Online nonuniformity correction and simulation for interference infrared spectrometer

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Abstract: Due to the particular structure of interference infrared imaging spectrometer, its online nonuniformity calibration and correction is always a difficult technical problem which has not been solved in engineering. Based on the in-depth analysis of principle and structure to the space-modulated interference infrared imaging spectrometer, an effective method of online nonuniformity calibration and correction was developed for this type spectrometer. The corresponding simulation model for the algorithm was given. The simulation results had shown the correctness and validity of the algorithm, which should make it possible for the on-orbit nonuniformity calibration and correction of spaceborne interference infrared imaging spectrometer.

Key words: space-modulated; interference infrared imaging spectrometer; nonuniformity; online calibration and correction; simulation

CLC number: TN215 **Document code:** A **DOI:** 10.3788/IRLA201645.0604002

红外干涉光谱仪非均匀性在线校正与仿真

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摘　要： 由于红外干涉成像光谱仪结构的特殊性，其非均匀性在线定标与校正是工程上一直没有得到有效解决的技术难题。通过对光谱仪结构的深入分析，对空间调制红外干涉光谱仪研究出了一种有效的非均匀性在线定标与校正方法，并建立了相应的仿真模型，实验结果表明算法是正确的和有效的。研究成果为星载空间调制红外干涉成像光谱仪非均匀性的在轨定标与校正奠定了良好的技术基础。

关键词： 空间调制； 红外干涉成像光谱仪； 非均匀性； 在线定标与校正； 仿真

收稿日期： 2015-10-05； **修订日期：** 2015-11-15

基金项目： 国家自然科学基金(61265006，61271119，61301038)

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0 Introduction

Spaceborne interference infrared imaging spectrometer relies on the carrier of space vehicle to implement the observation of ground targets[1-2]. It acquires the interferogram of each sample point on target by interferometer and gets its spectrum through the Fourier transform by the obtained interferogram[3-4]. The spectrometer identifies the target through the analysis to the target spectrum and has extensive and important applications in military and civilian fields[5-6]. Now it has become one of the hot topics of study in the world[7-8].

The spectrometer gets interferogram through the infrared focal plane array (IRFPA) detector. As the existence of nonuniformity of IRFPA, the interferogram is interfused with IRFPA nonuniformity noise[9-10]. As the recovery spectrum is obtained from the Fourier transform of interferogram and Fourier transform is sensitive to noise, minor noise of interferogram can cause larger error of recovery spectrum[11]. Therefore, the nonuniformity of IRFPA of spectrometer should be corrected effectively to ensure the accuracy of recovery spectrum.

Interferometer is adopted in the light path of interference infrared imaging spectrometer, so even if we do not consider the influence of the nonuniformity of IRFPA, when a uniform radiation is added to the input of spectrometer, the output interferogram of IRFPA is an intermittently bright and dark nonuniform signal because of the influence of interferometer. Hence, for the nonuniformity correction of interference infrared imaging spectrometer, usually a separate calibration of IRFPA should be done to obtain the calibration data before the spectrometer system's assembly, and then the nonuinformity of interferogram will be corrected by using the obtained calibration data in the subsequent spectrometer data processing system[11]. This calibration method not only can introduce noise easily, but also make it impossible to realize the IRFPA nonuniformity calibration again after the spectrometer is assembled. So to improve the correction accuracy of IRFPA, the method of online nonuniformity calibration and correction of interference infrared imaging spectrometer is needed.

In addition, the working environments for spaceborne spectrometer in space are quite different from that in ground. The working point of IRFPA of spectrometer usually experiences a degree of temperature drift because of the change of working environments. So it is bound to produce a larger deviation using the calibration data obtained before in ground to correct the nonuniformity of interferogram acquired by IRFPA with working point being drifted in the space, which will lead to a decline of precision of recovery spectrum. Hence to actualize the on-orbit nonuniformity calibration of IRFPA of spaceborne spectrometer, the method of online nonuniformity calibration and correction of interference infrared imaging spectrometer is required.

