On-Board Spectral Calibration for Chinese Medium Resolution Imaging Spectrometer

R.M. Fu, Y.X. Liu and M. Li

Abstract Spectral calibration is the basis for space-borne spectral imager to obtain accurately quantified spectral imaging data. The random vibrations during the launch process and the change of space environment will influence the veracity of ground spectral calibration. So the on-board spectral calibration is necessary to a space-borne spectral imager. Considering the specific mission requirements including the spectral range and 1 nm wavelength accuracy of Chinese Medium Resolution Imaging Spectrometer (CMERIS), the on-board spectral calibration is achieved by rare earth doped diffuser plate combining the Fraunhofer absorption lines and oxygen A-band. And the ground simulation was introduced in Sect. 3, which employs well-defined equations to calculate spectral calibration through data processing including unitary calculation, peak searching and regression analysis. Finally, the results of the simulation were verified by the standard lines of mercury lamp and the filter wavelengths. These results can satisfy the spectral calibration requirement of 1 nm wavelength accuracy.

Keywords Chinese medium resolution imaging spectrometer · On-board spectral calibration · Ground simulation

1 Introduction

Spectral imager is a kind of the optic remote sensing instrument, which can be used to obtain images and continuous spectral information at the same time [1].

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The accuracy calibration is important for spectral imagers because veracity and reliable quantified data is the basis for spectral imager's application. After launch and on-board activities, some characteristics of accessories of spectral imager will be changed due to the rough vibration and extreme outer-space environment. To obtain accurate spectral imaging data, on-board spectral calibration is considerable necessary for spectral imagers to revise the results of ground spectral calibration [2].

There are several on-board spectral calibration methods for a space-borne spectral imager. For example, MERIS [3] uses rare earth doped diffuser plate, Fraunhofer lines, oxygen A-band, Hyperion [4] uses Fraunhofer lines and atmospheric absorption lines, CHRIS [5] uses oxygen A-band and atmospheric absorption lines, OMI [6] uses atmospheric absorption lines, MOS-B [7] and MODIS [8] use filters and HISUI [9] uses filters and Mylar film. Space-borne spectral imagers usually use several on-board spectral calibration methods to improve the calibration accuracy by mutual complementation and verification.

CMERIS (Chinese Medium Resolution Imaging Spectrometer) has a spectral range from 400 to 950 nm with 1.25 nm spectral resolution and 1 nm wavelength accuracy. The spectral data is achieved by imaging via a dispersing grating onto a 2-D CCD array. Considering the mission requirements and characteristics of CMERIS, three on-board spectral calibration methods are chosen in Sect. 2 and the ground simulation is accomplished in Sect. 3. From ground simulation, the spectral calibration equation and uncertainty analysis are well modeled and conducted. Finally, to verify the precision of ground simulation results, the standard lines of mercury lamp test and the filter wavelengths test are introduced, the conclusion can be seen in Sect. 4.

2 The On-Board Spectral Calibration

2.1 System of On-Board Spectral Calibration

On-board calibration system of CMERIS consists of calibration disk, transmission mechanism, electromotor, resolver, light fender, lens hoods, earth window glass and other structures, which located at the front of the optical system. Calibration disk has 5 work positions: Earth diaphragm, radiometric calibration diffuser plate (main), radiometric calibration diffuser plate (backup), spectral calibration diffuser plate and shade position (see Fig. 1).

Radiometric calibration diffuser plate is made of Teflon, and spectral calibration diffuser plate is made of rare earth doped Teflon. From 400 to 950 nm, the reflectance of radiometric calibration diffuser plate is steady and high reflectance (95%). And the spectral calibration diffuser plate has 6 absorption peaks: 407.7, 451.9, 489.3, 521.4, 653.7 and 798.6 nm (see Fig. 2).

