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## Article

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# Efficient infrared radiation calibration method for wide dynamic range infrared radiation measurement systems

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## Abstract

To overcome the limitation of long calibration time of traditional infrared radiation calibration methods, the paper presents the efficient calibration method for wide dynamic range infrared radiation measurement systems. First, by analyzing the energy transfer mechanism in systems incorporating variable optical attenuator and adjustable integration time settings, we develop the comprehensive system response model that accounts for the effects of both optical attenuator and integration time, incorporating nonlinear corrections in both dimensions. The model is designed to be universally applicable and can be seamlessly integrated with the inner-outer calibration concept, enabling full calibration method coverage—from collimator-blackbody and close-range extended source to inner-outer calibration—within a unified efficient framework. Consequently, the efficient calibration algorithm is derived based on the model, utilizing nonlinear optimization for parameter estimation. Experiments demonstrate that the proposed method boosts calibration efficiency multiple times relative to traditional approaches. Furthermore, compared to Yang's fast calibration method, the approach does not require strict linearity in the attenuation and integration time dimensions, making it applicable to a broader range of infrared radiometric systems.

**Key words:** Infrared radiation calibration; Infrared radiation measurement; Infrared imaging

## 1.Introduction

Infrared radiation measurement is a non-contact technique for obtaining the infrared radiation emitted/reflected by targets. It plays an important role in target detection and perception, performance evaluation of infrared stealth materials, and non-contact temperature measurement. Due to the importance of infrared radiation measurement technology, many countries have deployed comprehensive detection architectures incorporating airborne, space-based, and ground-based components<sup>[1-4]</sup>. The ground-based infrared radiation system has been greatly developed due to its advantages such as large aperture and easy maintenance, playing an important role in the field of infrared radiation measurement<sup>[5,6]</sup>. As shown in **Fig.1**, in order to measure multiple types of airborne targets, ground-based infrared radiation measurement systems often need wide dynamic range measurement capabilities by adding optical attenuation settings and integration time settings.

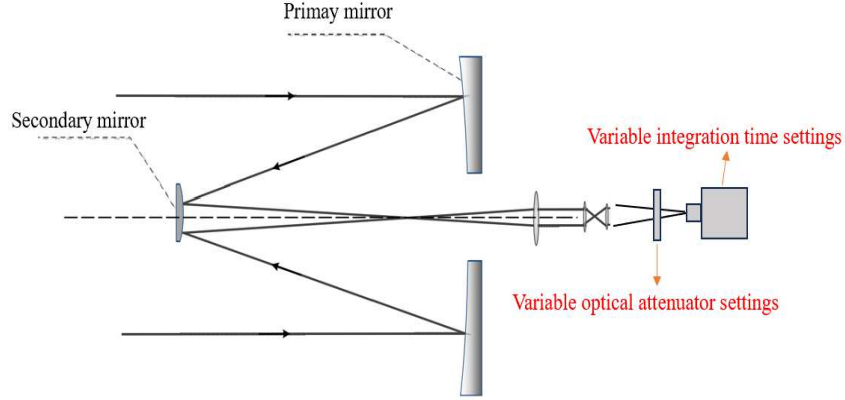


**Fig.1.** Infrared imaging system with variable attenuator and integration time.

Typically, three methods are employed to calibrate wide dynamic range infrared radiation measurement systems: collimator-blackbody calibration, the close-range extended source method, and inner-outer calibration<sup>[7,8]</sup>. As illustrated in **Fig.2(1)**, the collimator-blackbody calibration involves placing blackbodies at different temperatures at the focal plane of a collimator. The radiation passes through the entire collimator, becoming parallel light that completely covers the full optical path of the device, thereby establishing the relationship between blackbody radiation and system response. The outer calibration component of the inner-outer calibration is essentially the close-range extended source method, as shown in **Fig.2(2)**. In the approach, an extended-area blackbody is placed in front of the system lens, covering the full aperture. However, because extended-area blackbodies struggle to achieve high temperatures—the maximum temperature of existing large-area blackbodies is only 300°C—this method is limited to calibrating from ambient to medium temperature ranges. Both the collimator-blackbody calibration method and the close-range extended source method calibrate the full aperture and full optical path of the system; therefore, their data processing procedures are identical. As depicted in **Fig.2(2)**, the inner-outer calibration employs the close-range extended source method (covering ambient to medium temperatures) for full optical path calibration in the ambient temperature range (outer calibration), while a cavity blackbody (covering ambient to high temperatures) is used to calibrate the rear optical path across both ambient and high-temperature ranges (inner calibration). By leveraging the overlapping temperature range between inner and outer calibration, the high-temperature segment of the inner calibration is corrected, yielding the calibration equation for the full optical path across the entire temperature range.

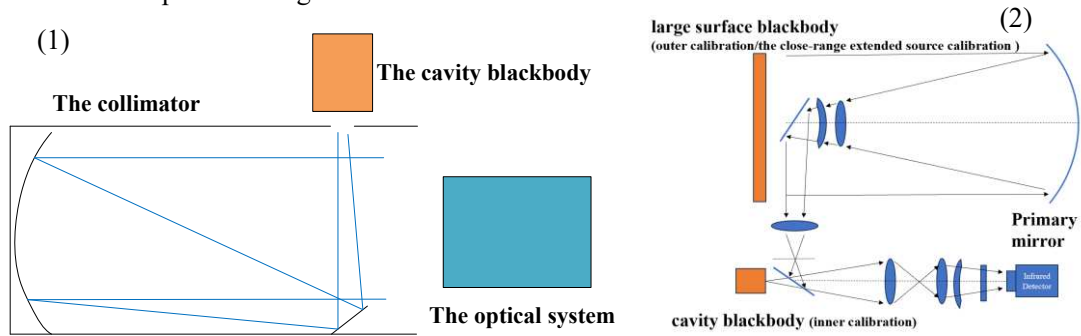


**Fig.2.** (1) The blackbody-collimator calibration; (2) The inner-outer calibration

the traditional calibration method uses the linear model to fit the calibration equation for each integration time setting and attenuation setting, which means that the number of detection settings

corresponds to the number of calibration equations (for example, a system with 3 attenuation settings and 4 integration time settings requires 12 calibration equations). Therefore, the traditional method requires a large number of calibration temperature points, resulting in a long calibration time (For the infrared imaging system with 3 attenuation settings and 4 integration time settings, perform the traditional calibration, and capture blackbody images for each setting starting from 50°C up to 1200°C in 50°C intervals. It took 22 hours and 10 minutes to complete the acquisition of these blackbody images. Capturing images at one blackbody temperature takes approximately one hour.) and inaccurate calibration coefficients caused by changes of ambient temperature during the calibration process<sup>[9,10]</sup>.

Due to the constraints of the traditional calibration model in wide dynamic range radiation measurement systems, researchers both domestically and internationally aim to integrate the influence of attenuators and integration time into the calibration model. This would enable the entire system to utilize a single calibration equation. In 2013, Luo examined how the response of infrared focal plane arrays are influenced by target radiation and integration time. Additionally, she proposed the least squares method to fit the response function relating the focal plane's output grayscale values to both target radiation and integration time<sup>[11]</sup>. In 2017, Li and Chang incorporated integration time into the calibration model and proposed the simplified and fast calibration method that only requires three blackbody images at two different integration time settings<sup>[12,13]</sup>. In 2020, Yang further incorporated the influence of attenuators into the calibration model and completed the simplified and fast calibration method using four blackbody images with different integration time settings and attenuator settings<sup>[14]</sup>. Existing methods have advanced the development of efficient infrared radiation calibration for wide dynamic-range infrared radiation measurement systems. However, these approaches still exhibit limitations. Luo, Li, and Chang only considered the influence of integration time in the calibration model. Although Yang further integrated the influence of the attenuators into the calibration model, the model relies on the assumption that the infrared radiation system's response must be strictly linear in both the integration time dimension and attenuation dimension. Consequently, the unknown parameters of the model can be determined by solving a linear equation system using four blackbody images with different integration time settings and attenuator settings. However, the applicability of this model is subject to stringent conditions. Moreover, none of these methods involve important inner-outer calibration, resulting in insufficient completeness for efficient and rapid calibration.

