Linearity measurement of FTIR infrared spectral emissivity measurement facility determined using flux superposition at NIM

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Abstract. A Fournier-Transform infrared (FTIR) spectrometer using a deuterated triglycine sulfate (DTGS) detector is the radiation detective unit of the infrared spectral emissivity measurement facility of standard reference of P. R. China at NIM. The linearity of the FTIR spectral responsivity in the NIM infrared spectral emissivity measurement facility has a significant contribution to emissivity measurement. The linearity of the FTIR using the DTGS detector is experimentally measured using a flux superposition principle. A linearity measurement system of FTIR spectral responsivity is established using a high- and mid-temperature standard reference cavity blackbody radiation sources, covered the temperature range (373-1373) K. The linearity characteristics are measured in the temperature range of (473~1273) K of the blackbody radiation sources. The measurement results with the uncertainties at the representative wavelengths of 3.9 μm and 10.6 μm are reported. The associated discussions about the linearity measurement results, including the difference at the two wavelengths, the effects caused by reflection and verifications are carried out. All the measurements in this paper are traceable to NIM.

Keywords: linearity, flux superposition method, FTIR, DTGS detector, blackbody radiation source

1. Introduction

The emissivity measurement method based on the blackbody discrete is obtained by the ratio of the spectral radiance of the blackbody and the sample, derived from the emissivity definition. When measuring low emissivity materials in the high temperature region, the spectral radiance variance between the blackbody and the sample usually would span multiple orders of magnitude. Due to the non-ideal linearity characteristics of the spectral responsivity of the FTIR as the spectral radiance detection device, the effects of the linearity of the spectral responsivity on the infrared spectrum measurements can be up to the order of 1 % in a wide spectral radiance range [1, 2]. It should be considered, for the high-accuracy infrared spectral emissivity measurement facility, about the
contributions of its linearity to the measurement uncertainties. The related research works have been carried out by relevant research institutions [3, 4, 5].

An FTIR infrared spectral emissivity measurement facility using DTGS detector is set up at NIM for the temperature range of (373–1373) K and the spectrums covered in the wavelength range of (3–14) μm. Based on the flux superposition method, the linearity is experimentally carried out to measurement in the paper. The linearity characteristics of the FTIR infrared spectral emissivity measurement facility, with the associated uncertainties, are described by taking measurement results at the wavelengths of 3.9 μm and 10.6 μm, which are near the center wavelengths of the two atmospheric windows at the wavelength ranges of (3–5) μm and (8–14) μm. The associated discussions about the reliability of the linearity measurement results are carried out. The FTIR linearity characteristics obtained are the important references for uncertainty evaluation of the infrared spectral emissivity measurement.

2. Flux superposition principle

The spectral output of the blackbody radiation source obtained by the FTIR, defined by the spectral radiation flux can be given as [6],

\[ S(\lambda, T) = R(\lambda, T)\phi(\lambda, T) + S_0(\lambda, T) \]  \hspace{1cm} (1)

where \( S \) is the spectral output of the measured blackbody radiation source, \( \lambda \) is the wavelength, \( T \) is the true temperature of the blackbody radiation source, \( R \) is the spectral responsivity, \( \phi \) is the spectral radiation flux, \( S_0 \) is the spectral output of the environmental background and the stray radiation of the inner instruments.

The linearity (LN) based on the flux superposition principle, commonly used, can be defined as,

\[ LN(\lambda) = \frac{R_{A\beta}(\lambda)\phi_{A\beta}(\lambda)}{R_{A}(\lambda)\phi_{A}(\lambda) + R_{A}(\lambda)\phi_{R}(\lambda)} \]  \hspace{1cm} (2)

The measurement scheme is shown in Figure 1. The flux superposition apertures are located at the parallel optical path of the optical system. The radiation flux measured by the FTIR measurement system is realized to multiply via the superposition of the aperture area, that is, the area of the Aperture 1 plus the area of the Aperture 2 is equal to the area of the Aperture 12. The mathematical description of the linearity, with respect to the spectrum output, which eliminates the effects of the stray radiation, can be expressed as,

\[ LN(\lambda) = \frac{S_{A\beta}(\lambda) - S_0}{[S_A(\lambda) - S_0] + [S_{A\beta}(\lambda) - S_0]} \]  \hspace{1cm} (3)

