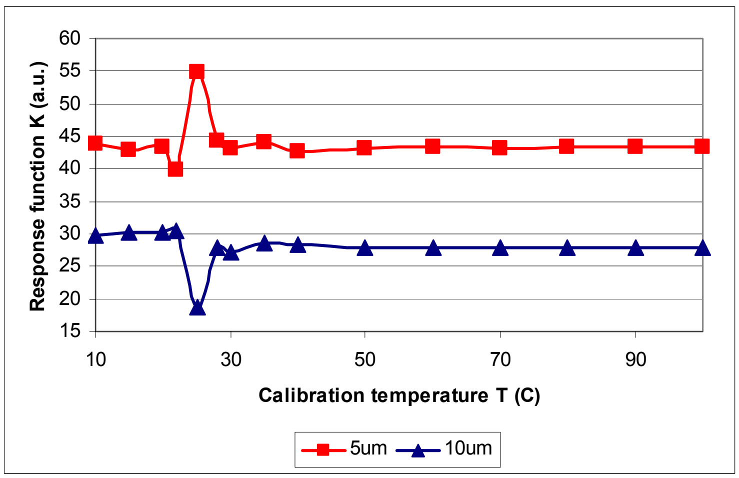

Figure 4. Typical measured values of the response function K(λ) at 5 and 10 μ at different calibration temperatures, showing systematic differences of ~4% at 5 μ and ~10% at 10 μ between the regions below and above room temperature.

Even without considering the temperature range 22-28 C, there is a systematic difference in the average K for temperatures below and above room temperature of~4% and 10% for 5 and 10 μ respectively. It is clear that with such uncertainties in K for different temperatures, one cannot hope to measure blackbody radiance with 1% accuracy, following the standard algorithm of equations (7) and (8) for the whole specified temperature range.

Now, noting that this unwanted K behavior is systematic, we devised a multi-point method of calibration, hoping that it will improve the measurement accuracy in the whole temperature range. It turns out that this hope is fulfilled, as seen below.

5. MULTI-POINT CALIBRATION CONCEPT FOR BLACKBODY RADIANCE MEASUREMENTS

We divide the temperature region 5 to 100 C into a number of sub-regions in which Equations (7) and (8) are valid separately with a different response function K(λ) in each one. Each K(λ) function is calculated using equation (8) from a blackbody spectrum measurement at a calibration temperature T within its specific sub-region. When an unknown blackbody spectrum is measured, first it is compared to the blackbody spectra previously measured at the calibration temperatures, in order to find to which sub-region it belongs to; then, by using the corresponding K(λ) it is calibrated to radiance units, and finally the unknown temperature is determined by best fit to the closest Planck function. It turns out, from the measurements carried out so far, that the sought 1% accuracy or better is achieved. The instrument software is designed so that the whole procedure of measuring the unknown blackbody is done automatically.

Mathematically, this procedure is as follows. We record n spectra $S_i(\lambda)$ for each measured blackbody radiance at n different calibration temperatures (i=1,…,n) in the range 5 to 100 C. Then, the measured spectrum $S_m(\lambda)$ of a blackbody at an unknown temperature is compared with the set of recorded spectra $S_i(\lambda)$, and the unknown temperature is found by interpolation as follows.

According to equation (8) we write, for the n calibration spectra (i=1 to n):

$$S_C{}^i(\lambda) = K_i(\lambda)\left[P(\lambda,T_i) - P(\lambda,T_{\text{int}})\right], \tag{9}$$

and according to (7):

$$S_m(\lambda) = K'(\lambda)\left[P(\lambda,T_m) - P(\lambda,T_{\text{int}})\right]. \tag{10}$$

The subscript m is for the quantities of the unknown blackbody to be measured.

All $K_i(\lambda)$'s are derived from (9) by dividing both sides by the square parenthesis.