The research process of the paper is shown in **Fig.3**. Aiming to address the long calibration time for wide dynamic range infrared radiation measurement systems, this paper proposes the new efficient and rapid radiation calibration methodology. Compared to the traditional linear calibration model, we develop the system response model that accounts for the effects of both optical attenuator and integration time, incorporating nonlinear corrections. Crucially, this model is designed for universal applicability; it can be seamlessly integrated with the inner-outer calibration concept. This integration allows the proposed efficient framework to achieve full calibration method coverage—encompassing collimator-blackbody, close-range extended source, and inner-outer calibration—within a unified approach. Consequently, the entire system can utilize a single calibration equation, enabling all working settings to be calibrated as a whole and eliminating the need for individual calibration of each setting. Compared to existing calibration models, the proposed calibration model incorporates nonlinear factors in both the optical attenuator dimension and integration time dimension, and employs nonlinear optimization algorithms to solve the model parameters. This

approach enhances the universality of the proposed method, making it applicable to a wider range of infrared radiation measurement systems.

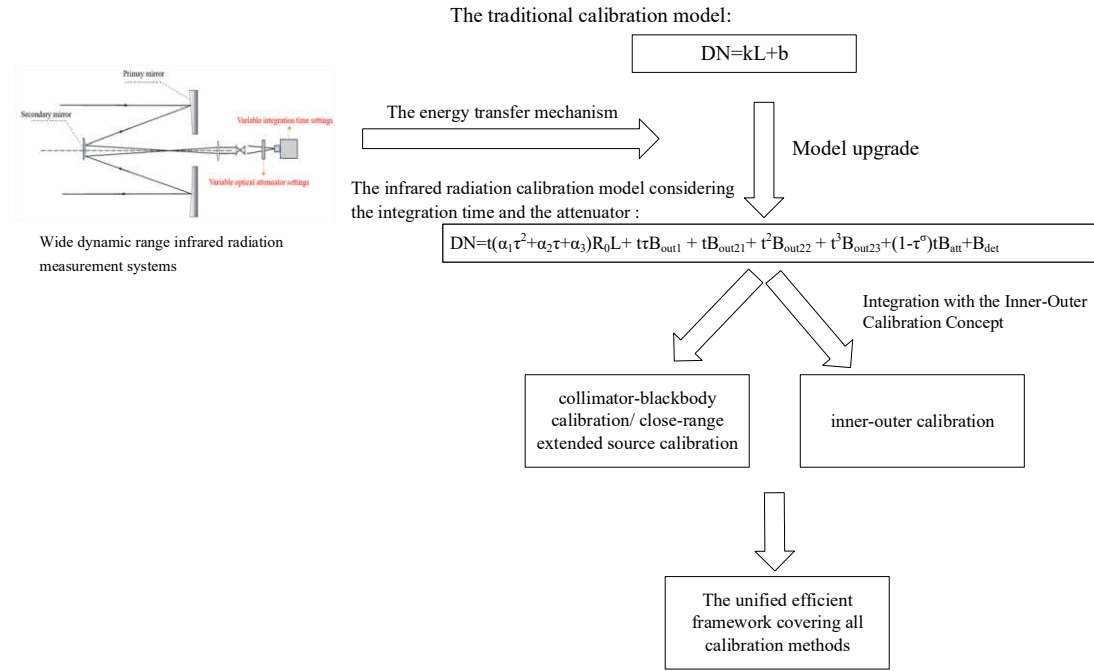


**Fig.3.** The research roadmap

## 2. The infrared radiation calibration model considering integration time and attenuator

### 2.1 The calibration model considering integration time and optical attenuator

The purpose of radiation calibration is to establish the quantitative relationship between the target radiation and the digital number output from the infrared radiation measurement system. The traditional infrared radiation calibration model can be written as

$$DN = R \cdot L + B \quad (1)$$

In the formula, DN is the digital number of the calibrated blackbody image; L is blackbody radiance, R is the system response gain, B is the system response offset. When the integration time is incorporated into the calibration model, the response gain R of infrared detectors exhibits a strong proportionality to the integration time. The response offset B of the system primarily consists of two components: the offset contributed by the detector's dark current and the offset arising from the thermal stray radiation of the infrared system. The detector-induced offset remains independent of the integration time, whereas the offset caused by thermal stray radiation is directly proportional to the integration time. Therefore, the infrared radiation calibration model considering integration time can be written as

$$DN = t \cdot R_0 \cdot L + t \cdot B_{out} + B_{det} \quad (2)$$

In the formula, t is integration time, R<sub>0</sub> is the system response gain for 1ms integration time, B<sub>out</sub> is the offset caused by the thermal stray radiation of the infrared system, B<sub>det</sub> is the offset caused by detector dark current. The offset may be treated as a constant, because its change is extremely small relative to all other offsets in the model. If the influence of the attenuators is further considered in the calibration model, the infrared radiation before the attenuator will be attenuated by the attenuator, and the attenuator itself will also produce infrared radiation. The infrared radiation

calibration model considering the integration time and the attenuator can be written as

$$DN = t \cdot \tau \cdot R_0 \cdot L + t \cdot \tau \cdot B_{out1} + t \cdot B_{out2} + t \cdot \varepsilon \cdot B_{att} + B_{det} \quad (3)$$

In the formula,  $\tau$  is the transmittance of the attenuator,  $B_{out1}$  is the offset caused by the stray radiation of the system before the attenuator,  $B_{out2}$  is the offset caused by the stray radiation of the system behind the attenuator,  $\varepsilon$  is the emissivity of the attenuator,  $B_{att}$  is the offset caused by the attenuator radiation.

However, there may be some deviation between the actual transmittance and the design transmittance for the attenuator. And the transmittance of the attenuator may also change over time. Therefore, directly inputting the design transmittance into the calibration model will cause significant errors and is not conducive to long-term use of the model. In an ideal scenario, the actual transmittance of the attenuator would match the designed transmittance exactly. However, in practice, these values primarily exhibit a linear relationship. To address the deviation between the ideal and actual performance, a quadratic correction is required. Furthermore, the emissivity of attenuators  $\varepsilon$  of the attenuator is also unknown and can be expressed empirically as  $\varepsilon = 1 - \tau^\sigma$ .  $\tau$  is the transmittance of the attenuator.  $\sigma$  is a correction parameter of emissivity. The infrared radiation calibration model considering the integration time and the attenuator can be further written as

$$DN = t \cdot (\alpha_1 \tau^2 + \alpha_2 \tau + \alpha_3) \cdot R_0 \cdot L + t \cdot \tau \cdot B_{out1} + t \cdot B_{out2} + (1 - \tau^\sigma) \cdot t \cdot B_{att} + B_{det} \quad (4)$$

In the formula,  $\alpha_1 \tau^2 + \alpha_2 \tau + \alpha_3$  is the functional relationship between the actual transmittance and the design transmittance for attenuators,  $1 - \tau^\sigma$  is the emissivity of the attenuator (According to Kirchhoff's law, under thermal equilibrium, the absorption and emission of heat by an object are proportional.  $1 - \tau$  represents the reflection and absorption losses of the attenuator,  $\sigma$  is a correction parameter to transform the attenuator losses into an emissivity.  $1 - \tau^\sigma$  is the empirical relationship of the attenuator emissivity). The integration time and system response may exhibit nonlinearities. The quadratic and cubic correction coefficients of the integration time are substituted into the calibration model. The final radiation calibration mathematical model considering integration time and the attenuator can be obtained

$$DN = t \cdot (\alpha_1 \tau^2 + \alpha_2 \tau + \alpha_3) \cdot R_0 \cdot L + t \cdot \tau \cdot B_{out1} + t \cdot B_{out21} + t^2 \cdot B_{out22} + t^3 \cdot B_{out23} + (1 - \tau^\sigma) \cdot t \cdot B_{att} + B_{det} \quad (5)$$

In the formula,  $B_{out22}$  is the offset related to the quadratic correction of integration time,  $B_{out23}$  is the offset related to the cubic correction of integration time.

## 2.2 Integration with the Inner-Outer Calibration Concept

According to Model (5), the mathematical expression for outer calibration in the common temperature range can be written

$$DN = t \cdot (\alpha_{w1,g} \tau^2 + \alpha_{w2,g} \tau + \alpha_{w3,g}) \cdot R_{w0,g} \cdot L_w + t \cdot \tau \cdot B_{w,out1,g} + t \cdot B_{w,out21,g} + t^2 \cdot B_{w,out22,g} + t^3 \cdot B_{w,out23,g} + (1 - \tau^{\sigma_{w,g}}) \cdot t \cdot B_{w,att,g} + B_{w,det,g} \quad (6)$$

The subscript  $w$  is the outer calibration identifier, and  $g$  is the common temperature range identifier.

