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Linearity Study of a Spectral Emissivity Measurement Facility

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Abstract Linearity is one of the important characteristics of a spectral radiation measurement facility. Basically, it depends on the linearity of the spectral responsivity of the detector and amplifier at different wavelengths. As spectral emissivity is measured over wide wavelength and temperature ranges and the detection system has significant drift and noise, it is not easy to measure the linearity of this facility accurately using only one standard radiator. A simple double-blackbody method has been adopted to simulate reference emissivity samples and test the linearity of the spectral emissivity measurement facility developed at the National Institute of Metrology. Good linearity results were obtained from 3 μm to 15 μm. This method minimizes the influence of drift on the emissivity measurement over a wide ratio of measurement signals and wide spectral range.

Keywords Double-blackbody method · Linearity · Spectral emissivity · Spectral responsivity

1 Introduction

The characterization of the linearity of the spectral responsivity of precision radiation thermometers, radiometers, or radiation ratio instruments is one of the most important measurements. In the 1970s, fundamental techniques for linearity measurement (superposition, dual aperture, and calibrated attenuator methods) were established and used to characterize the response of nonlinear detectors such as photomultipliers,

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photocells, and silicon photodiodes [1–4]. In the infrared region, infrared quantum photodetectors, e.g., PbS, InSb, and HgCdTe detectors, are widely used and their linearity has been investigated [5–7]. For infrared spectrometers, especially Fourier-transform infrared spectrometers, the nonlinear behavior of the detectors was investigated in detail [8–10]. The sources employed for testing the linearity are usually superimposed lamps, calibrated lamps, or blackbody radiators of known temperature.

Recently, a grating-monochromator-based spectral emissivity measurement facility has been developed at the National Institute of Metrology (NIM), Beijing, China [11]. In this paper, a double-blackbody method, which needs no special testing facility except an extra blackbody radiator adapted to simulate the reference emissivity samples for linearity testing of the spectral emissivity measurement facility at NIM, is presented.

2 Facility and Principle of Spectral Emissivity Measurement

Measurement methods of spectral emissivity include direct and indirect methods based on whether Kirchhoff's law is used to obtain the spectral emissivity [10,12–16]. Several widely used measurement approaches by means of the direct method are based on Fourier-transform spectrometer, band-pass radiometer [10,12–14], and grating or prism spectrometer schemes [15,16].

The measurement scheme introduced in this paper uses a grating monochromator. Its characteristics, simple and clear in the theoretical model and a continuous spectral measurement with a narrow bandpass, are advantageous to precision measurement even though the disadvantages of weak signal and time-consuming operation have to be faced.

The directional spectral emissivity can be measured by this facility in the temperature range from 200 °C to 730 °C and the spectral range from 2 µm to 15 µm.

2.1 Measurement Facility

A schematic diagram of the spectral emissivity measurement facility is shown in Fig. 1. The temperature controller (3) controls the temperature of a measured sample fixed on the sample heater (1). The measured sample or blackbody radiator is imaged by the concave spherical mirror (4) and the plane mirror (5) onto the entrance slit of the grating monochromator (8) through the cut-off filter on the filter wheel (7). The radiation from the exit slit of the monochromator is received by the photoconductive (PC) HgCdTe detector (9), and the output voltage of the detector pre-amplifier is measured by the lock-in amplifier (10), Model SF830. The optical chopper (6) located in front of the entrance slit is employed to modulate the entrance beam and provide the reference signal to the lock-in amplifier. The measured sample and the blackbody radiator can be moved horizontally by the motorized linear stage (11) to change the measured object, and the measured sample can be rotated by the motorized rotation stage (12) to change the normal to the measured sample in the horizontal plane for measuring the directional spectral emissivity.

