Article

Research on a partial aperture factor measurement method for the AGRI onboard calibration assembly

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Abstract: A partial aperture onboard calibration method can solve the onboard calibration problems of some large aperture remote sensors, which is of great significance for the development trend of increasingly large apertures in optical remote sensors. In this paper, the solar diffuser reflectance degradation monitor (SDRDM) in the onboard calibration assembly (CA) of the FengYun-4 (FY-4) advanced geostationary radiance imager (AGRI) is used as the reference radiometer for measuring the partial aperture factor (PAF) for the AGRI onboard calibration. First, the linear response count variation relationship between the two is established under the same radiance source input. Then, according to the known bidirectional reflection distribution function (BRDF) of the solar diffuser (SD) in the CA, the relative reflectance ratio coefficient between the AGRI observation direction and the SDRDM observation direction is calculated. On this basis, the response count value of the AGRI and the SDRDM is used to realize the high-precision measurement of the PAF of the AGRI B1 ~ B3 bands by simulating the AGRI onboard calibration measurement under the illumination of a solar simulator in the laboratory. According to the determination process of the relevant parameters of the PAF, the measurement uncertainty of the PAF is analyzed; this uncertainty is better than 2.04% and provides an important reference for the evaluation of the onboard absolute radiometric calibration uncertainty after launch.

Keywords: onboard calibration; partial aperture factor; solar diffuser; absolute radiometric calibration, remote sensors.

1. Introduction

The level of remote sensing data quantification is an important aspect of the advanced technology of remote sensing. The quality of remote sensing data directly affects the correctness of the research directions of the natural sciences and the accuracy of the results. The types, functions and working methods of space remote sensors differ with the rapid development of science and technology and the diverse needs of in-depth research on the earth. The corresponding radiometric calibration methods and technical research have always explored the radiometric calibration schemes of various remote sensors and continuously improved the radiometric calibration accuracy. In addition to precise and comprehensive measurement calibration before launch, most of the remote sensors mainly depend on on-orbit alternative calibration and onboard calibration after launch. For onboard calibration, the full aperture all-optical path onboard calibration method is the best choice. However, when the remote sensor has a large aperture or the available space of the remote sensor is insufficient, onboard calibration methods based on the solar diffuser (SD) such as the partial aperture all-optical path and partial optical path full aperture methods are used; for example, both the advanced baseline imager (ABI) of the Geostationary Operational Environmental Satellite-16

(GOES-16) of the United States[1] and the advanced geostationary radiance imager (AGRI) of the FengYun-4 (FY-4) of China used the partial aperture all-optical path onboard calibration scheme. In fact, the partial aperture onboard calibration scheme reduces the volume of the calibrator by sacrificing the complexity of the onboard calibration physical model. The partial aperture factor (PAF) is one of the key parameters of the AGRI in realizing onboard radiometric calibration. Its measurement method and measurement uncertainty directly affect the function and uncertainty of the AGRI onboard calibration. The partial aperture on-board calibration scheme actually reduces the scaler volume by sacrificing the complexity of the on-board calibration physical model. The measurement of the PAF is one of the key processes to realize the on-board radiance calibration by using this calibration scheme. The improvement of the PAF measurement method and the reduction of measurement uncertainty play a decisive role in reducing the uncertainty of the on-board absolute radiometric calibration of remote sensor.