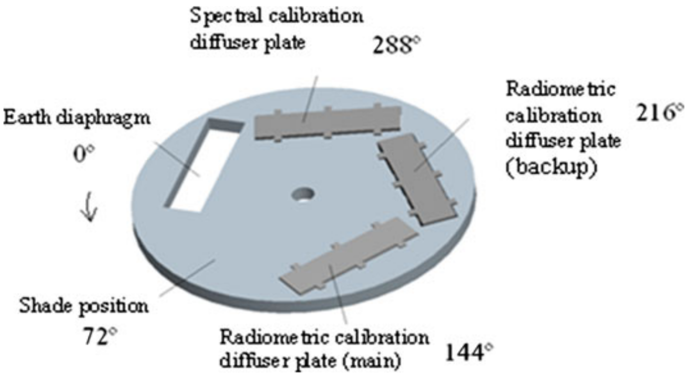
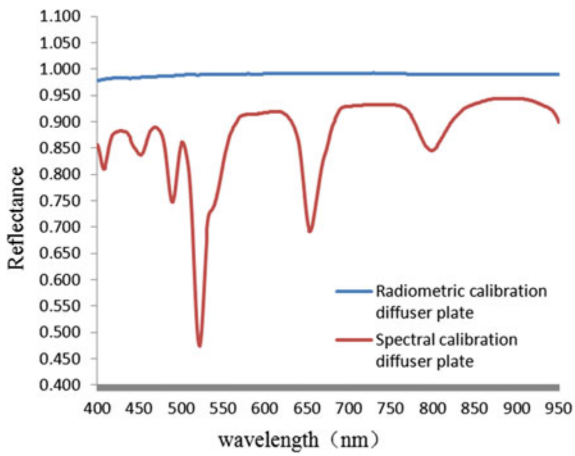


Fig. 1 Five positions of the calibration disk

Fig. 2 Reflectance of radiometric calibration diffuser plate and spectral calibration diffuser plate



2.2 *Procedure of On-Board Spectral Calibration*

Three methods, rare earth doped diffuser plate, Fraunhofer lines and oxygen A-band, are chosen to achieve on-board spectral calibration by CMERIS.

(a) Rare earth doped diffuser plate
When sunlight enters the solar window, turns the calibration disk to radiometric calibration diffuser plate position and gets the first frame of data. Then, turn the calibration disk to spectral calibration diffuser plate position and get the second frame of data. The corresponding relation between the number of pixels and absorption peaks by contrasting the two frames of data near absorption peaks of spectral calibration diffuser plate can be perceived. The last step, calculate the spectral calibration equation using regression analysis.

(b) Fraunhofer lines When sunlight enters the solar window, turns the calibration disk to radiometric calibration diffuser plate position and acquires data. The corresponding relation between the number of pixels and Fraunhofer absorption lines (486.13, 589.00, 656.28, 854.21 and 866.22 nm) through data processing can be perceived. Then, calculate the spectral calibration equation with regression analysis.

(c) Oxygen A-band When the ground images enter the Earth window turn the calibration disk to Earth diaphragm position and receive data. The corresponding relation between the number of pixels and Oxygen A-band (near 760 nm) can be accurately acquired by peak searching.

2.3 Uncertainty Analysis of On-Board Spectral Calibration

The influence factors of calibration precision can be found through analysing the process of on-board spectral calibration. The influence factors include: (a) the uncertainty of absorption peak positions got by ground calibration as σ_a; (b) the uncertainty of wavelength positions which induced by the temperature changing on board as σ_b; (c) the shift of wavelength positions on focal plane which induced by the temperature changing on board as σ_c; (d) the uncertainty of peak searching as σ_d; (e) the uncertainty of regression analysis as σ_e.

Table 1 shows the estimate of every influencing factor. The uncertainty σ of on-board spectral calibration can be calculated by Eq. (1).