Based on the profound analysis to the principle and structure of space-modulated spectrometers, an effective method of online nonuniformity calibration and correction for this type spectrometer was studied out after the spectrometer assembly being completed. The simulation model for the method was presented and the simulation results had proved the correctness and validity of the method.

1 IRFPA nonuniformity correction of spectrometer

1.1 Nonuniformity radiation calibration method for IRFPA of spectrometer

Normally, the basic principle of radiation calibration of IRFPA nonuniformity for interference infrared imaging spectrometer is shown in Fig.1, which is used to acquire the IRFPA nonuniformity information before the spectrometer is assembled by a separate nonuniformity calibration to IRFPA. In this case, a uniform radiation source being used to illuminate the IRFPA directly, in the dynamic response range of IRFPA, the output images of IRFPA under different illuminating uniform radiation are acquired through the A/D, which are called as calibration images. Then these calibration images are used to correct the nonuniformity of interferogram of spectrometer after the completion of spectrometer assembly.

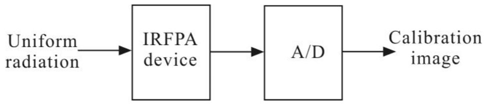


Fig.1 IRFPA radiation calibration principle

As seen from Fig.1, the fundamental of the IRFPA radiation calibration is to make the radiation irradiated to the detector directly as uniform, so that the calibration data with the nonuniformity information of IRFPA device can be obtained at the output of the detector.

Due to the lack of optical system support, this calibration method as shown in Fig.1 is easy to introduce noise of unequal distribution of light into the calibration images and makes the calibration data processing very complicated[12].

Figure2 is the basic principle of interference infrared imaging spectrometer. First, the target's infrared radiation is injected into the interferometer system through the optical system, then the interferometer system exports the target's interferograms, and the target's interferograms are imaged in IRFPA detector and converted to digital interference image by A/D, and then the digital interference image is transmitted into the spectrometer data processing system, finally the target′s spectrum information is obtained through the spectrum recovery algorithm by the digital interference image in the spectrometer data processing system.

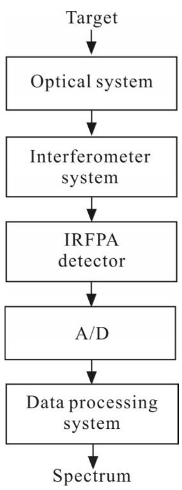


Fig.2 Interference imaging spectrometer principle

As seen from Fig.2, due to the influence of interferometer, even if the input of spectrometer is a uniform radiation, the incident radiation of IRFPA is a nonuniform interference signal, which makes it impossible for us to perform the online nonuniformity calibration of IRFPA after the completion of spectrometer assembly.

Also, as shown in Fig.2, if we can find a way to make the incident radiation to the IRFPA being uniform (or a locally uniform) when the input of spectrometer is a uniform radiation, we can make the online spectrometer nonuniformity calibration after the spectrometer assembly be finished. This way of calibration can not only correct the nonuniformity of IRFPA, but also correct the other nonuniformities introduced by optical system and circuit system etc., and can calibrate the spectrometer repeatedly, and thus make it possible for people to realize the on-orbit nonuniformity calibration to the spaceborne interference infrared imaging spectrometer.

The calibration images can be used to estimate the magnitude of IRFPA nonuniformity. Assuming IRFPA is an $M\times N$ array, $S_{ij}(\varphi)(i=1, 2, \cdots, M; j=1, 2, \cdots, N)$ is the calibration image under a uniform irradiance φ, then the nonuniformity of IRFPA can be estimated as follows[13]:

$$U=\frac{1}{\bar{S}}\sqrt{\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}[S_{ij}(\varphi)-\bar{S}]^2} \tag{1}$$

Where

$$\bar{S}=\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}S_{ij}(\varphi) \tag{2}$$

The nonuniformity of IRFPA is obtained by the actual measurement to IRFPA; its magnitude is related to the measuring conditions.

