A Study on Calibration Error Correction Method for Measurement of Infrared Radiation on Ships

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Abstract. Radiation calibration is one of the important factors affecting the accuracy of IR characteristics measurement. Radiation calibration is mainly completed by measuring blackbody. However, a certain type of ship mounted theodolite has a large blackbody area, long heating time, and low temperature uniformity, which leads to significant system calibration errors. This article evaluates and corrects the calibration parameters K and B values of the system by installing a portable blackbody at the bow of the ship. The results were verified by measuring portable blackbody at different temperatures, regions, sea areas, and distances. The inversion temperature error decreased from an average of 18.5℃ to 6.1℃, indicating that a certain distance calibration method significantly improves the measurement accuracy of the wave IR characteristics of the shipborne theodolite.

Keywords: Theodolite Medium Wave Infrared; Measurement of IR Characteristics; System calibration error; Portable Blackbody

1. Introduction

The error in measuring the infrared radiation(IR) characteristics of shipborne theodolites is a key factor that restricts the further expansion of the equipment's application functions. The main sources of measurement errors in the IR characteristics of a theodolite are system errors, atmospheric transmission and interference errors, and differences between targets and blackbody errors[1]. System errors are reflected in equipment stability and calibration accuracy, and can be corrected through blackbody calibration[2-3]. The atmospheric transmission error is mainly caused by the deviation between the atmosphere on the optical path and the instrument measurement in meteorological environments that are relatively complex compared to standard meteorology. Among them, the atmospheric transmittance has the greatest impact on targets above 100℃. The effects of atmospheric transport have been studied by many researchers[4-6]. The target blackbody approximation error mainly refers to the general tracking of irregular objects such as rocket tails, re-entry atmospheric targets, aircraft engine tails, ship chimneys, etc., whose IR temperature is also uneven, and the target is not a blackbody. The measurement angle error is relatively large, which may also be a comprehensive reflection of selective radiation and multiple material superimposed radiation. Its relative error can be analyzed for a certain type or type of equipment[7-8]. Therefore, generally only brightness temperature can be used to equivalent the target radiation temperature, and this article uniformly uses inversion temperature to represent it.

A certain type of shipborne theodolite has a large area of surface source blackbody installed inside the dome, but the calibration of this blackbody ignores atmospheric transmission errors, has a large area and low uniformity[9], and has low controllability, resulting in low calibration accuracy of the theodolite. This article mainly corrects the calibration parameters of the portable blackbody installed at the bow of the ship through a theodolite. The correctness of the parameters is verified through portable blackbody measurements at different temperatures, regions and sea areas, and distances. The target temperature is inverted, and the error changes are analyzed. After verification, the measurement accuracy of the IR characteristics of the shipborne theodolite has been significantly improved, which has high application value for the expansion and application of the IR characteristics measurement of the theodolite.

2. Principles of measuring IR characteristics

2.1 Basic Principles of Target IR

Any object above absolute zero will emit electromagnetic waves, and the blackbody satisfies the Planck blackbody radiation function [10] due to temperature radiation of electromagnetic waves, i.e

$$L_{b\lambda}(T)=\frac{2hc^2}{\lambda^5\{\exp[hc/k\lambda T]-1\}} \tag{1}$$

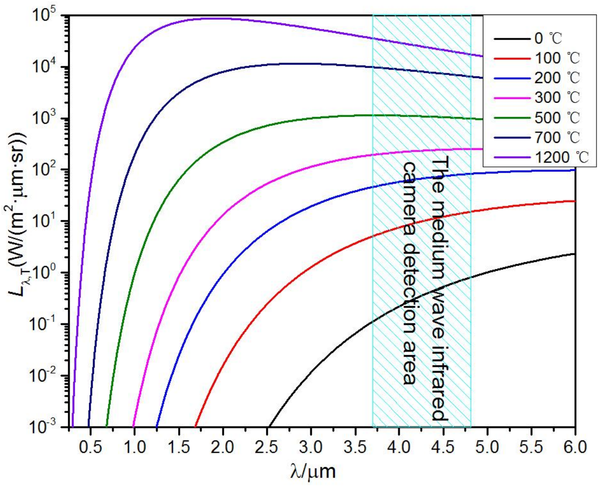
Among them, $L_{b\lambda}(T)$ is the radiance per unit wavelength of blackbody radiation, and its unit is W/(m^2·sr·μm); $h=6.6256\times10^{-34}$J·s is the Planck constant; $c=2.9979\times10^{8}$m/s is the speed of light in vacuum; λ is the electromagnetic wave length, its unit is μm; $k=1.3806\times10^{-23}$J/K is the Boltzmann constant; T is the Kelvin temperature of blackbody (=degrees Celsius+273.15).