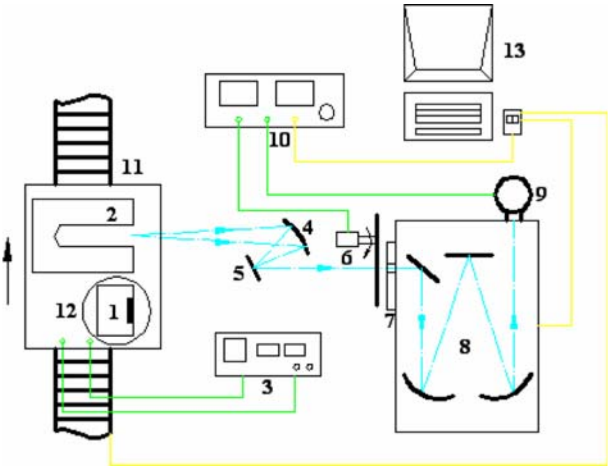

Fig. 1 Schematic diagram of the spectral emissivity measurement facility: 1—sample and its heater; 2—blackbody radiator; 3—sample temperature controller; 4—spherical mirror; 5—plane mirror; 6—chopper; 7—filter wheel; 8—monochromator; 9—detector; 10—lock-in amplifier; 11—motorized linear stage; 12—motorized rotation stage; 13—computer

The PC HgCdTe detector is liquid-nitrogen cooled and has a $2\times2\,\text{mm}^2$ sensitive area and (2–15) µm spectral response range. The grating monochromator, Model SPB300, has a 300 mm focal length. Its grating is a left-right split joining two 67 lines·mm^{-1} gratings with 3.14 µm and 10.25 µm blaze wavelengths, respectively. The wavelength range is (2–25) µm, and the wavelength uncertainty after calibration is less than 10 nm. Its dispersion is approximately 49 nm · mm^{-1}. During measurements, the widths of the entrance and exit slits are set at 3 mm and the spectral bandwidth is then 147 nm. A set of four cut-off filters is employed to block the second and higher orders. The concave spherical mirror is 50 mm in diameter and has a 150 mm focal length. The objective distance and image distance are 600 mm and 200 mm, respectively, and the target sizes are 9 mm wide and 6 mm high in this case. All the mirrors are gold-plated for high reflectance.

The blackbody radiator, Isotec 976, has an emissivity greater than 0.995, a 65 mm diameter aperture, and can be operated from 50 °C to 550 °C. Its temperature stability is better than 0.2 °C and a precision platinum resistance thermometer measures the blackbody cavity temperature.

A sheathed thermocouple of 1 mm diameter inserted into a hole in the sample measures its temperature.

2.2 Measurement Principle

At a known ambient temperature T_{am}, the effective spectral radiance in a given direction with respect to the measured sample surface at temperature T_{s} is given by

$$L_{\text{eff}}(\lambda, T_{\text{s}}) = L(\lambda, T_{\text{s}}) + [1 - \varepsilon(\lambda, T_{\text{s}})]\, L_{\text{b}}(\lambda, T_{\text{am}}) \tag{1}$$

where $L(\lambda, T_s)$ is the effective spectral radiance of the measured sample, $L_b(\lambda, T_{am})$ is the spectral radiance of a blackbody at ambient temperature, and $\varepsilon(\lambda, T_s)$ the directional spectral emissivity of the measured sample at wavelength λ and temperature T_s.

The effective normal spectral radiance of the chopper wheel at ambient temperature T_{am} is given by

$$L_{meff}(\lambda, T_{am}) = L_b(\lambda, T_{am}) \tag{2}$$

The output voltage for the sample measurement, U_s, is proportional to the difference in the effective spectral radiance in a given direction from the measured sample and the effective normal spectral radiance of the chopper wheel:

$$U_s = K\left[L_{eff}(\lambda, T_s) - L_{meff}(\lambda, T_{am})\right]\eta(\lambda)R(\lambda)\Delta\lambda \tag{3}$$

K is an instrument factor, $R(\lambda)$ is the relative spectral responsivity of the detector, $\eta(\lambda)$ is the spectral efficiency of monochromator, and $\Delta\lambda$ is the bandwidth which depends on the widths of the entrance and exit slits of monochromator.

Correspondingly, the output voltage for the blackbody radiator measurement, U_b, is given by

$$U_b = K\left[L_{reff}(\lambda, T_b) - L_{meff}(\lambda, T_{am})\right]\eta(\lambda)R(\lambda)\Delta\lambda \tag{4}$$

where $L_{reff}(\lambda, T_b)$ is the normal spectral radiance of the blackbody.

