Comparison of different calibration algorithms for the medium resolution spectral imager in infrared band

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Abstract. As a key payload on the Fengyun-3C (FY-3C) polarorbit meteorological satellite, the medium resolution spectral imager (MERSI) is installed to provide the global coverage of top-of-atmosphere radiances. In order to ensure the on-orbit radiometric data quality of the MERSI, the modified calibration equation for the thermal infrared channel can be obtained by the blackbody (BB) and deep space view (SV). Different calibration algorithms are investigated to obtain the time series of the calibration coefficients $a_0$, $a_1$ and $a_2$, and the accuracy of the radiometric calibration is evaluated by comparing the BB irradiance calculated by those calibration coefficients and the standard BB irradiance, whose irradiance differences are within the order of $10^{-4}$ W/m²/μm/sr. Moreover, the differences of the BB inversed and equivalent temperatures by different algorithms show a similar behavior, whose values changing from 0.26 K to 0.28 K. These works provide important information for tracking the instrument performance along with the quantitative remote sensing application.

1. Introduction

The satellite infrared imagery is valuable for detecting the cloud characteristics and ocean surface temperatures, especially for detecting the different surfaces of the earth [1]. With the increasing of the detecting instrument and channels, the same satellite is equipped with the similar infrared detection channels, and the temperature difference of the same place detected by these channels directly depends on the calibration accuracy of the infrared channel, spectral response function and other factors.

Fengyun-3 (FY-3) series satellite is the second generation of Chinese polar-orbiting meteorological satellite [2], which is the first high performance integrated exploration satellite in China. The FY-3 carries 11 remote sensing instruments, including a scan radiometer (VIRR) [3] and a medium resolution imager (MERSI) [4]. As one of the main remote sensors, the MERSI sets a window region channel with a spatial resolution of 250 m in the thermal infrared band, which has the ability of detecting 20 channels from the visible to thermal infrared regions [5]. Not only can the MERSI thermal infrared channel observation system detect the surface and ocean temperatures, but it also provides the thermal infrared image for the cloud detection and other remote sensing product generation. Because of its high spatial resolution, the MERSI thermal infrared channel can also be adopted for monitoring the urban heat island [6]. To realize the high resolution earth observation, the
pixel size of the MERSI detector is 0.10 mm×0.10 mm, together with the corresponding instantaneous field of view of 0.3 [7-9].

In order to ensure the on-orbit radiometric data quality of the sensor, the MERSI must be comprehensively tested before launch, and continuously monitored to characterize the temporal variations using the reliable references [10]. The on-orbit radiation calibration for the medium and long wave infrared channels can be achieved by scanning the black body (BB) on the star. The temperature stability of the BB together with its uniformity play a decisive role in the on-orbit calibration accuracy because of the radiation energy of the surface source BB mainly related to its temperature and surface emissivity [11]. In order to realize the real-time calibration in the infrared channel, the MERSI scans the signals of the BB and SV when acquiring the earth target signal, and the radiometric calibration is performed by using the on-board BB and SV as references [12].

To determine the optimization algorithm of the thermal infrared radiometric calibration, two cases of the linear and nonlinear fitting are analyzed and discussed in detail in this paper. The calibration coefficients calculated by the linear fitting algorithm can reflect the pixel and frame differences, and the maximum of the BB irradiance together with its surface bright temperature evaluated by this calibration algorithm are reasonable. Compared with the linear fitting algorithm, the calibration coefficients obtained by the nonlinear fitting algorithm does not improve the precision of the BB surface bright temperature, and the values of the earth irradiance together with its surface bright temperature acquired by these calibration coefficients are significantly higher.

2. Observation scenario of the FY-3C/MERSI together with its calibration principle
The FY-3C/MERSI is a cross-track scanning radiometer, which makes an earth observation of the field of view at the sub-stellar point with the scanning period of 1.5s via a 45° scanning mirror and a racemization mirror, and its on-orbit observation mode is depicted in Figure 1.