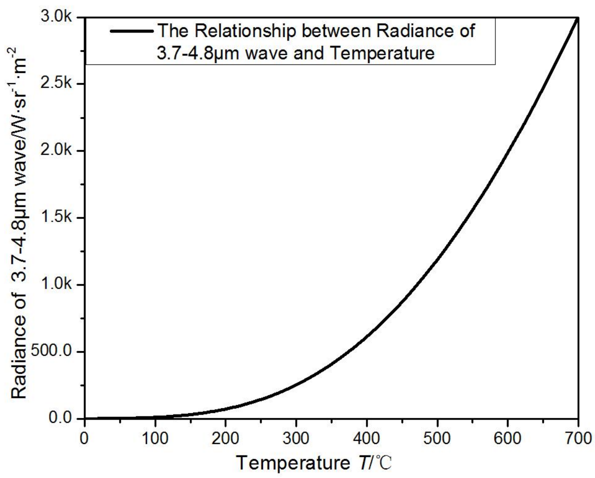
For practical objects that satisfy Lambert's cosine law, the electromagnetic waves of thermal radiation are generally selective radiators or gray bodies. For known materials, selective radiators can be approximated as gray bodies in some bands. This article only discusses wavelengths ranging from 3.7 to 4.8 μm for a certain type of shipborne theodolite , if the target source in the M-band is similar to a blackbody in mid wave infrared, then there is

$$L_{\mathrm{MIR}}(T)\approx\int_{3.7\mu\mathrm{m}}^{4.8\mu\mathrm{m}}L_{b\lambda}(T)\mathrm{d}\lambda \tag{2}$$

Among them, $L_{MIR}(T)$ represents the radiance of wavelength within the 3.7-4.8 μm band of the target source, and its unit is W/(m^2·sr).

Deng Mingde et al. [11] specifically studied the definite integral analysis of equation (2). The relationships between $L_{b\lambda}(T)$, wavelength and blackbody temperature in Celsius are shown in Fig. 1(a), while the relationships between $L_{MIR}(T)$ and blackbody temperature in Celsius are shown in Fig. 1(b). This definite integral is difficult to solve, and Fig. 1(b) shows the theoretical correspondence for MATLAB integral solution. The target radiation formula mentioned in the following text represents radiation within 3.7-4.8 μm band will no longer be labeled with MIR subscripts, unless otherwise specified.





(a) The Relationships between Radiatce, Wavelength and Blackbody Celsius Temperature in Blackbody Theory

(b) The Relationship between Wave Radiation Brightness and Blackbody Celsius Temperature in Blackbody Theory

Fig.1 The Relationships between Radiatce and blackbody temperature in Blackbody Theory in Celsius

From Fig. 1(b), it can be seen that for medium waves 3.7-4.8 μm There is an L=f(T) relationship between the IR brightness and temperature T, and the inverse function $T=f^{-1}(L)$ is also satisfied, which means that L and T have a one-to-one correspondence. After the target is determined, the corresponding target temperature T can be obtained by knowing the wave radiation brightness of the target.

2.2 IR transmission and theodolite measurement

From the target to the measurement end of the theodolite, it needs to be transmitted through the atmosphere, and the specific expression is:

$$L(T_{\mathrm{r}})=\tau_{\mathrm{a}}[\varepsilon_{\mathrm{R}}L(T_{\mathrm{R}})\cos\theta_{\mathrm{s}}+(1-\varepsilon_{\mathrm{R}})L(T_{\mathrm{B}})]+(1-\tau_{\mathrm{a}})L(T_{\mathrm{a}}) \tag{3}$$

Among them, $L(T_r)$ is the radiance of the entrance pupil measured by the theodolite; τa is the atmospheric transmittance; εR is the emissivity of the target source, which is the emissivity of the gray body relative to the black body, and is a constant value between 0 and 1, dimensionless; $L(T_R)$ target radiance; θs is the angle between the line connecting the theodolite and the target source and the normal of the radiation surface of the target source, in degrees; $L(T_B)$ is the background radiation brightness of the target; The radiance of the atmosphere along the $L(T_a)$ transmission path.[1]

Measure the radiation characteristics of a target at a certain distance that satisfies the gray body approximation, and the radiation illuminance formula is:

$$E(T_r)=\frac{L(T_r)\cdot A_s\cdot\cos\theta}{l^2} \tag{4}$$

Among them, $E(T_r)$ is the irradiance of the target at the measurement point, in W/m^2; θ is the angle between the line connecting the theodolite lens and the target and the normal of the theodolite lens, measured in degrees; As is the target radiation area, in square meters; L is the distance between the target and the theodolite, in meters.