K, $R(\lambda)$, $\eta(\lambda)$, and $\Delta\lambda$ are considered to be constant when measuring U_s and U_b at the same wavelength and with the same instrument conditions. Dividing Eq. 3 by Eq. 4, the directional spectral emissivity can be calculated as

$$\varepsilon(\lambda, T_s) = \varepsilon_b(\lambda, T_b)Ratio C \tag{5}$$

where $\varepsilon_b(\lambda, T_b)$ is the normal spectral emissivity at wavelength λ and temperature T_b, Ratio is the ratio of the output signals U_s and U_b,

$$Ratio = \frac{U_s}{U_b} \tag{6}$$

and C is the correction for nonisothermality of the measured sample and the blackbody radiator,

$$C = \frac{L_b(\lambda, T_b) - L_b(\lambda, T_{am})}{L_b(\lambda, T_s) - L_b(\lambda, T_{am})} \tag{7}$$

3 Linearity Measurement by the Double-Blackbody Method

3.1 Measurement Principle

Good linearity of the spectral radiation measurement is one of the keys to accurate emissivity measurement. For linearity testing over a wide spectral range and a wide radiance range, a blackbody radiator is a good reference radiation source. However, the drift of the spectral radiation measuring instrument during the period required to change and stabilize the temperature of the blackbody radiator is very large for an accurate linearity test. A double-blackbody method was adopted to reduce the influence of drift of the measurement system.

With the double-blackbody method, two identical (or substantially similar) blackbody radiators are employed. One of them has the same role as that of the blackbody radiator during a 'real' emissivity measurement, and the other one is used in place of the measured sample, as a standard sample whose spectral characteristic is known. For the linearity test, one blackbody radiator is set at a test temperature, T_b, and the standard sample radiator can be set at a series of lower temperatures, T_s. Thus, different spectral radiances from samples of different emissivity can be simulated by changing the temperature of the 'standard sample' (the second blackbody).

When testing the linearity of the spectral responsivity of a spectral radiation-measuring instrument, the spectral responsivity cannot necessarily be considered constant and can be expressed as a function of the temperature of the blackbody radiator. Therefore, Eqs. 3 and 4 can be written as

$$U_s = K\left[L_{\text{eff}}(\lambda, T_s) - L_{\text{meff}}(\lambda, T_{\text{am}})\right]\eta(\lambda)R(\lambda, T_s)\Delta\lambda \tag{8}$$

and

$$U_b = K\left[L_{\text{reff}}(\lambda, T_b) - L_{\text{meff}}(\lambda, T_{\text{am}})\right]\eta(\lambda)R(\lambda, T_b)\Delta\lambda \tag{9}$$

where $R(\lambda, T_s)$ and $R(\lambda, T_b)$ are the spectral responsivities of the spectral radiation measuring instrument when measuring the standard sample and the blackbody radiator, respectively. Dividing Eq. 8 by Eq. 9,

$$\frac{U_s}{U_b} = \frac{\varepsilon_b(\lambda, T_s)}{\varepsilon_b(\lambda, T_b)} \cdot \frac{L_b(\lambda, T_s) - L_b(\lambda, T_{\text{am}})}{L_b(\lambda, T_b) - L_b(\lambda, T_{\text{am}})} \cdot \frac{R(\lambda, T_s)}{R(\lambda, T_b)} \tag{10}$$

The emissivities of the two blackbody radiators, $\varepsilon_b(\lambda, T_s)$ and $\varepsilon_b(\lambda, T_b)$, are approximately equal. Then, the linearity is given by

$$LN(T_s, T_b) = \frac{R(\lambda, T_s)}{R(\lambda, T_b)} = \frac{\varepsilon_b(\lambda, T_b)}{\varepsilon_b(\lambda, T_s)} Ratio \cdot C \approx Ratio \cdot C \tag{11}$$

The linearity *LN* equals the ratio of the measured output voltage ratio ($Ratio$) to the ideal measurement signal ratio ($1/C$), and is equal to the value of the simulated emissivity.

3.2 Noise and Drift Rejection

When measuring spectral emissivity or testing linearity, the noise and drift of the radiation detection system are significant, especially with the conditions of lower temperature and shorter and longer wavelengths. Therefore, a statistical measurement method has to be used to reject the effect of the noise and the comparative method is adopted to remove the effect of the linear component of the drift at each wavelength. The blackbody measurement signals, $\overline{U_{b1}}$ and $\overline{U_{b2}}$, are, respectively, measured before and after measuring the sample measurement signal $\overline{U_s}$. The signal ratio can be calculated as

$$Ratio_j = \frac{2\overline{U_s}}{\overline{U_{b1}} + \overline{U_{b2}}} \tag{12}$$