1.2 IRFPA nonuniformity correction method for spectrometer

Upon scaling to the IRFPA nonuniformity of spectrometer, using the obtained calibration image data, the output interference image at the spectrometer normal working time can be corrected to get rid of the nonuniformity noise. According to the number of calibration images, there are mainly two types of IRFPA nonuniformity correction algorithms such as two-point correction algorithm and multipoint correction algorithm based on radiation source scaling mode[13-14]. The two-point correction algorithm is suitable for the IRFPA of higher linear response characteristics with the advantage of fast calculation speed. And the multipoint correction algorithm is suitable for the IRFPA of nonlinear response characteristics with the specialties of high correction accuracy and large amount of calculation. At present, due to the progress of technology, the response linearity of IRFPA is above 95% , and so the two-point correction algorithm is mainly adopted to correct the nouniformity of spectrometer on engineering.

Assuming that under two different uniform radiation φ_1 and φ_2, the two calibration images outputted by spectrometer are $S_{ij}(\varphi_1)$ and $S_{ij}(\varphi_2)$ ($i=1, 2, \cdots, M; j=1, 2, \cdots, N$) respectively. Now calculating the average on them respectively, we have:

$$\bar{S}_1=\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}S_{ij}(\varphi_1) \tag{3}$$

$$\bar{S}_2=\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}S_{ij}(\varphi_2) \tag{4}$$

Assuming that the output value of the (i, j) detection unit of IRFPA is $S_{ij}(\varphi)$ when the input of the spectrometer is an arbitrary radiation φ, then the correction value $S_{ij}'(\varphi)$ for the (i, j) detection unit of IRFPA is :

$$S_{ij}'(\varphi)=K_{ij}S_{ij}(\varphi)+Q_{ij}(\varphi), {}_{j=1-N}^{i=1-M} \tag{5}$$

Where

$$K_{ij}=\frac{\bar{S}_2-\bar{S}_1}{S_{ij}(\varphi_2)-S_{ij}(\varphi_1)} \tag{6}$$

$$Q_{ij}=\frac{S_{ij}(\varphi_2)\bar{S}_1-S_{ij}(\varphi_1)\bar{S}_2}{S_{ij}(\varphi_2)-S_{ij}(\varphi_1)} \tag{7}$$

If ordering $S'=[S_{ij}'(\varphi)]$, $S=[S_{ij}(\varphi)]$, $K=[K_{ij}]$, $Q=[Q_{ij}]$, the available matrix for correction algorithm can be expressed as:

$$S'=K.*S+Q \tag{8}$$

In the Formula(8), the dot product ".*" means that the matrix K and S is multiplied by corresponding elements respectively.

2 Nonuniformity correction for spectrometer

2.1 Online nonuniformity calibration and correction for space-modulated spectrometer

The typical space-modulated interference imaging spectrometer is joined the Sagnac interferometer in the optical path, whose principle is shown in Fig.3[15]. It is mainly composed of a front telescopic optical system, an incident slit, a Sagnac prism, Fourier lens, cylindrical lens and the array detector etc. Its working principle is that: The scene target is imaged at the incident slit by the front telescopic optical system, the incident slit is set at the front focal plane of the Fourier lens, the emitted light at each point of the incident slit interferes after the light is passed through the Sagnac prism, then the produced interference signal is imaged by the Fourier lens and cylindrical lens on a row of the array detector, so the interference signal generated from different point at the incident slit should be imaged at the different rows of the array detector correspondingly, the target spectral information at the corresponding point of the incident slit could be obtained by the Fourier transformation to the interference signal at the corresponding row of the array detector. Now, if we proceed with the nonuniformity calibration to the spectrometer by using the uniform radiation source, which means using the uniform radiation source as the input signal of the spectrometer, ignoring the influence of noise, then the radiation intensity of each point at the incident slit must be equal, so the interference signals are identical after the light is passed through the interferometer and

