Design of On-Orbit Radiation Calibration Scheme of Optical Remote Sensing Systems

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Abstract. For quantitative application of space remote sensing, strict radiation calibration before launch, to determine the initial spectral radiation response characteristics of remote sensing, due to space particle radiation, pollution, components aging will cause the degradation of remote sensing performance, to change the spectral radiation response characteristics, therefore, regularly for radiation calibration, meet the requirements of long-term quantitative application of remote sensing data. When the earth-observation remote sensing system with NIR and SWIR infrared spectrum works, the radiation received by the remote sensing device is greatly affected by the sun. For the remote sensing device with large field of view greater than 100 degrees, multi-perspective calibration is required to reduce the calibration error. Generally, external scene calibration sources (such as large desert area on the ground, the sun, the moon, the cryogenic space, etc.) or built-in calibration devices (such as lamps, silicon carbide sticks, blackbody, etc.) could be selected to reduce the calibration uncertainty. When the infrared remote sensing system uses blackbody for radiometric calibration, by using accurate blackbody radiation model and highly stable blackbody emission performance, the uncertainty of radiation calibration could be reduced. The designing of infrared optical remote sensing was introduced, and the method of calibration accuracy analysis was introduced in the paper.

Keywords: Remote sensing system · On-orbit Radiation Calibration · Blackbody · Calibration Accuracy · Quantitative Application

1 Introduction

Infrared remote sensing could be used not only in civil fields such as meteorology and hydrology, resource exploration, agricultural survey, but also in astronomical observation science applications, with a wide range of applications [1]. At present, scientific research requires high accuracy of quantitative inversion of space infrared remote sensors.

Due to a series of factors such as non-uniformity of detector chip substrate material, detector doping level, detector bias voltage, readout circuit noise level, and inconsistency between multiple parallel output channels, spatial infrared remote sensor has non-uniformity in focal plane array response. In addition, the image illumination uniformity of optical system design, stray radiation of optical system, and changes in operating temperature of optical system, Will affect the stability of the output. Before launching, the

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laboratory vacuum radiation calibration shall be strictly carried out, and the ground pixel by pixel calibration shall be completed to obtain the parameter difference between pixels, so as to determine the initial spectral radiation response characteristics of the remote sensor [2]. During the orbit flight of the remote sensor, due to the radiation of space particles, pollution, aging of components, etc., the performance of the remote sensor will be degraded, thus changing the spectral radiation response characteristics. Therefore, it is necessary to regularly calibrate the remote sensor on satellite radiation to meet the user's requirements for long-term quantitative application of remote sensing data. Generally, external scene calibration sources (such as large desert area on the ground, the sun, the moon, the cryogenic space, etc.) or built-in calibration devices (such as lamps, silicon carbide sticks, blackbody, etc.) could be selected to reduce the calibration uncertainty.

When the infrared remote sensing system uses blackbody for radiometric calibration, by using accurate blackbody radiation model and highly stable blackbody emission performance, the uncertainty of radiation calibration could be reduced. The uncertainty of radiation calibration of space remote sensing instruments has reached the best level of 2%–3%. At the same time, it is easy to achieve full aperture, full optical path and full field of view absolute radiation calibration, such as MODIS, AATSR SPECTRA and etc.all use blackbody for on orbit calibration. The long-term decay of blackbody emissivity in orbit could be monitored by other calibration methods. For example, ASTRO-F could observe stars during its orbit, and it uses the sensitivity of far-infrared detector and the brightness of point source to carry out the absolute radiation calibration of stars; SPIRIT III also carried out absolute radiometric calibration using stars in orbit. The high resolution satellite IKONOS has chosen the scheme of using stars for radiometric calibration, and the error between it and the calibration scheme of NASA team is 2.5%.

2 Radiation Calibration Scheme Design

The high temperature and low temperature area source blackbody were both used as the standard source for absolute radiometric calibration. The stability of area source blackbody will affect the calibration accuracy [3]. Because the radiation of stars is relatively stable, the calibration results of blackbody are corrected by observing stars. It is a better method of satellite calibration for infrared remote sensor [4].

There are many factors to be considered in the design of radiometric calibration scheme, including the working spectrum, calibration accuracy, life, reliability and constraints from spacecraft and aerospace optical remote sensors.

2.1 Blackbody Calibration

The blackbody surface is designed with V-shaped slots at a certain angle and the surface is anodized and blackened, which could ensure that the blackbody has good radiation uniformity and high radiation emissivity [5, 6].

The onboard blackbody design parameters of a remote sensing camera are as follows:

1) Blackbody temperature: could cover the target and scene equivalent blackbody temperature, adjustable;
2) Effective size in bold: could cover the entrance pupil of the camera);

3) Normal emissivity: $\geq$0.98;
4) Temperature uniformity: $\leq$0.2K;
5) Temperature control accuracy of blackbody surface: $\pm$ 0.1K;
6) Temperature measurement accuracy: $\leq$0.1K.

