

Article

Radiometric Cross-Calibration of GF6-PMS and WFV Sensors with Sentinel 2-MSI and Landsat 9-OLI2

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Abstract: A panchromatic and multispectral sensor (PMS) and a wide-field-of-view (WFV) sensor were fitted aboard the Gaofen6 (GF6) satellite, which was launched on 2 June 2018. This study used the Landsat9-Operational Land Imager 2 and Sentinel2-Multispectral Instrument as reference sensors to perform radiometric cross-calibration on GF6-PMS and WFV data at the Dunhuang calibration site. The four selected sensor images were all acquired on the same day. The results indicate that: the calibration results between different reference sensors can be controlled within 3%, with the maximum difference from the official coefficients being 8.78%. A significant difference was observed between the coefficients obtained by different reference sensors when spectral band adjustment factor (SBAF) correction was not performed; from the two sets of validation results, the maximum mean relative difference in the near-infrared band was 9.46%, with the WFV sensor showing better validation results. The validation of calibration coefficients based on synchronous ground observation data and the analysis of the impact of different SBAF methods on the calibration results indicated that Landsat9 is more suitable as a reference sensor for radiometric cross-calibration of GF6-PMS and WFV.

Keywords: cross-calibration; Landsat9-OLI2; Sentinel2-MSI; SBAF



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1. Introduction

As remote sensing technology continues to penetrate various fields, its quantification has emerged as an important development trend [1]. The disparities in performance among different sensors often preclude joint observations, making it challenging for a single sensor to swiftly cover a broad spectrum of research areas. Consequently, it becomes imperative to assess the differences between multiple sensors and adjust their radiometric performance promptly. Radiometric calibration is used to convert the Digital Number (DN) value of a sensor into a characterization with physical parameters [2], allowing the DN value in the visible and near-infrared (NIR) bands to be converted into equivalent radiance or reflectance for subsequent processing steps. The methods for radiometric calibration in the visible and NIR bands are categorized based on the sensor's operational status during pre-launch laboratory calibration and on-orbit satellite radiometric calibration, among other aspects. Since the 1980s, a plethora of radiometric calibration techniques for satellite sensors such as Landsat [3], SPOT [4], and AVHRR [5] have been developed and extensively applied. On-orbit radiometric calibration encompasses four principal types: on-board, site, and scene calibration techniques as well as radiometric cross-calibration. On-board calibration, relying on a solar diffuser plate [6] or the Moon [7] as calibration sources, stands out as a particularly precise method for satellite sensor calibration. This approach significantly mitigates the effects of the atmospheric conditions on calibration accuracy. Notably, sensors such as MODIS and VIIRS are equipped with on-board calibration features.

Slater and others proposed three site calibration methods based on reflectance, irradiance, and radiance using the White Sands test site as a target, and these methods have been widely applied in the radiometric calibration of various sensors, such as the Landsat series [8] and VIIRS [9] satellites. The reflectance-based method primarily measures the reflectance of the Earth's surface and atmospheric parameters during satellite overpass, using a radiative transfer model to simulate the sensor-received equivalent radiance to obtain calibration coefficients [10,11]. Compared with the irradiance-based method, a radiative transfer model assumes aerosol models and atmospheric modes, resulting in lower accuracy, with uncertainty controlled at around 5% [12]. The irradiance-based method measures the ratio of diffuse ground irradiance to global downward irradiance, thereby reducing the uncertainty introduced by assumed aerosol models. The radiance-based method involves direct measurement of the site's radiance using drones or similar devices under equivalent observation conditions during satellite sensor overpass for calibration [10]. Although these three calibration methods offer higher accuracy, they require significant human and material resources and are often affected by weather conditions during satellite overpass, making long-term monitoring of radiative performance challenging [13]. Radiometric cross-calibration uses well-calibrated reference sensors to calibrate target sensors through radiance conversion, and has become a research focus due to its lower cost and ability to calibrate historical data [14]. Radiometric cross-calibration is one of the various post-launch calibration methods and is known for its high accuracy and low calibration cost. This method has been widely used for multispectral satellite sensors. Voskanian [15] conducted radiometric cross-calibration for the Operational Land Imagers (OLI) of Landsat8 and Landsat9, comparing the results with measurements from the RadCalNet sites. Tang [16] conducted radiometric cross-calibration for the Ziyuan3, Gaofen1, and Landsat8 satellites at the Dunhuang calibration site in Gansu Province, China, comparing and analyzing the calibration coefficients obtained by different methods. Han [17], using the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Landsat8 OLI as reference sensors, proposed a new method of radiometric cross-calibration based on radiometric block adjustment for the Gaofen-4 PMS sensor. Shin [18] conducted radiometric cross-calibration using Landsat8 and KOMPSAT-3A, highlighting the necessity of correcting for differences in spectral response functions between different sensors. Overall, the challenge of radiometric cross-calibration lies in the differences in spectral band ranges and overpass times of different sensors; these differences may reduce the calibration accuracy as a result of changes in land and atmospheric conditions [19]. Therefore, it is necessary to select a stable test site and minimize the observation interval between the two types of sensors.

The Gaofen 6 (GF6) satellite was launched on 2 June 2018, primarily for use in precision observations and surveys of agricultural and forestry resources as well as for use in other industries. This marked China's first inclusion of the "red edge" spectral bands, which can effectively reflect the unique spectral characteristics of crops, significantly enhancing the monitoring capabilities for agriculture, forestry, grasslands, and other resources. The GF6 satellite is equipped with a 2 m panchromatic/8 m multispectral sensor (GF6-PMS) and a 16 m multispectral medium-resolution wide-field-of-view sensor (GF6-WFV). The GF6-PMS and GF6-WFV have fields of view spanning 90 and 800 km, respectively. The operational network of the GF6 with Gaofen1 has reduced the temporal resolution of remote sensing data acquisition from 4 to 2 days, providing significant support for the development of agriculture and rural areas and the construction of an ecologically sound civilization.

This paper describes radiometric cross-calibration of the visible and NIR bands of the GF6-PMS and WFV sensors, using the Landsat9-OLI2 and Sentinel2-Multispectral Instrument (MSI) sensors as reference sensors. The selected images for the uncalibrated and reference sensors were taken on the same day, and the relative difference of the radiometric cross-calibration results obtained from different reference sensors was analyzed. In Section 2, we introduce the test sites, sensors, and data sets. Subsequently, Section 3 details the radiometric cross-calibration method used in this study. Section 4 analyzes the results of radiometric cross-calibration and the verification of calibration coefficients when

choosing different reference sensors. Section 5 discusses the results of the radiometric cross-calibration, analyzes the impact of different calibration methods on the results, and validates the calibration results with ground-measured data. Finally, Section 6 concludes the paper.

2. Materials and Methods

2.1. Test Sites

The Dunhuang test site was selected as the calibration site for this study; this site serves as an important location for the radiometric calibration of remote sensing satellites in China. Situated in Dunhuang City, Gansu Province, it is located at 40.1°N and 94.4°E at an elevation of 1253 m above sea level. The Dunhuang test site covers about $30 \times 30 \text{ km}$ [14]. The ground surface of the site is composed of various rocky debris such as gravel, sandstone, and a small amount of clay (Figure 1). The area is primarily composed of a Gobi Desert landscape with dunes; such landscapes are susceptible to the effects of strong winds. Because of the minimal industrial activity in the Dunhuang area, the impact of sulfur and nitrogen compound emissions on atmospheric transparency is negligible. In summary, the Dunhuang calibration site, as an important location for the radiometric calibration of remote sensing satellites in China, features flat terrain, uniform land cover, and favorable atmospheric observation conditions, making it suitable to meet the requirements needed for remote sensing radiometric calibration [20].

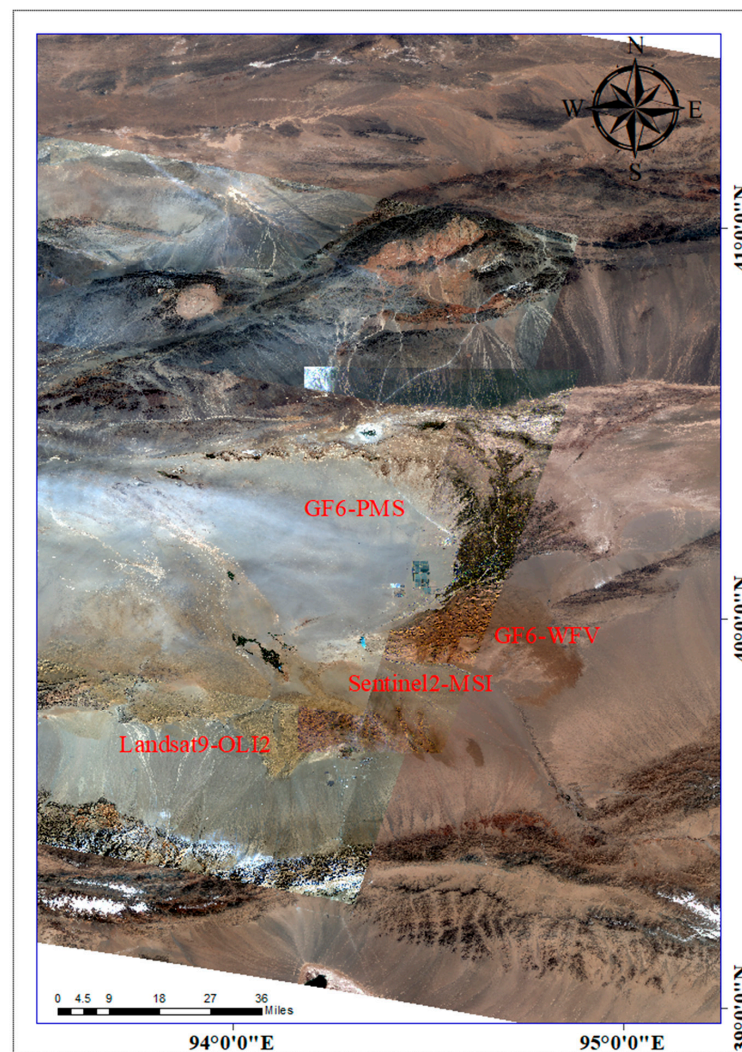


Figure 1. Dunhuang calibration site.