On the premise that the theodolite can produce clear images, the formula for the size of the theodolite object image can be expressed as follows

$$M = \frac{M_1 \times f}{M_2 \times l} \tag{5}$$

Among them, M is the number of imaging pixels, dimensionless; M1 is the size of the target line, in meters; M_2 is the pixel line size, in meters; F is the focal length in meters.

For a single pixel M=1 in target imaging, since M2 remains constant and f remains almost constant, M_1 is approximately proportional to l, that is $A_s = M_1^2 = \frac{M_2^2}{f^2} \cdot l^2$. For point targets, it is necessary to calculate the number of target imaging pixels based on target size and measurement distance, and then calculate the equivalent grayscale of target imaging pixels based on effective average grayscale, background grayscale, etc., and then calculate the target radiation brightness.

For the active tracking of targets by a theodolite, there are θ≡0°, the radiation energy received by the theodolite is the radiance of the target in front of the theodolite lens multiplied by the area of the theodolite lens, which is the input power $P(T_r)$.

$$P(T_r) = E(T_r) \cdot A \tag{6}$$

Where A is the lens area of the theodolite, in square meters.

Theodolite imaging grayscale formula:

$$G = \kappa \cdot P(T_r) + \mathrm{B} \tag{7}$$

Among them, G is the grayscale value of the infrared measurement image of the theodolite; Measure the system response coefficient of the measuring instrument (related to optical system transmittance, filter settings, camera single pixel response power, camera integration time, etc.); B is the system compensation for theodolite imaging.

For a single pixel of a surface target, if the theodolite constant is uniformly represented, then

$$G = \mathrm{K} \cdot \{\tau_a [\varepsilon_R L(T_R) \cos\theta_s + (1 - \varepsilon_R) L(T_B)] + (1 - \tau_a) L(T_a)\} + \mathrm{B} \tag{8}$$

Among them, $\mathrm{K} = \kappa \cdot \pi r^2 \cdot M_2^2 / f^2$ the calibration coefficient of the theodolite is related to the theodolite lens radius r, system response coefficient, pixel size M_2, focal length f, etc., and is independent of the incident radiation[9].

Equation (8) is the basic principle of imaging in the mid wave infrared system of a theodolite.

In practical device applications, K and B values are obtained through zero distance blackbody calibration. The system parameter values corresponding to different filters and integration times for the calibrated medium wave infrared 800mm focal length of our ship's theodolite are shown in Table 1.

Table 1 Calibration state parameter values of a certain system under the wavelength infrared 800mm focal length of the theodolite

Integral time/ms	Filter 1		Filter 2		Filter 3		Filter 4		Filter 5	
	K	B	K	B	K	B	K	B	K	B
0.6	322.61	1601.27	322.33	1590.50	106.53	1904.0	37.79	2048.59	22.70	1822.95
2.5	1343.	2271.49	1342.06	2481.75	444.45	3560.9	157.49	3885.7	94.58	2921.3

	96					2		3		8
3.0	1612.19	2446.69	1607.93	2724.29	533.06	3998.34	188.99	4368.78	113.51	3210.42
3.5	1880.72	2625.35	1875.73	2961.52	621.41	4437.29	220.45	4855.51	132.44	3499.22
4.0	2149.08	2798.63	2143.71	3198.83	710.46	4872.82	251.96	5337.41	151.36	3788.33
5.0	2686.79	3149.93	2679.92	3672.65	887.80	5746.94	314.95	6307.90	189.20	4367.76
6.0	3224.32	3502.81	3216.76	4145.59	1064.30	6627.93	377.96	7272.13	227.05	4947.14

For a certain side of a radiator, formula (8) can be rewritten as

$$L(T_{\mathrm{R}})=\frac{1}{\varepsilon_{\mathrm{R}}\cos\theta_{\mathrm{s}}}\cdot\left\{\frac{1}{\tau_{\mathrm{a}}}\cdot\left[\frac{(G-\mathrm{B})}{\mathrm{K}}-(1-\tau_{\mathrm{a}})L(T_{\mathrm{a}})\right]-(1-\varepsilon_{\mathrm{R}})L(T_{\mathrm{B}})\right\} \quad (9)$$

Equation (9) is a formula for inverting the target radiation brightness based on the imaging grayscale of the theodolite. By combining equation (9) with the corresponding relationship in Fig. 1(b), the actual temperature TR of the target can be obtained.

3. Measurement test of IR characteristics of Theodolites

3.1 Introduction to the experiment

The shipborne theodolite adopts the system's built-in calibration blackbody, which has a large volume and a large radiation surface. In practical use, there are problems such as slow heating and low temperature uniformity, resulting in a short sampling interval during calibration and inability to evaluate atmospheric model errors in the application environment. Based on the above considerations, a portable blackbody CEM BX-500 is purchased, with a maximum heating temperature of 500 ℃. Place the portable blackbody at the bow of the ship, with the radiation surface facing the theodolite. Turn on the atmospheric parameter measurement equipment such as LiDAR, solar photometer, and visibility meter, and use the theodolite's medium wave infrared system to capture images at different temperatures. Perform inversion analysis on captured images. The experiment was conducted in the waters near the Pacific equator with clear weather and a small amount of high-level clouds. The photos of the experimental process are shown in Fig. 2.