where \( S_{A\beta} \) is the spectral output of the blackbody radiation source limited by the Aperture 12, \( S_A \) is the spectral output of the blackbody radiation source limited by the Aperture 1, \( S_2 \) is the spectral output of the blackbody radiation source limited by the Aperture 2, \( S_0 \) is the spectral output of the stray radiation.
When measured over a wide dynamic multi-order radiance range, the spectral flux of the blackbody radiation source is multiplied from the measurement starting point $\phi_{12,1}$ by $i$ steps to $\phi_{12,n}$. That is, the linearity is carried out with the superposition by $i$ steps, as well. Thus, the integrated linearity ($ILN$) concept calculated by a recursion formula is introduced, expressed as,

$$ILN_i(\lambda) = \prod_{n=1}^{i} LN_n(\lambda)$$  \hspace{1cm} (4)

**Figure 1.** Schematic diagram of the FTIR linearity measurement system.

3. **Linearity measurement results**

The linearity is measured in the temperature range of (473~1273) K at the wavelength of 3.9 μm and 10.6 μm. The spectral radiance has carried on 7 times multiplication at the wavelength of 3.9 μm and spans two orders of magnitude. It has carried on 3 times multiplication at the wavelength of 10.6 μm and spans one order of magnitude. The single spectrum measurement time is approximately 1 s at the wavelength range of (3~14) μm.
Figure 2. The spectral outputs ($S$) of the blackbody at 473 K and stray radiation.

Figure 3. Results of the linearity ($LN$) with the uncertainties.

The uncertainties ($u_{LN}$) in the linearity measurements are taken as the standard deviation of the average of multiple measurements. The drifts caused by stray radiation $S_0$, defined as $S/S_0$, have contributions to the uncertainties less than 0.01%, taken an example at 473 K, as shown in Figure 2, which can be ignored. The contributions to the uncertainties caused by stray radiation will be lower with the blackbody temperature increase. The uncertainties of the integrated linearity ($u_{ILNi}$) are given as,

$$u_{ILNi} = \sqrt{\sum_{i=1}^{n} (u_{LNi})^2}$$

(5)
The linearity, the integrated linearity and the associated uncertainties, at the wavelength of 3.9 μm and 10.6 μm, are represented respectively in Figure 3 and Figure 4.

![Figure 3 and Figure 4](image)

**Figure 4.** Results of the integrated linearity ($ILN_i$) with the uncertainties.

4. Discussions

(1) The basic results of the measurements as shown in Figure 3 and Figure 4 have some unexpected features, as seen the differences between 3.9 μm and 10.6 μm. One reason is that the irradiant power at 3.9 μm is much larger than that at 10.6 μm at the temperature range (473–1273) K. The linearity performance is different in the different spectral radiance ranges. The irradiant ($E$) on the detector is calculated, as shown in Figure 5. When investigating the linearity in the same irradiance range, the differences between the two wavelengths seems to be not very big and with the similar variations. The differences in the single linearity at the two wavelengths are small except on the first measurement points in the irradiance range (0.005–0.05) mW/cm², as seen in Figure 5. The differences are also repeatable obtained by multiple measurements.

(2) In the measurement experiments, the effects of some reflection effects are considered and tried to avoid the effects by some experimental designs [7]. The flow diagram is shown in Figure 6. Firstly, the emittance radiation measurement using FTIR, not transmittance measurement is just carried out. There is no sample in the sample compartment of the FTIR measurement system. It has no effect caused by reflection of a sample on measurements. Secondly, the blackbodies are used as the radiation sources. As known, a blackbody is a diffuse reflection source and has the characteristic of totally absorbing radiation. For blackbodies, it is considered that there are almost no reflection effects in the experiments. Thirdly, a reflective optical system is used. The flux superposition apertures are located between the sub-mirrors of the optical system and far away from the entrance. All the apertures are rough and coated with the high-absorption black coating. Their surfaces can be regarded as the diffuse reflection surfaces. The optical system and apertures are all protected by a water-cooled radiation...
shield during the experiments. The inner-wall of the shield is also coated black. The field of view is restricted by stops to form a small spot reaching on the detector. Therefore, it is considered that the reflections caused by coupling of blackbody radiation sources, optical system and apertures just have minimal effects on linearity measurement in the normal direction of the detection surface, and can be ignored.

