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Compensation to the output drift for cooled infrared imaging systems at various ambient temperatures

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A method is proposed to compensate the output drift for cooled infrared imaging systems at various ambient temperatures. By calibrating the cryogenic infrared detector which absorbs the radiant flux of blackbody directly, the internal factors can be obtained. Then, by combining the calibration result of infrared imaging system at an arbitrary ambient temperature, the output drift can be calculated and compensated at various integration time and ambient temperatures. Experimental results indicate that the proposed method can eliminate the effect of ambient temperature fluctuation on the system output efficiently.

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Radiometric measurement is an important way to acquire the radiance, intensity and temperature of targets, owing to its advantages of noncontact and harmlessness to targets[1-3]. Whereas, the ambient temperature difference between the calibration and measurement results can lead to significant radiometry errors due to the fact that the calibration must be conducted prior to measurement[4]. Besides, the ambient temperature fluctuation during the measurement process will generate output drift as well[5]. The output drift not only influences the radiometry accuracy but also gives rise to the nonuniformity which will affect the image quality[6].

To remove the effect of ambient temperature on infrared imaging systems, Zhang et al[7] proposed a weighted-based compensation method. By calibrating the infrared system for a period of time at a stable temperature, the relation between the drift and the operation time can be summarized, then the drift can be compensated. However, when the ambient temperature changes, experiments must be conducted once again. Chang et al[5] introduced a method to remove the effect of ambient temperature on radiometric calibration. By calibrating the infrared system at two different ambient temperatures, the compensation coefficient can be acquired. Yet, its drawback lies in the fact that for large-aperture infrared systems, it is hard to control them at two ambient temperatures.

In this paper, a method is proposed to compensate the output drift for cooled infrared imaging systems at various ambient temperatures. This method requires only one calibration result at an arbitrary ambient temperature to compensate output drift at various temperatures and integration time, which has the advantages of simple implementation, low demand for experimental conditions and so on.

The near-extended-source method is adopted for radiometric calibration[8,9]. For cooled infrared imaging systems, the output gray values exhibit a linear relationship with the incident radiance, which can be expressed as [10,11]

$$h=t\cdot G_0\cdot L_B+B, \tag{1}$$

where h is the output gray value of detector pixel in the focal plane array, t is the integration time in units of ms, G_0 denotes the response of detector pixel to the incident radiance at unit integration time, and B refers to the offset. Fig.1 exhibits the schematic of the near-extended-source method.

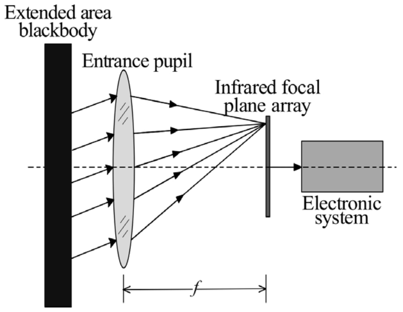

Fig.1 Schematic of the near-extended-source method

The offset B results from the self radiation of infrared imaging system namely stray radiation and the internal factors of the cryogenic infrared detector, such as the dark current

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and the cold stop[4]. Therefore, the offset B can be rewritten as

$$B=t\cdot G_0'\cdot \Phi_{\text{stray}}+h_{\text{det}}, \tag{2}$$

where G_0' is the response to the incident radiation flux at unit integration time, Φ_{stray} is the stray radiation flux that strikes the detector pixel, and h_{det} denotes the internal factors of the cryogenic infrared detector.

For the cryogenic infrared detector, experiments have demonstrated that the internal factor, namely h_{det}, is linearly related to the integration time, which can be expressed as[12]

$$h_{\text{det}}(t)=t\cdot h_{\text{det1}}+h_{\text{det2}}. \tag{3}$$

For the stray radiation flux of an infrared imaging system, it is in direct proportion to the radiance of an ideal blackbody at the ambient temperature, which can be expressed as[13]

$$\Phi_{\text{stray}}(T_{\text{amb}})=K_{\text{stray}}\cdot L(T_{\text{amb}}), \tag{4}$$

where K_{stray} denotes the geometry factor between the radiance and the stray radiation flux.