2.2. Satellites

The GF6 satellite is equipped for monitoring resources in agriculture, forestry, and grasslands, with a designed operational lifespan of 8 years [21]. The PMS sensor onboard GF6 has a spatial resolution of 8 m and includes four bands (blue, green, red, and NIR). The WFV sensor onboard GF6 has a spatial resolution of 16 m and includes eight bands (blue, green, red, NIR, coastal, yellow, and two red-edges), with the WFV sensor's observation field of view reaching up to 800 km [19]. Although the GF6 satellite underwent laboratory calibration before launch, its radiative performance may undergo unpredictable changes due to environmental influences and hardware aging while in orbit. Therefore, it is necessary to monitor its radiative performance, and radiometric cross-calibration offers an effective low-cost method for this procedure.

For many years, the Landsat series of satellites have been referred to as the “gold standard” due to their rich data volume, short coverage cycle, and global imaging capabilities, and they are often used for comparison with other sensors [22]. Landsat9 was launched on 27 September 2021, carrying the OLI2 and Thermal Infrared Sensor2 sensors, which are essentially the same as the OLI and Thermal Infrared Sensor sensors on Landsat8, which are capable of capturing data in 11 spectral bands. Landsat9 provides traceable, consistent observations of top-of-atmosphere (TOA) reflectance across a wide dynamic range (i.e., over land, snow/ice, and water bodies), with an absolute uncertainty of <5% ($k = 1$) in terms of TOA spectral radiance and <3% ($k = 1$) in TOA reflectance for each spectral band [15].

Sentinel2 is a high-resolution Earth observation satellite developed jointly by the European Space Agency and the European Commission. Comprising Sentinel2A and Sentinel2B, Sentinel2 has high spatial and temporal resolution and a high revisit frequency, offering new prospects for remote sensing monitoring research. The MSI sensor on Sentinel2 can capture remote sensing data across 13 spectral bands from visible to NIR and short-wave infrared, with resolutions of 10, 20, and 60 m depending on the band; the 5-day revisit period provides frequent and accurate remote sensing data [23]. With an on-orbit radiometric calibration accuracy of up to 3% and a wide spectral radiance range, Sentinel2-MSI has often been used as a reference sensor for radiometric calibration [24,25].

This paper describes radiometric cross-calibration of the visible and NIR bands of GF6-PMS and WFV sensors using the Landsat9-OLI2 and Sentinel2-MSI sensors as reference sensors. The Spectral Response Functions (SRFs) of the four sensors are shown in Figure 2, revealing that the differences in the SRFs among the sensors are smaller in the blue bands and larger in other bands, with the largest difference in the NIR bands, especially as the bandwidth of the NIR band of OLI2 is narrower when compared with the other three sensors. Therefore, it was necessary to eliminate errors caused by differences in SRFs during radiometric cross-calibration to improve the calibration accuracy.

2.3. Data Set

The Dunhuang calibration site was selected for radiometric cross-calibration, using Landsat9 and Sentinel2 as reference sensors for the GF6-PMS and WFV sensors. Factors affecting the accuracy of radiometric cross-calibration include differences in sensor performance and the impact of observation time on land and atmospheric parameters. Therefore, when selecting images, it is essential to minimize the observation time difference between different sensors. To ensure the accuracy of radiometric cross-calibration, it is preferable that images taken on the same day are selected, and the atmospheric clarity of the calibration site at the time of the overpass should also be considered. After screening, it was determined that all four sensors passed over the Dunhuang calibration site on the same day, on 15 February 2022, under good atmospheric conditions. In addition to acquiring images from different sensors, radiometric cross-calibration also requires atmospheric parameters and land reflectance data, with atmospheric parameters derived from MODIS' s 550 nm aerosol optical depth (AOD) and sand reflectance at the Dunhuang calibration site. The

observation parameters of the four sensors on 15 February 2022 are shown in Table 1, and the measured sand reflectance is shown in Figure 3.

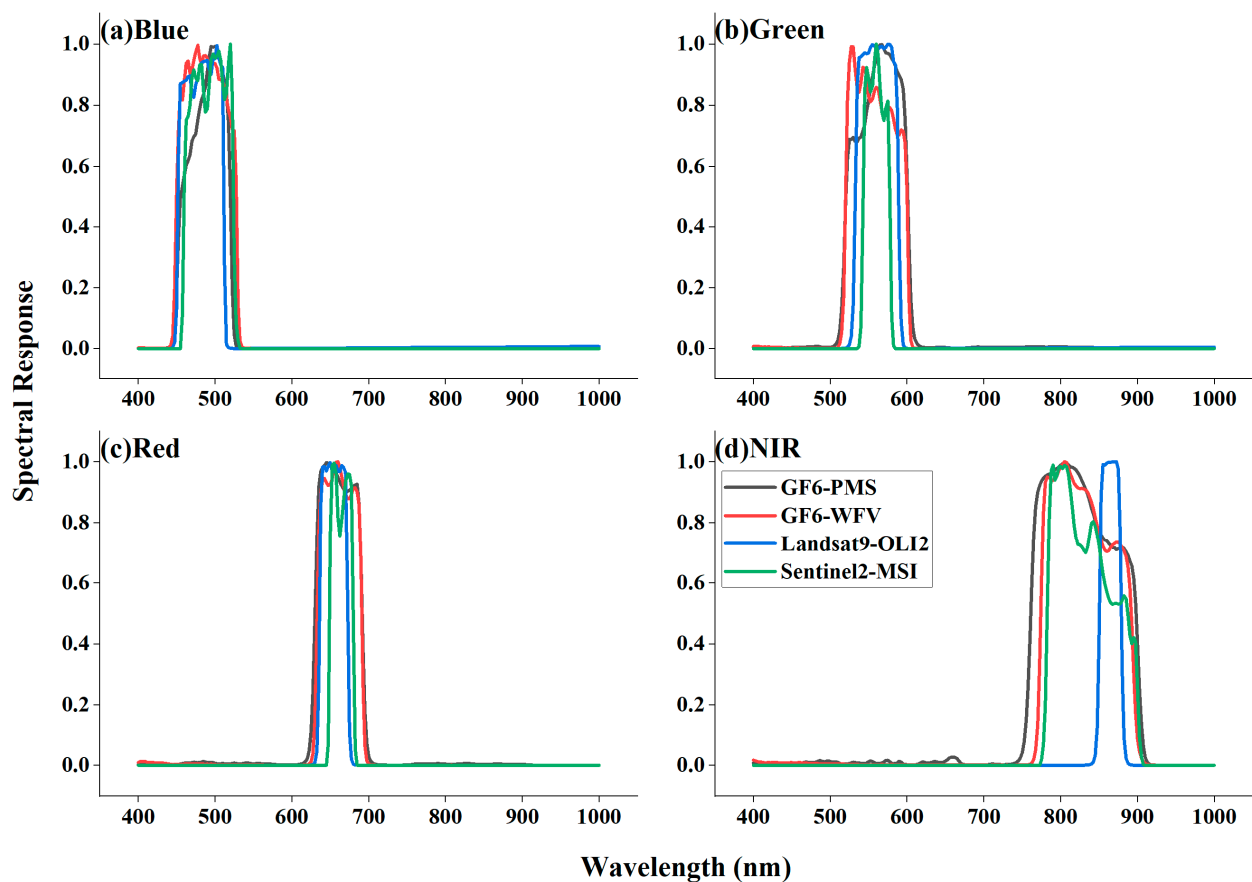


Figure 2. Spectral response functions of Landsat9-OLI2, Sentinel2-MSI, GF6-PMS, and GF6-WFV.

Table 1. Overpass parameters of the Landsat9-OLI2, Sentinel2-MSI, GF6-PMS, and GF6-WFV sensors at the Dunhuang calibration site on 15 February 2022.

Sensor	PMS	WFV	OLI2	MSI
Time (UTC)	05:01	05:01	04:26	04:28
Solar Zenith (°)	54.35	54.34	56.78	55.81
Solar Azimuth (°)	163.90	163.71	153.47	156.99
Sensor Zenith (°)	6.03	6.32	7.05	4.31
Sensor Azimuth (°)	14.08	24.99	286.86	106.28
AOD (550 nm)	0.056			

Table 1 shows that the time difference between the overpasses of GF6-PMS and WFV and the two reference sensors, OLI2 and MSI, was about 30 min on 15 February 2022. To reduce the uncertainty in radiometric cross-calibration caused by changes in atmospheric conditions and land reflectance, the corresponding aerosol model and atmospheric mode were selected based on the climate characteristics and aerosol properties of the Dunhuang calibration site in February [14]. The AOD came from MODIS's MCD19A2 V6.1 data, with a resolution of 1 km, formed by joint observations from the Terra and Aqua sensors, providing AODs of 470 and 550 nm. Figure 3 shows the measured land reflectance at the Dunhuang site, with reflectance values ranging from 0.25 to 0.14, increasing with wavelength.