The AGRI has 6 observation channels in the solar reflective band. It adopts the onboard calibration mode of the partial aperture all-optical path. The calibration assembly (CA) is a passive diffuse reflector that quantitatively scatters sunlight outside the atmosphere into the AGRI. Unlike the ABI, the CA of the AGRI is equipped with an SD stability monitoring device – a solar diffuser reflectance degradation monitor (SDRDM)[1]. Based on the relative relationship between the characteristics of the AGRI CA and the actual work of the AGRI, this paper proposes a method to measure the PAF of the AGRI calibration optical path by using the SDRDM in the CA as the reference radiometer. First, the SDRDM and the AGRI are used to observe the same radiance source with different energy levels, and the numerical relationship between them under the same radiance input is established. Then, the outgoing radiance in the SDRDM observation direction is corrected to obtain the radiance in the AGRI observation direction[5-8] according to the bidirectional reflectance factor (BRF)[2-4] of the SD. Based on the measured relative relationship between the AGRI and the SDRDM with the full aperture response according to the observations the radiance source, the ratio between the calculated full aperture response value of the AGRI and the actual partial aperture measurement response is obtained, and then the PAF of the AGRI is determined. Finally, the PAF measurement equation is analyzed, and it is evaluated that the uncertainty of the PAF measured by this method can be better than 2.04%, which provides key parameters for the physical model of the AGRI on-board absolute radiometric calibration after launch, and is also the basis for the evaluation of the uncertainty of the AGRI on-board radiometric calibration.

2. Basic principles

2.1 Calibration principle of the partial aperture based on the SD

The onboard partial aperture all-optical path calibration based on the SD mainly limits the radiance flux received by the remote sensor at the calibration time through the partial aperture. Combined with the PAF measured before launch and the radiance response model, the relationship of the full aperture sensor response is obtained with the response count measured by the partial aperture on the satellite. The partial aperture all-optical path marking diagram of the AGRI CA is shown in Figure 1. The AGRI is mainly composed of the SD, the SDRDM, partial aperture stop (PAT) and CA box structure. The SDRDM is equipped with three SD monitoring bands, 450 nm, 550 nm and 750 nm, which are close to the AGRI measurement band. It can measure the sun for

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self-calibration, measure the SD outgoing radiance and monitor the relative SD reflectivity of the three bands[6].

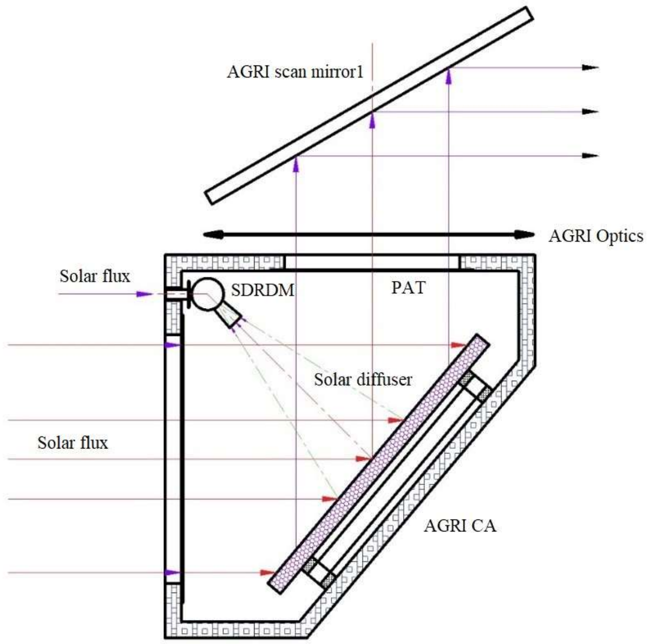

Figure 1. Composition diagram of the AGRI CA

With the known spectral radiance of the SD, the response correction coefficient $F(B_j)$ of the AGRI sensor can be expressed as

$$F(B_j) = \frac{k(B_j)L_{SD}(B_j)}{L_e(B_j)} \tag{1}$$

In equation 1, $k(B_j)$ is the PAF of bandB_j, $L_{SD}(B_j)$ is the equivalent radiance of band B_j output by the SD, and $L_e(B_j)$ is the radiance of band B_j determined by the laboratory radiance response model of the AGRI according to the onboard calibration account. The PAT is set at the front of the AGRI optical path, which has no influence on the AGRI's own imaging optical path and does not change its optical system parameters. The radiance flux entering the AGRI at the calibration time is mainly considered to be determined by the light passing area of the PAT. That is, the equivalent pupil radiance of the SD observed by the AGRI through the PAT relative to the full aperture pupil radiance can be expressed as:

$$L_{\mathrm{TP}}(\theta_{SD}, \phi_{SD}; \theta_v, \phi_v; B_j) = L_{SD}(\theta_{SD}, \phi_{SD}; \theta_v, \phi_v; B_j) * k(B_j) \tag{2}$$