The mathematical expression for inner calibration in the common temperature range can be written

$$DN = t \cdot (\alpha_{n1,g} \tau^2 + \alpha_{n2,g} \tau + \alpha_{n3,g}) \cdot R_{n0,g} \cdot L_n + t \cdot \tau \cdot B_{n,out1,g} + t \cdot B_{n,out21,g} + t^2 \cdot B_{n,out22,g} + t^3 \cdot B_{n,out23,g} + (1 - \tau^{\sigma_{n,g}}) \cdot t \cdot B_{n,att,g} + B_{n,det,g} \quad (7)$$

The subscript  $n$  is the inner calibration identifier.

Based on the conventional inner-outer calibration, the relationship between the incident radiation for outer calibration and inner calibration is<sup>[7,8]</sup>

$$L_n = a \cdot L_w + b \quad (8)$$

In the formula,  $L_n$  denotes the radiance of the cavity blackbody during inner calibration,  $L_w$  represents the radiance of the extended-surface blackbody during outer calibration,  $a$  is the attenuation coefficient of the front optical system, and  $b$  accounts for the background radiance introduced by the front optical system.

By substituting formula (4) into the inner-outer calibration mathematical model in the common temperature range, the equation can be derived

$$t \cdot (\alpha_{w1,g} \tau^2 + \alpha_{w2,g} \tau + \alpha_{w3,g}) \cdot R_{w0,g} = t \cdot (\alpha_{n1,g} \tau^2 + \alpha_{n2,g} \tau + \alpha_{n3,g}) \cdot R_{n0,g} \cdot a \quad (9)$$

$$t \cdot \tau \cdot B_{w,out1,g} + t \cdot B_{w,out21,g} + t^2 \cdot B_{w,out22,g} + t^3 \cdot B_{w,out23,g} + (1 - \tau^{w\sigma,g}) \cdot t \cdot B_{w,att,g} + B_{w,det,g} =$$

$$t \cdot (\alpha_{n1,g} \tau^2 + \alpha_{n2,g} \tau + \alpha_{n3,g}) \cdot R_{n0,g} \cdot b + t \cdot \tau \cdot B_{n,out1,g} + t \cdot B_{n,out21,g} + t^2 \cdot B_{n,out22,g} + t^3 \cdot B_{n,out23,g} +$$

$$(1 - \tau^{n\sigma,g}) \cdot t \cdot B_{n,att,g} + B_{n,det,g} \quad (10)$$

According to formula (5), the inner-outer calibration response correction coefficients can be obtained

$$a = \frac{(\alpha_{w1,g} \tau^2 + \alpha_{w2,g} \tau + \alpha_{w3,g}) \cdot R_{w0,g}}{(\alpha_{w1,n} \tau^2 + \alpha_{w2,n} \tau + \alpha_{w3,n}) \cdot R_{w0,n}} \quad (11)$$

Because the transmittance ( $\tau$ ) of different attenuation filters is nonlinear, the number of inner-outer calibration response correction coefficients matches the number of attenuation filter settings.

The offset ( $B_{det}$ ) caused by detector dark current can be approximated as a constant. Moreover, the quadratic correction ( $B_{out22}$ ) and the cubic correction ( $B_{out23}$ ) of integration time in the inner calibration can remain consistent with the outer calibration (It's necessary to ensure that the outer calibration model in common temperature range is sufficiently accuracy, while the inner calibration is only used to estimate the variation trend of outer calibration in high-temperature range. Therefore, the inner calibration does not need to be so precise, as long as it reflects the linear variation trend). Equation (6) can be simplified as

$$\tau \cdot B_{w,out1,g} + B_{w,out21,g} + (1 - \tau^{w\sigma,g}) \cdot B_{w,att,g} = (\alpha_{n1,g} \tau^2 + \alpha_{n2,g} \tau + \alpha_{n3,g}) \cdot R_{n0,g} \cdot b$$

$$+ \tau \cdot B_{n,out1,g} + B_{n,out21,g} + (1 - \tau^{n\sigma,g}) \cdot B_{n,att,g} \quad (12)$$

Since  $(\alpha_{n1,g} \tau^2 + \alpha_{n2,g} \tau + \alpha_{n3,g}) \cdot R_{n0,g}$  corresponds to a constant for each attenuation setting, the inner-outer calibration bias correction coefficients can be written as

$$B = \{ \tau \cdot B_{w,out1,g} + B_{w,out21,g} + (1 - \tau^{w\sigma,g}) \cdot B_{w,att,g} \} - \{ \tau \cdot B_{n,out1,g} + B_{n,out21,g} + (1 - \tau^{n\sigma,g}) \cdot B_{n,att,g} \} \quad (13)$$

Like the response correction coefficients, the number of inner-outer calibration bias correction coefficients also matches the number of attenuation filter settings.

The mathematical expression for inner calibration in the full temperature range can be written

$$DN = t \cdot (\alpha_{n1,q} \tau^2 + \alpha_{n2,q} \tau + \alpha_{n3,q}) \cdot R_{n0,q} \cdot L_n + t \cdot \tau \cdot B_{n,out1,q} + t \cdot B_{n,out21,q} + t^2 \cdot B_{n,out22,q}$$

$$+ t^3 \cdot B_{n,out23,q} + (1 - \tau^{n\sigma,q}) \cdot t \cdot B_{n,att,q} + B_{n,det,q} \quad (14)$$

The subscript  $q$  is the full temperature range identifier.

By substituting the inner-outer calibration correction coefficients of formula (11) and (13) into formula (14), the calibration mathematical model after correction for the complete optical path and full temperature range is obtained.

$$DN = t \cdot (\alpha_{n1,q} \tau^2 + \alpha_{n2,q} \tau + \alpha_{n3,q}) \cdot R_{n0,q} \cdot a \cdot L_w + t \cdot \tau \cdot B_{n,out1,q} + t \cdot B_{n,out21,q}$$

$$+ t^2 \cdot B_{n,out22,q} + t^3 \cdot B_{n,out23,q} + (1 - \tau^{n\sigma,q}) \cdot t \cdot B_{n,att,q} + B_{n,det,q} + t \cdot B \quad (15)$$

### 3. The efficient infrared radiation calibration method

The traditional calibration process is time-consuming and labor-intensive due to the lengthy blackbody temperature stabilization period and the overly dense selection of calibration points for

blackbody-collimator method, extended-area blackbody method, and inner-outer method. Therefore, the key to the efficient calibration method lies in how to reduce calibration temperature points while ensuring calibration accuracy.

### 3.1 The efficient infrared radiation calibration for blackbody-collimator method

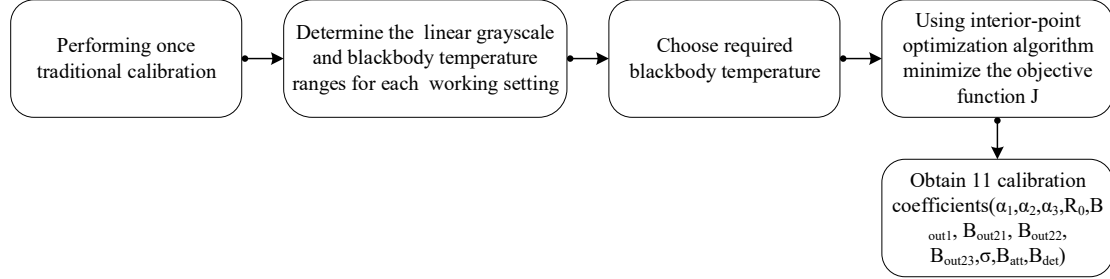


**Fig.4.** The flow chart of the efficient calibration for blackbody-collimator method

The radiation calibration model involving integration time and attenuator has 11 unknowns, necessitating at least 11 valid data points for calibration. These data points should cover all attenuator settings to ensure proper parameter estimation. The specific process is shown in **Fig.4**, and the steps are as follows.

(a) Determine the linear grayscale and blackbody temperature ranges for each attenuator setting and each integration time setting by performing once traditional calibration.

(b) According to (a), for each attenuator setting, choose one blackbody temperature ensuring that the resulting output grayscales stay in the linear range under as many integrated time settings as possible. Then, increase 1-2 blackbody temperatures for the attenuator with a larger calibration temperature range, and cover the low temperature range. These selected blackbody temperatures ensure that the number of valid data output by the system is not less than 11. Collect the infrared images (DN<sub>n</sub>) of all settings at these blackbody temperatures.