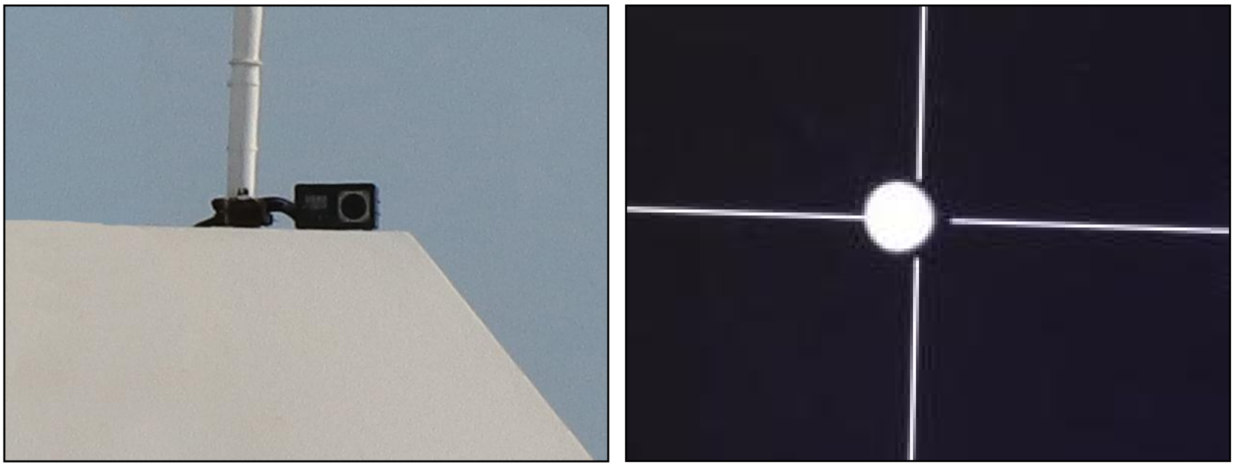


Fig. 2 Portable Blackbody Photo and Blackbody Imaging of Ship Bow Installation

3.2 Analysis of experimental results

Set the portable blackbody temperatures of 110℃, 160℃, 200℃, 250℃, 300℃, and 400℃ respectively, and use the mid wave infrared system of a theodolite to detect them. A total of 61 sets of effective experimental data were obtained during the calibration stage, and the difference in inversion temperature is shown in Fig. 3.