By Eq. (1), the uncertainty of on-board spectral calibration is ±0.60 nm, which satisfies the spectral calibration requirement of 1 nm wavelength accuracy.

$$\sigma = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \sigma_d^2 + \sigma_e^2} \quad (1)$$

3 The Ground Simulation

The ground simulation of rare earth doped diffuser plate is been conducted during our experiment. The light of solar simulator enters the solar window with the same angle of on-board spectral calibration (see Fig. 3). First, turn the calibration disk to shade position and record the data of every pixel on CCD as D_{ij}, which is dark current. Second, turn the calibration disk to spectral calibration diffuser plate position and record the data A_{ij}. Then, turn the calibration disk to radiometric

Table 1 Uncertainty of on-board spectral calibration

Influence factor	σ_a	σ_b	σ_c	σ_d	σ_e
Uncertainty (nm)	0.45	0.10	0.04	0.33	0.19

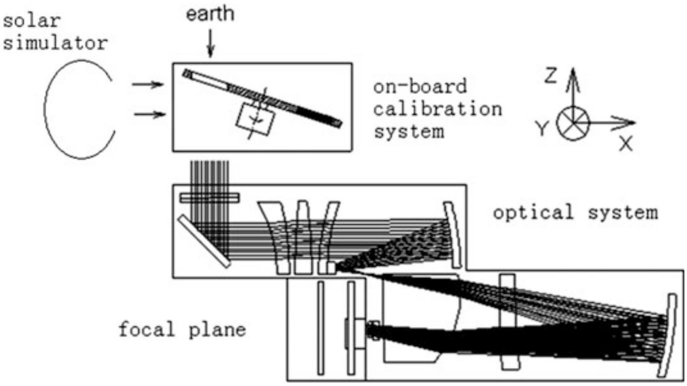


Fig. 3 Ground simulation of rare earth doped diffuser plate

calibration diffuser plate position and record the data B_{ij}. Processing the data as Eq. (2), the ratio C_{ij} of spectral calibration diffuser plate and radiometric calibration diffuser plate without noise can be calculated.

$$C_{ij} = \frac{A_{ij} - D_{ij}}{B_{ij} - D_{ij}} \tag{2}$$

i is the number of row meaning the number of pixels in spectral dimension; j is the number of array meaning the number of pixels in spatial dimension.

Make $j = 500$, the corresponding relation of C_{ij} and the number of pixels in spectral dimension at central field (see Fig. 4) can be perceived, which is demonstrated in Fig. 4, the 6 absorption peaks of spectral calibration diffuser plate is obvious.

For every spatial dimension ($1 < j < 1024$), repeatedly matching the peak wavelengths to the number of pixels by peak searching at the 6 absorption peak positions and using the regression analysis to the data groups of the peak wavelengths and the number of pixels by least squares method, the spectral calibration equation of CMERIS can be calculated.

Gaussian fitting is chosen to search the peaks. Equation (3) is Gaussian function.

$$S_j(X) = K \exp\left[\frac{1}{2}\left(\frac{X - X_j}{\sigma_j}\right)^2\right] \tag{3}$$

X is the number of continuous pixels near one absorption peak at array j; S_j is the unitary result of X; K, X_j and σ_j are solved-for parameters expressing as peak value, peak position and peak width of Gaussian curve.

We can get the data groups of peak positions and peak wavelengths [X_{ij}, Y_{ij}] of the absorption peaks S_j by peak searching. In the data groups, X_{ij} is the pixel number of absorption peak, and Y_{ij} is the peak wavelength of absorption peak.

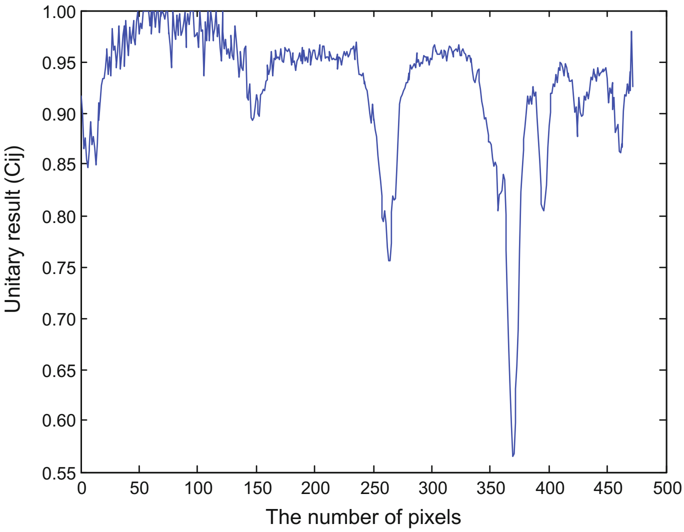


Fig. 4 Unitary result at central field

Table 2 Absorption peaks of spectral calibration diffuser plate and the number of pixels at central field

