Direct atmospheric correction for high precision radiometry on infrared small target

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Abstract: Atmospheric correction is one of important steps to obtain the intrinsic radiance of the target for an infrared radiometry system. Traditionally, the mean to calculate atmospheric transmittance and atmospheric path radiance are calculated by an atmospheric radiance transport calculation software. A method based on standard reference direct amending atmospheric attenuation was proposed, which was applied for high precision precision measurement and inversion on a small target. The based principle and procedure of this method were introduced, and then the model of wide dynamic calibration was employed. Radiometric experiments were performed on a mid-wave infrared system with a Φ600 mm aperture. The radiometry results indicated that the radiance inversion precision for a small target, using the proposed method, is 0.97%–1.03%, while the precision using a conventional atmospheric transport calculation software method is 7.30%–7.36%, which demonstrates that the proposed method provides a high-precision result.

Key words: infrared radiance; atmospheric path radiance; calibration; atmospheric correction
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直接修正大气实现小目标高精度辐射测量

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摘 要: 实现大气的传输修正是地基红外辐射测量系统获取目标真实辐射亮度的重要步骤之一,传统获取大气透过率和大气程辐射的方法是通过大气传输修正软件计算得到的。提出利用标准参考源实现大气修正,并将该方法实现对小目标的高精度辐射特性测量余反演。文中对宽动态范围的辐射定标模型和方法进行理论推导,实验采用 600 mm 口径的辐射测量系统进行辐射测量验证。实验数据分析表明采用本文提出方法对小目标的辐射反演误差在 0.97%~1.03%,而相比传统采用大气传输软件计算的辐射反演误差在 7.3%~7.36%,因此所提出的方法具有更高的辐射测量与反演精度。

关键词: 红外辐射; 大气程辐射; 校正; 大气修正

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0 Introduction

The infrared radiometric system is one of the most important means to acquire aviation signatures and space target recognition. The specific process of radiometry includes calibration and radiance inversion[1]. Calibration of infrared radiometric systems is performed in order to establish a quantitative relationship between the input and output[2]. During radiance inversion, atmospheric correction is an indispensable step. Currently, the conventional method to correct atmospheric attenuation is using atmospheric radiance transport software, such as MODTRON, in an indirect way, which calculates atmospheric transmittance and air path radiance using atmospheric observation devices, and is combined with a model of the local atmosphere [3]. Considering this, such as Wei Heli devotes his mind to the software of atmospheric correction and Yang Ciyin researches the effect of atmospheric transmission on IR radiance feature of target and background[4-5]. The error in atmospheric transmittance is obtained using a conventional software calculation method, and is about 20%-30%[6-7]. In this paper, a method to directly correct atmospheric attenuation, based on the standard reference, is presented; then, the method is verified for high precision on a small infrared target.

Wide dynamic calibrations are performed in Section 1. Following this, the method of direct corrected atmospheric attenuation, as well as an in-detail method, performed on a small target is described in Section 2. Then, radiometric experiments, based on a MWIR system with a Φ600 mm diameter, are carried out in order to verify the theories described in Section 3. It is concluded in Section 4 that the proposed method yields high-precision results for small target radiometry.

1 Wide dynamic calibration

A cooled infrared focal plane array (IRFPA) typically displays excellent performance. The output of the detector is linear with the input of the radiance[8]. Therefore, Eq. (1) can describe this result. For the purposes of efficiency and accuracy, when a calibration is conducted, a near extend-blackbody would be employed, which is shown in Fig.1.

$$G_{i,j}=R_{i,j}\cdot L(T)+G_{\mathrm{det}i,j} \tag{1}$$

where $G_{i,j}$ is the gray value of (i,j)th detector; $R_{i,j}$ is response of the system; $L(T)$ is the radiance; and $G_{\mathrm{det}i,j}$ is the offset caused by infrared radiometry system itself and the ambient.