Now $K'(\lambda)$ is found by linear interpolation wavelength by wavelength between the two closest of the $K_i(\lambda)$ set, $K_{j-1}(\lambda)$ and $K_j(\lambda)$, such that $S_C{}^{j-1} < S_m < S_C{}^j$. The constant of interpolation α is such that:

$$\alpha = \frac{I_m - I_{j-1}}{I_j - I_{j-1}}, \tag{11}$$

where I_i (for i=1,…,n) and I_m are the integral radiometric signals in volts (between 3 and 5 microns or between 8 and 12 microns, according to the case), of the calibration blackbody source at temperature T_i, and of $S_m(\lambda)$:

$$I_i = \int_{\lambda_1}^{\lambda_2} S_C{}^i(\lambda)d\lambda \tag{12}$$

$$I_m = \int_{\lambda_1}^{\lambda_2} S_m(\lambda)d\lambda \,. \tag{13}$$

So

$$K'(\lambda) = (1-\alpha)K_{j-1}(\lambda) + \alpha K_j(\lambda)\,. \tag{14}$$

The result of (14) is used in (10) to find $P(\lambda,T_m)$, which can be done since $S_m(\lambda)$ is measured and T_{int} is known from the continuous internal blackbody monitoring present in the instrument. We find T_m by best fitting the function $S_m(\lambda)/K'(\lambda)+P(\lambda,T_{int})$ as derived from equation (10) by dividing it by the square parenthesis, to the closest Planck function. Finally, once we have T_m and its corresponding Planck function, we can calculate:

$$\int_{\lambda_1}^{\lambda_2} P(\lambda,T_m)d\lambda = \text{total radiance output of the blackbody in the relevant wavelength range.} \tag{15}$$

Now we want to find out how much T_m deviates from the "true" radiometric temperature T_m' of the measured blackbody, and this gives how accurately the SR 5000WNV measures blackbody radiance.

First we define T_m' as that temperature such that:

$$\int_{\lambda_1}^{\lambda_2} P(\lambda,T_m')d\lambda = \int_{\lambda_1}^{\lambda_2} [\varepsilon P(\lambda,T_{set}) + (1-\varepsilon)P(\lambda,T_{room})]d\lambda \tag{16}$$

Where T_{set} is the set temperature on the blackbody, and T_{room} is the room temperature at the time of the measurement. Figures 5 and 6 show the results of this comparison for the two bands 3-5 and 8-12 microns.

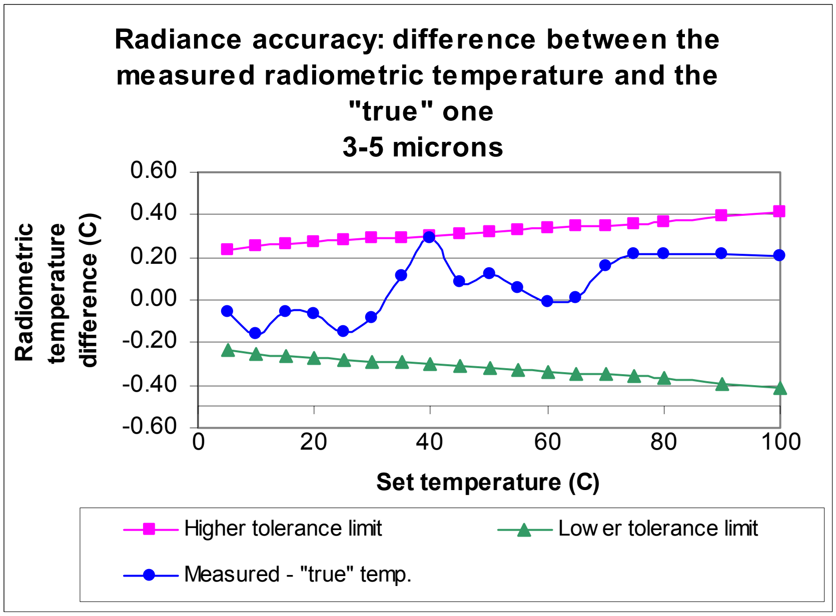

Figure 5. The radiometric temperature measurement by the SR 5000WNV in the 3-5 micron range does not differ from the "true" radiometric temperature by more than an amount equal to 1% of the respective radiance at all temperatures in the range 5-100 C. The pink and green curves are the tolerance limits according to figure 3. Note that the average of the radiometric temperature difference is 0.13 C, corresponding to 0.7 to 0.33 % of radiance, depending on the wavelength.