Peak wavelengths (nm)	407.7	451.9	489.3	521.4	653.7	798.6
Number of pixel	460.641	425.517	395.216	369.610	262.659	147.291

Make j = 500, to get the absorption peaks of spectral calibration diffuser plate and the number of pixels at central field (see Table 2).

Due to the low sample points towards the longer wavelength, the precision of spectral calibration equation may not meet the requirement standard at longer wavelengths. Thus, the ground simulation of Oxygen A-band and Fraunhofer lines is introduced as supplements.

At the ground simulation of Oxygen A-band and Fraunhofer lines experiments, the data is acquired when sunlight enter the solar window with the specific radiometric calibration diffuser plate position being conducted for the calibration disk. The corresponding relationship between the number of pixels and Oxygen A-band (760.0 nm) and Fraunhofer absorption lines (486.13, 589.00, 656.28, 854.21 and 866.22 nm) through data processing can be perceived (see Table 3). Since the bandwidth of Fraunhofer lines is narrow that the precision can only reach half pixel.

The model of spectral calibration equation is built by polynomial fitting as Eq. (4). Least squares method is chosen to make regression analysis to the data groups of Tables 2 and 3 as Eq. (5).

Table 3 Oxygen A-band, Fraunhofer lines and the number of pixels at central field

Peak wavelengths (nm)	760.0	486.13	589.00	656.28	854.21	866.22
Number of pixel	177.729	398.0	315.5	261.0	102.0	92.5

$$Y_{ij} = a_{0j} + a_{1j}X_{ij} + a_{2j}X_{ij}^2 + \cdots + a_{nj}X_{ij}^n \quad (4)$$

$$\begin{pmatrix} N & \sum_{i=1}^{N} X_{ij} & \cdots & \sum_{i=1}^{N} X_{ij}^k & \cdots & \sum_{i=1}^{N} X_{ij}^n \\ \sum_{i=1}^{N} X_{ij} & \sum_{i=1}^{N} X_{ij}^2 & \cdots & \sum_{i=1}^{N} X_{ij}^{k+1} & \cdots & \sum_{i=1}^{N} X_{ij}^{n+1} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \sum_{i=1}^{N} X_{ij}^k & \sum_{i=1}^{N} X_{ij}^{k+1} & \cdots & \sum_{i=1}^{N} X_{ij}^{2k} & \cdots & \sum_{i=1}^{N} X_{ij}^{n+k} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \sum_{i=1}^{N} X_{ij}^n & \sum_{i=1}^{N} X_{ij}^{n+1} & \cdots & \sum_{i=1}^{N} X_{ij}^{n+k} & \cdots & \sum_{i=1}^{N} X_{ij}^{2n} \end{pmatrix} \begin{pmatrix} a_{0j} \\ a_{1j} \\ \vdots \\ a_{kj} \\ \vdots \\ a_{nj} \end{pmatrix} = \begin{pmatrix} \sum_{i=1}^{N} Y_{ij} \\ \sum_{i=1}^{N} X_{ij}Y_{ij} \\ \vdots \\ \sum_{i=1}^{N} X_{ij}^k Y_{ij} \\ \vdots \\ \sum_{i=1}^{N} X_{ij}^n Y_{ij} \end{pmatrix} \quad (5)$$

a_{ij} (i = 0, 1, ..., n) are the coefficients of spectral calibration equation; N is the number of absorption peaks and N = 12 in this equation.