(c) According to (5), the weighted least squares method is used to establish an objective function for solving the calibration coefficients:

$$J = \sum_{i=1}^{n>11} \{(L_T - L_M) / L_T\}^2 \quad (16)$$

$$L_M = (DN_n - t \cdot \tau \cdot B_{out1} - t \cdot B_{out21} - t^2 \cdot B_{out22} - t^3 \cdot B_{out23} - (1 - \tau^\sigma) \cdot t \cdot B_{att} - B_{det}) / (t \cdot (\alpha_1 \tau^2 + \alpha_2 \tau + \alpha_3) \cdot R_0) \quad (17)$$

$L_T$  is the theoretical value of blackbody radiance.  $L_M$  is the measured value of blackbody radiance According to (5). Using interior-point optimization algorithm minimize the objective function  $J$  and obtain 11 calibration coefficients  $(\alpha_1, \alpha_2, \alpha_3, R_0, B_{out1}, B_{out21}, B_{out22}, B_{out23}, \sigma, B_{att}, B_{det})^{[13]}$ .

### 3.2 The efficient infrared radiation calibration for inner-outer method

According to the mathematical principle of the inner-outer calibration, not all working settings require inner calibration correction. Instead, only those settings whose dynamic range cannot be covered by outer calibration require inner calibration correction. Efficient and rapid inner-outer calibration primarily aims to ensure calibration accuracy while reducing the number of calibration temperature points. It involves completing efficient outer calibration in the common temperature range, efficient inner calibration in the common temperature range, and efficient inner calibration in the full temperature range. The specific process is shown in **Fig.5**, and the steps are as follows.

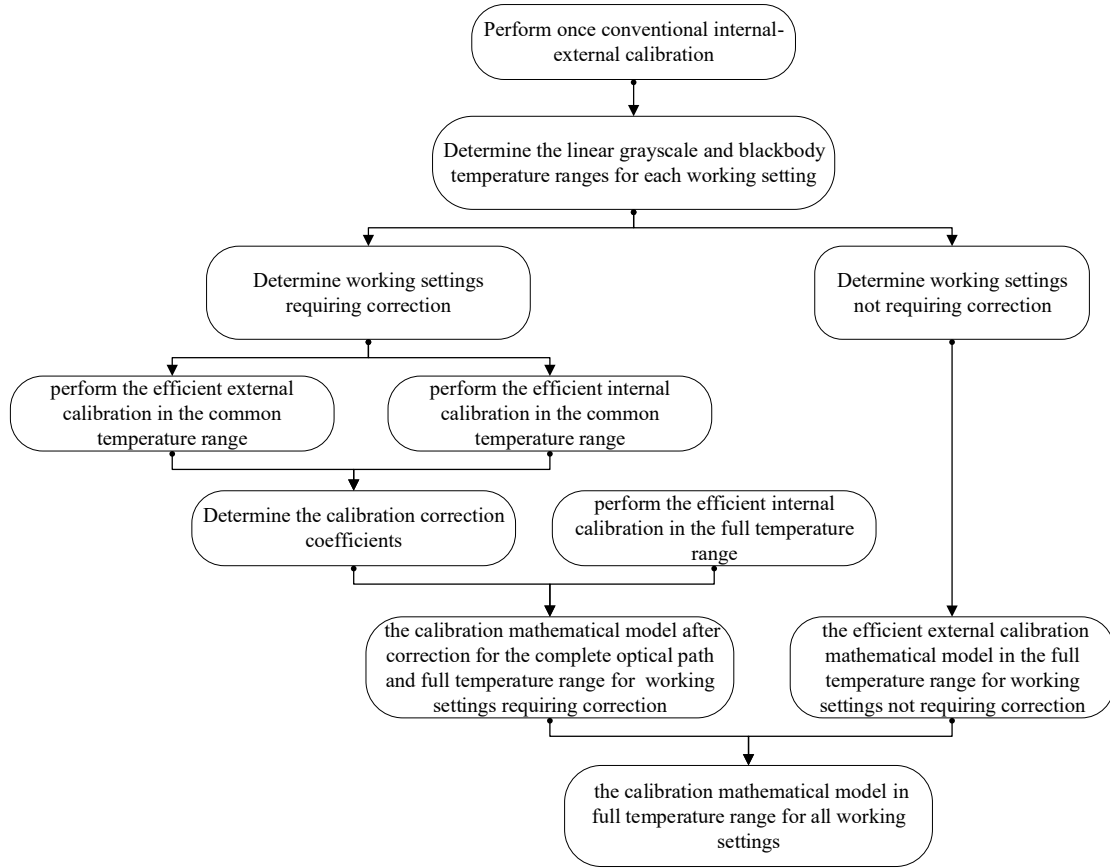


**Fig.5.** The flow chart of the efficient inner-outer calibration method

(a) In the laboratory, the conventional inner-outer calibration is performed on the infrared radiometric system. Based on the calibration results, determine the linear grayscale and blackbody temperature ranges for each attenuation setting and integration time setting.

(b) Based on (a), identify the working settings that require inner-outer calibration correction. For working setting requiring correction, determine the calibration temperature points of efficient outer calibration in the common temperature range, efficient inner calibration in the common temperature range, and efficient inner calibration in the full temperature range. For working setting not requiring correction, determine the calibration temperature points of efficient outer calibration in the full temperature range.

(c) For working setting requiring correction, perform the efficient inner-outer calibration in the common temperature range. And, determine the calibration correction coefficients.

(d) For working setting requiring correction, perform the efficient inner calibration in the full temperature range. By substituting the inner-outer calibration correction coefficients into formula (10), the calibration mathematical model after correction for the complete optical path and full temperature range is obtained.

(e) For working setting not requiring correction, the efficient outer calibration mathematical model in the full temperature range is adopted. For working setting requiring correction, the calibration mathematical model after correction for the complete optical path and full temperature range is adopted.

## 4. The experiment

### 4.1 The efficient radiation calibration

#### (1) The efficient radiation calibration for blackbody-collimator method

The infrared radiation measurement system is the 600mm aperture infrared imaging system. The detected band is 3.7-4.8  $\mu$  m. The detector has the resolution of  $640 \times 512$  and the pixel size of 15  $\mu$  m, the bit depth of 14 bits, and  $F \# = 1.93$ . The integration time settings used in the experiment is 0.02ms, 0.1ms, 0.5ms, 2.5ms. Three optical attenuators with transmittance of 100%, 10%, and 1% were placed in front of the detector. And, different attenuators were switched by rotating the target wheel.

First, perform the traditional calibration, and capture blackbody images for each attenuator and integration time starting from 50°C up to 1200°C in 50°C intervals on February 3, 2023. It took 22 hours and 10 minutes to complete the acquisition of these blackbody images. Then Perform linearity assessment on different blackbody-temperature images to determine the grayscale linear range and the associated blackbody temperature range for each setting shown in **Table 1**.

**Table 1.** The grayscale linear range and the associated blackbody temperature range for each setting

| Integration time/ms | The grayscale linear range for the 100% transmittance attenuator | The blackbody temperature linear range for the 100% transmittance attenuator/°C | The grayscale linear range for the 10% transmittance attenuator | The blackbody temperature linear range for the 10% transmittance attenuator/°C | The grayscale linear range for the 1% transmittance attenuator | The blackbody temperature linear range for the 5% transmittance attenuator/°C |
|---------------------|------------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------|-------------------------------------------------------------------------------|
| 0.02                | 1264~6924                                                        | 50~350                                                                          | 3297~7090                                                       | 600~900                                                                        | 1257~2233                                                      | 300~1200                                                                      |
| 0.1                 | 1517~11426                                                       | 50~250                                                                          | 1545~13975                                                      | 150~650                                                                        | 1655~6375                                                      | 400~1200                                                                      |
| 0.5                 | 2803~13025                                                       | 50~150                                                                          | 2587~13367                                                      | 125~350                                                                        | 2631~13770                                                     | 300~850                                                                       |
| 2.5                 | 9266~14509                                                       | 50~75                                                                           | 6879~9846                                                       | 100~150                                                                        | 5706~12754                                                     | 150~400                                                                       |