![Figure 1. On-orbit observation mode for the MERSI.](image)

The MERSI collects the data at two spatial resolutions: 250 m and 1000 m, which can cover a swath of 2900 km (cross-track) by 10 km (along-track) for each scan with multiple detectors (10 or 40), enabling the global coverage once a day. There are 350 along-track detectors: 40 detectors per band for the channels with a 250-m pixel resolution, and 10 detectors per band for the channels with a 1-km pixel resolution.

According to the optical properties of the MERSI, the radiometric calibration equation in the infrared channel is expressed as follows:

\[ L = a_d + a_n \cdot dn + a_2 \cdot dn^2, \]  \hspace{1cm} (1)

where and stand for the observed irradiance and output digital number of the instrument, while , and represent the calibration coefficients determined by the laboratory vacuum measurement. Because of the changes of the thermal environment on the planet together with the diurnal and orbital cycles, the output digital number is corrected as:

\[ dn = DN - DN_{SV}, \]  \hspace{1cm} (2)

Based on Eqs. (1) and (2), the aperture irradiances for the blackbody (BB) and space view (SV) are written as:
\[
\begin{align*}
L_{\text{bb}} &= a_0 + a_1 \cdot D_{\text{nn}} + a_2 \cdot D_{\text{nn}}^2, \\
L_{\text{sv}} &= a_0 + a_1 \cdot D_{\text{sv}} + a_2 \cdot D_{\text{sv}}^2, \\
dn_{\text{bb}} &= DN_{\text{bb}} - DN_{\text{sv}}.
\end{align*}
\]  

(3)

here \(DN_{\text{bb}}\) and \(DN_{\text{sv}}\) together with \(L_{\text{bb}}\) and \(L_{\text{sv}}\) represent the digital numbers and aperture irradiances of the BB and SV, respectively, and the value of \(DN_{\text{sv}}\) approximately takes the dark current of the photoelectric coupler. If considering the spectral response, the average spectral irradiance \(L\) is

\[
L = \frac{\int L(\lambda) \cdot \Phi(\lambda) d\lambda}{\int \Phi(\lambda) d\lambda},
\]  

(4)

where \(L(\lambda)\) and \(\Phi(\lambda)\) are named as the spectral irradiance and spectral response function corresponding to the wavelength \(\lambda\), and \(L(\lambda)\) is solved by the Planck function. Taking the calibration coefficients \(a_0, a_1\) and \(a_2\) obtained by different calibration algorithms together with the earth scanning digital number \(dn_{\text{ev}}\) to Eq. (1), the earth irradiance \(L_{\text{ev}}\) corresponding to each sampling point is calculated as:

\[
L_{\text{ev}} = a_0 + a_1 \cdot dn_{\text{ev}} + a_2 \cdot dn_{\text{ev}}^2,
\]  

(5)

and the inversed temperature of the earth is given as:

\[
T_{\text{ev}} = \frac{10^8 hc}{\lambda k} \left[ \ln \left(1 + \frac{2 \times 10^{24} hc^2}{\lambda^3 L_{\text{ev}}} - \frac{1}{L_{\text{ev}}} \right) \right]^{-1},
\]  

(6)

Here \(h\), \(c\) and \(k\) are the Planck constant, velocity of light and Boltzmann constant, respectively.

3. Optimization of the thermal infrared radiometric calibration algorithms

According to the domestic and overseas research results, the on-orbit calibration equation of the MERSI is expressed by a nonlinear quadratic form, which can provide the real-time coefficients that reflect the abrupt and secular changes of the satellite-bronze sensors. It should be noted that the MERSI on-orbit calibration is performed by adopting one fixed-temperature BB and SV as two references. For each side, each pixel and each scan, there are 24 and 96 measurements for the BB and SV, respectively. To reduce the influence of the noise, the average values of all the measurements and should be used to determine the coefficients.