![Figure 5](image.png)

**Figure 5.** Linearity ($LN$) and integrated linearity ($ILN$) in irradiance ($E$) range (0.005–0.05) mW/cm²

![Figure 6](image.png)

**Figure 6.** Flow diagram of FTR linearity measurement.

For the reflection effects inside FTIR, in particular, caused through the interferometer, their effects are analyzed via experimental data, taken the integrated linearity at 3.9 µm as an example. Under the condition of ignoring reflection outside FTIR, if there are extra significant reflections inside the FTIR, the integrated linearity ($ILN$) at each point would contain these reflection radiation components in their integrated calculations. Thus, the amount of variation between each point would be gradually enlarged. In the paper, the curve of integrated linearity ($ILN$) formed by flux multiple superposition is quasi-linear, as shown in Figure 7. It is considered that reflections inside FTIR have little effects.
Figure 7. Integrated linearity (ILN) at 3.9 μm. X axis: flux superposition number.

In the linearity measurement using superposition principle, linearity is obtained by spectrum ratio, that is $S_{12}/(S_1+S_2)$. The extra reflection spectral output, compared with the effective emittance spectral output, is a small amount, and can be eliminated approximately by ratio. The FTIR measurement system is used to emissivity measurement. We hope that the experimental conditions of linearity measurement are as same as those of emissivity measurement. Moreover, the accuracy of emissivity measurement is on the order of 0.1%. And it of linearity measurement is on the order of 0.01%.

(3) Other tests of linearity are necessary to check the consistency of the results reported in the paper. We compare the single linearity (LN) with that achieved via the comparison measured spectral ratios taken with $S_{12}$ (the aperture was fully open) to the Planckian ratios at the measured blackbody temperatures [8]. According to definition, the spectral output $S$, related to the spectral radiance $L$, is defined as,

$$S(\lambda,T) = R(\lambda,T)L(\lambda,T) + S_0(\lambda,T)$$ (6)

Thus, for the different blackbody temperatures $T_n$, the linearity (defined as $\text{RatioC}$) achieved via the comparison measured spectral ratios to the Planckian ratios is given as,

$$\text{RatioC} = \frac{R(\lambda,T_1)}{R(\lambda,T_1)} = \frac{[S_2(\lambda,T_2) - S_0(\lambda,T_0)]L_\lambda(\lambda,T_1)}{[S_1(\lambda,T_1) - S_0(\lambda,T_0)]L_\lambda(\lambda,T_2)}$$ (7)

where $T_1$ and $T_2$ are two adjacent temperature measurement points. The spectral radiance $L$ is achieved via Planck’s law. The comparison between the single linearity (LN) and $\text{RatioC}$, taken as an example of results at 3.9 μm is shown in Figure 8.

The differences between the $\text{RatioC}$ and linearity (LN) at most measurement points are small, and the curves are similar. In theory, the double-aperture method based on the flux superposition principle is a suitable experimental way for the linearity measurement. Thus, for the linearity measurement results, it is just expected that linearity (LN) in the paper and $\text{RatioC}$ have the small variations. And the
comparison between the single linearity ($LN$) and $RatioC$ have met our expectation.

In addition, the linearity in the paper is verified via using a double-blackbody method [9]. In this method, the linearity ($LN$) equals the ratio of the measured spectral signal output ratio to the ideal measurement radiance ratio, and is equal to the value of the simulated emissivity. Because of using two blackbody radiation sources, the nominal temperatures and true temperatures of each blackbody are required to be strictly equal at each temperature measurement point. Thus, this is prone to measurement errors. The linearity variation range at 3.9 $\mu$m obtained via the double-blackbody method is 0.010; the linearity difference value between it at 480 K and 1273 K is 0.0046. The variation range of the linearity at 3.9 $\mu$m in the paper via the flux superposition method is 0.011; the linearity difference value between it at 480 K and 1273 K is 0.0041. The linearity variation characteristics are much approximate in the two methods.

![Figure 8. Comparison between the single linearity ($LN$) in the paper and $RatioC$.](image)

5. Conclusions
The linearity and the integrated linearity of the FTIR infrared spectral emissivity measurement facility at are measured using the flux superposition principle. The linearity measurement system with low reflection characteristics using the double-aperture method is set up. The measurements of the linearity and the integrated linearity, with the associated uncertainties, are carried out and reported in this article. The comparison of the linearity through different methods proves the reliability of the linearity measurement results. The linearity measurement method would evaluate the contributions of the spectral responsivity variation of the FTIR infrared spectral emissivity measurement facility at NIM to the emissivity measurement uncertainty.

Acknowledgements
The authors acknowledge funding from National Natural Science Foundation of China (NSFC, No. 11772318) and Jilin Province Science and Technology Development Plan Project (20190701024GH).

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