Select several required blackbody temperatures based on the linear temperature range of each attenuator and integration time in the Table 1. Select a blackbody temperature under each attenuator so that the output grayscales for the maximum number of integrated time setting are in the linear region. 50°C blackbody temperature can be selected for the 100% transmittance attenuator. 150°C blackbody temperature can be selected for the 10% transmittance attenuator. 550°C blackbody temperature can be selected for the 1% transmittance attenuator. In order to improve the performance of calibration in the low radiation range and high radiation range, the 100°C blackbody temperature and 850°C were added. Because the fitting errors at both high-temperature and low-temperature points are difficult to control, additional data need to be included to mitigate it. 850°C is a relatively high temperature, and it covers integration times of 0.02ms, 0.1ms, 0.5ms for 1% transmittance attenuator, and 0.02ms for 10% transmittance attenuator. Similarly, 100°C is a relatively low temperature, and it covers integration times of 0.02ms, 0.1ms, 0.5ms for 100% transmittance attenuator, and 2.5ms for 10% transmittance attenuator. Confirm the integration time, the transmittance of the attenuator, and corresponding blackbody radiance of each data. Establish the objective function based on the equation (7). And optimize it using the interior point method to obtain the calibration coefficient ( $R_0=54.32$   $\alpha_1=337.06$   $\alpha_2=963.90$   $\alpha_3=-1.01$   $B_{out1}=535.93$

$B_{out21}=702.62$   $B_{out22}=163.01$   $B_{out23}=-68.19$   $B_{att}=965.26$   $\sigma=7.96$   $B_{det}=1200.20$ ). Therefore, the calibration equation considering integration time and attenuator is

$$DN=t \cdot (337.06\tau^2 + 963.90\tau - 1.01) \cdot 54.32 \cdot L + t \cdot \tau \cdot 535.93 + t \cdot 702.62 + t^2 \cdot 163.01 - t^3 \cdot 68.19 + (1 - \tau^{7.96}) \cdot t \cdot 965.26 + 1200.20$$

The variation of the objective function is shown in the **Fig.6**, the measured data and fitted data is shown in the **Fig.7(1)**, and the relative error of each data is shown in the **Fig.7(2)**.

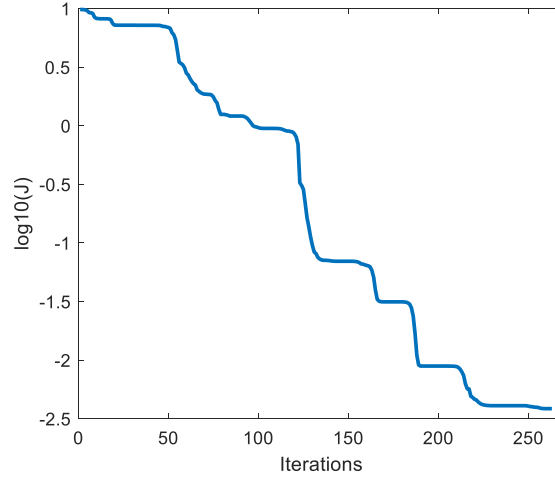


**Fig.6.** The variation of the objective function

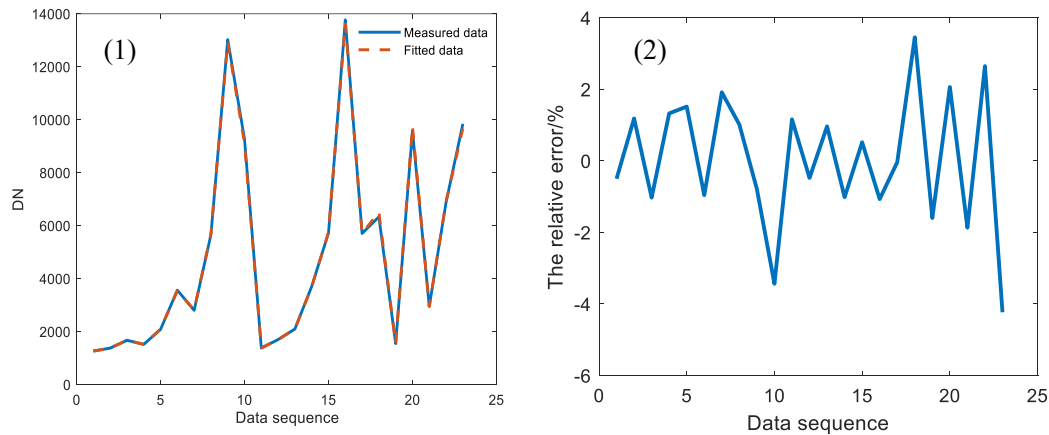


**Fig.7.** (1) The comparison of measured data and fitted data (2) The relative error of the standard blackbody radiance and the fitted radiance

It can be seen that the objective function has been reduced to a relatively small value. And, the relative error of each data point is also very small within 5%. This indicates that the model output values fit well with the measured values, thus successfully completing the efficient calibration of the model considering integration time and attenuator through 5 blackbody temperature points.

(2) The efficient radiation calibration for inner-outer method

For inner-outer method, the infrared radiation measurement system is the 450mm aperture infrared imaging system. The detected band is 3.7-4.8  $\mu m$ . The detector has the resolution of  $640 \times 512$  and the pixel size of 15  $\mu m$ , the bit depth of 14 bits, and  $F \# = 1.93$ . The integration time settings used in the experiment is 0.1ms, 0.25ms, 0.5ms, 1ms, 1.5ms and 3ms. Three optical attenuators with transmittance of 100%, 10%, and 1% were placed in front of the detector. And, different attenuators were switched by rotating the target wheel. The inner calibration used the cavity blackbody (HFY-

D1200) produced by Shanghai Fuyuan Photoelectric Technology company, with an aperture diameter of 50mm and a temperature range of ambient +15°C to 1200°C. Since the extended-surface blackbody used for outer calibration has a maximum temperature of 300°C, making it impossible to verify the superiority of inner-outer calibration method. The alternative approach using a blackbody combined with a collimator is adopted for the outer calibration. The approach can achieve the same temperature range as the inner calibration, spanning from ambient +15°C to 1200°C. Perform the blackbody-collimator calibration and the inner calibration, with the calibration temperature range of 50°C~1200°C (The calibration temperature above 300°C for blackbody-collimator calibration is used to verify the correction results of inner-outer calibration). The calibration temperature intervals are 30°C below 300°C and 50°C above 300°C. The calibration temperature range in the linear digital number of blackbody images for each working setting is shown in the **Table 2** and **Table 3**.

**Table 2.** The calibration temperature range in the linear digital number for each working setting using blackbody-collimator calibration

| Integration time<br>Attenuator | 0.1ms          | 0.25ms         | 0.5ms         | 1ms           | 1.5ms         | 3ms           |
|--------------------------------|----------------|----------------|---------------|---------------|---------------|---------------|
| 100% transmittance             | 140~260<br>°C  | 140~170<br>°C  | 140°C         | —             | —             | —             |
| 10% transmittance              | 140~450<br>°C  | 140~450<br>°C  | 140~290<br>°C | 140~260<br>°C | 140~200<br>°C | —             |
| 1% transmittance               | 260~1200<br>°C | 260~1150<br>°C | 260~800<br>°C | 260~550<br>°C | 260~450<br>°C | 200~260<br>°C |

**Table 3.** The calibration temperature range in the linear digital number for each working setting using inner calibration

| Integration time<br>Attenuator | 0.1ms      | 0.25ms    | 0.5ms     | 1ms       | 1.5ms     | 3ms |
|--------------------------------|------------|-----------|-----------|-----------|-----------|-----|
| 100% transmittance             | 80~170°C   | 50~110°C  | —         | —         | —         | —   |
| 10% transmittance              | 170~350°C  | 140~290°C | 140~230°C | 110~170°C | —         | —   |
| 1% transmittance               | 290~1100°C | 260~750°C | 200~550°C | 200~400°C | 170~290°C | —   |

It can be seen that the working settings requiring correction for outer calibration include integration time of 0.1ms, 0.25ms, and 0.5ms under the 10% transmittance attenuator, as well as integration time of 0.1ms, 0.25ms, 0.5ms, 1ms and 1.5ms under the 1% transmittance attenuator. For working settings requiring correction, the efficient outer calibration is performed at blackbody temperatures of 140°C, 170°C, 200°C, and 260°C.

$$DN = t \cdot (999.42\tau^2 + 994.71\tau - 0.095) \cdot 56.67 \cdot L_w + t \cdot \tau \cdot 173.75 + t \cdot 1828.06 + t^2 \cdot 111.41 - t^3 \cdot 26.55 + (1 - \tau^{420}) \cdot t \cdot 1609.05 + 78 \quad (18)$$

For working settings requiring correction, the efficient inner calibration is performed at blackbody temperatures of 140°C, 170°C, 200°C, and 260°C.

$$DN = t \cdot (1000.8\tau^2 + 1007.3\tau - 1.07) \cdot 165.43 \cdot L_w + t \cdot \tau \cdot 132.61 + t \cdot 2454.85 + t^2 \cdot 111.41 - t^3 \cdot 26.55 + (1 - \tau^{90}) \cdot t \cdot 2329.9 + 78 \quad (19)$$

Based on Equations (7) and (9), we can obtain the inner-outer calibration correction coefficients ( $a_{10\%} = 0.3416$ ,  $a_{1\%} = 0.3745$ ,  $b_{10\%} = -1343.53$ ,  $b_{1\%} = -1347.24$ ).