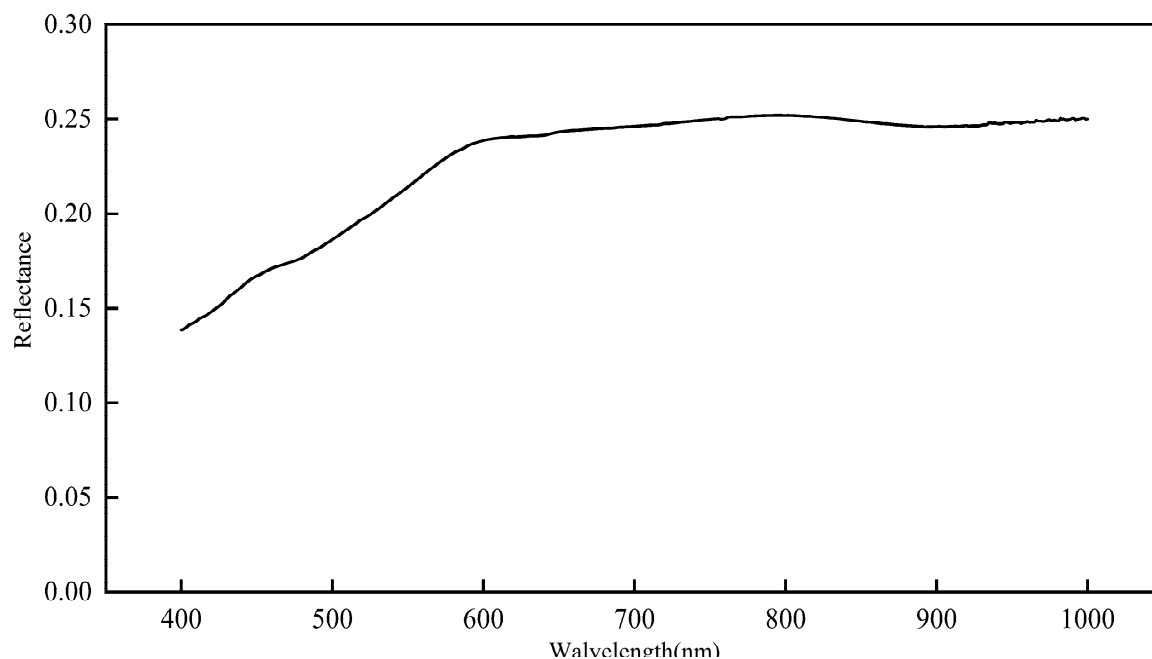


Figure 3. Ground reflectance of the Dunhuang calibration site.

3. Methodology

Radiometric cross-calibration, as a more efficient calibration method when compared with site calibration, allows for the monitoring of the radiative performance and calibration of sensors using historical data. Compared with traditional site radiometric calibration processes, radiometric cross-calibration is relatively straightforward but requires consideration of various factors that affect calibration accuracy, such as the observational geometry of different sensors, atmospheric conditions, and SRF. For the radiometric cross-calibration study of the GF6-PMS and WFV sensors, this study implemented a cross-radiometric calibration method based on the Spectral Band Adjustment Factor (SBAF), with the specific process illustrated in Figure 4.

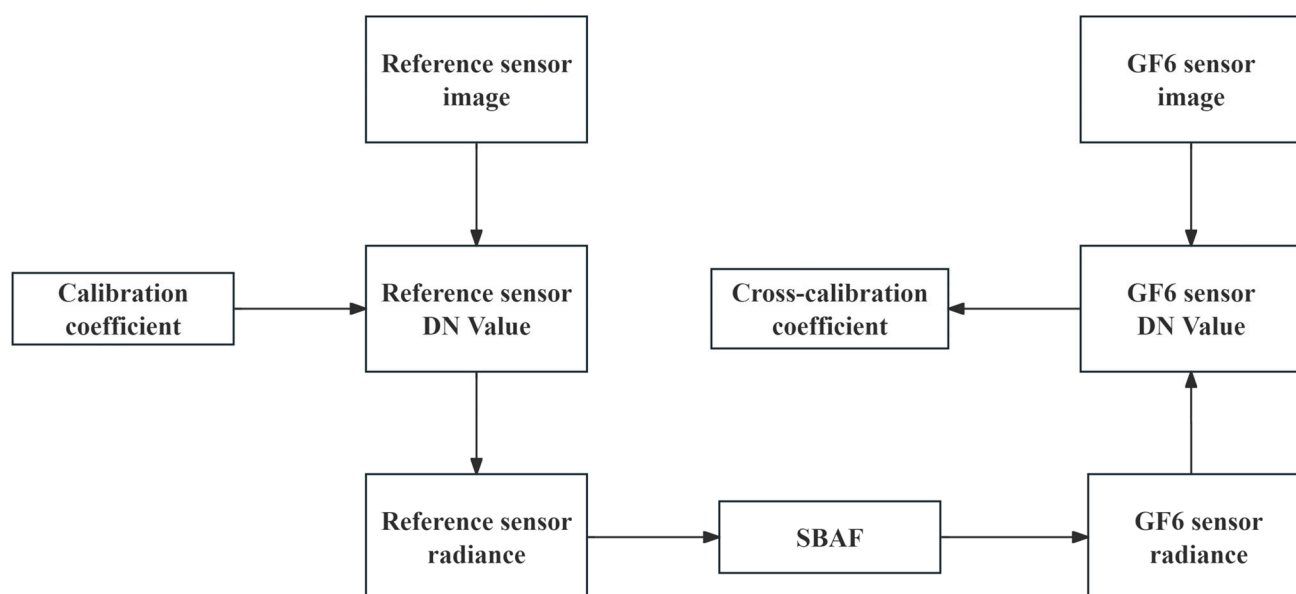


Figure 4. Radiometric cross-calibration process diagram.

As shown in Figure 4, the current method for radiometric cross-calibration primarily involves calculating the SBAF to link two sensors of interest [26]. The SBAF is the ratio of the simulated radiance values between the two sensors of interest. Radiometric calibration involves converting the original image DN values into TOA equivalent radiance:

$$L_{band} = DN \cdot G_{band} + B_{band} \quad (1)$$

where L_{band} ($\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \mu\text{m}^{-1}$) represents the radiance at the sensor's aperture for a specific band, and G_{band} and B_{band} are the gain and offset calibration coefficients of the sensor, respectively. The TOA equivalent radiance, L_{band} can be expressed as

$$L_{band} = \frac{\int_{\lambda_1}^{\lambda_2} S_{band}(\lambda) L(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S_{band}(\lambda) d\lambda} \quad (2)$$

where $S_{band}(\lambda)$ denotes the sensor's SRF for that band, λ represents the wavelength, and λ_1 and λ_2 represent the start and end wavelengths, respectively. In addition, $L(\lambda)$ is the radiance at the TOA across all wavelengths (hyperspectral radiance profile) incident on the sensor [14]. The conversion of TOA reflectance to radiance can be represented as

$$\rho_{TOA,band} = \frac{\pi L_{band} d^2}{E_s \cos \theta} \quad (3)$$

where $\rho_{TOA,band}$ is the reflectance at the TOA for a given band, E_s denotes the exoatmospheric solar irradiance for that sensor band, $\cos \theta$ is the cosine of the solar zenith angle at the time of the sensor's overpass, and d represents the distance between the earth and the sun in astronomical units [27]. The spectral band adjustment factor $SBAF_{band}$ refers to the ratio of two simulated radiance values for the corresponding bands of two sensors of interest, as shown in Equation (4):

$$SBAF_{band} = \frac{L_{band,cal}}{L_{band,ref}} \quad (4)$$

where $L_{band,ref}$ and $L_{band,cal}$ represent the TOA radiance for the reference sensor and the sensor to be calibrated, respectively. The TOA radiance for different sensors can be derived based on their SRFs, observational conditions, and atmospheric parameters using the radiative transfer model. Subsequently, these radiances were corrected and their ratios were calculated. The calculation process is illustrated in Figure 5. For this study, the 6S model was selected for simulating sensor radiance. The 6S (Second Simulation of the Satellite Signal in the Solar Spectrum) model was developed based on the 5S model and is currently among the most widely used atmospheric radiative transfer models [28]. The SBAF results calculated using the 6S model based on the overpass parameters of the four sensors (Table 1) and their corresponding SRFs are shown in Table 2. From the results in the table, it can be seen that, due to the significant difference in SRF between the NIR band of Landsat9-OLI2 and the NIR bands of GF6-PMS and WFV, their SBAF values are also relatively large.

Table 2. GF6-PMS and WFV SBAF results using Landsat9-OLI2 and Sentinel2-MSI as reference sensors.

Sensor	Band	Reference Sensor	
		Landsat9	Sentinel2
GF6-PMS	Blue	1.0553	1.0167
	Green	1.0612	1.0133
	Red	1.0452	1.0235
	NIR	1.1162	1.0510

Table 2. Cont.