Consequently, the output of a given cooled infrared imaging system at a certain ambient temperature, such as T_{amb0}, can be expressed as

$$h(t,T_{\text{amb0}})=t\cdot G_0\cdot L_B+B_1= t\cdot G_0\cdot L_B + t\cdot G_{\text{system}}\cdot L(T_{\text{amb0}})+t\cdot h_{\text{det1}}+h_{\text{det2}}, \tag{5}$$

where $G_{\text{system}}= G_0'\cdot K_{\text{stray}}$.

When the ambient temperature is stable, the output will not drift. Nevertheless, if the ambient temperature changes, the system output needs to be updated according to current ambient temperature to maintain the radiometric accuracy. Assuming that the ambient temperature changes from T_{amb0} to T_{amb}, the output drift can be calculated by

$$\Delta h=h(t,T_{\text{amb}})-h(t,T_{\text{amb0}})=t\cdot G_{\text{system}}\cdot [L(T_{\text{amb}})-L(T_{\text{amb0}})]. \tag{6}$$

Eq.(6) indicates that if we can acquire the parameter G_{system}, the output drift can be calculated and compensated at various integration time and ambient temperatures.

To acquire G_{system}, we suppose that the cryogenic infrared detector was calibrated previously at preselected integration time, namely t_0, and the calibration of the infrared detector is sketched in Fig.2. The calibration formula can be expressed as

$$h=t_0\cdot G_{\text{det}}\cdot L_B+h_{\text{det}}(t_0)= t_0\cdot G_{\text{det}}\cdot L_B+t_0\cdot h_{\text{det1}}+h_{\text{det2}}, \tag{7}$$

where G_{det} is the response of detector pixel without optics.

Then the whole system is calibrated at the same integration time, namely t_0, and the ambient temperature is assumed to be T_{amb1}. Therefore, the calibration result can be expressed as

$$h(t_0,T_{\text{amb1}})= t_0\cdot G_0\cdot L_B+B_0= t_0\cdot G_0\cdot L_B+ t_0\cdot G_{\text{system}}\cdot L(T_{\text{amb1}})+ t_0\cdot h_{\text{det1}}+h_{\text{det2}}. \tag{8}$$

By combining Eq.(7) and Eq.(8), the parameter G_{system} can be calculated by

$$G_{\text{system}}=\frac{B_0-h_{\text{det}}\left(t_0\right)}{t_0\cdot L\left(T_{\text{amb1}}\right)}. \tag{9}$$

Thus, the system output drift caused by ambient temperature fluctuation at arbitrary integration time can be calculated by

$$\Delta h=t\cdot\frac{B_0-h_{\text{det}}\left(t_0\right)}{t_0\cdot L\left(T_{\text{amb1}}\right)}\cdot\left[L\left(T_{\text{amb}}\right)-L\left(T_{\text{amb0}}\right)\right]. \tag{10}$$

The output drift can be compensated by adding Δh to the system output at the current ambient temperature.

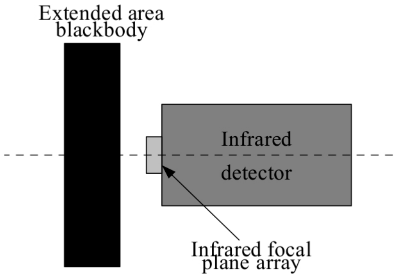


Fig.2 Calibration of the infrared detector

Since the cooled infrared detector operates in the cryogenic dewar, where the temperature is kept constant (i.e., 77 K), the internal factor can be regarded as a constant. In practical applications, we can calibrate the detector to acquire the internal factor which can be considered as an intrinsic parameter of the system. Besides, the detector can be calibrated periodically to update $h_{\text{det}}(t_0)$.

To validate the method proposed above, several experiments were conducted with a mid-wave infrared (MWIR) imaging system. The aperture of the system is 50 mm, and the focal length is 100 mm. The cryogenic MWIR detector of forward looking infrared (FLIR) systems operates in 3.7—4.8 μm and has a large-scale focal plane array of 640 pixel×512 pixel with a 14 bit digital output. The area blackbodies of CI systems are selected as the reference sources.