To reject the effect of the nonlinear component of the drift, the Ratio in Eqs. 5 and 11 is measured statistically in practice:

$$\overline{Ratio} = \frac{1}{m}\sum_{j=1}^{m} Ratio_j \tag{13}$$

3.3 Results and Uncertainty Estimation

The statistical measurement method mentioned above was adopted to restrain the influences of drift and noise of the measurement facility on the linearity testing. The typical measurement results for the linearity of the spectral radiation detection system under different test conditions are shown in Table 1 and the simulated emissivity values, $1/C$, for the test conditions in Table 1 are shown in Table 2. The temperatures of the simulated emissivity test, T_b, were set at 200 °C, 350 °C, and 550 °C and different emissivity values, $1/C$, were simulated by changing the standard sample temperature, T_s.

According to Eq. 11, the uncertainty of the linearity testing is comprised of the uncertainties of $\varepsilon_b(\lambda, T_b)$, $\varepsilon_b(\lambda, T_s)$, Ratio, and C. Assuming all the uncertainty components are independent and considering that the two blackbody radiators have the same emmisivity, the linearity uncertainty can be represented as

Table 1 Typical linearity test results of spectral radiation detection system under different test conditions

λ(μm)	t_b (°C)									
	200			350			550			
	t_s (°C)									
	100	150	200	200	300	350	200	350	450	550
3	1.037	1.019	1.000	1.044	1.008	1.000	1.036	1.010	1.002	0.996
6	1.011	1.009	0.999	1.011	1.001	0.999	1.007	1.002	1.002	0.997
9	1.012	1.007	1.000	1.006	1.003	1.000	1.003	1.001	1.002	0.999
12	1.011	1.007	1.001	1.006	1.003	1.001	1.005	1.001	1.001	1.000
15	1.035	0.987	0.995	1.025	1.003	0.995	0.999	1.003	1.001	0.996

Table 2 Simulated emissivity value, $1/C$, for the test conditions in Table 1

λ(μm)	t_b (°C)									
	200			350			550			
	t_s (°C)									
	100	150	200	200	300	350	200	350	450	550
3	0.066	0.306	1.000	0.090	0.516	1.000	0.014	0.158	0.452	1.000
6	0.215	0.524	1.000	0.282	0.707	1.000	0.107	0.378	0.656	1.000
9	0.299	0.609	1.000	0.389	0.774	1.000	0.188	0.483	0.728	1.000
12	0.343	0.648	1.000	0.443	0.802	1.000	0.237	0.534	0.760	1.000
15	0.367	0.669	1.000	0.473	0.817	1.000	0.265	0.561	0.776	1.000

$$\frac{u_{LN}^2}{LN^2} = 2\frac{u_{\varepsilon_b}^2}{\varepsilon_b^2} + \frac{u_R^2}{Ratio^2} + \frac{u_C^2}{C^2} \tag{14}$$

where u_{ε_b}, u_R, and u_C are the uncertainties of the blackbody radiator emmisivity, Ratio measurement, and correction item, C, respectively.

3.3.1 Blackbody Radiator Emmisivity

The blackbody radiator (Isotec 976) emmisivity can be represented as 0.9975 ± 0.0025. Its standard uncertainty is $u_{\varepsilon_b} = 0.0025/\sqrt{3}$.

3.3.2 Ratio Measurement

The repeatability of the Ratio measurement is better than 0.01, except at 100 °C and 15 μm where it is 0.023. The uncertainty from the size-of-source effect for the linearity test can be neglected because both blackbody radiators employed by the test are the same model.

The correction for nonideal blocking of the cut-off filter for the second-order spectrum at 7.5 μm has been done, and the uncertainty is estimated from 0.00 to 0.02, depending on T_s and T_b.

3.3.3 Correction Item C

The uncertainty of the correction item C is

$$\frac{u_C^2}{C^2} = \left(\frac{1}{C}\frac{\partial C}{\partial \lambda}u_\lambda\right)^2 + \left(\frac{1}{C}\frac{\partial C}{\partial T_b}u_{T_b}\right)^2 + \left(\frac{1}{C}\frac{\partial C}{\partial T_s}u_{T_s}\right)^2 + \left(\frac{1}{C}\frac{\partial C}{\partial T_{am}}u_{T_{am}}\right) \tag{15}$$

If $T_s = T_b$, $\frac{\partial C}{\partial \lambda} = 0$. If $T_s \neq T_b$, $\left|\frac{1}{C}\frac{\partial C}{\partial \lambda}\right| < 2 \times 10^{-7}$nm. The wavelength accuracy of the monochromator after correction is 10 nm, so $\frac{1}{C}\frac{\partial C}{\partial \lambda}$ can be neglected.