Sensor	Band	Reference Sensor	
		Landsat9	Sentinel2
GF6-WFV	Blue	1.0613	1.0225
	Green	1.0672	1.0190
	Red	1.0460	1.0243
	NIR	1.1233	1.0577

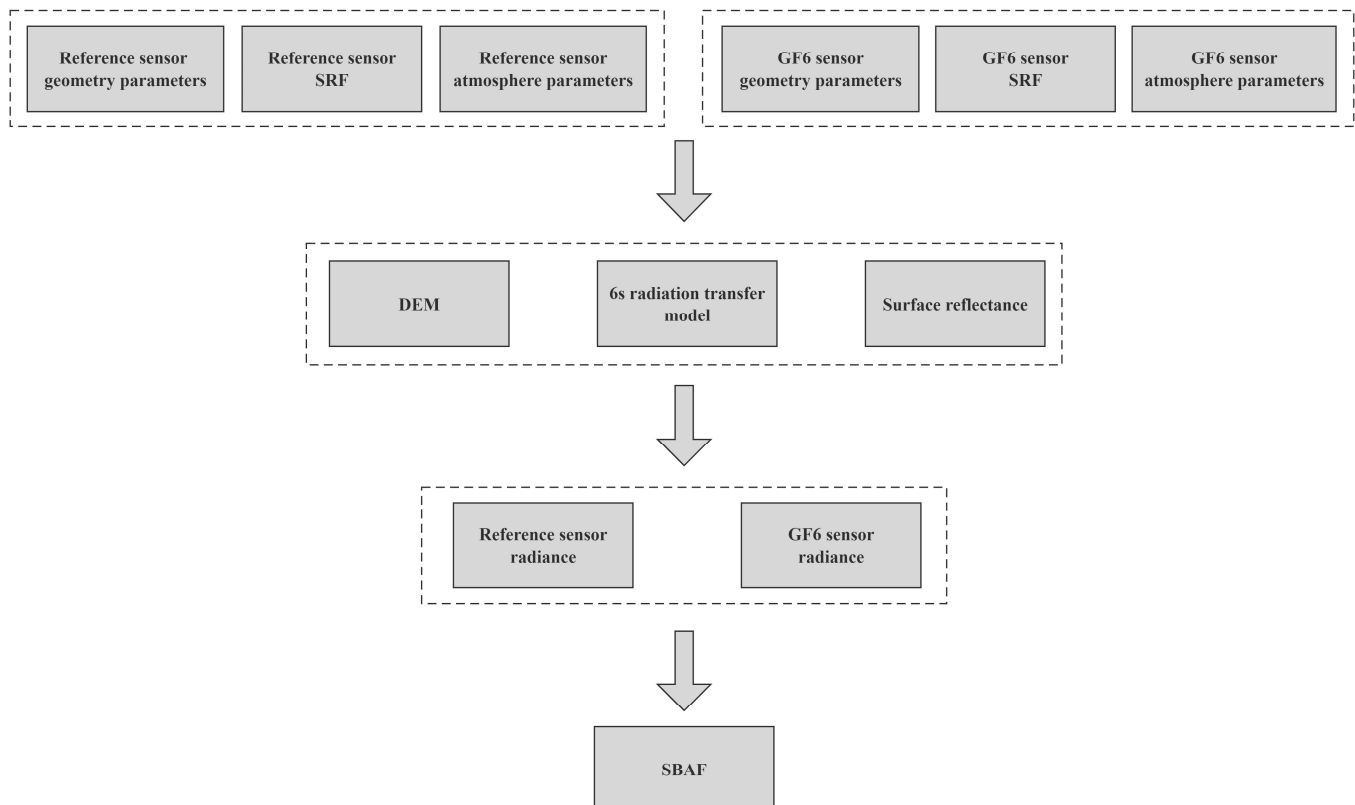


Figure 5. Calculation process diagram for SBAF.

After obtaining the SBAF value, the radiance of the reference sensor can be corrected using SBAF to derive the radiance for the sensor to be calibrated. Finally, by performing a linear fit (with zero offset) between the calibrated sensor radiance and DN values, the calibration coefficients can be obtained. Since the resolution of images from different sensors is different, it is necessary to resample images from different sensors to the same resolution during radiometric cross-calibration processing.

4. Results

4.1. Comparison of Radiance between Different Reference Sensors

In this study, the Landsat9-OLI2 and Sentinel2-MSI sensors were selected as reference sensors to perform radiometric cross-calibration with the GF6-PMS and WFV sensors. All four sensors passed over the Dunhuang calibration site on the same day (Table 1). To assess the differences between the two reference sensors and the necessity of SBAF correction, this paper presents a comparison of the pre- and post-SBAF correction radiance of the Landsat9-OLI2 and Sentinel2-MSI reference sensors as they passed over the Dunhuang calibration site on 15 February 2022, along with their mean ratio (MR) and mean relative difference (MD; Figure 6).

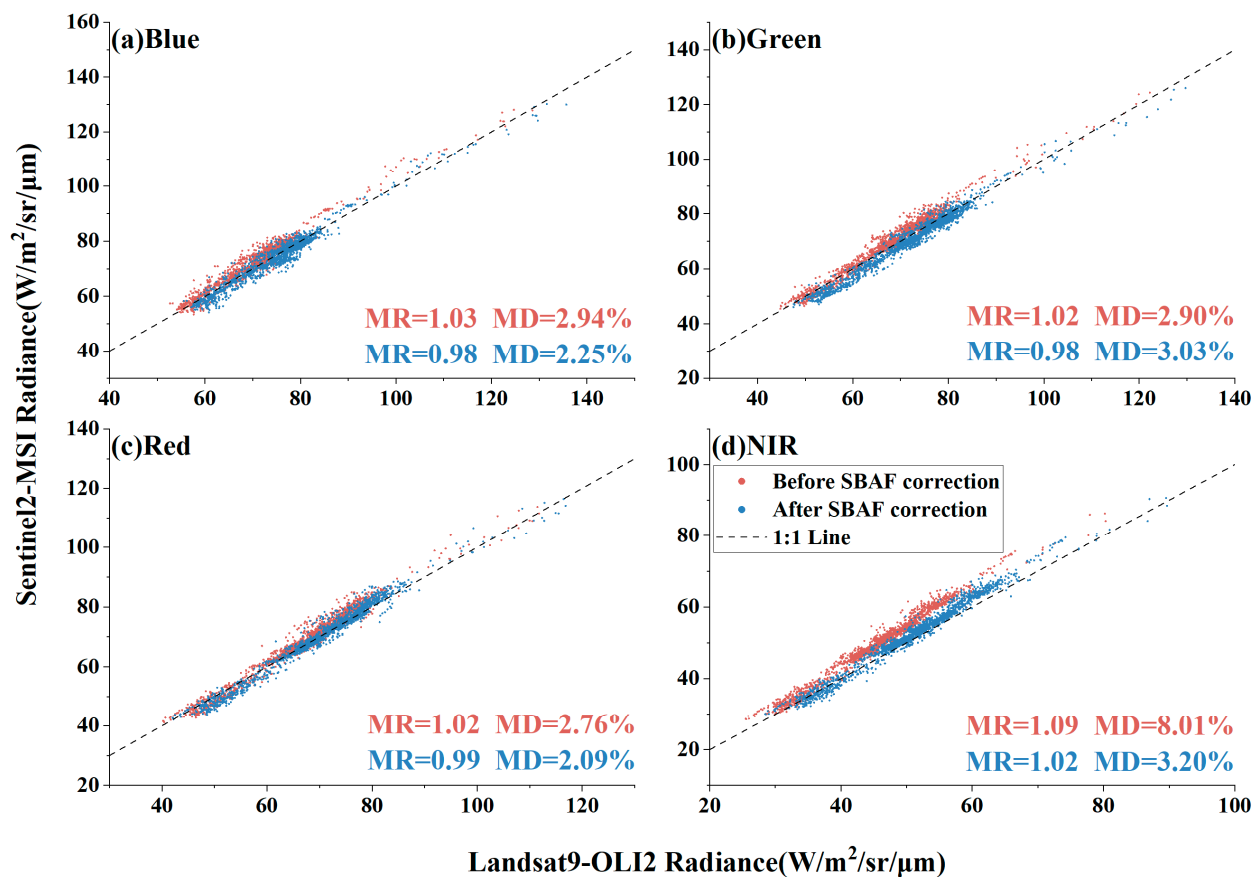


Figure 6. Comparison of radiance between Landsat9-OLI2 and Sentinel2-MSI pre-and post-SBAF correction (MD and MR are the mean relative difference and mean ratio, respectively).

Excluding the green band, it is evident from Figure 6 that the MD between the reference sensors shows a significant reduction after SBAF correction, particularly in the NIR band, where the MD decreased from 8.01 to 3.20%. In the post-SBAF correction, the radiance ratios of the four bands are closer to a 1:1 line, with an average MD across bands of only 2.64%. This indicates that SBAF effectively minimizes radiance discrepancies arising from differences in observation geometry and SRF, thereby enhancing the precision of radiometric cross-calibration.

4.2. Calibration Result Using Difference Reference Sensors

The linear fitting results of radiometric cross-calibration for the GF6-PMS sensor using Landsat9-OLI2 and Sentinel2-MSI as reference sensors, along with the selected DN Range and number of pixels (N) for the uncalibrated sensor, are illustrated in Figure 7. Coefficients obtained using Landsat9 as the reference sensor were higher in the blue and green bands, while the opposite was true for the red and NIR bands. The smallest discrepancy was observed in the red band, with calibration coefficients of 0.04979 and 0.04981 for the two reference sensors, respectively, where the fitted lines for the red band are nearly overlapping in Figure 7. Figure 8 presents the linear fitting results of radiometric cross-calibration for the GF6-WFV sensor and the selected DN Range and number of pixels for the uncalibrated sensor using Landsat9-OLI2 and Sentinel2-MSI as reference sensors. Compared with those of the PMS sensor, the calibration coefficients for the green and red bands of the WFV sensor were closer together. Additionally, when observing the same objects, the DN value range for the blue band of the WFV sensor was broader than that for the PMS sensor, resulting in a significant difference between the calibration coefficients for the blue band of the WFV and PMS sensors. The number of pixels selected for radiometric cross-calibration of the GF6-PMS and WFV sensors was around 2000, aiming to expand

the DN value range for each band as much as possible to ensure a good linear relationship between radiance and DN values, thereby obtaining more accurate calibration coefficients.