The observed targets generally vary extremely due to the large range of radiance or temperature in the outfield. Thus, an infrared radiometric system with wide dynamic range is essential[9]. In outfield, the alteration of integration time can improve the dynamic radiometry range efficiently, but the calibration was conducted one-by-one in each integration time by traditional method[10]. To overcome the drawback of traditional calibration, the model of wide range calibration can be given as:

$$G_{i,j}(t,T)=t\cdot(R_{i,j}\cdot L(T)+G_{\mathrm{out}i,j})+G_{\mathrm{in}i,j} \tag{2}$$

where $G_{\mathrm{det}i,j}=t\cdot G_{\mathrm{out}i,j}+G_{\mathrm{in}i,j}$, $G_{\mathrm{out}i,j}$ is the offset caused by ambient temperature, usually related with integration time and $G_{\mathrm{in}i,j}$ is the offset caused by internal factors without integration time.

From Eq.(2), switching the integration time could conduct the calibration at random integration time, so this notably improves the efficiency.

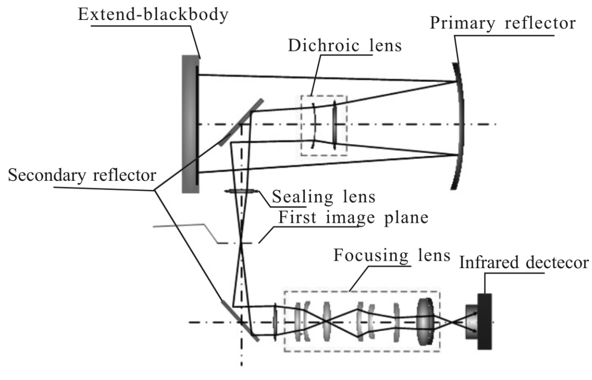


Fig.1 Schematic of near extended-blackbody calibration

2 High precision on small target by direct corrected atmospheric transmittance

2.1 Based on standard blackbody to correct atmospheric attenuation

Supposing that the integration time of the infrared radiometric system is t_0 and the initial temperature of the standard reference is T, the radiometry formula can be given as:

$$G(t_0,T)=t_0\cdot\tau_{atm}\cdot R_{i,j}\cdot L(T)+t_0\cdot(R_{i,j}\cdot L_{path}+G_{outi,j})+G_{ini,j} \quad (3)$$

Equation (3) can be written in another way:

$$G(t_0,T)=p\cdot L(T)+q \quad (4)$$

where $\begin{cases} p=t_0\cdot\tau_{atm}\cdot R_{i,j} \\ q=t_0\cdot(R_{i,j}\cdot L_{path}+G_{outi,j})+G_{ini,j}\end{cases}$.

If the temperatures of T_1 and T_2 have been known, the results can be given as:

$$\begin{pmatrix} p \\ q\end{pmatrix}=\begin{pmatrix} G(t_0,T_1) \\ G(t_0,T_2)\end{pmatrix}\cdot\begin{pmatrix} L(T_1) & 1 \\ L(T_2) & 1\end{pmatrix}^{-1} \quad (5)$$

Therefore, atmospheric transmittance τ_{atm} and path radiance L_{path} can be given as:

$$\begin{cases} \tau_{atm}=\dfrac{p}{t\cdot R_{i,j}} \\ L_{path}=\dfrac{q-G_{in}}{t\cdot R_{i,j}}-\dfrac{G_{out}}{R_{i,j}}\end{cases} \quad (6)$$

To reduce the error of the corrected results, the temperature of standard reference would change from T_1 to T_n[11]. Therefore, Eq.(5) can be expressed as:

$$\begin{cases} p=\dfrac{\sum_{i=1}^{n}(L(T_i)-\overline{L(T)})\cdot G(t_0,T_i)}{\sum_{i=1}^{n}(L(T_i)-\overline{L(T)})^2} \\ q=\overline{G(t_0,T)}-p\cdot\overline{L(T)}\end{cases} \quad (7)$$

where $\overline{G(T)}=\dfrac{\sum_{i=1}^{n}G(T_i)}{n}$, $\overline{L(T)}=\dfrac{\sum_{i=1}^{n}L(T_i)}{n}$.