For working settings requiring correction, the efficient inner calibration in full temperature range is performed at blackbody temperatures of 140°C, 200°C, 350°C, and 1050°C.

$$DN = t \cdot (1000.26\tau^2 + 1002.34\tau - 1.45) \cdot 163.18 \cdot L_w + t \cdot \tau \cdot 89.68 + t \cdot 2484.43 + t^2 \cdot 111.41 - t^3 \cdot 26.55 + (1 - \tau^{44}) \cdot t \cdot 2377.66 + 78 \quad (20)$$

By substituting the inner-outer calibration correction coefficients into formula (14), the calibration mathematical model after correction for the complete optical path and full temperature range is obtained.

$$DN = t \cdot (1000.26\tau^2 + 1002.34\tau - 1.45) \cdot 163.18 \cdot a \cdot L_w + t \cdot \tau \cdot 89.68 + t \cdot 2484.43 + t^2 \cdot 111.41 - t^3 \cdot 26.55 + (1 - \tau^{44}) \cdot t \cdot 2377.66 + 78 + t \cdot b \quad (21)$$

For working settings not requiring correction, the efficient outer calibration is performed at blackbody temperatures of 140°C, 170°C, 200°C, and 260°C.

$$DN = t \cdot (435.03\tau^2 + 1459.47\tau - 0.50) \cdot 40.53 \cdot L_w + t \cdot \tau \cdot 63.92 + t \cdot 1674.636 + t^2 \cdot 205.34 - t^3 \cdot 46.55 + (1 - \tau^{57}) \cdot t \cdot 1598.95 + 220.06 \quad (22)$$

Therefore, the calibration mathematical model in full temperature range for all working settings

$$DN = \begin{cases} t \cdot (1000.26\tau^2 + 1002.34\tau - 1.45) \cdot 163.18 \cdot a \cdot L_w + t \cdot \tau \cdot 89.68 + t \cdot 2484.43 + t^2 \cdot 111.41 - t^3 \cdot 26.55 + (1 - \tau^{44}) \cdot t \cdot 2377.66 + 78 + b & \text{working settings requiring correction} \\ t \cdot (435.03\tau^2 + 1459.47\tau - 0.50) \cdot 40.53 \cdot L_w + t \cdot \tau \cdot 63.92 + t \cdot 1674.636 + t^2 \cdot 205.34 - t^3 \cdot 46.55 + (1 - \tau^{57}) \cdot t \cdot 1598.95 + 220.06 & \text{working settings not requiring correction} \end{cases} \quad (23)$$

## 4.2 The calibration accuracy

### (1) The radiation accuracy for blackbody-collimator method

Perform the traditional calibration by using 24 blackbody temperature points to obtain the calibration equation for each integration time and attenuator setting. By incorporating values of integration time and attenuator transmittance into the proposed calibration model, the calibration equation for each integration time and attenuator setting can be calculated. The calibration coefficients of Yang's proposed calibration model were obtained by solving a system of linear equations using four blackbody images (Their specific details are shown in the **Table 4**). The integration time and attenuator transmittance of each setting were then substituted into Yang's calibration model to derive the calibration equation for each setting. The comparison of the calibration coefficients for the three methods is presented in the **Table 5**. It can be observed that the gains and offsets calculated for each setting by the method proposed in this paper are relatively close to those obtained by the traditional method, whereas the results computed by Yang's method show significant discrepancies.

**Table 4.** Integration time, attenuator and blackbody temperature information contained in four blackbody images for Yang's method

| Image | Blackbody temperature | Integration time | attenuator        | DN   |
|-------|-----------------------|------------------|-------------------|------|
| 1     | 300°C                 | 0.5 ms           | transmittance 10% | 9166 |
| 2     | 300°C                 | 0.1 ms           | transmittance 10% | 2784 |
| 3     | 450°C                 | 0.1 ms           | transmittance 10% | 6109 |
| 4     | 450°C                 | 0.1 ms           | transmittance 1%  | 1779 |

**Table 5.** The comparison of calibration coefficients of the traditional method, the proposed method and Yang's method

| Detected setting (attenuator transmittance and integration time) | The gain k for the traditional method | The offset b for the traditional method | The gain k for the proposed method | The offset b for the proposed method | The gain k for the Yang's method <sup>[12]</sup> | The offset b for the Yang's method <sup>[12]</sup> |
|------------------------------------------------------------------|---------------------------------------|-----------------------------------------|------------------------------------|--------------------------------------|--------------------------------------------------|----------------------------------------------------|
| transmittance 100%、0.02ms                                        | 1409.8                                | 1225.0                                  | 1412.2                             | 1225.0                               | 1072.3                                           | 1466.6                                             |
| transmittance 100%、0.1ms                                         | 7069.8                                | 1321.9                                  | 7060.8                             | 1325.6                               | 5361.3                                           | 2579.2                                             |
| transmittance 100%、0.5ms                                         | 35774.3                               | 1814.4                                  | 35304.3                            | 1851.7                               | 26807.0                                          | 8142.2                                             |
| transmittance 100%、2.5ms                                         | 176362.2                              | 4409.5                                  | 176521.6                           | 4249.8                               | 134033.6                                         | 35957.1                                            |
| transmittance 10%、0.02ms                                         | 103.3                                 | 1216.0                                  | 107.3                              | 1234.7                               | 107.2                                            | 1236.0                                             |
| transmittance 10%、0.1ms                                          | 537.7                                 | 1380.2                                  | 536.4                              | 1373.8                               | 536.1                                            | 1426.0                                             |
| transmittance 10%、0.5ms                                          | 2827.2                                | 2052.9                                  | 2681.8                             | 2093.1                               | 2680.7                                           | 2376.1                                             |
| transmittance 10%、2.5ms                                          | 14437.6                               | 5310.1                                  | 13409.3                            | 5457.1                               | 13403.3                                          | 7126.6                                             |
| transmittance 1%、0.02ms                                          | 9.3                                   | 1233.5                                  | 9.4                                | 1233.7                               | 10.7                                             | 1212.9                                             |
| transmittance 1%、0.1ms                                           | 46.8                                  | 1367.2                                  | 47.0                               | 1369.1                               | 53.6                                             | 1310.7                                             |
| transmittance 1%、0.5ms                                           | 234.1                                 | 2057.9                                  | 235.2                              | 2069.0                               | 268.0                                            | 1799.5                                             |
| transmittance 1%、2.5ms                                           | 1217.2                                | 5325.2                                  | 1176.1                             | 5336.5                               | 1340.3                                           | 4243.6                                             |

Using the traditional calibration method, Yang's proposed calibration method, and the calibration method presented in this paper, the radiance of the captured blackbody images was calculated for temperatures ranging from 50°C to 1200°C at 50°C intervals. The results were compared with the standard blackbody radiance, and the relative error was computed, as illustrated in **Fig.8 & Fig.9**. The blackbody image sequence corresponding to attenuator and integration time is shown in **Table 6**. The sequence number is related to the x-axis ranges shown in **Fig.8 & Fig.9**.