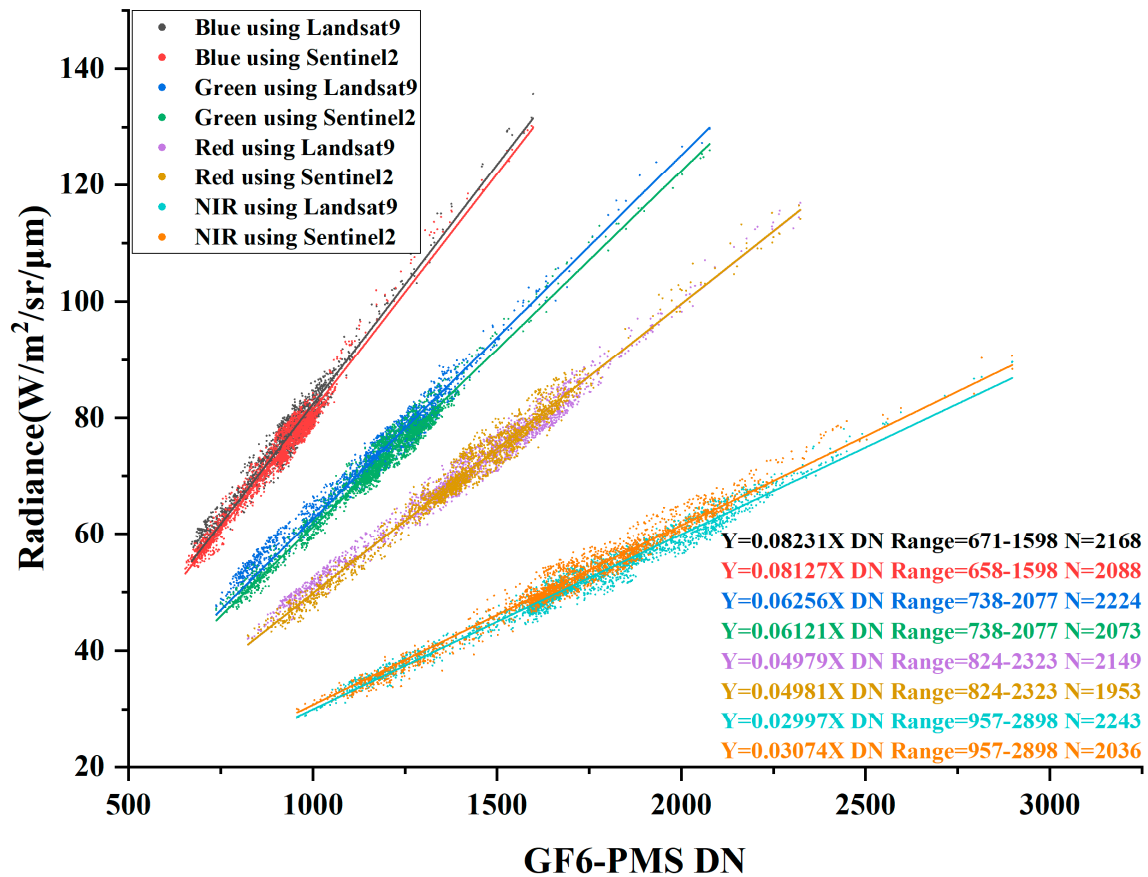


Figure 7. Linear fitting results of radiometric cross-calibration for GF6-PMS.

To facilitate a more thorough analysis of the differences between radiometric cross-calibration coefficients obtained from different reference sensors and the official coefficients, Table 3 presents the relative difference between the radiometric cross-calibration coefficients for the GF6-PMS and WFV sensors, corrected using the methodology described in this paper (SBAF) and the official coefficients. This table outlines the relative difference of radiometric cross-calibration coefficients between different reference sensors (D^a), the relative difference between the coefficients obtained using Landsat9 as the reference sensor and the official coefficients (D^b), and the relative difference between the coefficients obtained using Sentinel2 as the reference sensor and the official coefficients (D^c).

Table 3. Radiometric cross-calibration coefficients for GF6-PMS and WFV using different reference sensors and official coefficients.

Sensor	Band	Reference Sensor		Official Gain	Gain Difference		
		Landsat9-OLI2	Sentinel2-MSI		D^a	D^b	D^c
GF6-PMS	Blue	0.08231	0.08127	0.0821	1.26%	0.26%	1.01%
	Green	0.06256	0.06121	0.0671	2.16%	6.77%	8.78%
	Red	0.04979	0.04981	0.0518	0.04%	3.88%	3.84%
	NIR	0.02997	0.03074	0.031	2.57%	3.32%	0.84%
GF6-WFV	Blue	0.06501	0.06439	0.0633	0.95%	2.70%	1.72%
	Green	0.05105	0.04987	0.0532	2.31%	4.04%	6.26%
	Red	0.05058	0.05071	0.0508	0.26%	0.43%	0.18%
	NIR	0.03426	0.03515	0.0325	2.60%	5.42%	8.15%

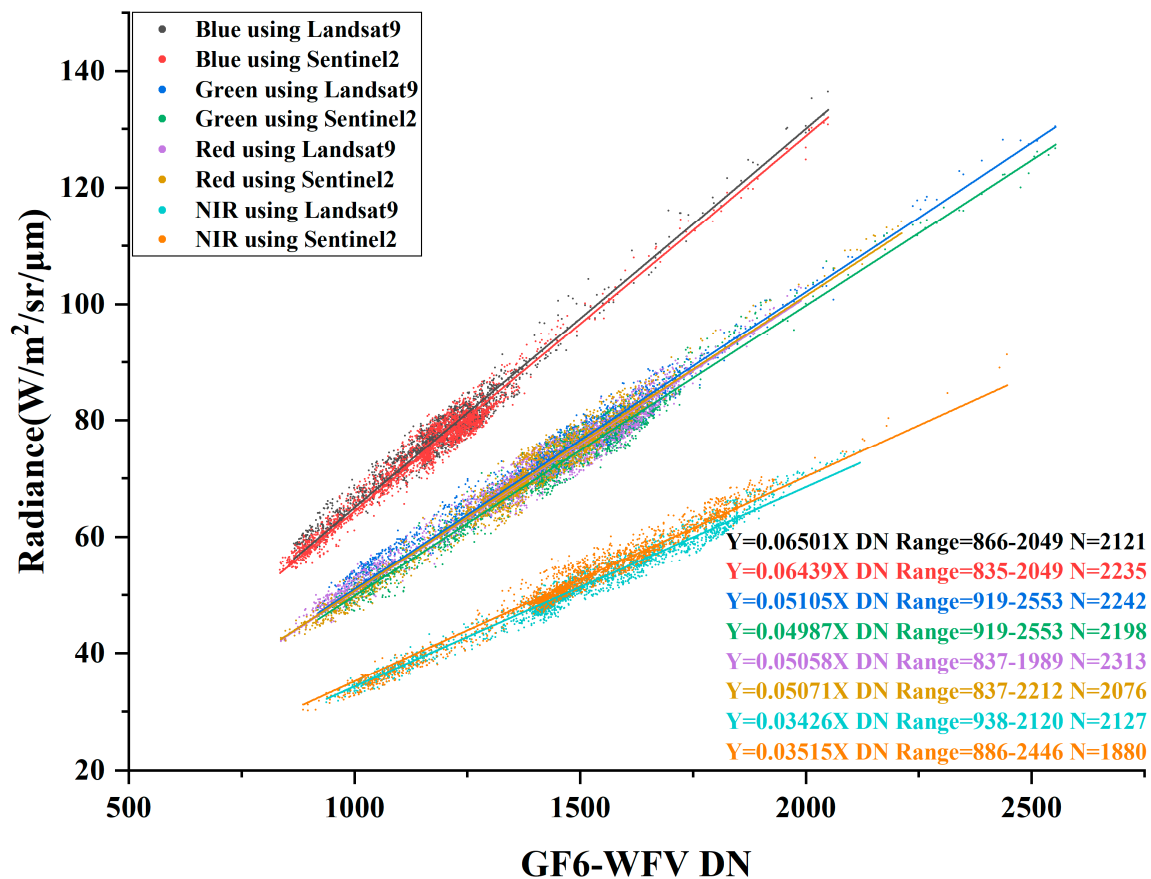


Figure 8. Linear fitting results of radiometric cross-calibration for GF6-WFV.

The results from the table indicate that the maximum D^a between radiometric cross-calibration coefficients for different reference sensors did not exceed 3%, with the GF6-PMS sensor's red band showing a minimal relative difference of only 0.04%, and the GF6-WFV sensor's NIR band exhibiting the maximum difference at 2.6%. A comparison of the PMS and WFV sensors' results revealed that D^a values were generally lower in the blue and red bands and higher in the NIR band. The significant difference in the SRFs of the two reference sensors in the NIR band is a contributing factor to the larger D^a values. Overall, the average D^a values for the GF6-PMS and WFV sensors were 1.51 and 1.53%, respectively. After SBAF correction, the influence of different reference sensors on the radiometric cross-calibration results was minimal, which, as illustrated in Figure 6, indicates that SBAF can effectively correct radiance discrepancies caused by varying observation conditions and sensor SRFs.