First of all, the infrared detector was calibrated. The integration time was set to be 1 ms, namely t_0, and the reference source was set to be 30 °C, 40 °C, 50 °C and 60 °C, respectively. The calibration formula is fitted as

$$h=2\,311.07\times L_B+347.07, \tag{11}$$

which means $h_{\text{det1}}+h_{\text{det2}}=347$.

Then, to ensure good performance, we put the whole experimental setup inside the chamber as shown in Fig.3. The chamber's temperature was set to be 20 °C, namely T_{amb1}, and the temperature of reference source was chosen as 30 °C, 40 °C, 50 °C and 60 °C, respectively. The calibration formula is fitted as

$$h=2\,086.24\times L_B+584.30. \tag{12}$$

Thus, $B_0=G_{\text{system}}\cdot L(20\ ^\circ\text{C})+h_{\text{det1}}+h_{\text{det2}}=584$.

According to Eq.(9), we can obtain G_{system} is equal to 243.34 $\text{m}^2\cdot\text{sr}\cdot\text{ms}^{-1}\cdot\text{W}^{-1}$. Therefore, the output drift at arbitrary integration time and an ambient temperature can be calculated by

$$\Delta h = 243.34 \times t \times \left[L\left(T_{\mathrm{amb}}\right) - L\left(T_{\mathrm{amb}0}\right) \right]. \qquad (13)$$

As we all know, the output gray value will certainly drift and lead to significant radiometric errors due to the ambient temperature fluctuation, unless the output drift has been appropriately calibrated. And the aim of the proposed method is to compensate the output drift caused by ambient temperature fluctuation.

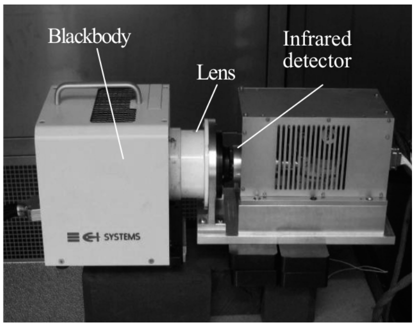
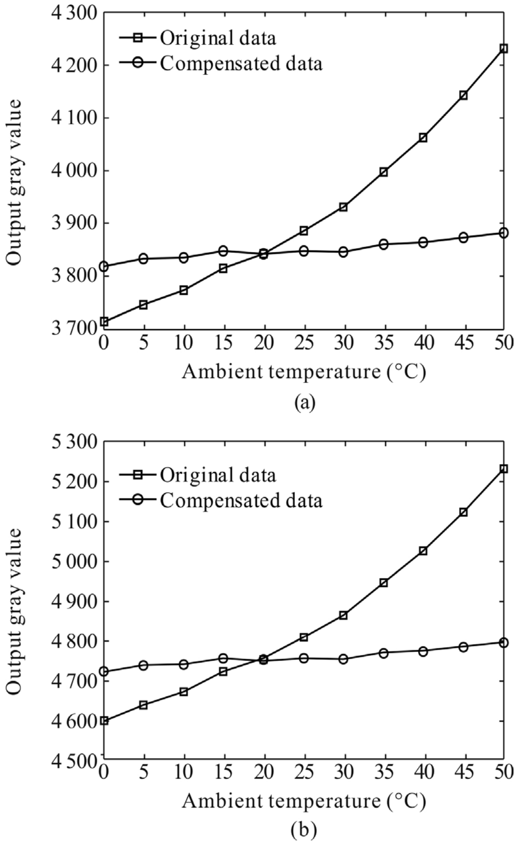


Fig.3 Photo of the experimental setup

To evaluate the performance of the proposed method, the integration time was set to be 0.8 ms, 1 ms and 1.8 ms, respectively, and the temperature of blackbody is set to be 40 °C. The chamber's temperature was changed from 0 °C to 50 °C with 5 °C as the interval. The output drift is defined as the difference between the output gray values at various ambient temperatures and that at 20 °C. The original outputs as well as the compensated ones are exhibited in Fig.4, and the output errors are exhibited in Fig.5.