2.2 Radiometry of a small infrared target

A small infrared target is one of the most typical structures in the outfield. If an observed target is far from the infrared radiometric system and is located in a high-altitude space, it can always be treated as a small target[12]. Due to the effect of atmospheric and optical system aberrations, the image of a small target would be dispersed into many pixels; in addition, the target is featured with micro-energy, which is likely to be covered by system noise. Therefore, for the inversion of radiance, a high precision and reliable method are required to gather the energy[13].

Assuming that the ideal imaging size is A_i, which can be given as:

$$A_i=M^2\cdot A_t=\frac{f^2}{S_1^2}\cdot A_t \quad (8)$$

where M is the paraxial magnification ratio; A_t is size of target; and S_1 is the distance of the target.

Near the target, the pixels of the detector are composed of "target pixels" and "background pixels". As is shown in Fig.2, region A_1 is selected, which contains the entire target, and a few backgrounds. The pixel numbers of N_1 are in this region. To remove the effects of background non-uniformity, instead of whole pixels, A_2 is selected, which contains N_2 pixels and the target region A_1. Hence, the average gray value of the background is G_b:

$$G_b=\frac{\sum_{i=1}^{N_2-N_1}G_i}{N_2-N_1} \quad (9)$$

where G_i, $i=1,2,\cdots,N_2-N_1$ is the gray value of background pixels.

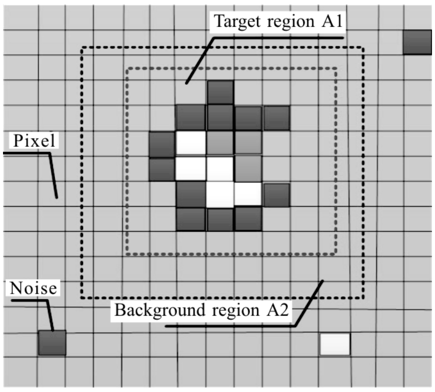


Fig.2 Basic processing principle of a small target

The number of background pixels in region A_1 can be determined as follows:

$$N_b=\frac{[A_d\cdot N_1-M^2\cdot A_t]}{A_d} \quad (10)$$

where $[A_d \cdot N_1 - M^2 \cdot A_t]$ is rounded to the nearest integer size.

Supposing that A_d is the size of a single pixel, the average gray value of a target in A_1 can be described as:

$$G_{\text{target}}=\frac{\sum_{i=1}^{N_1} G_i}{N_1}-\frac{\sum_{i=1}^{N_b} G_b}{N_b} \tag{11}$$

Therefore, the radiance of target is $L(T_0)$:

$$L(T_0)=\frac{\frac{G_{\text{target}}-G_{\text{ini},j}}{t}-G_{\text{out}i,j}-R_{i,j}\cdot L_{\text{path}}}{\tau_{\text{atm}}\cdot R_{i,j}} \tag{12}$$

3 Radiometric experiment

3.1 Experimental setup

To verify the validity of this method, a verification experiment is carried out. The infrared detector operates in the 3–5 μm waveband, and is composed of 640 pixel×512 pixel with a 14-bit digital output. The system has a diameter of 600 mm and a focal length of 1 200 mm; the temperature range is 0–125 ℃. The blackbody of SR200 is 100 mm×100 mm, and of SH800 300 mm×300 mm (both manufactured by CI systems). The temperature range is 0–125 ℃ and 0–600 ℃, respectively. In our experiments, SH800 acts as the standard reference, and SR200 was used as a small infrared target and the calibration site was given in Fig.3.

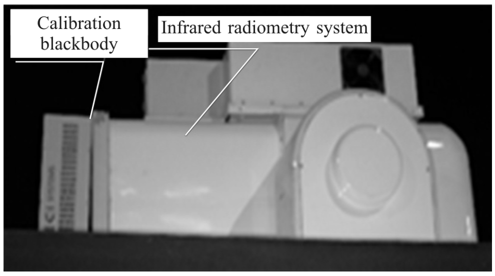


Fig.3 Site of calibration

3.2 Based on standard reference to correct atmospheric transmittance

During the experiment, the ambient temperature was about 15 ℃, the pressure was about 856 hPa, the relative humidity was about 20%, angle of pitch is 0°, the altitude was 1 400 m, and the visibility was about 23 km. The distance from the infrared radiometric system to the target was about 830 m. The average atmospheric transmittance and the path radiance were in the 3–5 μm waveband and was calculated using MODTRAN and the atmospheric devices were given in Fig.4 based on the above-measured parameters.