The uncertainty of the blackbody radiator temperature measurement is estimated as $0.0036t_b$, from the calibration, stability, and thermal conduction error of the standard

Table 3 Combined standard uncertainty for the linearity test

λ(μm)	t_b (°C)									
	200			350			550			
	t_s (°C)									
	100	150	200	200	300	350	200	350	450	550
3	0.015	0.015	0.014	0.014	0.014	0.014	0.013	0.013	0.013	0.012
6	0.011	0.010	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.008
9	0.009	0.006	0.006	0.007	0.006	0.006	0.007	0.006	0.006	0.005
12	0.009	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.006
15	0.029	0.015	0.005	0.016	0.011	0.005	0.016	0.011	0.006	0.005

platinum resistance thermometer (SPRT) and the largest component, the temperature inhomogeneity between the SPRT measurement position and the blackbody cavity bottom. $\left|\frac{1}{C}\frac{\partial C}{\partial T_b}\right|$ is larger at lower temperature and shorter wavelength. The uncertainty contributed to the linearity is about 0.02 at the shorter wavelength end and around 0.005 at the longer. The uncertainty of T_s is similar to that of T_b.

The ambient temperature is measured with 2 °C uncertainty. If $T_s = T_b$, $\frac{\partial C}{\partial T_{am}} = 0$. If $T_s \neq T_b$, $\left|\frac{1}{C}\frac{\partial C}{\partial T_{am}}\right|$ increases when T_s is close to T_{am} and the wavelength is increasing.

3.3.4 Combined Standard Uncertainty

The combined standard uncertainty of the linearity test is shown in Table 3.

4 Discussion

As for the results, a good 'linearity' of 1.000 ± 0.005 is found when $T_s = T_b$. These tests just validate the performance of the blackbody radiators employed for the linearity testing, and the results are not the true 'linearity' because nonlinearity does not contribute to the measurement results in this case.

The linearity for a wide wavelength range from 3 μm up to 15 μm, and a large simulated emissivity range was tested. Most of the data are within 1.000 ± 0.020, which is acceptable for the measurement uncertainty shown in Table 3 and for the emissivity measurement with a 4 % standard uncertainty [11], except the results tested at low signal conditions, at lower temperature and shorter or longer wavelengths. The standard sample emissivity was simulated for different lower limits at different wavelengths and at different temperatures up to an emissivity equal to one. The lower limits of the simulation are from 0.014 to 0.066 at 3 μm and from 0.265 to 0.367 at 15 μm.

An abnormality was found near 15 μm, and further study validated that the abnormality is caused by the non-ideal blocking of the cut-off filter for the second-order spectrum around 7.5 μm. The results at 15 μm shown in Table 1 have been corrected. Another abnormality was found at the shorter wavelength end. Compared with the uncertainty shown in Table 3, the linearity results near 2 μm and at lower temperature and 3 μm are notably greater than one and increase when reducing both wavelength and sample temperature. The main cause inferred was stray radiation in the monochromator, and this supposition will be investigated further by using a double-grating monochromator or adding different narrow-band filters to the single-grating monochromator in the near future.

In fact, the double-blackbody method does not show the real linearity of the spectral radiance ratio measured by the spectral emissivity measurement facility if the physical model of the testing does not agree with the ideal monochromatic model defined as Eq. 11. However, it tests the measurement accuracy of the ratio of the spectral radiance of the sample to that of a blackbody radiator and is helpful in finding the influence of other uncertainty factors.

5 Conclusion

The double-blackbody method, which does not employ a special testing facility other than an extra blackbody radiator, has been adopted to simulate reference emissivity samples for linearity testing of the spectral emissivity measurement facility at NIM. The results show that the facility has good linearity over the wavelength range from 3 μm to 15 μm and the test is valuable in identifying other uncertainty factors that influence the accuracy of the measurement results.

This simple linearity testing method minimizes the influence of facility drift on the emissivity measurement, for a wide ratio of measurement signals and a wide spectral range.

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