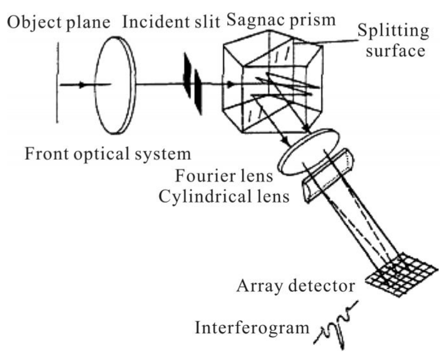


Fig.3 Space-modulated imaging spectrometer

incident to the corresponding rows of the array detector. That is to say, the input signals of all detection units along each column of the array detector are the same, this is equivalent to proceed the nonuniformity calibration for each column of the IRFPA detection with a uniform radiation source. Therefore the nonuniformity correction to the space-modulated imaging spectrometer can be processed firstly to acquire the calibration coefficient matrix by along the column of the calibration images and secondly to make the nonuniformity correction to the interference image outputted during the normal work of the spectrometer by using the two-point correction algorithm.

The detailed steps are as follows:

(1) Use the uniform radiation source as the input signal of the space-modulated interference infrared imaging spectrometer, which is called as the calibration source of spectrometer;

(2) Adjust the light radiation intensity of the calibration source, collect at least two frames of calibration images outputted by the imaging spectrometer under each different uniform irradiation;

(3) Using the each corresponding column data of two calibration images, according to the two-point correction algorithm, each column of the calibration images will be treated as a whole for calculating the corresponding correction coefficients of each column pixels;

(4) The correction coefficients of each column image pixels will be joined together into a complete correction coefficient matrix, and then by using the two-point correction algorithm, the nonuniformity correction could be performed to the output interference image of the interferometer at its normal work time.

2.2 On-orbit nonuniformity calibration and correction for spaceborne spectrometer

On the basis of front research, the on-orbit nonuniformity calibration and correction for the spaceborne space-modulated interference infrared imaging spectrometer can be done as follows:

(1) Close the camera lens cover of spaceborne spectrometer and collect a dark current image of IRFPA as the first frame of calibration image;

(2) Open the camera lens cover, adjust the camera to direction of uniform space and capture an image as the second frame of calibration image.

(3) Suppose the interferogram is line-by-line imaged on the IRFPA detector, the correction coefficient sub-matrixes for each column of the IRFPA can be obtained with the two calibration images according to the Formula (6) and (7).

(4) Join the correction coefficient sub-matrixes into a complete correction coefficient matrix K and Q.

(5) Use the Formula (8) to correct the nonuniformity of interferogram of spectrometer at normal working time.

3 Simulation

3.1 Establishment of simulation model

According to what we have mentioned above, the nonuniformity correction simulation model for the space-modulated interference infrared imaging spectrometer is set up as shown in Fig.4.