Table 4 shows spectral wavelengths of different polynomial fitting at the same pixel number. The difference of results can be neglected when the degree of polynomial reaches 3. Make n = 3, we can get the spectral calibration equation at central field as Eq. (6) and Fig. 5.

$$Y_{500} = 982.216 - 1.257X_{500} + 4.740 \times 10^{-5}X_{500}^2 - 5.526 \times 10^{-8}X_{500}^3 \quad (6)$$

Y is the value of wavelength; X is the row number of pixel, from 1 to 472; subscript 500 expresses the 500th array of spatial dimension corresponding to central field.

Table 4 Spectral wavelengths of different polynomial fit at central field

Degree of polynomial	Number of pixel (nm)						
	150	200	250	300	350	400	450
1	794.634	732.396	670.157	607.919	545.680	483.442	421.204
2	794.631	732.375	670.128	607.891	545.663	483.444	421.235
3	794.557	732.285	670.084	607.913	545.730	483.495	421.164
4	794.527	732.264	670.069	607.924	545.701	483.451	421.148

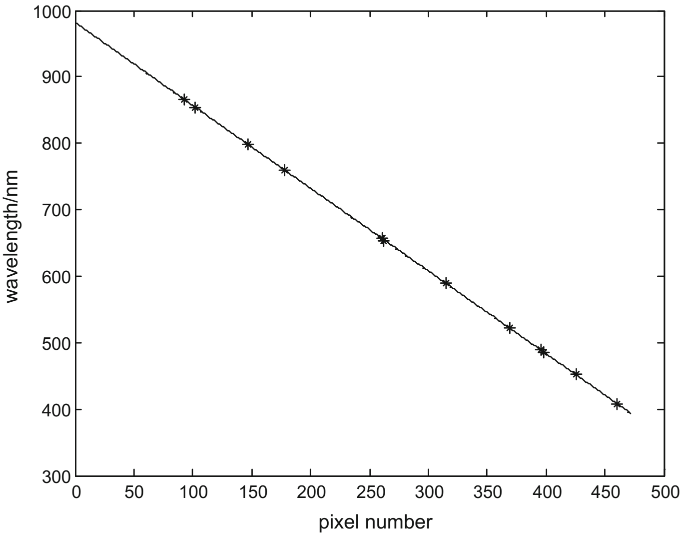


Fig. 5 Spectral calibration result at central field

Table 5 Comparison result of the mercury lamp standard lines at central field

Number of pixel	Standard lines of mercury lamp (nm)	Calibration wavelength (nm)	Error (nm)
463.325	404.66	404.532	0.128
437.927	435.84	436.225	0.385
349.420	546.07	546.452	0.382
324.387	576.96	577.488	0.528

Table 6 Comparison result of the filter wavelengths at central field

Number of pixel	Filter wavelengths (nm)	Calibration wavelength (nm)	Error (nm)
430.131	445.6	445.947	0.347
357.448	536.0	536.464	0.464
318.263	535.4	535.204	0.196
246.967	673.6	673.356	0.256
194.011	739.5	739.740	0.240
139.767	807.4	807.315	0.085
88.996	870.6	870.691	0.091

4 Verification of Precision

At the wavelength range from 400 to 950 nm, 4 standard lines of mercury lamp and 7 filter wavelengths are chosen to verify the precision of spectral calibration equation. The most error is less than 0.6 nm at central field (see Tables 5 and 6).

5 Conclusion

Considering the mission requirements and characteristics of CMERIS, rare earth doped diffuser plate combining the Fraunhofer absorption lines and oxygen A-band are chosen to achieve the on-board spectral calibration. From the ground simulation, the equation of spectral calibration was calculated. And, the precision of ground simulation was verified by the standard lines of mercury lamp and the filter wavelengths experiments, which has proved that this method satisfies the spectral calibration requirement of 1 nm wavelength accuracy. Furthermore, this ground simulation also validated the feasibility of rare earth doped diffuser plate in on-board spectral calibration, which can offer technical reference for follow-up applications.

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