In order to solve the calibration coefficients, two calibration algorithms are analyzed. The nonlinear fitting algorithm refers that letting the quadratic coefficient \(a_2 \neq 0\), including the sampling point nonlinear fitting (SPNF) and sampling point nonlinear steady quadratic fitting (SPNSQF) algorithms. The SPNSQF algorithm is a special case of the SPNF algorithm, and the quadratic coefficient \(a_2\) is assumed as a constant which is measured by the laboratory vacuum measurement before launched. Because of the quadratic coefficient mainly describing the shape of the calibration curve, it is still kept unchanged after orbit injection. The linear fitting algorithm includes the individual sampling point linear fitting (ISPLF) and average sampling point linear fitting (ASPLF) algorithms, letting the quadratic coefficient \(a_2 = 0\). The ISPLF algorithm adopts the digital number of each sampling point to calculate the calibration coefficients \(a_0\) and \(a_1\), while the arithmetic mean value of each sampling point is adopted for the ASPLF algorithm.

3.1. Influence of the nonlinear quadratic term on the calibration coefficient

The calibration coefficients obtained by the SPNF, SPNSQF and ISPLF algorithms are shown in Figures 2 and 3, which are calculated by forty pixels of the MERSI/FY-3C thermal infrared channel sensor. Where the nonlinear steady quadratic fitting coefficient is taken as and for two different sides. From Figures 2 and 3, the calibration coefficients derived by the ISPLF algorithm show great changes for different pixels and small differences for different frames. Conversely, there are
small differences for different pixels and larger random changes for each frame corresponding to the calibration coefficients and calculated by the SPNF algorithm. In order to determine the known quadratic calibration coefficient in the SPNSQF algorithm, the SPNF algorithm is adopted to obtain the calibration coefficient corresponding each scanning side, and then the average value of corresponding to all pixels is obtained as shown in Figure 4. Although the values of and calculated by the SPNSQF algorithm are different from those of the SPNF algorithm, they have similar variation characteristics and trends. That is, there are larger differences between different pixels while the variation range between each frame is smaller. Thereby, if only the calibration coefficients and are determined, the results are similar whether the quadratic coefficient is assumed as zero or a constant.

![Figure 2. Zeroth-order coefficient $a_0$ derived by the SPNSQF algorithm (a), the ISPLF algorithm (b) and the SPNF algorithm (c).](image)

![Figure 3. First-order coefficient $a_1$ derived by (a) the SPNSQF algorithm, (b) the ISPLF algorithm and (c) the SPNF algorithm.](image)

![Figure 4. Second-order coefficient $a_2$ derived by the SPNF algorithm, where (a), (b), (c) and (d) are corresponding to the pixels 1-10, 11-20, 21-30 and 31-40, respectively.](image)

The on-orbit calibration irradiance calculated by the BB digital number and calibration coefficient is compared with the standard irradiance calculated by the BB temperature and Planck function, as shown in Figure 5, corresponding to the SPNSQF, ISPLF and SPNF algorithms, respectively. From Figure 5, the irradiance difference is within the order of $10^4 \text{ W/m}^2/\text{um/sr}$, which indicates that the irradiances calculated by different algorithms are in good agreement with that obtained by the BB equivalent temperature. For a specific pixel and side, there is a fairly stable difference between two BB irradiances for each frame. Besides, the irradiance differences for different algorithms show a very similar trend for different pixels and frames, while the BB irradiance values are different. The BB irradiance difference obtained by the SPNF algorithm is very close to that by the SPNSQF algorithm, and it is about $2.0\times10^4 \text{ W/m}^2/\text{um/sr}$. This shows that the BB irradiance can be better fitted with the nonlinear term.
Figure 5. BB irradiance difference $\Delta L$ derived by (a) the SPNSQF algorithm, (b) the ISPLF algorithm and (c) the SPNF algorithm.