The range of D^b between the radiometric cross-calibration coefficients using Landsat9 as the reference sensor and the official coefficients varied between 0.26 and 6.77%, with the GF6-PMS sensor's green band showing the maximum D^b value, and its blue band showing the minimum. The range of D^c between the radiometric cross-calibration coefficients using Sentinel2 as the reference sensor and the official coefficients spanned from 0.18 to 8.78%, where the GF6-PMS sensor's green band had the highest D^c value, and the GF6-WFV sensor's red band had the lowest. Considering the calibration results for both the PMS and WFV sensors, the green and NIR bands' D^a , D^b , and D^c values were significantly higher compared with other bands, indicating these bands are more susceptible to various factors, leading to greater uncertainty in radiometric cross-calibration results. Moreover, the average D^b and D^c values for the GF6-PMS bands were 3.56 and 3.62%, respectively, while for the GF6-WFV bands, they were 3.15 and 4.08%, respectively, suggesting that radiometric cross-calibration coefficients obtained using Landsat9 as the reference sensor were, overall, closer to the official coefficients for both GF6-PMS and WFV sensors.

4.3. Verification of Calibration Results

To verify the accuracy of the radiometric cross-calibration coefficients calculated for the GF6-PMS and WFV sensors, this study selected images from the Dunhuang calibration site captured during two overpasses of the GF6-PMS and WFV sensors, along with corresponding images from Landsat9 or Sentinel2 that passed over on the same days. The overpass information is detailed in Table 4. Note that on 10 June 2022, GF6 and Sentinel2 were overpassed on the same day, and similarly, GF6 and Landsat9 were overpassed on 21 July 2023. The radiance from Landsat9 or Sentinel2 was corrected to the GF6-PMS and WFV radiance, referred to here as Simulated Radiance, using the SBAF. The Calibrated Radiance for GF6-PMS and WFV was calculated using the radiometric cross-calibration coefficients derived from both reference sensors as previously discussed. The verification of the radiometric cross-calibration coefficient results involved comparing the values of the two types of radiance and calculating their MR and MD across different pixels. The verification results for the GF6-PMS and WFV sensors on 10 June 2022 are illustrated in Figures 9 and 10.

Table 4. Overpass information of different sensors at the Dunhuang calibration site on 10 June 2022 and 21 July 2023.

Sensor	PMS	WFV	MSI	PMS	WFV	OLI2
Time (UTC)	05:03	05:03	04:27	04:55	04:55	04:19
Solar Zenith (°)	19.21	19.23	21.66	22.82	22.85	27.28
Solar Azimuth (°)	150.77	150.31	137.61	145.95	145.56	130.64
Sensor Zenith (°)	6.05	6.34	4.23	7.95	7.33	4.63
Sensor Azimuth (°)	13.89	24.78	108.95	329.53	337.19	112.89
AOD (550 nm)		0.223			0.145	

The results depicted in Figure 9 indicate that the largest discrepancy in the verification of the GF6-PMS sensor occurs in the NIR band, with the MD reaching 9.46% when using Landsat9 as the reference sensor, and the ratio being only 0.91. The average MD across all bands was 7.08% when using Landsat9 as the reference sensor and 7.3% when using Sentinel2. Compared with the PMS sensor, the WFV sensor demonstrated, overall, better verification results, with the highest MD in the NIR band at 4.5% and the lowest MD in the blue band at 1.14%, with its MR close to 1. The average MD across all bands was 2.40% when using Landsat9 as the reference sensor and 2.39% when using Sentinel2. The verification results for the GF6-PMS and WFV sensors on 21 July 2023 are shown in Figures 11 and 12. For the GF6-PMS sensor, the largest discrepancy in verification results was again found in the NIR band, with the MD reaching 7.50% when using Landsat9 as the reference sensor, and the ratio being only 0.92. The average MD across all bands was 3.68% when using Landsat9 as the reference sensor and 3.8% when using Sentinel2. Similar to the previous verification results, the WFV sensor outperformed the PMS sensor, with the highest MD in the NIR band at 5.52%, while the average MD across all bands was 3.09% when using Landsat9 as the reference sensor and 2.99% when using Sentinel2. The comparison of MD and MR across bands revealed that the NIR band consistently shows poorer verification results, aligning with the relative difference between the radiometric cross-calibration coefficients and official calibration coefficients, indicating a lower accuracy in radiometric cross-calibration for the NIR band.

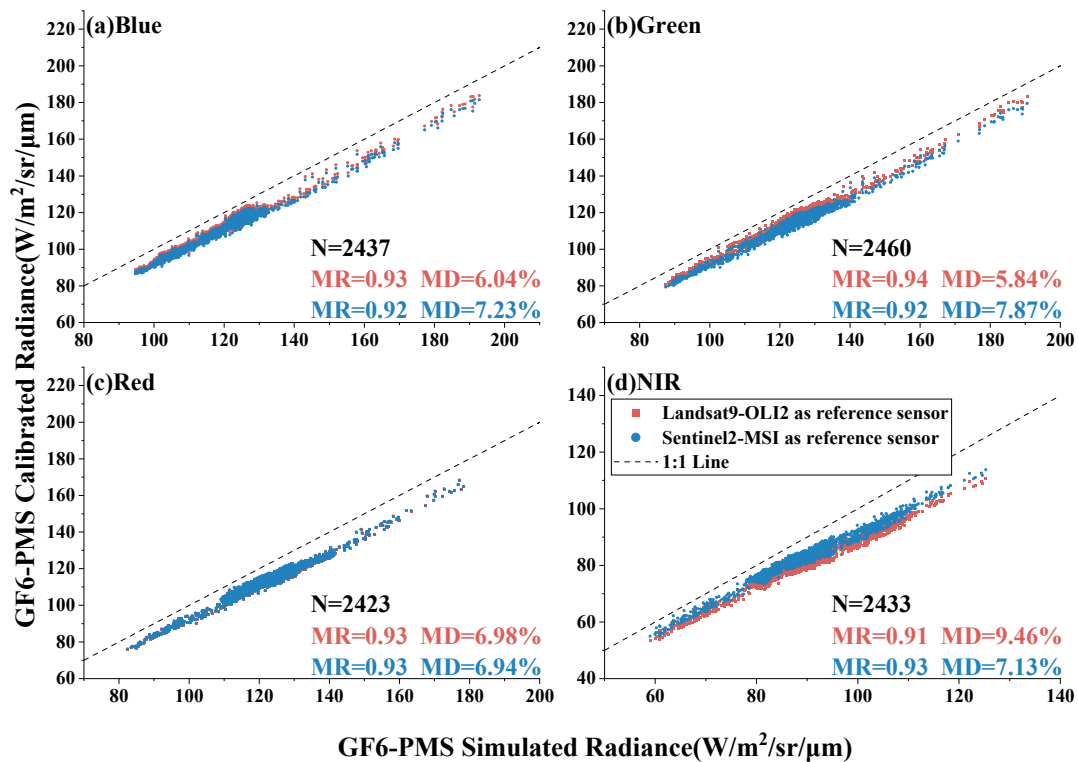


Figure 9. Evaluation and validation of radiance results for GF6-PMS simulated using Sentinel2-MSI versus calculated using radiometric cross-calibration coefficients (MD and MR are the mean relative difference and mean ratio, respectively).

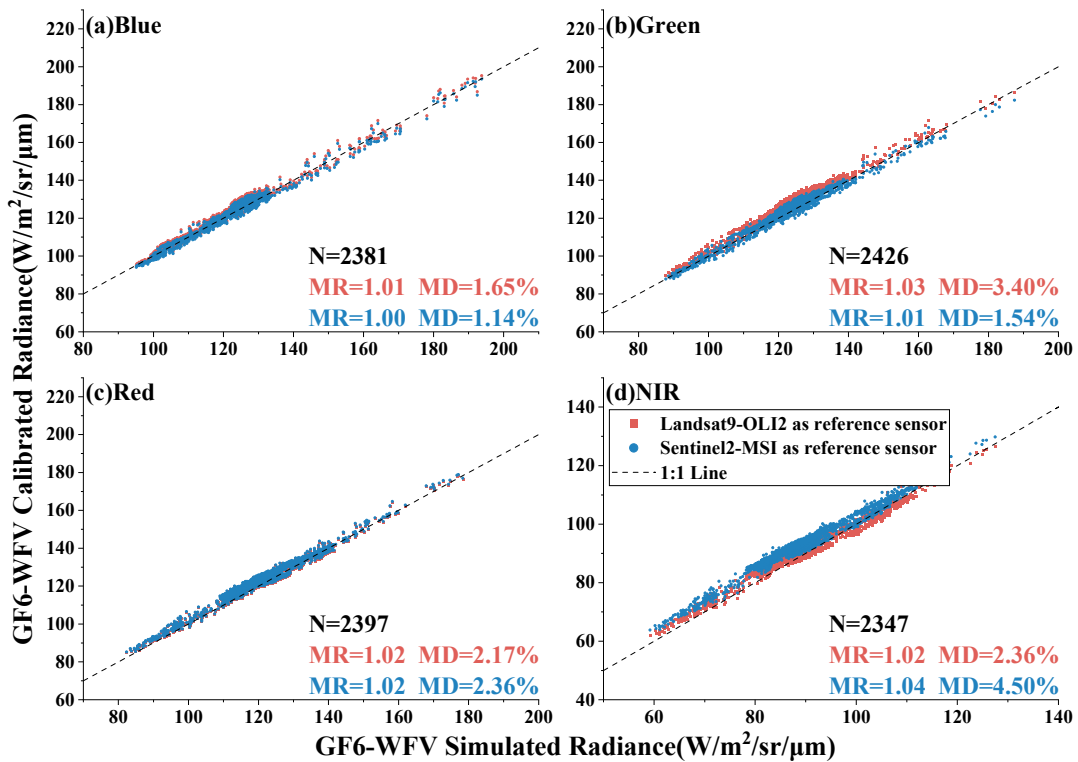


Figure 10. Evaluation and validation of radiance results for GF6-WFV simulated using Sentinel2-MSI versus calculated using radiometric cross-calibration coefficients (MD and MR are the mean relative difference and mean ratio, respectively).