The SD spectral radiance of the AGRI CA in the calibration period can be determined by equation 3:

$$L_{SD}(\theta_{SD}, \phi_{SD}; \theta_v, \phi_v; B_j) = cos\,\theta_{SD,t} \times H_{on-orbit}(B_j, t) \times \int_{\lambda_{j_1}}^{\lambda_{j_2}} \frac{E_s(\lambda_j)}{D(t)^2} \alpha(\lambda_j, t_0) \times f_{SD,t}(\theta_{SD}, \phi_{SD}; \theta_v, \phi_v; \lambda_j)\, d(\lambda_j) \tag{3}$$

where $L_{\mathrm{SD}}(\theta_{\mathrm{SD}},\mathrm{f}_{\mathrm{SD}};\theta_v,\mathrm{f}_v;\mathrm{B}_j)$ is the SD radiance of band B_j along the AGRI view at the calibration time; $E_s(\lambda_j)$ is the solar spectral irradiance outside the atmosphere; $D(t)$ is the sun to

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earth relative distance correction factor at the calibration time; θ_{SD}, ϕ_{SD} are the zenith angle and azimuth angle of the solar incidence in the SD coordinate at calibration time, θ_V, ϕ_V are the zenith angle and azimuth angle of the AGRI SD view, and λ_j is the wavelength; $f_{SD,t}(\theta_{SD}, \phi_{SD}; \theta_v, \phi_v; \lambda_j)$ is the bidirectional reflection distribution function (BRDF) of the AGRI SD view at the calibration time measured in the laboratory; $\alpha(\lambda_j, t_0)$ is the reflectivity change of the SD and is one of the correction factors for the degradation of the SD BRDF before launch; $H_{on-orbit}(B_j, t)$ is the degradation correction coefficient of the SD BRDF of band B_j at the time of onboard calibration t determined by the SDRDM long-term monitoring and measurement in the space environment after launch[7-8].

2.2 The measurement of the AGRI PAF

Ideally, the same radiance source provides radiance input for the AGRI imaging optical path and the calibration optical path. The AGRI PAF can be expressed as the ratio of the calibration optical path response count value to the imaging optical path response count value, that is,

$$k(B_j) = \frac{C_{ca,p}\ (B_j)}{C_{im,f}\ (B_j)} \tag{4}$$

Where Cim(Bj) is the response count value of the imaging optical path of band Bj and Cca(Bj) is the response count value of the calibration optical path of band Bj. According to the common working mode of the AGRI CA shown in Figure 1, it is difficult to use the same radiance source as the input reference for the imaging optical path and the calibration optical path. After the AGRI is assembled, it is impossible to accurately measure the spectral radiance input in the observation direction of the AGRI both in the imaging optical path and calibration path. Considering that the direction of the SDRDM viewing the SD has a fixed geometric relationship with the AGRI viewing the SD and that the setting of the SDRDM band is consistent with that of the AGRI, the same type of photoelectric sensors are used in visible and near-infrared bands, and they have very close spectral response characteristics. On this basis, a method for measuring the aperture factors of the AGRI based on the relative response relationship between the SDRDM and the AGRI under the same radiance input is proposed:

The linear response relationship between the SDRDM and the AGRI is established by observing the same radiance source at different energy levels. According to the laboratory BRDF measurement data of the SD, the relative proportion between the reflectance of the SDRDM observation direction and the AGRI observation direction under the same illumination conditions is established. Under the same illumination angle, the full aperture response count value with the equivalent radiance input of the AGRI is calculated by the count value of the SDRDM observing the SD in the CA. The PAF is obtained by comparing the measured value of the AGRI calibration optical path with the full aperture response value in equation 4. This can be expressed as:

$$k(B_j) = \frac{C'_{ca,p}\ (B_j)}{C'_{im,f}\ (B_j)} = \frac{C'_{ca,p}\ (B_j) \times f_{SD,lab}(\theta_{SD}, \phi_{SD}; \theta_r, \phi_r; B_j)}{(a \times C_{\mathrm{SDRDM}}\ (B_j) + b) \times f_{SD,lab}(\theta_{SD}, \phi_{SD}; \theta_v, \phi_v; B_j)} \tag{5}$$

where $C'_{ca,p}\ (B_j)$ is the response count value of the SD measured by the calibration optical path of the AGRI, $C'_{im,f}\ (B_j)$ is the full aperture response count value of the AGRI at the same radiance input equivalent converted according to the outgoing radiance level of the SD in the

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calibration optical path, $C_{\mathrm{SDRDM}}\ (B_j)$ is the response count value of the SDRDM observing the SD, a and b is the conversion relationship coefficient of the response count value for the same radiance source observed by the SDRDM and the AGRI, and $f_{SD,lab}(\theta_{SD},\phi_{SD};\theta_v,\phi_v;B_j)$ and $f_{SD,lab}(\theta_{SD},\phi_{SD};\theta_r,\phi_r;B_j)$ are the BRDF values of the AGRI observation direction and the SDRDM observation direction under the same lighting conditions, respectively.

Before the assembly of the AGRI and its CA, a large aperture integrating sphere is used as a stable radiance reference source. Based on the dynamic range of the AGRI response model, four radiance levels from high to low are set to provide radiance input for the SDRDM and the AGRI at the same time, as shown in Figure 2. The AGRI and integrating sphere radiance source are kept relatively fixed, and the relative response relationship between the SDRDM and the AGRI under the same radiance input is established by bringing the SDRDM into and out of the central area of the optical outlet of the integrating sphere radiance source, as shown in Figure 3; the abscissa and ordinate are the response values of the SDRDM and the AGRI observing the same radiance source, respectively (the B3 band is also similar).

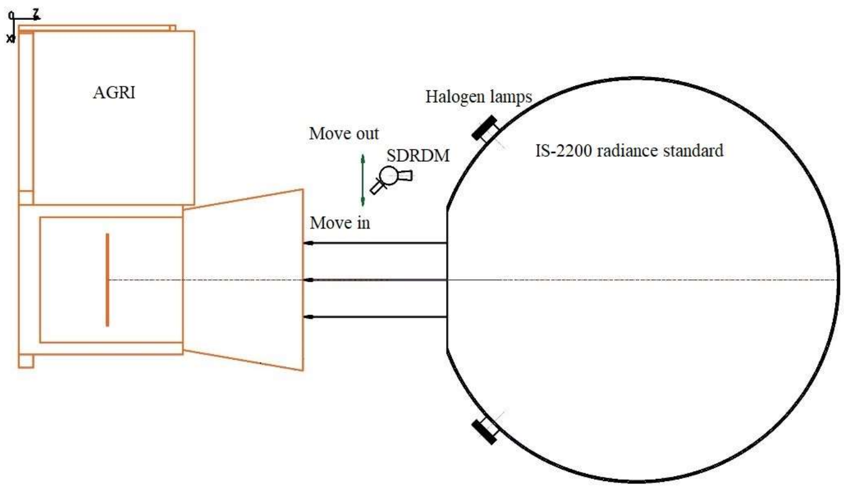

Figure 1. The AGRI and the SDRDM calibration

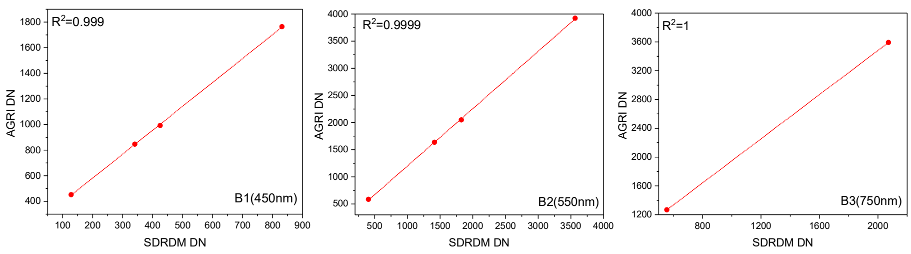

Figure 2. Response relationship of the AGRI and the SDRDM with the same radiance input