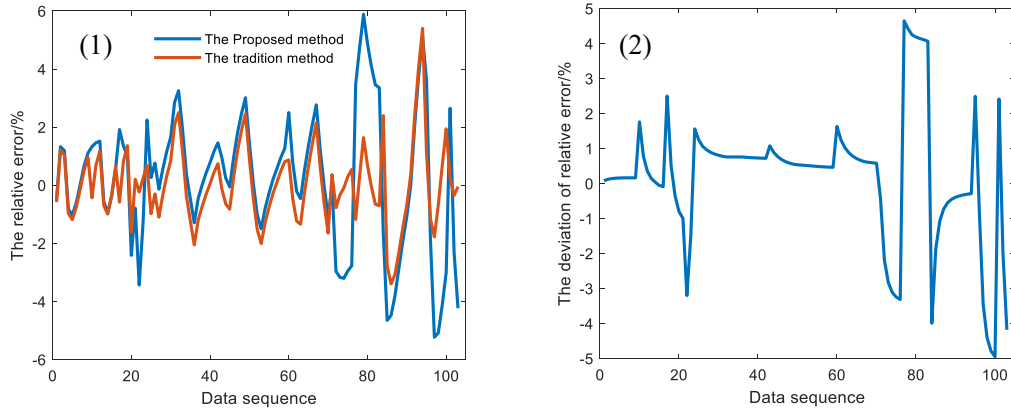


**Fig.8.** (1) The comparison of relative errors between the proposed method and the traditional method (2) The deviation of relative errors between the proposed method and the traditional method

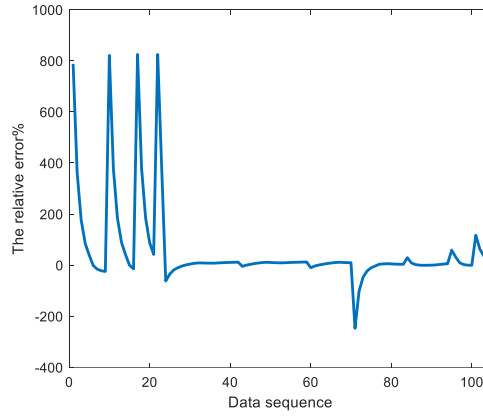


**Fig.9.** The relative errors of Yang's proposed method

**Table 6.** The blackbody image sequence corresponding to attenuator and integration time

| Attenuator         | Integration time |       |        |         |
|--------------------|------------------|-------|--------|---------|
|                    | 0.02ms           | 0.1ms | 0.5ms  | 2.5ms   |
| 100% transmittance | 1-9              | 10-16 | 17-21  | 22-23   |
| 10% transmittance  | 77-83            | 84-94 | 95-100 | 101-103 |
| 1% transmittance   | 21-42            | 43-59 | 60-70  | 71-76   |

It can be seen that the relative error of the calibration method in this article is relatively close to that of the traditional calibration method. The average relative error of traditional calibration methods is 1.03%, while the average relative error of our method is 1.81%; Their average relative error deviation is 0.8%. Only a few points have significant deviations, but the relative error of the method proposed in this article can still be maintained within 6%. However, Yang's proposed method requires the infrared radiation measurement system to exhibit good linearity in both the integration time dimension and the attenuation filter dimension, making it unsuitable for achieving satisfactory calibration results with the system described in this paper. The relative error at the 100% transmittance attenuator and 10% transmittance attenuator is significantly better than that of the 1% transmittance attenuator. This is likely because the four blackbody images used to calculate the calibration coefficients included information from the 100% and 10% transmittance attenuators but did not incorporate data from the 1% transmittance attenuator. For both the 100% transmittance and 10% transmittance attenuation filters, there are still some blackbody images with relatively large errors in integration time. This is likely due to the weakening linear relationship between system response and integration time as the number of detection settings increases.

#### (2) The radiation accuracy for inner-outer method

For working settings not requiring correction, the calibration coefficients of the proposed method and the conventional blackbody-collimator calibration method are shown in the **Table 7**.

**Table 7.** The calibration slope/offset of the proposed method and the conventional blackbody-collimator calibration method for working settings not requiring correction

| working settings not requiring correction   | the proposed method |        | the conventional method |        |
|---------------------------------------------|---------------------|--------|-------------------------|--------|
|                                             | k                   | b      | k                       | b      |
| 100% transmittance, 0.1ms integration time  | 7676.9              | 395.9  | 7547.7                  | 433.3  |
| 100% transmittance, 0.25ms integration time | 19192.3             | 666.8  | 19492.4                 | 611.5  |
| 100% transmittance, 0.5ms integration time  | 38384.6             | 1134.9 | 26352.6                 | 4385.0 |

|                                            |        |         |        |         |
|--------------------------------------------|--------|---------|--------|---------|
| 10% transmittance, 0.1ms integration time  | 6071.7 | 3658.8  | 6070.4 | 3658.5  |
| 10% transmittance, 0.25ms integration time | 9107.6 | 5444.9  | 9086.0 | 5455.5  |
| 10% transmittance, 0.5ms integration time  | 1719.1 | 10634.0 | 1714.8 | 10631.4 |

Using the proposed method and the conventional blackbody-collimator calibration method, the radiance of the captured blackbody images was calculated. The results were then compared with the standard blackbody radiance, and the relative error was computed, as illustrated in Fig.10.

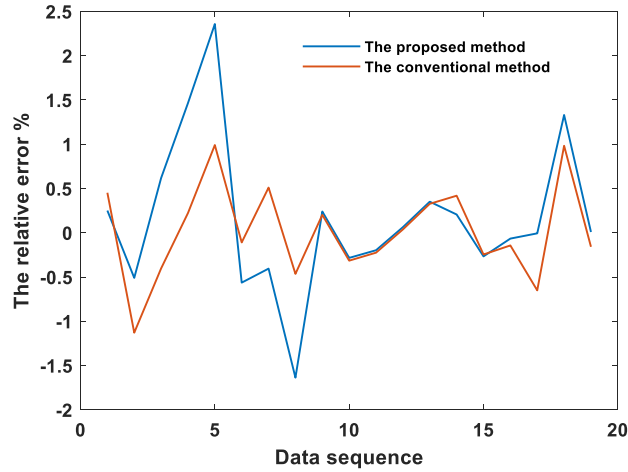


**Fig.10.** The comparison of relative errors between the proposed method and the conventional method

The average relative error of the proposed method is 0.57%, compared to 0.42% for the conventional method, indicating that the two methods have very similar relative errors. From the calibration coefficients of the proposed method and the conventional method in the Table 3, it can also be seen that their calibration gain (k) and offset (b) are quite close. It's noteworthy that for the setting (100% transmittance attenuator, 0.5ms integration time), the calibration gain (k) and offset (b) differ significantly between the two methods. It's because only 140°C blackbody image falls with the linear range of the detector for the setting, and the conventional method can't accurately calculate the two unknown parameters with only one input. In contrast, the proposed method takes into account the influence of the optical attenuator and integration time in the calibration model, allowing for extrapolation along these two dimensions while maintaining accurate calculations.

For working settings requiring correction, the calibration coefficients of the blackbody-collimator method in the full temperature range, the blackbody-collimator method in the common temperature range, and the proposed method are shown in the Table 8.

**Table 8.** The calibration slope/offset of the proposed method, the conventional inner-outer method, the blackbody-collimator method in the full temperature range and the blackbody-collimator method in the common temperature range for working settings not requiring correction

| working settings not requiring correction | the blackbody-collimator method in the full temperature range |   | the proposed method |   | the blackbody-collimator method in the common temperature range |   | the conventional inner-outer method |   |
|-------------------------------------------|---------------------------------------------------------------|---|---------------------|---|-----------------------------------------------------------------|---|-------------------------------------|---|
|                                           | k                                                             | b | k                   | b | k                                                               | b | k                                   | b |

|                                               |        |        |        |        |        |        |        |        |
|-----------------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10% transmittance,<br>0.1ms integration time  | 618.9  | 430.3  | 606.5  | 431.8  | 638.5  | 422.6  | 574.8  | 542.0  |
| 10% transmittance,<br>0.25ms integration time | 1496.6 | 961.6  | 1516.2 | 966.4  | 1530.9 | 948.2  | 1485.9 | 975.8  |
| 10% transmittance,<br>0.5ms integration time  | 3038.7 | 1858.2 | 3032.4 | 1866.3 | 3038.7 | 1858.2 | 3093.8 | 1753.7 |
| 1% transmittance, 0.1ms<br>integration time   | 53.8   | 429.7  | 53.0   | 430.7  | 61.0   | 413.9  | 47.1   | 602.7  |
| 1% transmittance,<br>0.25ms integration time  | 130.2  | 963.6  | 132.5  | 963.5  | 146.5  | 929.1  | 118.7  | 1296.8 |
| 1% transmittance, 0.5ms<br>integration time   | 261.6  | 1881.9 | 265.0  | 1860.4 | 292.8  | 1818.4 | 242.7  | 2480.8 |
| 1% transmittance, 1ms<br>integration time     | 537.8  | 3672.0 | 529.9  | 3678.6 | 573.5  | 3603.5 | 491.7  | 4868.2 |
| 1% transmittance, 1.5ms<br>integration time   | 816.9  | 5446.8 | 794.9  | 5512.7 | 863.6  | 5360.6 | 761.5  | 7168.1 |

The correction coefficients can be derived using the conventional inner-outer calibration method (as described in Reference 8) with the combinations of optical attenuator, integration time, and blackbody temperature listed in the **Table 9** and **Table 10**.

$$\alpha = \frac{\alpha_w}{\alpha_n} = \frac{6.04 \times 10^4}{1.74 \times 10^5} = 0.349 \quad \beta = \frac{W_w - W_n}{\alpha_n \cdot \tau_{\text{filter}}} = \frac{3592 - 5213}{1.74 \times 10^5 \cdot 0.1} = -0.093 \quad (18)$$

In the formular,  $\alpha$  is the calibration gain correction coefficients,  $\alpha_w$  and  $\alpha_n$  are system response gain of the conventional outer calibration and inner calibration, respectively.  $\beta$  is the calibration offset correction coefficients,  $W_w$  and  $W_n$  are the offset caused by the system stray radiation of the conventional outer calibration and inner calibration, respectively.  $\tau_{\text{filter}}$  is the transmittance of the attenuator.