The on-orbit calibration temperature inversely calculated by the BB calculated irradiance is compared with the equivalent temperature, as shown in Figure 6. From Figure 6, the BB temperature differences obtained by three different algorithms show a very similar trend between different pixels and frames, and their values change from 0.26 K to 0.28 K. Namely, the BB inversely calculated temperature shows a certain systematic error relative to the BB equivalent temperature. For a specific pixel and side, the BB temperature difference obtained by the data of each frame is fairly stable, which indicates that the BB temperatures calculated by different algorithms are in good agreement with the BB equivalent temperature. Compared with the linear fitting algorithm, the nonlinear fitting algorithm can better calculate the BB irradiance, but it does not provide the new information for estimating the BB temperature.

Figure 6. BB inversely calculated temperature difference $\Delta T$ derived by (a) the SPNSQF algorithm, (b) the ISPLF algorithm and (c) the SPNF algorithm.
3.2. Influence of the BB and SV scanning sampling on the calibration coefficient
The calibration coefficients $a_0$ and $a_1$ calculated by the ISPLF and ASPLF algorithms are shown in Figures 7 and 8. From Figures 7 and 8, the values of $a_0$ and $a_1$ obtained by two algorithms are almost identical, because the scanning digital numbers of the BB and SV are equivalent in the linear case if not considering the numerical calculation error. The on-orbit calibration irradiance is compared with the standard irradiance as shown in Figure 9. Based on Figure 9, the BB irradiance difference obtained by two algorithms shows a very similar trend for different pixels and frames, and the BB irradiance difference by the ASPLF algorithm is about $4.0 \times 10^{-3}$ W/m$^2$/μm/sr, which is much smaller than that calculated by the ISPLF algorithm. This shows that the ASPLF algorithm can better fit the BB irradiance, which effectively suppress some random changes. The on-orbit calibration temperature inversely calculated by the BB irradiance is compared with the equivalent temperature, as shown in Figure 10. From Figure 10, the BB temperature differences obtained by two algorithms show a very similar trend for different pixels and frames, and the BB inversely calculated temperature shows a certain systematic error relative to the BB equivalent temperature.

To sum up, due to the lack of the information, the calibration coefficients $a_0$, $a_1$ and $a_2$ determined by the nonlinear fitting algorithm can better fit the BB irradiance while not providing the new information and result for estimating the BB inversely calculated temperature. The calibration coefficients $a_0$ and $a_1$ determined by the linear fitting algorithm can reflect the pixel difference and are relatively stable between each frame. Although the error of adopting the calibration coefficients $a_0$ and $a_1$ calculated by the linear fitting algorithm to obtain the BB irradiance and inversely calculated temperature is larger, it can reach the accuracy of the same order as the nonlinear fitting algorithm.

4. Conclusion
This paper gives the scanning imaging mode of the FY-3C/MERSI together with its calibration equation considering the influence of the dark current on the SV. In order to determine the optimization of the thermal infrared radiometric calibration algorithm, the time series of the calibration coefficients $a_0$, $a_1$ and $a_2$ are obtained by different calibration algorithms, and the BB irradiances calculated by those calibration coefficients are compared with the standard BB irradiance. The irradiance differences are within the order of $10^4$ W/m$^2$/μm/sr, which indicates that the irradiances
calculated by different algorithms are in good agreement with the standard irradiance. The differences between the BB inversed and equivalent temperatures by different algorithms show a very similar trend between different pixels and frames, and their values change from 0.26 K to 0.28 K. By comparing different calibration algorithms, the linear fitting algorithm is an optimal choice for the MERSI infrared radiometric calibration, and the calibration coefficients $a_0$ and $a_1$ determined by the linear fitting algorithm can reflect the pixel difference and are relatively stable between each frame. The BB irradiance and its inversed temperature determined by these coefficients can reach the accuracy of the same order as the nonlinear fitting algorithm.

Funding, acknowledgments, and disclosures
This research was supported by the National Key Research and Development Program of China (2017YFC0209704), the National Natural Science Foundation of China (11704213), Qingdao University of Science and Technology 2019 Student Innovation Training Program Project (X20191042624).

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