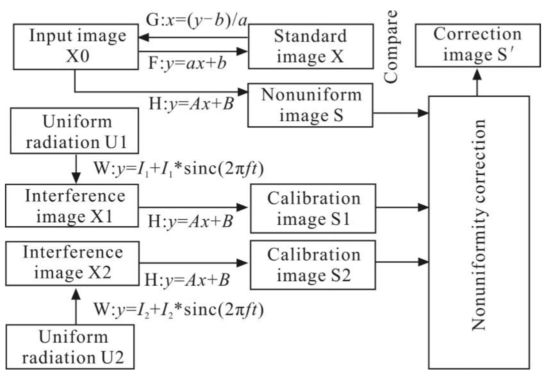


Fig.4 IRFPA nonuniformity correction simulation model

In Fig.4, assuming that the ideal response characteristic of IRFPA is F:$y=ax+b$, its inverse transformation is G:$x=(y-b)/a$. And the nonuniformity response characteristic of IRFPA is H:$y=Ax+B$ (in which $A=a+r_a$*randn(M, N), $B=b+r_b$*randn(M, N)). First of all, the input image X0 of the IRFPA is generated by a standard image X according to the inverse transformation G:$x=(y-b)/a$, then the output nonuniformity image S of IRFPA is generated according to the IRFPA nonuniformity response characteristic model H:$y=Ax+B$; At the same time, the output interference images X1 and X2 of the interferometer are produced by the input of uniform radiation U1 and U2 according to the interferometer response characteristic model W: $y=I_k+I_k*\mathrm{sinc}(2\pi ft)(k=1,2)$. Then according to the IRFPA nonuniformity response model h the IRFPA nonuniformity calibration images S1 and S2 are produced. Finally the pixel correction coefficients of each column of the image are calculated by the calibration image S1 and S2 along each column and are spliced into a complete correction coefficient matrix K and Q. According to the Formula (8) the corrected image S′ is got from the nonuniformity image S.

Comparing to the nonuniformity image S, the corrected image S′ and the standard image X, we can evaluate the correction effect of the algorithm.

Before correction, the nonuniformity of S is:

$$U_a=\frac{1}{\overline{X}}\sqrt{\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}[S_{ij}-X_{ij}]^2} \tag{9}$$

After correction, the nonuniformity of S′ is:

$$U_b=\frac{1}{\overline{X}}\sqrt{\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}[S_{ij}'-X_{ij}]^2} \tag{10}$$

Where

$$\overline{X}=\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}X_{ij} \tag{11}$$

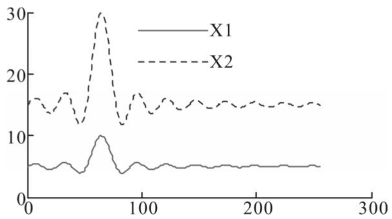
3.2 Simulation results

According to the simulation model above, we select an interference image got early from the spectrometer on FY-xxx meteorological satellite as the standard interference image X to perform the simulation test. The simulation results are shown in Fig.5 and Fig.6.

Fig.5(a) shows the interferogram curves of each line of the two interference images of X1 and X2 which are produced correspondingly by the uniform radiation U1 and U2 as the input signals of spectrometer. Fig.5(b) is the image of interference image X1. Fig.5(c) is the calibration image S1 obtained from the interference image X1. Fig.5(d) is the standard interference image X. Fig.5(e) is the nonuniformity interference image S to be corrected with the nonuniformity of 10.185 3%. Fig.5(f) is the corrected interference image S′ with the nonuniformity of 0.934 68%.

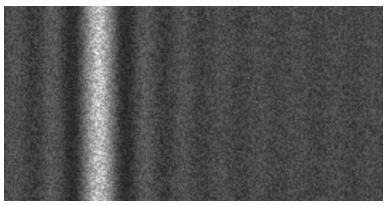
The nonuniformity of the corrected interference image S′ is reduced by 10.897 1 times as compared with that of the interference image S before correction.

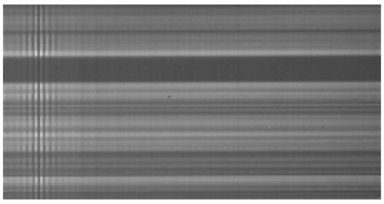
Fig.6(a) is the interferogram of the 100th row of Fig.5(d). Fig.6(b) is the recovery spectrum of Fig.6(a). Fig.6(c) is the interferogram of the 100th row of Fig.5(e) with relative mean square error of 9.76% compared with Fig.6(a). Fig.6(d) is the recovery spectrum of Fig.6(c) with relative mean square error of 290.95% compared with Fig.6(b). Fig.6(e) is the interferogram of the 100th row of Fig.5(f) with relative mean square error of 0.91% compared with Fig.6(a). Fig.6(f) is the recovery spectrum