For working settings requiring correction, perform the conventional inner calibration in the full temperature range. By substituting the conventional inner-outer calibration correction coefficients into the conventional inner calibration in the full temperature range, the correction calibration coefficients can be obtain in the **Table 8****Table 9**.

**Table 9.** the combinations of optical attenuator, integration time, and blackbody temperature used in conventional outer calibration

| Attenuator | Integration time | Blackbody temperature | the digital number of blackbody images | $\alpha_w$         | $W_w$ | $DN_w$ |
|------------|------------------|-----------------------|----------------------------------------|--------------------|-------|--------|
| 10%        | 0.5              | 170/0.4492            | 3231                                   | $6.09 \times 10^4$ | 3592  | 64.7   |
|            | 0.5              | 200/0.7271            | 4077                                   |                    |       |        |
|            | 1                | 170                   | 6394                                   |                    |       |        |
|            | 1                | 200                   | 8082                                   |                    |       |        |

**Table 10.** the combinations of optical attenuator, integration time, and blackbody temperature used in conventional inner calibration

| Attenuator | Integration time | Blackbody temperature | the digital number of blackbody images | $\alpha_n$ | $W_n$ | $DN_n$ |
|------------|------------------|-----------------------|----------------------------------------|------------|-------|--------|
|------------|------------------|-----------------------|----------------------------------------|------------|-------|--------|

|     |     |     |       |                    |      |    |
|-----|-----|-----|-------|--------------------|------|----|
| 10% | 0.5 | 170 | 6616  | $1.74 \times 10^5$ | 5213 | 97 |
|     | 0.5 | 200 | 9038  |                    |      |    |
|     | 1   | 170 | 13137 |                    |      |    |

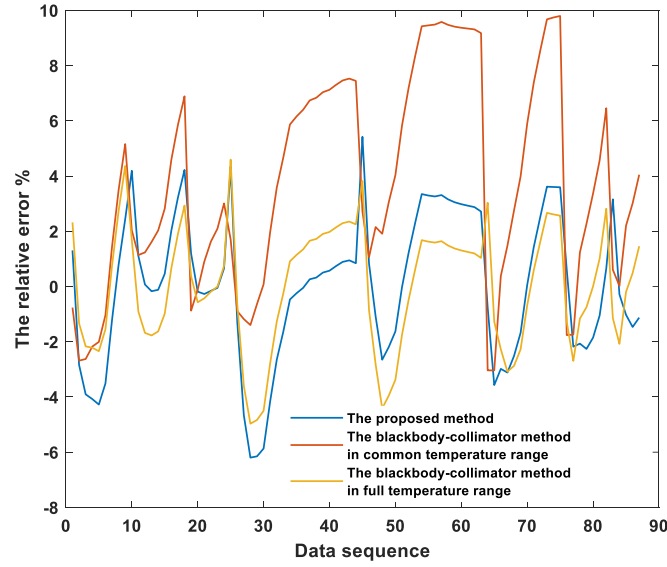


**Fig.11.** The comparison of relative errors among the proposed method, the blackbody-collimator method in full temperature range and the blackbody-collimator method in common temperature range

Using the proposed method, the blackbody-collimator method in full temperature range, the blackbody-collimator method in common temperature range, the conventional inner-outer method, the radiance of the captured blackbody images was calculated. The results were then compared with the standard blackbody radiance, and the relative error was computed, as illustrated in **Fig.11** and **Fig.12**.

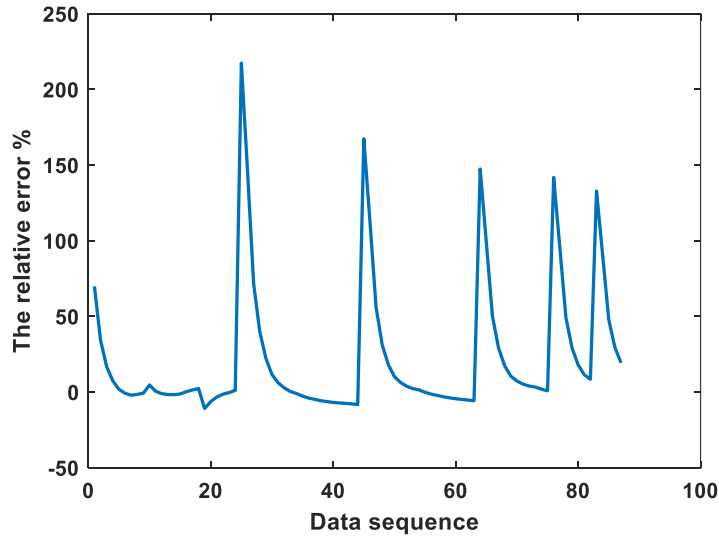


**Fig.12.** The relative errors of the conventional inner-outer method

For the blackbody-collimator method in full temperature range, the average relative error is 1.84%, and the maximum relative error is 4.97%. For proposed method, the average relative error is 2.08%, and the maximum relative error is 6.20%. For the blackbody-collimator method in

common temperature range, the average relative error is 4.34%, and the maximum relative error is 9.80%. For the conventional inner-outer method, the average relative error is 25.80%, and the maximum relative error is 217.35%. The average relative error of proposed method is two times smaller than that of the blackbody-collimator method in common temperature range. And, its relative error is already close to that of the blackbody-collimator method in full temperature range. It demonstrates that the proposed calibration method can significantly improve calibration accuracy. The conventional inner-outer calibration method exhibit excessively high average and maximum relative errors, thus is inapplicable to the system. It's because the method only considers 1 attenuator and 2 integration time during inner-outer correction, which requires the system to have good linear extrapolation in both the attenuator dimension and the integration time dimension. As shown in Fig.12, the relative error is relatively small for the working settings used in inner-outer correction, but it becomes exceptionally large for the working settings not used in inner-outer correction. Moreover, the proposed method requires only 6 calibration temperature points (140°C, 170°C, 200°C, 260°C, 350°C, and 1050°C), whereas the blackbody-collimator method and the conventional inner-outer calibration method require much denser calibration temperature points. Therefore, the proposed method can improve calibration efficiency by at least several times.

## 5. Conclusion

The paper proposes the efficient calibration method suitable for wide dynamic range systems to address the time-consuming nature of traditional calibration methods. By establishing a nonlinear response model that simultaneously considers integration time and attenuators, the method incorporates secondary correction of attenuator transmittance, attenuator self-radiation, and nonlinear terms of integration time, resulting in a total of 11 parameters solved through nonlinear optimization. The model also deeply integrates the inter- outer calibration concept, enabling unified coverage of the collimator-blackbody calibration, close-range extended source calibration, and internal-external calibration. Experiments show that in the collimator-blackbody calibration, the paper requires only five calibration temperature points, improving efficiency nearly fivefold compared to the traditional method's 24 calibration temperature points, with a relative error of 1.81%, close to the traditional method's 1.03%. In contrast, Yang's rapid calibration method, which fails to account for nonlinear factors in both modeling and algorithms, exhibits a relative error that severely exceeds acceptable limits. In the inner-outer calibration, the paper requires only six calibration temperature points, achieving a fourfold efficiency improvement over the traditional inner-outer calibration method's 26 calibration temperature points, with a relative average error of 2.08%, far superior to the traditional inner-outer calibration method's 25.8%. This method achieves efficient and rapid radiation calibration with full coverage of collimator-blackbody calibration, close-range extended source calibration, and internal-external calibration. It offers efficient and fast radiation calibration capabilities, playing a positive role in reducing calibration time, increasing system task response efficiency, and mitigating the impact of environmental temperature changes during the calibration process, holding significant scientific value and engineering application prospects.

**Disclosures.** The authors declare no conflicts of interest.

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### **Data availability**

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

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