After the assembly of the AGRI with its CA, the light receiving angle of the AGRI CA at the working face of the solar simulator light source (SSLS) is adjusted so that its attitude is consistent with the illumination state of incident light when the declination angle of onboard calibration is 0°, and solar incident working conditions during onboard calibration of the AGRI are simulated, as shown in Figure 1, in which the solar flux is provided by the SSLS. When the SD is illuminated by the SSLS, both the AGRI and the SDRDM begin to collect the response value of the SD radiance

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at the same time (the imaging light path is completely blocked to avoid the influence of ambient stray light). The SD is not an ideal Lambertian. Under the same illumination angle, the outgoing radiance in the AGRI observation direction is different from that in the SDRDM observation direction. According to the BRDF measured in the laboratory before launch, the radiance measured by the SDRDM is corrected to the outgoing radiance in the AGRI observation direction. The BRDF in the two observation directions is shown in Figure 4. The SD has excellent spectral flatness at 400 nm ~ 900 nm. Under the same incidence and observation angle, the relative BRF is approximately 1.0285, and the relative change is approximately 0.06%.

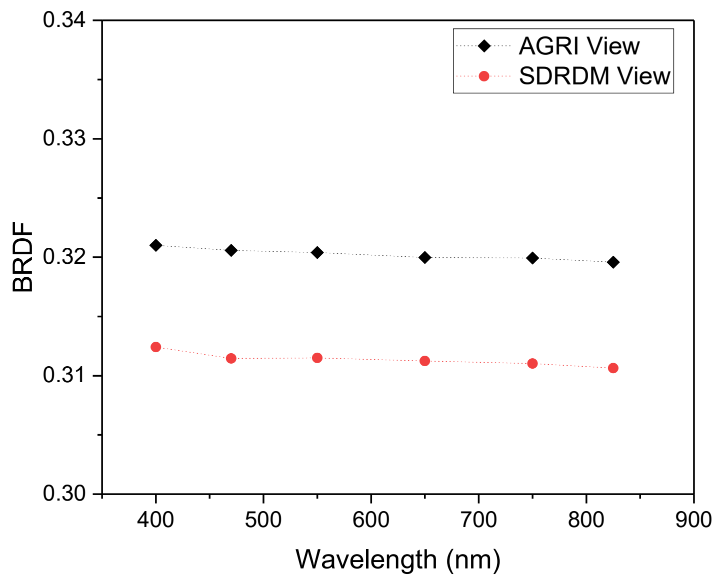

Figure 4. BRDF of the AGRI and SDRDM views with a fixed incident angle

According to the relationship between the response count values of the same radiance source being observed by the AGRI and the SDRDM and combined with the measured response count values of the AGRI calibration optical path, the same radiance source observed in the same direction as the AGRI is simulated, and the PAF of B1 ~ B3 is obtained according to equation 5, as shown in Table 1. With the AGRI calibration optical path, the PAF is measured twice. The measurement repeatability of the PAF is better than 0.26%, and there are certain differences in the PAF values of various bands due to many factors such as the placement error between various components of the instrument and the inconsistency of the stray light level.