These results show that the measured radiometric temperature does not differ from the "true" radiometric temperature by more than an amount corresponding to 1% of the Planck function radiance at the measurement temperature, as required. This is seen in figures 5 and 6 by the fact that the measured curves are contained within the higher and lower temperature tolerance limits equivalent to 1% of blackbody radiance as reported in figure 3.

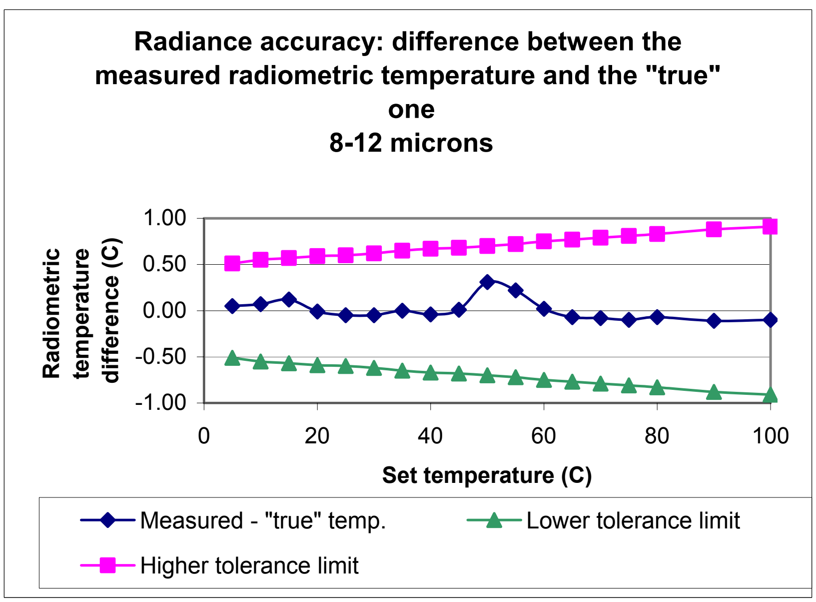

Figure 6. The radiometric temperature measurement by the SR 5000WNV does not differ from the "true" radiometric temperature by more than an amount equal to 1% of the respective radiance at all temperatures in the range 5-100 C, and actually there is spare left. The pink and green curves are the tolerance limits according to figure 3. Note that the average of the radiometric temperature difference is 0.09 C, corresponding to 0.2 to 0.1 % of radiance, depending on the wavelength, which is 5-10 times better than specified.

In fact, in the 3-5 micron range, the average value of the radiometric temperature difference is 0.13 C, and in the 8-12 micron range it is 0.09 C. These values correspond to a radiometric error of 0.7% to 0.33% in the 3-5 microns range, and of 0.2% to 0.1% in the 8-12 micron range. In the latter case, the result is 5-10 better than specified.

6. SUMMARY

We have built and demonstrated an IR spectroradiometer system (the SR 5000WNV) capable of measuring the radiometric temperature of blackbodies with a factor of 5 better sensitivity, and a factor of 5 to 10 higher accuracy than previously achieved. The SR5000WNV is a modified standard SR 5000 spectroradiometer, a proven, modular and easy to use instrument, developed by CI in previous years. The much improved performance has been achieved by a number of engineering changes made on the SR 5000, the conceptual modeling of which has been shown in this paper, together with the most important test results.

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