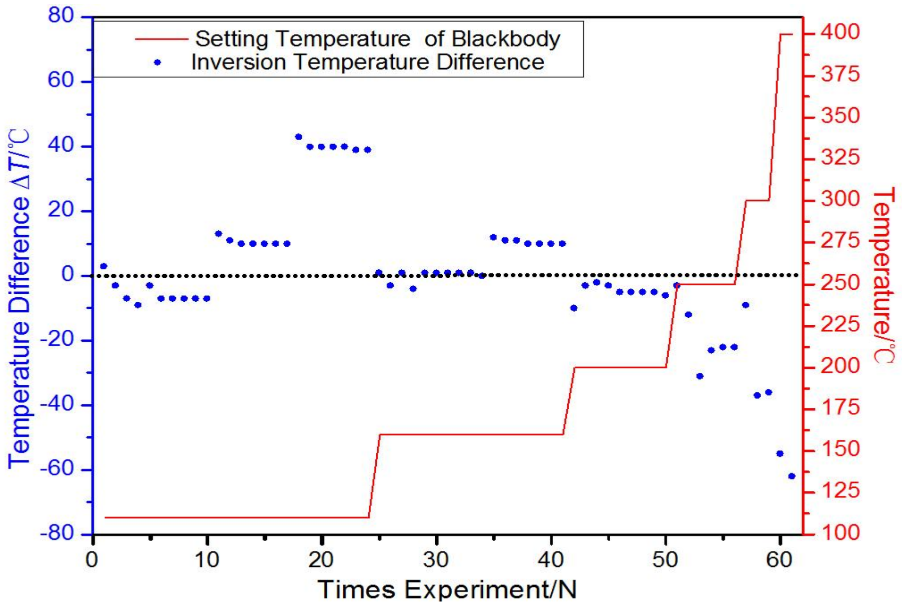


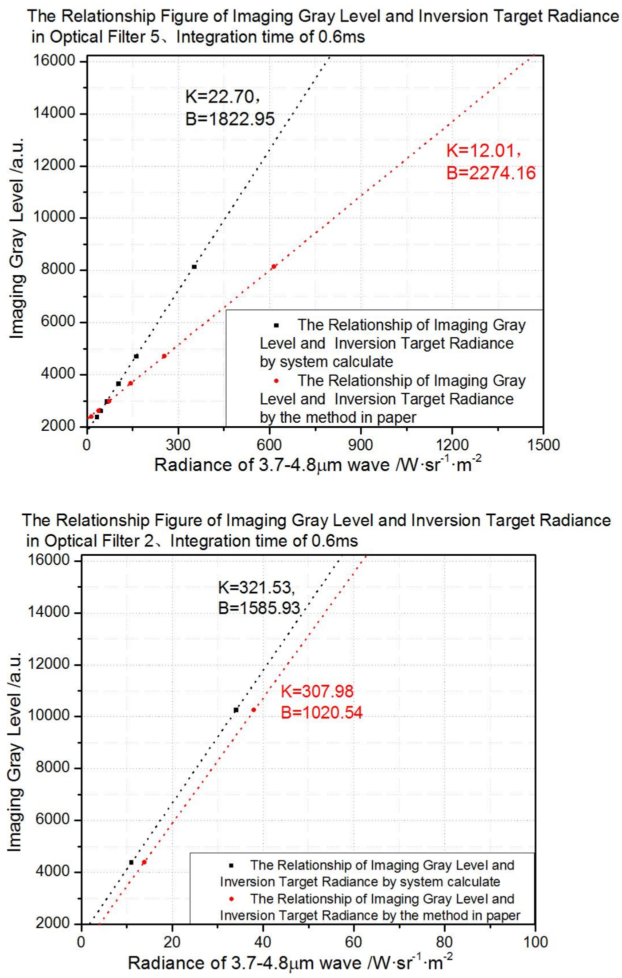
Fig. 3 Comparison of ΔT Inverted from Different Temperature Theodolites in Portable Blackbody Experiments

It can be seen that there is a significant regularity deviation in the inversion of blackbody temperature from Fig. 3. This regularity error is mainly caused by errors in the calibration parameters K and B of the theodolite, which can be reduced by correcting the K and B values.

4. Calibration parameter error correction based on portable blackbody

4.1 K and B parameter correction based on portable blackbody

Substitute the portable blackbody temperature T into formula (2), calculate the corresponding radiance L and the measured grayscale G of the theodolite into formula (8), and use CART software[12] to calculate the atmospheric parameters of the measured meteorological data τ_a. Load $L(T_B)$ and $L(T_a)$ into formula (8). Correct the K and B values under this experimental state. As shown in Fig. 4, a comparison diagram of the relationship between grayscale and radiance of some theodolites K and B parameters before and after correction is shown. The specific correction results at a focal length of 800mm are shown in Table 2.



(a) Filter 5, integration time 0.6ms. (b) Filter 2, integration time 0.6ms.

Fig. 4 Schematic diagram of the relationship between self calibration of the theodolite, calibration K and B values using the method described in this article, and the imaging grayscale *G* of the theodolite with the target medium wave radiation brightness *L*

Table 2 Parameter values of calibration state for close range blackbody correction at a focal length of 800mm in the mid wave infrared of the theodolite※

Integral time/ms	Filter 1		Filter 2		Filter 3		Filter 4		Filter 5	
	K	B	K	B	K	B	K	B	K	B

0.6	306.77	1838.77	307.98	1020.54	98.05	1796.17	31.94	2199.65	12.01	2274.16
2.5	1327.65	2507.58	1326.12	1920.48	416.12	2943.51	135.80	4545.12	58.32	4666.38
3.0	1596.31	2683.58	1594.05	2157.30	499.82	3245.44	163.49	5010.17	63.94	5236.26
3.5	1864.96	2859.59	1861.98	2394.13	583.53	3547.37	184.46	5698.09	78.13	5753.32
4.0	2133.61	3035.59	2129.91	2630.95	667.23	3849.30	210.89	6294.20	89.21	6356.62
5.0	2670.92	3387.59	2665.77	3104.60	834.63	4453.17	260.09	7529.68	111.19	7576.40
6.0	3208.22	3739.60	3201.63	3578.25	1002.04	5057.03	314.64	8714.36	127.45	8885.31

※The blue data in the table represents the calibration results using the method described in this article, while the red data represents the calculation results based on the K and B parameter patterns and referring to the original system parameters.

Due to the proximity of the portable blackbody to the theodolite, the energy loss is relatively small. Filters 1 and 2 have already saturated at an integration time of 2.5ms. After comparing the 0.6ms system self calibration results of filters 1 and 2 with the portable blackbody calibration coefficient, the K and B variation rules are used to refer to the original parameter results for correction. The data of filters 3 and 4 are calculated based on the calibrated K and B values according to the variation rules. Compare the K and B data before and after revision, as shown in Fig. 7.