The high-temperature blackbody component is mainly composed of blackbody, heating sheet, thermal insulation gasket and thermal insulation gasket. Aluminum alloy 2A12 with good thermal conductivity, light weight and high hardness is selected to be processed into high-temperature black body, and thermal insulation gasket is processed from polyimide. Titanium alloy screws with poor thermal conductivity are used to connect the high-temperature blackbody and the scanning base.

The low-temperature blackbody component is mainly composed of blackbody, semiconductor cooler, fixing block (used to fix semiconductor cooler and heat pipe), heat pipe, thermal insulation gasket and thermal insulation gasket. The low-temperature black body is made of aluminum alloy 2A12 with good thermal conductivity, light weight and high hardness. The connection between the low-temperature black body and the scanning base and the fixing block is made of titanium alloy screws with poor thermal conductivity.

Optimization of high precision temperature control measures for blackbody:

1) The enclosure is arranged outside the blackbody component, and the temperature is controlled through the radiation of the enclosure to meet the temperature requirements. The external surface of the enclosure is arranged with an active temperature control heating circuit; The inner surface of the outer cover is blackened to enhance the radiation heat transfer between the outer cover and the blackbody component. The outer surface of the outer cover is covered with multi-layer thermal insulation materials to reduce radiation heat leakage. The outermost side of the multi-layer is black polyimide carburized film;
2) The two sides of the blackbody are sandwich structures, and the middle layer could be a 0.5 mm-thick-graphite film to improve the temperature uniformity in the area of the optical path. The back of the blackbody is covered with multi-layer thermal insulation materials to reduce heat leakage after cutting into the optical path;
3) Thermal insulation installation between blackbody and supporting structure to reduce mutual influence of temperature;
4) The blackbody support structure is arranged with an active temperature control heating circuit, and the support structure and the camera main frame are installed with thermal insulation.

Through the thermal design and thermal analysis of the high and low temperature blackbody, the temperature level and uniformity of the blackening side of the high and low temperature blackbody that affect the radiometric calibration accuracy are shown in the following Table 1 (Fig. 1).

2.2 Solar Calibration of Diffuse Reflective Plate

The solar diffuser has been widely used in high-precision absolute the solar radiation calibration. Using accurate solar radiation model and highly stable solar diffuser reflection performance, could achieve high calibration accuracy.

Fig. 1. High temperature blackbody component and cryogenic blackbody component

Table 1. Calculation results of high temperature blackbody and cryogenic blackbody

ITEMS	Temperature Stability	Temperature Uniformity
High temperature blackbody	<0.1 °C/min	0.3 °C
Low temperature blackbody	<0.1 °C /min	0.3 °C

1) Design of the diffuse reflection plate components.

   Reflection plate adopts high temperature fusion PTFE diffuse reflective plate with superior optical reference characteristics and certain spatial adaptability, could be approximated as ideal Lambert; and slightly backscattering; its BRDF precision 2%, The surface uniformity could be controlled within 1%. The reflectivity of the solar diffuser is higher than 90%.
2) The protection design of the diffuse reflection plate components is small.

   The solar diffuser would be organic polluted on orbit, which will directly affect its optical reference characteristics and its stability. Therefore, reliable protection is required during the diffuse plate making, storage, detection and transportation: the first layer is optical protection, the diffuse plate under the protective plate is made of PTFE with the same material and cleanliness as the diffuse plate while protecting the diffuse plate; the second layer is physical protection, the components containing the protective plate is installed in the stainless steel nitrogen box, and then tighten the sealing circumference and cover plate, and effective prevent the damage.
3) Diffuse reflection plate performance monitoring,

   The furnace test plate is installed under the diffuse plate protection and next to the product. Once the protection is removed, the furnace test plate is exposed to the same laboratory environment. Remove the furnace test plate before launch, the difference from the diffuse plate is delivered, and the BRDF correction factor of the diffuse plate for sample monitoring before launch is obtained.

The solar diffuser stability monitoring radiometer monitors the changes of the bidirectional reflection distribution function of the incident light in the outgoing direction after a surface reflection, and corrects the reflection illumination [7] (Fig. 2).