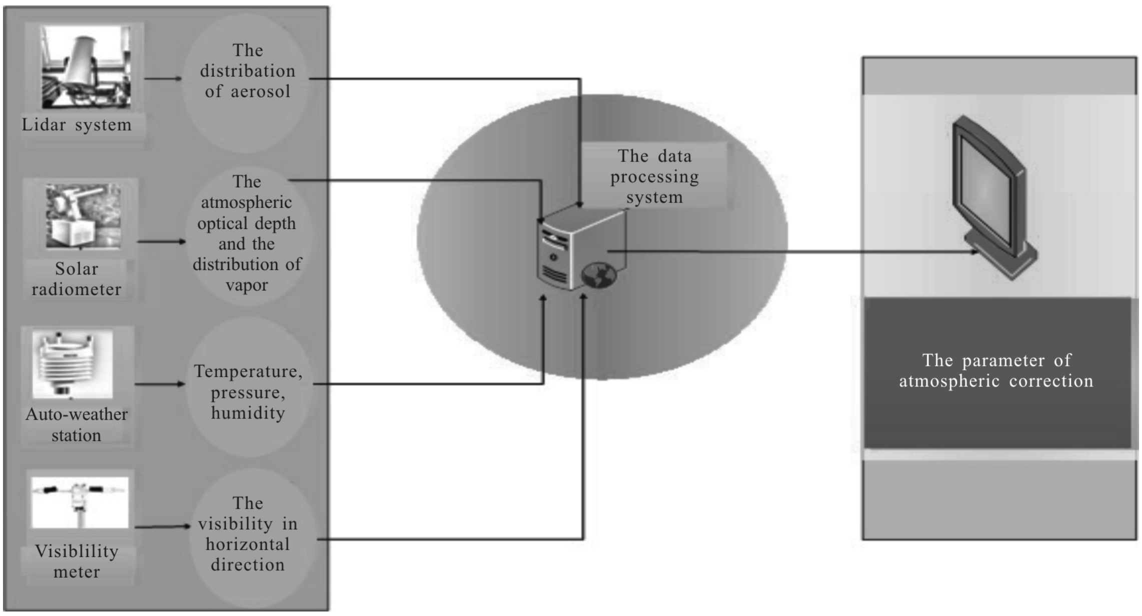


Fig.4 MODTRAN atmospheric transmittance correction sub-system

$$\begin{cases}\tau_{atm1}=0.739\,9\\L_{path1}=0.194\,2\ \mathrm{W\cdot m^{-2}\cdot sr^{-1}}\end{cases}\quad(13)$$

In this paper, to obtain a higher-precision radiometry, a method based on a standard reference to correct atmospheric transmittance and path radiance has been introduced. To reduce errors, the standard reference varied from 50 ℃ to 120 ℃, at intervals of 10 ℃, at different integration times of 2 000, 3 000, and 3 500 μs; results are given in Tab.1 and the site of radiometry is given in Fig.5.

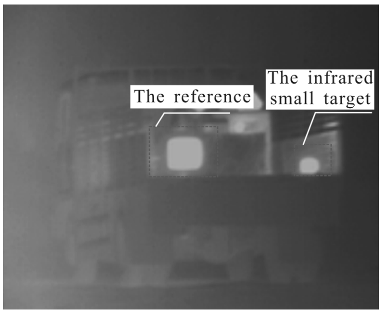


Fig.5 Site of the radiometry

Tab.1 Results of atmospheric transmittance and path radiance

Integration time/μs	τ_2	L_{path2}/ $\mathrm{W\cdot m^{-2}\cdot sr^{-1}}$
2000	0.687 7	0.732 3
3000	0.663 7	0.729 2
3500	0.692 9	0.726 1
Average value	0.681 4	0.729 2