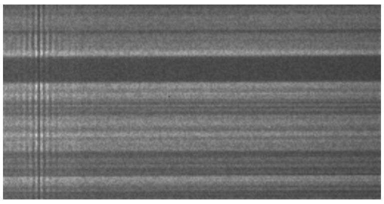


(a) Interferogram X1 and X2


(b) Interference image for X1


(c) Calibration image for S1


(d) Standard image X


(e) Nonuniform image S(10.19%)

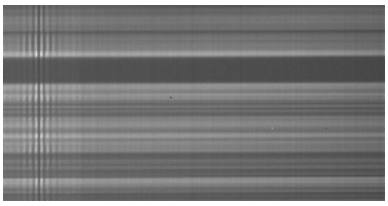
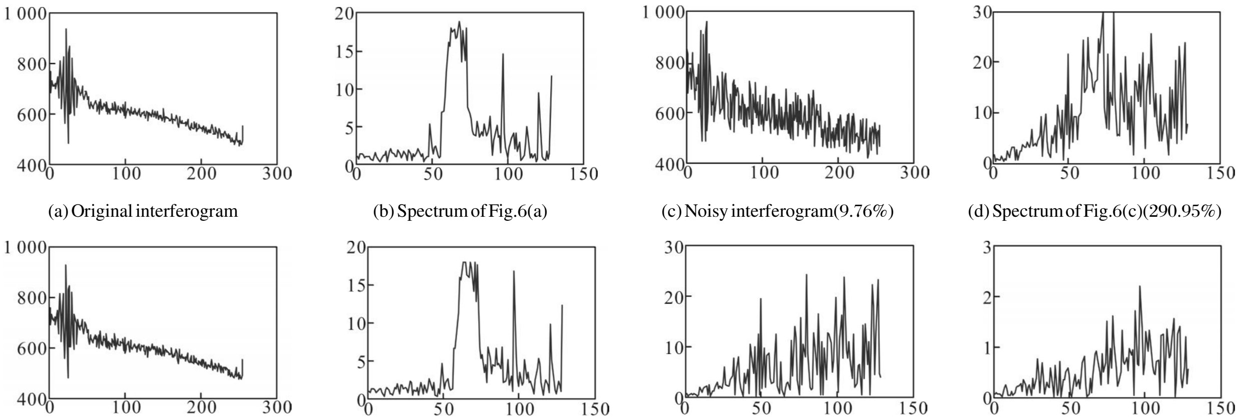

(f) Corrected image S′(0.93%)

Fig.5 Spectrometer nonuniformity correction results



(a) Original interferogram (b) Spectrum of Fig.6(a) (c) Noisy interferogram(9.76%) (d) Spectrum of Fig.6(c)(290.95%)

(e) Corrected interferogram(0.91%) (f) Spectrum of Fig.6(e)(24.1%) (g) Error of Fig.6(d) and Fig.6(b) (h) Error of Fig.6(f) and Fig.6(b)

Fig.6 Interferogram and recovery spectrum

of Fig.6(e) with relative mean square error of 24.1% compared with Fig.6(b). Fig.6(g) is the absolute error between Fig.6(d) and Fig.6(b). Fig.6(h) is the absolute error between Fig.6(f) and Fig.6(b).

Here, to ensure the correctness of the recovery spectrum, the dc component of interferogram must be removed by difference.

As seen from Fig.6, we can reach the conclusion that the nouniformity correction of interferogram can effectively improve the precision of recovery spectrum.

4 Conclusions

(1) Aiming at the space-modulated interference infrared imaging spectrometer, we had worked out an effective method of online nonuniformity calibration and correction to remove the nonuniformity for this type spectrometer.

(2) With advantages such as easy to handle and high precision, the nonuniformity correction method proposed in this paper could perform the online nonuniformity calibration and correction during the spectrometer normal working time.

(3) The effective simulation model of online nonuniformity calibration and correction was given for the space-modulated interference infrared imaging spectrometer. The experimental results had proved the correctness and validity of the algorithm.

(4) The algorithm has made it possible for the on-orbit nonuniformity calibration and correction of the spaceborne interference infrared imaging spectrometer.

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