Table 1. the PAF of the AGRI

Band	PAF	Repeatability(%)
B1 (450 nm)	0.12011	0.02814
	0.12006	
B2 (550 nm)	0.10940	0.25899
	0.10980	
B3 (750 nm)	0.10346	0.09953
	0.10360	

3. Analysis and Discussion

The AGRI imaging light path is not completely consistent with the calibration light path, and the switching between the two paths is mainly completed by adjusting the direction of the AGRI scanning mirror. As shown in Figure 5, considering the environmental stray light and the different areas of the scanning mirror for the incident light of the imaging light path and the calibration light path, the response difference between the imaging light path and the calibration light path with the same radiance source input is not completely determined by the light passing area of the aperture diaphragm. There are many factors affecting the PAF value, and the best method for determining it is through a system-level test, but it is very difficult to directly realize the same radiance input in the imaging optical path and calibration optical path. An SSLS with color temperature and ray divergence angle close to those of the sun is used as the irradiance source to obtain the calibration light path response value of the PAF, and the response count value of the SD is observed with the SDRDM to calculate the response count value that the AGRI imaging light path should have under the same radiance source to indirectly realize a state where the same radiance source provides radiance input for the AGRI calibration light path and imaging light path, Thus, the aperture factor value of the three AGRI visible near-infrared bands is calculated according to the PAF definition.

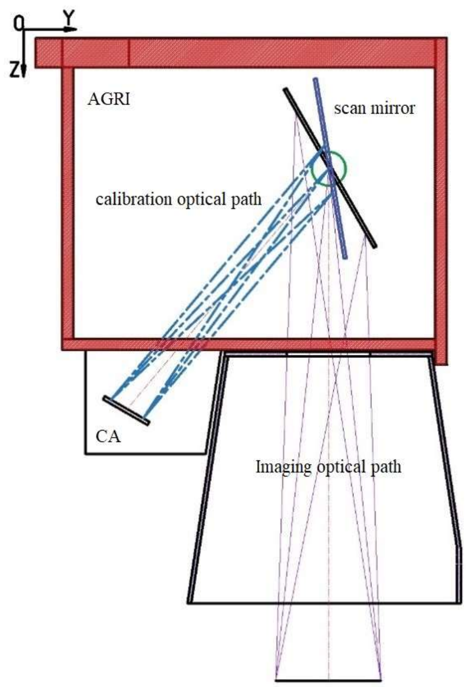

Figure 5. Calibration optical path and imaging optical path of the AGRI

The PAF is not only the key parameter for realizing onboard absolute radiometric calibration of the partial aperture all-optical path but also the largest source of uncertainty of this onboard calibration method. The uncertainty of some aperture factors measured based on the SDRDM mainly includes the following aspects:

The uniformity and stability of the integrating sphere radiance source while determining the relationship between the response values of the SDRDM and the AGRI under the same radiance input affect the uncertainty. The test time of the SDRDM and AGRI is approximately 5 minutes at every energy level. The integrating sphere radiance source includes a halogen lamp light source that has excellent stability, better than 0.25%/30 minutes, as shown in Figure 6. The radiance surface of the diffuser used in the actual test of the AGRI is approximately the middle area of 1/4 of the light output area of the integrating sphere radiance source, and the uniformity of the radiance source can be better than 0.4%. Figure 7 shows the numerical diagram of the nonuniformity of the central area scanned at 70 mm intervals.