3.3 Radiometry of small infrared targets

For the radiometry of a small infrared target, an gray value image of the target is given in Fig.6; the target was imaged at about 10 pixel×10 pixel. Therefore, it can be treated as a small target. As shown in Fig.7 and Fig.8, the results that were calculated using MODTRON at 2 000 μs show that the maximum error is 13.81% and the average error is 6.73%; on the whole, the system error of the RMS (Root-Mean-Square) was 7.36%. The results using the proposed method demonstrated that the maximum error was 2.20% and the average error was 0.73%, RMS of the system error was merely 0.97% at 2 000 μs.

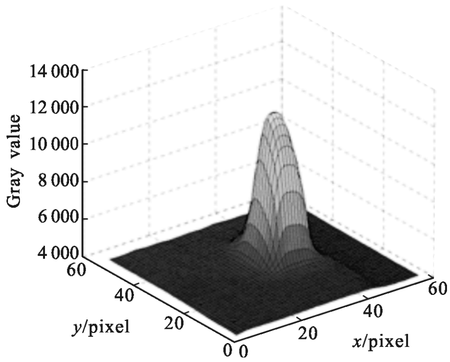
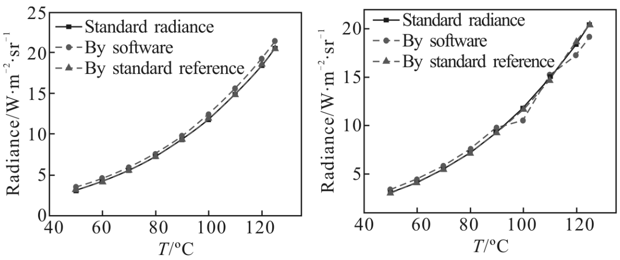


Fig.6 Image of a small infrared target



(a) Comparative results between the conventional and proposed methods at 2 000 μs (b) Comparative results between the conventional and proposed method at 3 000 μs

Fig.7 Precison results of radiometry

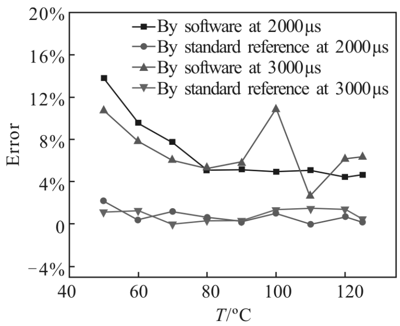


Fig.8 Radiometric error results at 2 000 μs and 3 000 μs

Similarly, at 3 000 μs, the results using the software showed that the maximum error was 10.86%, the average error was 6.88%, and the RMS of the system error was 7.30%. By contrast, the results using the standard reference presented a maximum error of 1.49%, the average error was 0.87%, and the RMS of the system error was only 1.03%.

Experimental results of the different integration times revealed that the method based on the standard reference for radiometry of small infrared targets was more accurate than that of the traditional method using software; moreover, the error of the proposed method tended to be moderate.

4 Conclusion

This paper introduced an approach to directly correct atmospheric transmittance, based on a standard reference for radiometry of small targets. A model with a wide dynamic calibration was employed. Then, based on the standard reference, an approach to calculate atmospheric transmittance and path radiance was proposed. Finally, radiometry experiments were performed, based on a MWIR system with a Φ600 mm diameter. Experimental results at 2 000 μs and 3 000 μs indicated that this method yielded a high precision for radiometric results, compared with the results of the software. Compared with the software calculations, to directly correct atmospheric attenuation, the higher radiometry could be obtained. Instead of expensive atmospheric observation devices, such as laser radar and solar radiometers, the method cut costs and complex calculations. It has to be pointed out that when the results are constricted to the standard reference, the method can be applicable for targets at high altitudes. However, it is prospective for radiometry in horizontal direction for direct corrected atmospheric transmittance.

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