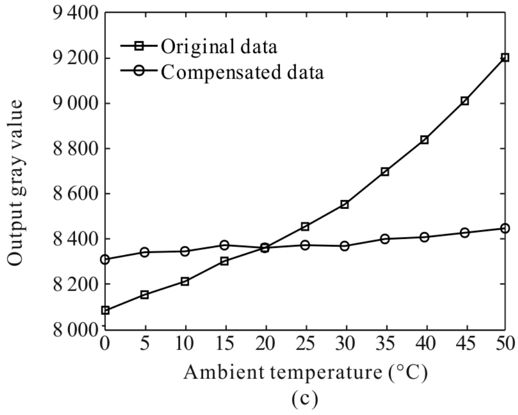


Fig.4 Output drift as a function of ambient temperature with integration time of (a) 0.8 ms, (b) 1 ms and (c) 1.8 ms

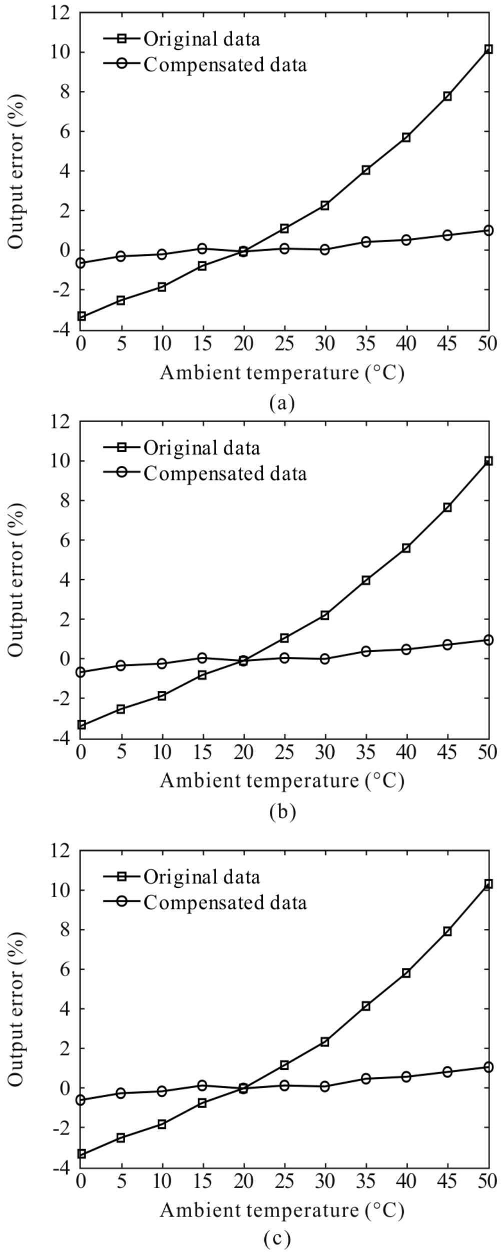


Fig.5 Output error as a function of ambient temperature with integration time of (a) 0.8 ms, (b) 1 ms and (c) 1.8 ms

It is shown in Fig.4 that the output gray value increases rapidly with the ambient temperature rising. After calibration, the system's outputs become stable compared with the original ones, even though the integration time and the ambient temperature have been changed. Fig.5 shows that the maximum output errors reach 10.12%, 9.97% and 10.14% for integration time of 0.8 ms, 1 ms and 1.8 ms, respectively, which are unacceptable in practical applications. After modification, the output errors are limited to 1.04%, 0.79% and 0.76%, which means that the system can be used for an accurate quantitative analysis. The experimental results above prove that the proposed method is valid at an arbitrary ambient temperature and integration time. Moreover, there is no tendency for the output error to rise or decrease with the variation of integration time and ambient temperature, which means the proposed method is stable.

This paper has introduced a compensation method for cooled infrared imaging systems at various ambient temperatures. The calibration formula has been deduced considering the integration time and ambient temperature. Then, the quantitative relation between the system output drift and the ambient temperature has been derived. The output drift can be compensated by adding the drift to system output at the current ambient temperature. The experimental results indicate that the proposed method can achieve high-accuracy output drift compensation at an arbitrary ambient temperature. Furthermore, the proposed method is applicable for arbitrary integration time and ambient temperature. Only one calibration result is needed to compensate the output drift, which can effectively reduce the compensation complexity.

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