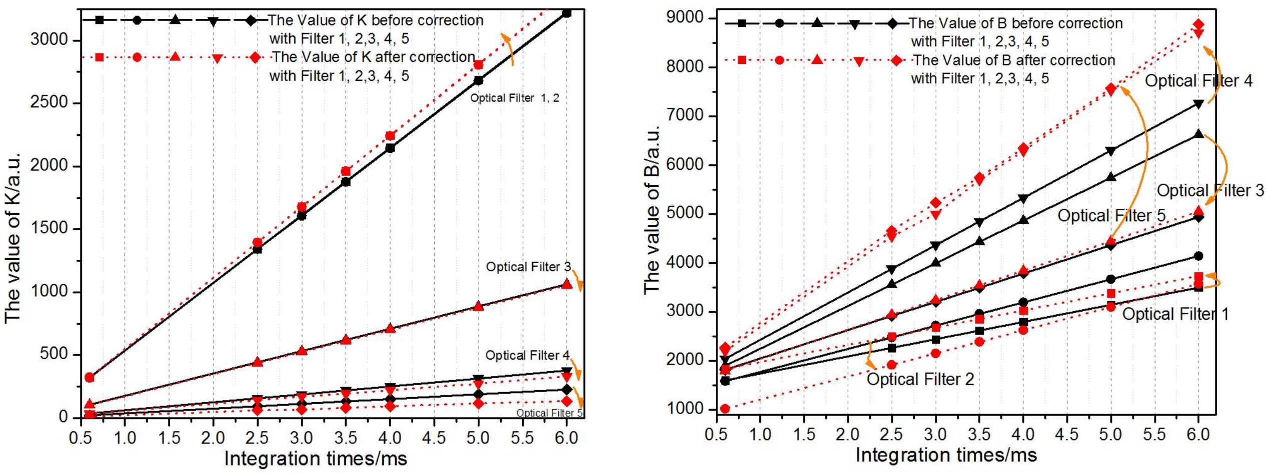


Fig. 5 Comparison of changes in K and B values before and after correction

4.2 Verify the accuracy of K and B parameters and invert temperature errors

4.2.1 Set portable blackbody temperature inversion error for different temperature tests

Inversion calculations were performed on the theodolite measurement images of portable blackbody temperatures of 390, 386, 350, 180 and 100℃ in a certain open sea. The results are shown in Table 3.

Table 3 Verification of calibration results by setting other temperatures on the calibration day

Set T /℃	Filter	Integra -tion time/ms	System Inversion L /W·m-2·sr-1	System Inver -sion Tempera- ture /℃	System Inversion Diff- Temp ΔT/℃	Inversion using the method in this paper L /W·m-2·sr-1	Inverted temperature using the method in this paper T/℃	Inversion Diff-Temp using the method in this paper ΔT /℃
390	5	0.6	329.00	330	-60	605.21	398	-2
386	4	0.6#	361.50	340	-46	448.21	361	-25
350	5	0.6	241.60	295	-51	407.01	350	0
180	5	2.5	53.75	180	0	51.50	178	-2
180	5	3.0	52.65	179	-1	53.24	180	0
180	4	2.5	52.31	178	-2	54.75	182	2
180	3	0.6	49.13	175	-5	56.23	183	3
100	5	0.6	28.06	145	45	8.40	91	-9
100	3	2.5	8.71	89	-11	10.10	99	-1

#The portable blackbody has a temperature of 386℃, an emissivity of 0.95, and an atmospheric transmittance of 0.79156. The entering radiation brightness of the theodolite is 414.58W/m^2·sr, corresponding to the imaging grayscale of 15441. The theodolite will provide protection when the grayscale exceeds 15000, and the results often cannot accurately reflect the target brightness. Therefore, the inversion result has a large error.

From Table 3, it can be seen that the temperature error of the black body inversion of the theodolite in the same environment after K and B value correction is significantly reduced, with an average error of less than 3℃, thus proving the accuracy of K and B values.

4.2.2 Using historical blackbody measurement test data to verify inversion temperature errors

The calculation of test data for ships located in the Indian Ocean and domestic ports is shown in Table 4.