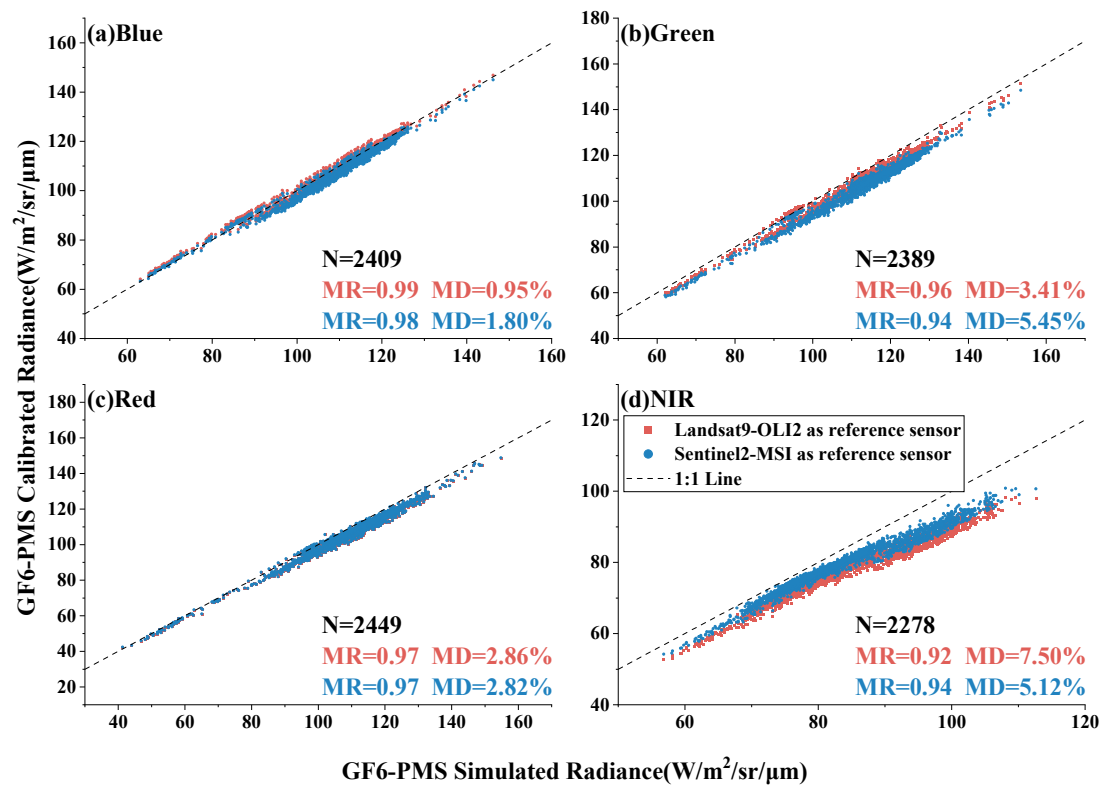


Figure 11. Evaluation and validation of radiance results for GF6-PMS simulated using Landsat9-OLI2 versus calculated using radiometric cross-calibration coefficients (MD and MR are the mean relative difference and mean ratio, respectively).

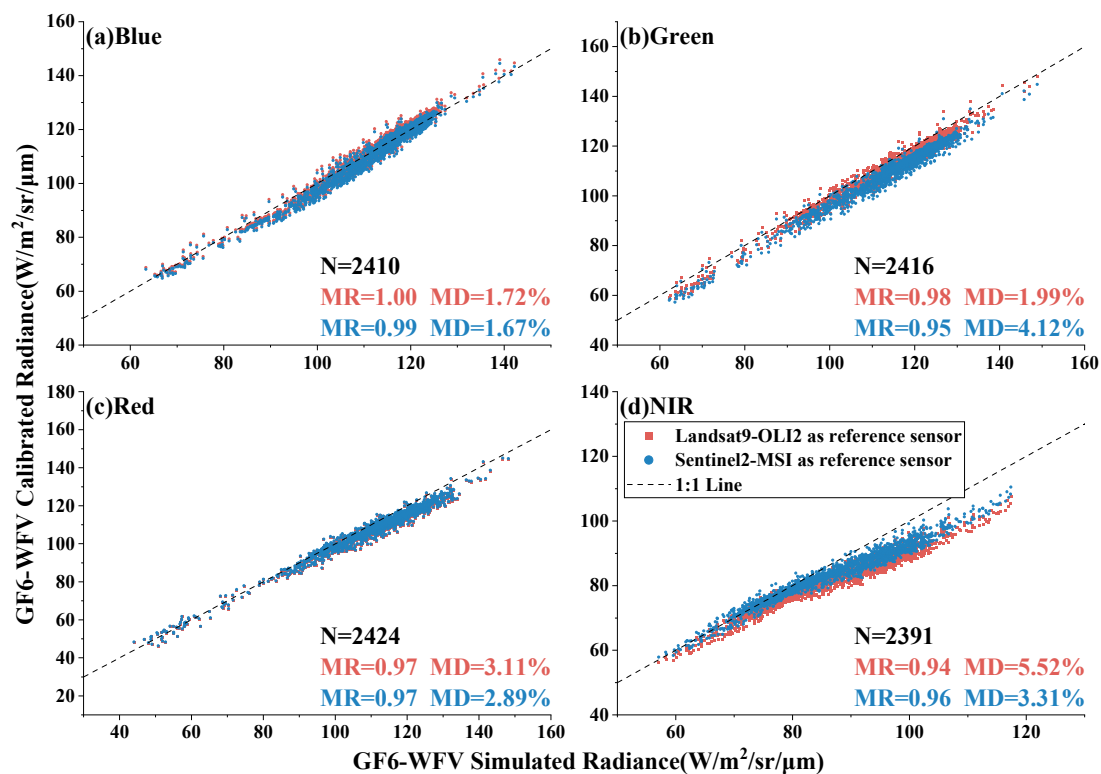


Figure 12. Evaluation and validation of radiance results for GF6-WFV simulated using Landsat9-OLI2 versus calculated using radiometric cross-calibration coefficients (MD and MR are the mean relative difference and mean ratio, respectively).

5. Discussion

5.1. Cross-Calibration Results without SBAF Correction

To obtain consistent data, images from the reference sensors and the sensors awaiting calibration were selected on the same day. The results of the radiometric cross-calibration coefficients without applying the SBAF are presented in Table 5. In comparison with the results obtained with the SBAF correction, a direct radiometric cross-calibration without SBAF correction revealed a significant discrepancy between the results from different reference sensors, with the D^a reaching up to 10.04%. When SBAF correction is applied, the D^a value can be controlled within 3%. Furthermore, compared with the official calibration coefficients, the maximum D^b without SBAF correction was 13.23%, and the maximum D^c was 9.39%, indicating a noticeable increase in result discrepancies. These findings suggest that despite the proximate overpass times of the two sensors over the same location, SBAF correction is still necessary due to the differences in SRFs and observation geometry of the various sensors.

Table 5. Radiometric cross-calibration results without SBAF correction.

Sensor	Band	Reference Sensor		Official Gain	Gain Difference		
		Landsat9-OLI2	Sentinel2-MSI		D^a	D^b	D^c
GF6-PMS	Blue	0.0782	0.0804	0.0821	2.81%	4.75%	2.07%
	Green	0.059	0.0608	0.0671	3.05%	12.07%	9.39%
	Red	0.0477	0.0492	0.0518	3.14%	7.92%	5.02%
	NIR	0.0269	0.0296	0.031	10.04%	13.23%	4.52%
GF6-WFV	Blue	0.0614	0.0632	0.0633	2.93%	3.00%	0.16%
	Green	0.0478	0.0493	0.0532	3.14%	10.15%	7.33%
	Red	0.0485	0.0501	0.0508	3.30%	4.53%	1.38%
	NIR	0.0307	0.0337	0.0325	9.77%	5.54%	3.69%

5.2. Comparison of Results from Different Cross-Calibration Methods

The SBAF calculated in this study, denoted as $SBAF_{Rad}$, is based on the radiance differences between various sensors. Another common method for calculating SBAF involves using the TOA reflectance between different sensors, denoted as $SBAF_{Ref}$. The radiometric cross-calibration method based on $SBAF_{Ref}$ involves converting image radiance to TOA reflectance using Equation (3). Subsequently, this reflectance is corrected to another sensor's TOA reflectance using $SBAF_{Ref}$, and finally converted back to radiance and DN values for linear fitting to obtain the calibration coefficients. To analyze the impact of different SBAFs on radiometric cross-calibration coefficients, this study compared the radiometric cross-calibration results of GF6-PMS and WFV using various SBAFs (Table 6).

From Table 6, it can be inferred that when selecting Landsat9 as the reference sensor, the maximum relative difference in calibration coefficients obtained through different SBAF methods was only 0.96%, with identical calibration coefficients for the red band of GF6 PMS obtained through fitting. In contrast, when selecting Sentinel2 as the reference sensor, the relative difference in calibration coefficients obtained through different SBAF methods increased significantly compared with those obtained with Landsat9, with the maximum relative difference reaching 3.27% in the red band of GF6-WFV, while the minimum relative difference was only 1.1%. Therefore, it can be concluded that when Landsat9 is selected as the reference sensor, the calibration results obtained by different SBAF methods have relatively small differences.

Table 6. Results of different SBAF radiometric cross-calibration methods.