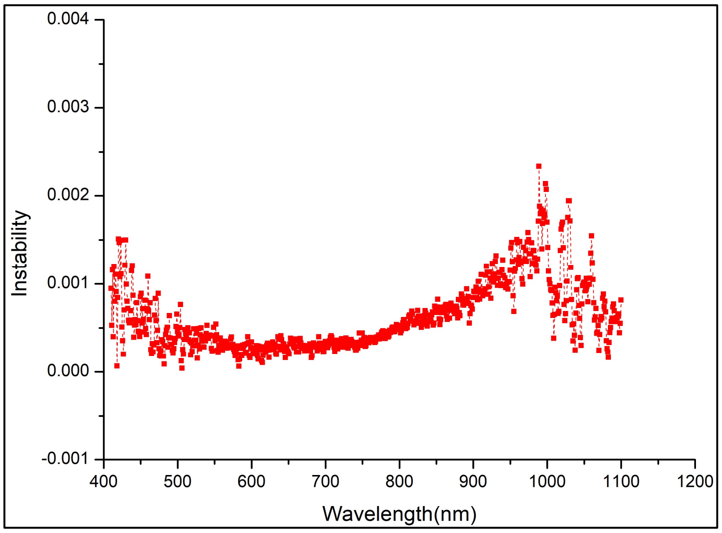

Figure 6. Radiance instability of the integrating sphere in 30 minutes

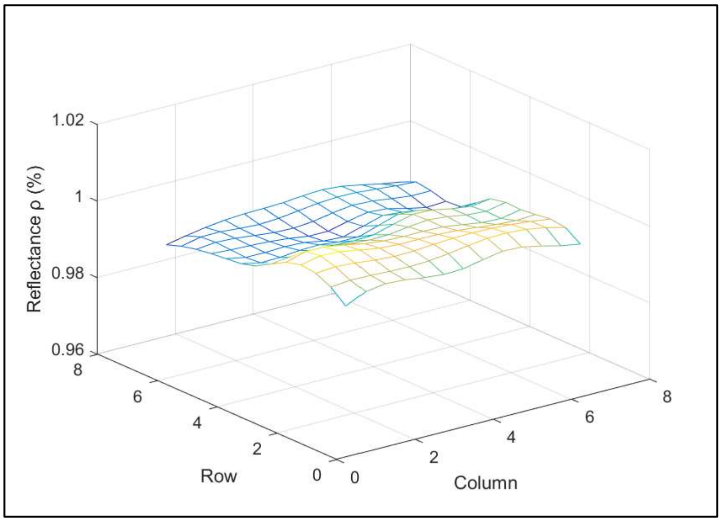

Figure 7. Nonuniformity of the integrating sphere

The solar simulation light source includes a short arc xenon lamp as the illuminant. Affected by gravity and the stability of the power supply, the stability of the spectral irradiance near the working face can reach better than 0.3% within 10 minutes, as shown in Figure 8. According to the observation of the area of the SD and the zenith angle of the light source incident on the SD by the AGRI through a partial aperture, it is necessary to evaluate the light source nonuniformity of the irradiance body at ±100 mm from the working face before and after in Φ300 mm; nonuniformity numerical diagrams of three positions between the theoretical working face of the solar simulator and the relative ± 160 mm distance are shown in Figure 9, and the nonuniformity of the light source body within this distance range is better than 1.6%;