Table 4 Inversion Results of Indian Ocean and Terminal Test Data

Set T /℃	Filter	Integra -tion time/ ms	System Inversion L /W·m-2·sr-1	System Inver -sion Tempera- ture /℃	System Inversion Diff-Temp ΔT /℃	Inversion using the method in this paper L /W·m-2·sr-1	Inverted temperature using the method in this paper T /℃	Inversion Diff-Temp using the method in this paper ΔT /℃
400	5	0.6	400.54	350	-50	664.36	411	11
300	5	0.6	166.56	261	-39	274.11	308	8
3	4	0.6	227.63	290	-10	257.26	301	1

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250	5	0.6	112.37	231	-19	152.35	254	4
250	5	2.5	110.94	230	-20	154.12	255	5
250	5	3.0	110.44	229	-21	153.39	255	5
250	4	0.6	132.54	242	-8	139.45	247	-3
200	5	0.6	67.19	194	-6	72.66	200	0
200	5	3.0	67.06	194	-6	68.33	196	-4
200	5	4.0	66.01	193	-7	71.94	199	-1
200	4	0.6	65.87	193	-7	69.01	197	-3
200	4	2.5	66.73	194	-6	68.11	195	-5
160	4	0.6	37.99	160	-0	37.09	159	-1
160	3	0.6	27.58	142	-18	29.50	147	-13
160	3	2.5	26.82	141	-19	28.72	146	-14
160	3	3.0	25.99	140	-20	28.69	146	-14
110	5	4.0	29.47	145	-35	14.37	112	2

110	4	3.0	10.69	99	-11	11.09	101	-9
110	3	2.5	10.72	99	-11	11.58	102	-8
110	2	0.6	11.06	100	-10	13.96	110	0
110	1	0.6	14.35	112	2	14.01	110	0

From Table 4, it can be seen that the corrected K and B values in this article have a significant improvement on the error of the theodolite inversion of blackbody temperature. The average error has decreased from 15.5℃ to 5.3℃.

4.2.3 Erecting blackbody on calibration towers to verify temperature inversion errors

The portable blackbody data of the dynamic measurement calibration tower before the ship docks was inverted and calculated, and the results are shown in Table 5.

Table 5 Inversion results of blackbody test data for variable distance tracking calibration tower

Set T /℃	Distance /km	Target Type	Filter	Integration Time /ms	System Inversion L /W·m-2·sr-1	System Inversion Temperature /℃	System Inversion Diff-Temp ΔT /℃	Inversion using the method in this paper L /W·m-2·sr-1	Inverted temperature using the method in this paper T /℃	Inversion Diff-Temp using the method in this paper ΔT /℃
300	1.30	point	4	2.5	204.33	279	-21	230.06	291	-9
300	1.14	point	4	2.5	211.76	282	-18	238.79	294	-6
300	0.87	point	4	2.5	218.90	286	-14	247.19	298	-2
200	3.40	point	4	2.5	40.41	163	-37	53.41	180	-20
200	2.80	point	4	2.5	56.27	183	-17	56.06	183	-17
2	2.20	poi	4	2.5	46.96	172	-28	65.12	193	-7

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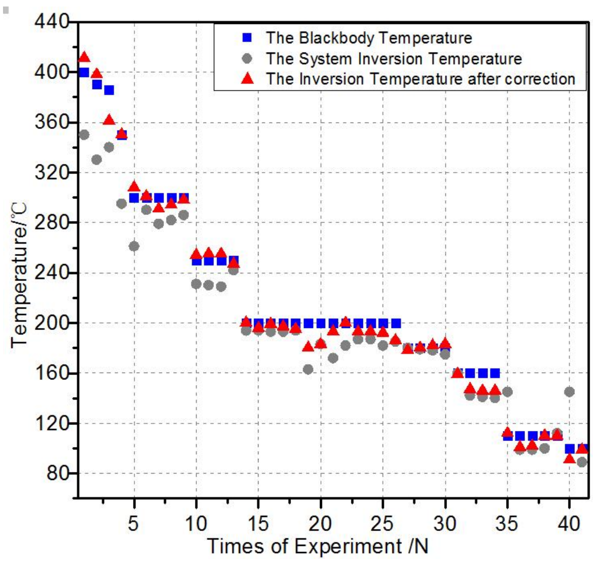
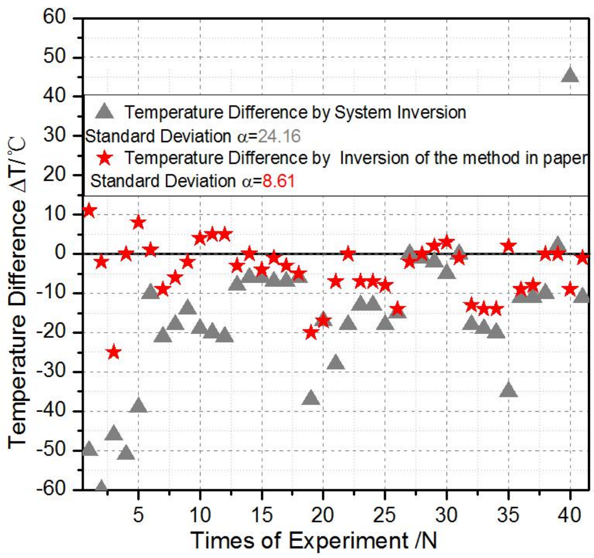
200	0.87	point	4	0.6	55.78	182	-18	72.77	200	0
200	0.87	point	4	2.5	60.05	187	-13	65.50	193	-7
200	0.87	point	4	3.0	59.62	187	-13	65.87	193	-7
200	0.87	point	2	0.6	55.87	182	-18	63.01	192	-8
200	0.87	point	2	2.5	58.45	185	-15	58.07	186	-14