Sensor	SBAF TYPE	Landsat9 as Reference Sensor				Sentinel2 as Reference Sensor			
		Band				Band			
		Blue	Green	Red	NIR	Blue	Green	Red	NIR
GF6-PMS	SBAF _{Ref}	0.08283	0.06242	0.04979	0.03024	0.08038	0.06311	0.05134	0.03122
	SBAF _{Rad}	0.08231	0.06256	0.04979	0.02997	0.08127	0.06121	0.04981	0.03074
	(SBAF _{Ref} − SBAF _{Rad})/SBAF _{Rad} × 100%	0.63	−0.22	0.00	0.90	−1.10	3.10	3.07	1.56
GF6-WFV	SBAF _{Ref}	0.06555	0.05078	0.05078	0.03459	0.06362	0.05134	0.05237	0.03572
	SBAF _{Rad}	0.06501	0.05105	0.05058	0.03426	0.06439	0.04987	0.05071	0.03515
	(SBAF _{Ref} − SBAF _{Rad})/SBAF _{Rad} × 100%	0.83	−0.53	0.40	0.96	−1.20	2.95	3.27	1.62

5.3. Ground Synchronous Observation Verification and Evaluation

In this study, images from Landsat9 and Sentinel2 were selected in order to evaluate and analyze the radiometric cross-calibration coefficients for GF6-PMS and WFV. For a comprehensive assessment of the calibration coefficient results, synchronous ground observation data were acquired for surface reflectance and atmospheric parameters (40.14°N, 94.32°E) for GF6-PMS and WFV during their overpass over the Dunhuang calibration site on 25 November 2022. The surface reflectance data were measured using a spectrometer within half an hour before and after the satellite overpass, and the atmospheric parameters were obtained through synchronous observations using a CE-318 Sunphotometer. The synchronous ground observation data were used with the 6S radiative transfer model to simulate the radiance of GF6-PMS and WFV for evaluating the calibration coefficients obtained through cross-calibration. The surface reflectance is shown in Figure 13, and the atmospheric parameters are presented in Table 7.

Table 7. Atmospheric parameters from ground synchronous observation at the Dunhuang calibration site on 25 November 2022.

Sensor	PMS	WFV
Time (UTC)	04:59	04:59
Solar Zenith (°)	61.37	61.35
Solar Azimuth (°)	171.87	171.70
Sensor Zenith (°)	6.02	6.32
Sensor Azimuth (°)	14.03	24.94
AOD (550 nm)	0.16	

Based on the synchronous ground observation data and the radiance simulated by the radiative transfer model for GF6-PMS and WFV, a comparison of the radiance results calculated using the calibration coefficients obtained in this study is presented in Table 8. The discrepancy between the radiance simulated using the GF6-PMS calibration coefficients and the radiance simulated from synchronous ground observation data was relatively small compared with that from the GF6-WFV. When using Sentinel2 as the reference sensor, the relative difference in the green band was only 0.03%, with the average relative difference across all bands being 3.25 and 1.78% for Landsat9 and Sentinel2 as reference sensors, respectively. The discrepancy between the radiance simulated using GF6-WFV calibration coefficients and the radiance simulated from synchronous ground observation data was large because the wide observational swath of WFV reached 800 km; the Bidirectional Reflectance Distribution Function (BRDF) properties during radiative transfer simulation were not considered, leading to a larger relative difference, with the maximum reaching 10.11% in the red band. The average relative difference across all bands was 6.44 and 6.33% for Landsat9 and Sentinel2 as reference sensors, respectively. Although in some bands

the relative difference was smaller when Sentinel2 was used as the reference sensor, the fluctuation in relative difference results across bands was larger. However, considering the differences between results across different bands, the impact of different calibration methods, satellite overpass cycles, and other factors, the results of the present study indicate that Landsat9 is more suitable as a reference sensor.

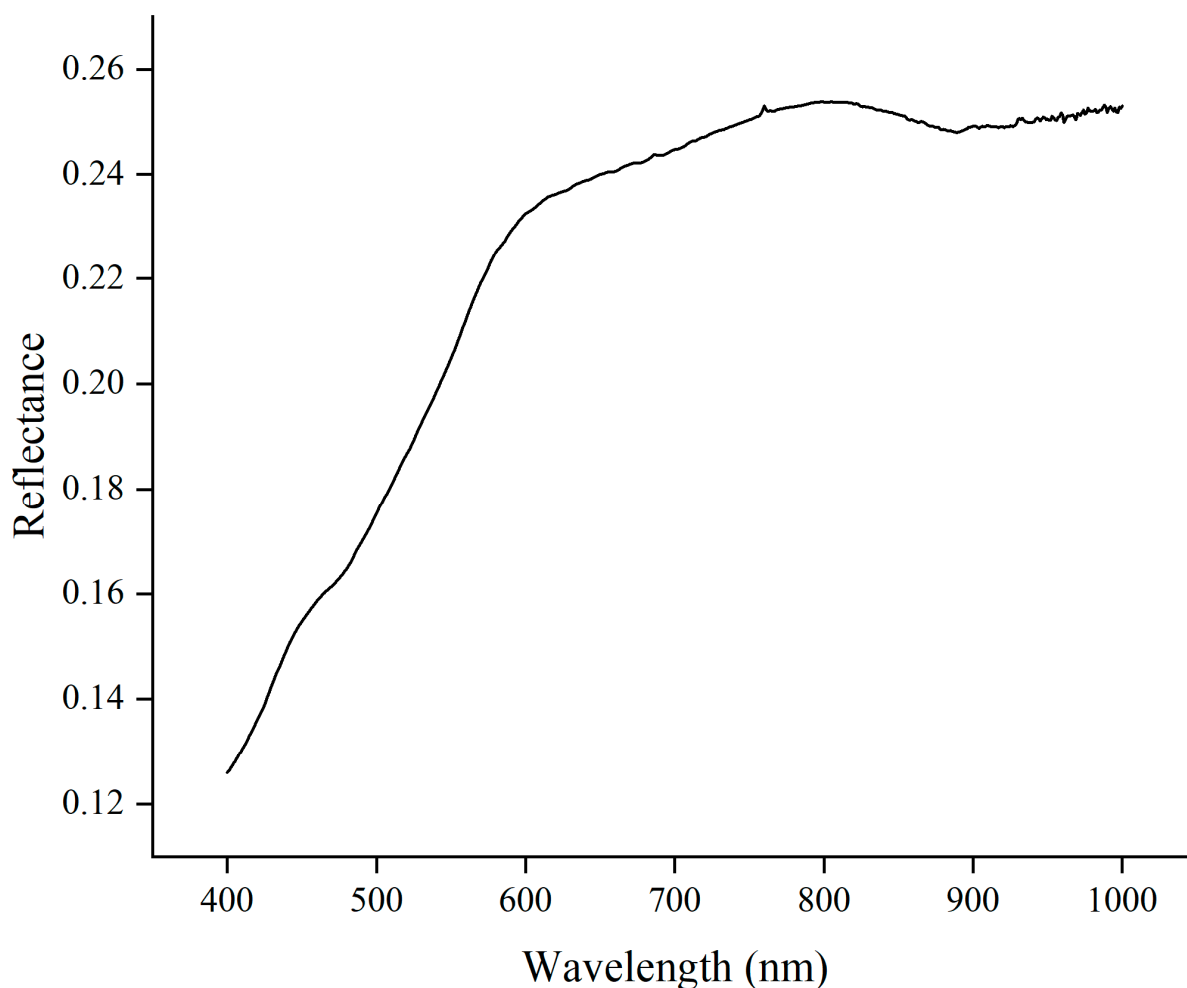


Figure 13. Surface reflectance from ground synchronous observation at the Dunhuang calibration site on 25 November 2022.

Table 8. Comparison of radiance simulated from ground synchronous observation data of GF6-PMS and WFV with radiance calculated using radiometric cross-calibration coefficients.

Sensor	Band	6S Simulated Radiance (W/m ² /sr/μm)	Cross-Calibration Coefficient Radiance of Different Reference Sensors (W/m ² /sr/μm)	
			Landsat9	Sentinel2
PMS	Blue	63.23	66.92	66.07
		Relative Difference	5.83%	4.50%
	Green	59.82	61.12	59.80
		Relative Difference	2.17%	0.03%
	Red	55.48	56.36	56.38
		Relative Difference	1.58%	1.63%
	NIR	39.88	38.51	39.50
		Relative Difference	3.43%	0.95%

Table 8. Cont.

Sensor	Band	6S Simulated Radiance (W/m ² /sr/μm)	Cross-Calibration Coefficient Radiance of Different Reference Sensors (W/m ² /sr/μm)	
			Landsat9	Sentinel2
WFV	Blue	63.54	66.83	66.19
		Relative Difference	5.18%	4.18%
	Green	59.64	63.40	61.94
		Relative Difference	6.31%	3.86%
	Red	55.17	60.59	60.75
		Relative Difference	9.82%	10.11%
	NIR	41.46	43.30	44.43
		Relative Difference	4.45%	7.16%

6. Conclusions

In this study, Landsat9-OLI2 and Sentinel2-MSI were selected as reference sensors for radiometric cross-calibration of the GF6-PMS and WFV sensors awaiting calibration. The calibration results between different reference sensors could be controlled within 3%, with the maximum difference from the official coefficients being 8.78%. In the two sets of validation results, the maximum MD in the NIR band was 9.46%, and the WFV sensor showed better validation results. Finally, considering the impact of different calibration methods on the results, and the validation performed using synchronous ground observation data, it was determined that using Landsat9 as the reference sensor provided more stable results for radiometric cross-calibration of GF6-PMS and WFV.

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