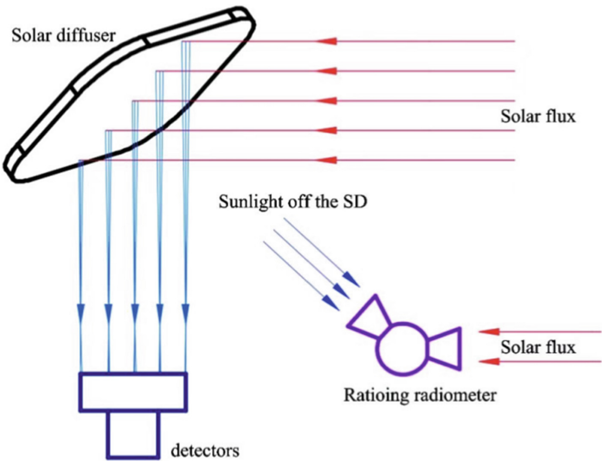

Fig. 2. Schematic diagram of solar calibration of diffuse reflective plate

2.3 Infrared Star Calibration and Data Correction Method

At present, the method of using stars for radiation calibration is mainly used in astronomical satellites and astronomical observations. The following factors need to be considered in the star calibration process:

1) The star is a typical point source target, and its solid angle is generally much smaller than the camera pixel's IFOV. The star position deviation caused by satellite attitude jitter or flutter, the image point extraction algorithm error in the point target speckle formed when the camera observed the star.
2) The influence of camera noise in the measurement process is also a part of the calibration error, so it is necessary to reduce the camera time noise as much as possible.

The camera response during star calibration could be calculated by the following formula.

$$V = k \cdot \frac{\int R(\lambda) \cdot E(\lambda) \cdot \eta d\lambda}{\Omega \cdot \cos^3(\omega) \int R(\lambda) d\lambda} \tag{1}$$

where, V: camera response; k: Radiation calibration coefficient; R(λ): Camera spectral response; E(λ): Stellar irradiance; η: Energy concentration; ω: Imaging photonics off-axis angle; Ω: instantaneous field angle of view of camera.

The calculation formula of point target receiving area source irradiance is:

$$\mathrm{E} = \frac{\Phi}{\mathrm{dA}^2} = \mathrm{I}_\theta \cdot \frac{\cos\theta}{\mathrm{l}^2} \tag{2}$$

Both infrared star calibration and onboard blackbody calibration could obtain high precision absolute radiometric calibration coefficients. However, considering the decay of onboard blackbody emissivity with time under long-term operation, the equivalent spectral radiance of onboard blackbody calculated according to operating temperature could not really represent the equivalent radiance of the phase machine entrance pupil. Therefore, the absolute radiometric calibration coefficient obtained by the black body on the star is defined as the calibration coefficient before correction, which is applied to the absolute radiometric correction after being corrected by the absolute radiometric calibration coefficient of the star [8, 9].

When the DN value of the blackbody radiometric calibration data and stellar radiometric calibration data of the pixel is the same

$$\mathrm{DN}(n) = K'(n) \times L'_e + C'(n) \tag{3}$$

where DN is the pixel gray value; L'_e is the equivalent spectral radiance of the calibrated blackbody on the satellite K', C' are respectively the gain and intercept of the absolute calibration coefficient on the satellite.

$$K'(n) = \frac{\mathrm{DN}_h(n) - \mathrm{DN}_l(n)}{L_{\mathrm{eh}} - L_{e\mathrm{l}}}, C' = \frac{\mathrm{DN}_l(n) \times \mathrm{L}_{\mathrm{eh}} - \mathrm{DN}_h(n) \times \mathrm{L}_{el}}{L_{\mathrm{eh}} - L_{e\mathrm{l}}}.$$

When calibrating stars, select 2 stars from the star library, and use their known spectral radiance data to analyze and obtain:

$$\mathrm{DN} = \mathrm{K(n)} \times \mathrm{L_e} + \mathrm{C(n)} \tag{4}$$

where, is the equivalent spectral radiance of the entrance pupil Is the gain and intercept of the absolute radiometric calibration coefficient.

The onboard blackbody radiation calibration coefficient is corrected by the following formula.

$$\mathrm{L_e} = \frac{\mathrm{K'(n)}}{\mathrm{K(n)}} \times \mathrm{L'_e} + \frac{\mathrm{C'(n)} - \mathrm{C(n)}}{\mathrm{K(n)}} \tag{5}$$

The correction coefficients $\mathrm{R_k}$ and $\mathrm{R_c}$ could be obtained: $\mathrm{R_k} = \frac{\mathrm{K'(n)}}{\mathrm{K(n)}}, \mathrm{R_c} = \frac{\mathrm{C'(n)-C(n)}}{\mathrm{K(n)}}$

For each new calibration data, new calibration coefficients could be obtained based on the calibration coefficients and correction coefficients $\mathrm{R_k}$ and $\mathrm{R_c}$ obtained from the new onboard blackbody calibration [10].