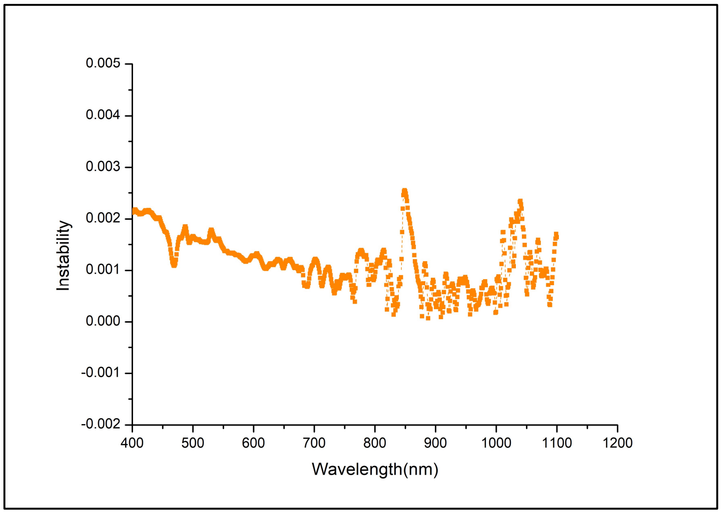

Figure 8. Irradiance instability of the SSLS in 10 minutes

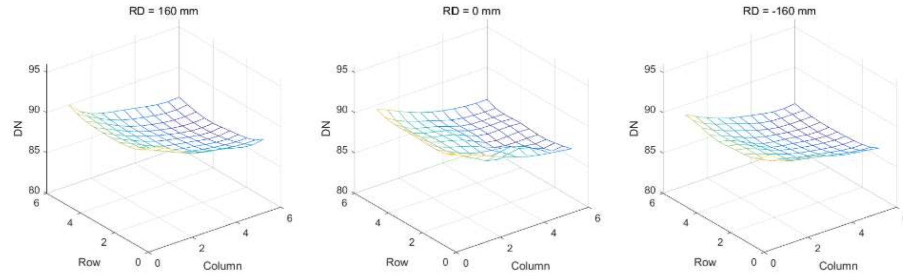

Figure 9. Volume nonuniformity of the SSLS

The direction of the SD observed by the SDRDM and AGRI is relatively fixed. Under the same incident angle, the relative change in reflectivity from the SD to the SDRDM and AGRI can be better than 0.5%[2-4].

The optical fiber of the spectrometer is set along the direction of the AGRI to observe the SD, to introduce the solar simulation light source to illuminate the SD of the CA to simulate the onboard solar illumination angle, and to simulate the incident light according to the variation range of the illumination angle at the onboard calibration time covering the whole year. The relative difference between the reflected signals of the SD in the states with and without the CA box is the proportion of stray light generated inside the box. The stray light contribution of the internal space of the CA to the outgoing radiance of the SD is 1%.

According to the B class uncertainty synthesis formula

$$U = \sqrt{\mu_1^2 + \mu_2^2 + \cdots + \mu_n^2 + 2\sum_{i=1}^{n}\sum_{j=1}^{n}\rho_{ij}\mu_i\mu_j} \tag{6}$$

The uncertainty of the AGRI PAF measurement is calculated, where μ_n is the uncertainty of each parameter determined in the PAF measurement and the correlation coefficient ρ_{ij} between each parameter is assumed to be 0.

Table 2. Uncertainty analysis of the PAF measurement

Sources	Uncertainty/%
Stability of the IS radiance source (μ1)	0.25
Nonuniformity of the IS radiance source (μ2)	0.40
Stability of the solar simulator source (μ3)	0.30
Volume nonuniformity of the solar simulator source (μ4)	1.60
Relative SD BRDF measurement (μ5)	0.50
Stability of the PAF measurement (μ6)	0.26
Stray light (μ7)	1.00
Total uncertainty (U)	2.04

4 Conclusion

The onboard calibration method of the partial aperture all-optical path based on the SD is characterized by decreasing the complexity of the calibration system to reduce the volume of the CA, which provides a solution for the onboard absolute radiometric calibration of large aperture remote sensors. In this paper, the implementation principle of the onboard calibration of partial aperture all-optical paths is analyzed in detail, and a PAF measurement method is proposed based on the response relationship between the SDRDM and the undetermined calibration remote sensor by testing the same radiance source to simulate the count value of the full aperture response of the imaging path of the undetermined calibration remote sensor. According to this method, the test results of some aperture factors in the B1 ~ B3 bands of the AGRI are given, and the test uncertainty of some aperture factors are analyzed in the test process. The uncertainty of this aperture factor test method is approximately 2.04%.

This paper provides a reference for the acquisition method of the PAF parameters of remote sensors using partial aperture all-optical path on-board calibration scheme before launch, which is of great significance to reduce the volume and weight of on-board calibrator and maintain a certain level of radiometric calibration accuracy. In addition, the AGRI has 6 bands in the solar reflective band, while the SDRDM has only 3 monitoring bands, so it can directly measure only the aperture factor values of B1 ~ B3, and the corresponding aperture factors can be calculated by the band ratio in other bands. The tests of some aperture factors cannot be decoupled from the remote sensor, so they must be determined by system-level tests. In this paper, some aperture factor tests are carried out for the state of 0° declination incidence on the satellite. Whether the aperture factor changes under different solar incidence angles in actual on-orbit applications has not been tested and verified and needs to be further studied.

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