Comparing 41 sets of experimental data in Tables 3-5, the comparison of set temperature, system inversion temperature, and inversion temperature after parameter correction is shown in Fig. 6(a). The comparison of inversion temperature difference before and after parameter revision is shown in Fig. 6(b). The standard deviation of temperature measurement before correction is 24.16, and the standard deviation of temperature measurement after correction is 8.61. The average temperature measurement error has decreased from 18.5℃ before correction to 6.1℃ after correction, and the temperature difference has decreased more significantly in the high temperature range.



(a) Blackbody set temperature, system inversion temperature, comparison of inversion temperature after parameter correction



(b) comparison of inversion temperature difference before and after parameter correction

Fig. 6 Comparison of Blackbody Temperature and Diff-Temperature Inverted by Theodolite Before and After Parameter Correction

5. Conclusion

The measurement error of the IR characteristics of the theodolite is an important limiting factor that affects its use as a target characteristic inversion method. The use of the system's built-in blackbody calibration results in large low-temperature calibration errors and environmental factors that cannot lead to parameter deviations in the calibration system. In this paper, a portable blackbody is installed at the bow of the ship to calibrate the K and B value parameters of some low transmittance filters in the wavelength infrared system of the theodolite at a focal length of 800mm, and to reference and correct parameters that have not been directly calibrated. After verification by different temperatures, regions and sea areas, and distances, the inversion temperature error was significantly reduced. The standard deviation of temperature difference in the verification experiment was reduced from 24.16 to 8.61, and the temperature measurement error was reduced from 18.5℃ to 6.1℃. The accuracy of IR characteristic measurement was significantly improved, which has high application value for the expansion and application of IR characteristic measurement in theodolites.

References

[1] Yang Li, Yang Zhen The principle and technology of infrared thermal imaging temperature measurement [M]. Science Press, 2012.

[2] Zheng Feng, Liu Liying, Liu Xiaoxi, etc. A method for radiometric calibration of a near-infrared fiber spectrometer based on a medium-temperature blackbody[J] Spectroscopy and spectral analysis 2015, 35(9).

[3] Yin Limei, Qiao Bing, Liu Junchi, etc. Joint radiometric calibration method for ground-based infrared radiation measurement system [J]. Journal of Optics, 2018,38(4) : 201-206

[4] Sun Zhiyuan, Zhu Wei, Qiao Yanfeng, etc. Study on correction of environmental effects in measurement of IR characteristics[J] . Laser and infrared, 2010,40(02): 162-165.

[5] Yang Ciyin, Zhang Jianping, Cao Lihua. A new method of target IR measurement based on real-time calibration [J]. Journal of infrared and millimeter waves, 2011, 30(03): 284-288.

[6] Liu Xinming, Li Zhou, Chen Deming, Cai Lihua, Wang Qianxue. Measurement of infrared radiation characteristics of ships by reference source method[J]. Advances in laser and optoelectronics, 2019,56(23) : 69-74.

[7] Li Yuanyuan, Qu Huiming, Liu Wenjun. Study on field target emissivity measurement method based on environmental radiation [J]. Laser and infrared, 2013,43(3): 4.

[8] Qiao Zhi, Wang Lin. The method of measuring the emissivity of infrared temperature measuring object: CN201110369338.0[P] . CN102519606B [2024-03-25].

[9] Li Zhou Research on Wide Dynamic Radiation Measurement of Ground Based Target Range infrared radiation Characteristics Measurement System [D] Changchun: University of the Chinese Academy of Sciences (Changchun Institute of Optics, Precision Mechanics and Physics, Chinese Academy of Sciences), 2018.

[10] Mao Hongxia, Liu Zhongling, Tian Yan. IR and target recognition [M] Science Press, 2022.

[11] Deng Mingde, Yin Jingyuan, etc. The product decomposition of blackbody radiation formula and its application in remote sensing information [J] 2002.1.

[12] Wei Heli, Dai Congming, Wu Pengfei, etc. Application of general atmospheric radiative transfer software CART in scene calculation (invited)[J]. Infrared and laser engineering, 2022,51(05): 11-20.