3 Radiometric Calibration Uncertainty

The calibration uncertainty of space optical remote sensor mainly depends on the stability of the calibration radiation source itself, measurement accuracy, calibration method and the stability of space optical remote sensor. From the point of view of the vacuum radiometric calibration energy transmission link, the factors that affect the vacuum radiometric calibration accuracy of the infrared camera during operation mainly include the following aspects:

1) Uncertainty of onboard blackbody temperature δ_{bb_Tacc}

   The blackbody radiation source is the reference source of the camera vacuum radiation calibration, and the blackbody temperature measurement error will affect the calibration accuracy. According to the target radiation characteristics, the equivalent blackbody temperature at the entrance pupil is converted and calibrated by the metrology institute.

2) On board blackbody emissivity error δ_{bb_emi}

   Through the standard transmission of emissivity, the blackbody standard could be traced back to the National Institute of Metrology, and the uncertainty of emissivity measurement mainly comes from the uncertainty of reference standards and instrument measurement error. Among them, standard traceability error is the main contribution. The emissivity test needs to ensure that the test distance and angle are as consistent as possible with the calibration. The emissivity of the calibrated blackbody is transmitted through the radiometer and compared with the standard blackbody.

3) Temperature uniformity of blackbody on satellite δ_{bb_Tuni}

   The uniformity of the blackbody radiation source includes the area uniformity and angle uniformity, which are the main factors affecting the relative radiometric calibration accuracy of the camera. The influence of the temperature non-uniformity of the blackbody radiation source is calculated by comparing the radiance difference with the reference blackbody radiance. At the same time, it is necessary to consider that the angular non-uniformity within the field of view angle range.

4) Temperature stability of blackbody on satellite δ_{bb_Tsta}

   The blackbody radiation source is the reference source for the camera vacuum radiation calibration. The blackbody emissivity uncertainty, temperature stability, temperature uniformity and temperature measurement error will affect the calibration accuracy.

5) Influence of camera optical and mechanical radiation fluctuation δ_{rad}

   The radiation energy emitted by the camera itself will reach the camera detector together with the target/atmospheric background. The optical mechanical radiation mainly includes the radiation of the optical lens itself and the radiation of the optical mechanical structure. The optical mechanical radiation fluctuation could be calculated by using Planck's law according to the change of the optical mechanical temperature telemetry value.

6) Camera noise δ_{cam_noise}

   The temporal noise of the camera is mainly composed of photon noise, detector readout noise, dark current noise and circuit noise. The temporal noise reflects the detection sensitivity of the camera, and the influence of the camera noise is shown as the random fluctuation of the output signal. The uncertainty introduced by the noise is 1.70% based on the estimation of the signal-to-noise ratio of the camera at the reference temperature.

7) Camera response nonlinearity δ_{res_non}

   According to the engineering experience of the radiation calibration process in the laboratory, the corresponding nonlinearity is calculated for the values within the dynamic response range (DN value) of 5%–95%.

8) Straylight radiation $\delta_{strlight}$

The space environment, including the sun, the moon, stars and the earth's atmosphere, will affect the calibration on the satellite and generate stray radiation. In addition, the heat accumulated by the black body's long-term work will also affect the calibration accuracy of the system.

The influence amount of each factor is integrated into the total error of the laboratory radiometric calibration. The calculation method is to calculate the square root of the influence amount of each factor, which could be solved by referring to the following formula:

$$\delta = \sqrt{\delta_{bb\_Tacc}^2 + \delta_{bb\_emi}^2 + \delta_{bb\_Tuni}^2 + \delta_{bb\_Tsta}^2 + \delta_{rad}^2 + \delta_{cam\_noise}^2 + \delta_{res\_non}^2 + \delta_{strlight}^2} \quad (6)$$

4 Conclusion

It is reasonable and feasible to calibrate the infrared space optical remote sensing camera in orbit by using blackbody+infrared star for all optical path calibration, focusing on the problems of blackbody working temperature uniformity, stability, absolute radiation performance monitoring, etc. By analyzing the factors influencing the calibration uncertainty of shortwave infrared remote sensor, the radiometric calibration accuracy could be effectively improved by improving the onboard calibration scheme, providing the blackbody temperature control accuracy of onboard calibration, and combining with the infrared star calibration method. The algorithm is verified by the ground laboratory test.

The advantage of full aperture and full optical path calibration is the low uncertainty of absolute radiometric calibration. However, for large aperture aerospace optical remote sensor, the size and weight of the onboard calibrator used to achieve full aperture and full optical path calibration are relatively large, and it requires moving parts to drive the calibrator to cut in/out the optical path, which limits its application. Therefore, it is necessary to select the onboard calibration scheme according to the specific conditions of the aerospace optical remote sensor. In the future, relevant test verification will be carried out on orbit to continuously improve the performance of infrared cameras to further reduce the uncertainty of radiometric calibration.

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