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Optical design of six-mirror Anastigmat(6MA) off-axis freeform system



Optical Design of Off-axis Six-mirror Anastigmat (6MA) Freeform System with Wide Field of View and Low distortion

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ABSTRACT

There is an urgent need for the imaging spectrometer with high spatial resolution and wide swathing range in the field of environment monitoring, agriculture evaluation and emergency disaster reduction. At the same time, higher request for the performance of spectrometers, such as signal-to-noise, is put forward to realize high-precision data inversion and quantitative detection. A telescope optical system with long focal length, large relative aperture and wide field-of-view is designed using for imaging spectrometer. The focal length is 1200 mm, the relative aperture is 1/3 and the field-of-view is $10^\circ \times 1^\circ$. A new re-imaging off-axis six-mirror anastigmat (6MA) configuration is adopted. It is beneficial to control the stray light and achieve the telecentric design in the image space. A real entrance pupil is located in front of the system to minimize the aperture of scanning mirror. The whole system is divided into two modules and each module can image perfectly at the axial field of view. Therefore, each module can be aligned and tested individually to reduce the alignment difficulty of the whole system. The off-axis freeform surface is used to control the distortion lower than 0.5% and advance the imaging quality. Finally, the manufacture and alignment tolerance are simulated and analyzed. The design and analysis results show that the six-mirror anastigmat (6MA) off-axis freeform system can satisfy the demand of high-performance hyperspectral imaging for earth monitoring. Good imaging quality and loose tolerances indicate that this optical system is of strong engineering application value.

Keywords: imaging spectrometer; 6MA; freeform surface; optical design

1. INTRODUCTION

Imaging spectrometer is a new type of optical remote sensing instrument which combines imaging technology with spectral technology. It can collect the spatial information, radiation information and spectral information of the target at the same time to form an integration data cube. It has important application value in the fields of atmosphere, land, ocean, agriculture and forestry, emergency disaster reduction and mineral resources investigation.

Typical spaceborne imaging spectrometers include Hyperion [1], COIS [2] and HypSI [3] et al. The spatial resolution of Hyperion and COIS is 30m, the spectral resolution is 10nm and the swathing width is 7.5km and 30km respectively. The spatial resolution of HypSI is 60m, the spectral resolution is 10nm and the swathing width is 150km. China has also developed the earth sensing imaging spectrometers carried on Tiangong-1[4], HJ-1A/B [5] and GF-5 satellites. The spatial resolution of the visible and shortwave infrared spectrometer on GF-5 satellite is 30m, the spectral resolution is 5nm and 10nm in the visible and shortwave infrared band respectively and the swathing width is over 60km [6].

At present, the spectral resolution of spaceborne imaging spectrometers is generally 5nm ~10nm, and the spatial resolution is ranged from 30m to 60m. However, the swathing width is quite different, which the minimum swathing width is only 7.5km and the maximum swathing width is 150km. Ecological environment monitoring, land resources and geological survey and other application fields often require high temporal resolution of remote sensor, which usually requires the swathing width could be greater than 100km. And the requirements of spatial resolution and spectral resolution are also higher and higher at the meantime. Current spectral data is hard to satisfy the application demand.

Therefore, in order to meet the urgent needs of high-performance imaging spectrometer, a telescope optical system with large field of view and large relative aperture is proposed in this paper. The working spectral range covers $0.4\mu\text{m} \sim 2.5\mu\text{m}$, the field of view is $10^\circ \times 1^\circ$ and the relative aperture is 1/3. The spatial resolution can reach 14.1m at the orbit of 705km, and the swathing width is over 120km. According to technical index requirement and imaging characters, the off-axis six-mirror optical system scheme is adopted. And the freeform surface is used to improve the imaging performance and reduce the distortion. Finally, the manufacture and alignment tolerances of the optical system are analyzed.

2. DESIGN REQUIREMENTS

The spectrum of the telescope ranges from 0.4 μm to 2.5 μm and is divided into two imaging channels of 0.4 μm ~1.0 μm (VNIR) and 1.0 μm ~2.5 μm (SWIR). The detectors used in two channels are both the high frame rate devices. The pixel size of two detectors is 24 μm \times 24 μm . The focal length of the optical system can be determined according to the pixel size, spatial resolution and orbit height. These parameters have the following relationship:

$$f' = \frac{d \times H}{G_{SD}} \quad (1)$$

Where f' is the focal length, d is the pixel size, H is the orbit height and G_{SD} is the ground space distance. When d is equal 24 μm , H is equal 705km and G_{SD} is equal 14.1m, we can get the f' is equal 1200mm.

The field of view can be calculated according to the orbit height and swathing width:

$$2\omega = 2\arctan\left(\frac{I_s/2}{H}\right) \quad (2)$$

Where ω is the half of the field of view, I_s is the swathing width. When I_s is equal to 120km and H is equal to 705km, we can get the field of view is 9.73 $^\circ$ and take 10 $^\circ$ to design the optical system.

The relative aperture of the optical system has a great influence on the signal-to-noise ratio (SNR) and the optical modulation transfer function (MTF). And it also determines the volume and engineering difficulty of the optical system. By comprehensively analyzing the requirements of the visible, near-infrared and the shortwave infrared spectrum on the SNR and the MTF, the relative aperture of the optical system is selected as 1/3. The MTF of diffraction limit is over 0.8@20.8lp/mm in all spectral bands. The signal-to-noise ratio of VNIR spectrum is greater than 200, and the signal-to-noise ratio of the SWIR spectrum is greater than 100.

In order to further improve the signal-to-noise ratio of the spectrometer, the scanning mirror is added in front of the system to compensate the integral time. The scanning angle is $\pm 7.3^\circ$ for the benefit of wider imaging area. The main technical parameters of the telescope optical system are summarized in Table 1.

Table.1 Technical parameters of optical system

Technical parameters	Values
Spectral band/ μm	0.4~1.0、 1.0~2.5
Field of view/ $^\circ$	10 \times 1
Focal length/mm	1200
Relative aperture	1/3
Scanning angle/ $^\circ$	± 7.3

3. DESIGN SCHEME AND ANALYSIS

According to the technical parameters of the telescope optical system, several key issues should be considered in choosing optical system configuration and design process:

(1) Long imaging size

The optical system has long focal length and large field of view. So, the length of image plane is up to 210mm and is much larger than the image length of the known imaging spectrometer currently in orbit and under development. The optical system structure with strong ability to suppress the off-axis aberration should be selected.

(2) High scanning accuracy

In order to improve the control accuracy of the scanning mirror, the aperture of the scanning mirror should be reduced as much as possible. When the scanning mirror is located near the entrance pupil of the system, it has the smallest aperture. Therefore, the optical system structure with the entrance pupil in front of the system should be considered.

(3) Good telecentricity in the image space

The spectral imaging system of the earth imaging spectrometer usually adopts the Offner structure. In order to match with the Offner spectral imaging system, the telescope optical system should have good telecentricity in the image space.

(4) Lower straylight

Compared with panchromatic and multispectral imaging systems, stray light has a more serious impact on hyperspectral imaging systems. Therefore, the telescope optical system used in the imaging spectrometer should strictly control the straylight. The intermediate image plane is an important way to suppress the stray light of the optical system. Therefore, the re-imaging configuration with the intermediate image plane will be a better choice.

Considering the technical requirements and imaging characteristics of the optical system, the optical system in this paper adopts the design scheme as shown in Figure 1 below. The optical system has the intermediate image to suppress the stray light of the optical system effectively. The aperture stop is located in front of the primary mirror and is close to scanning mirror to reduce its size. The overall system is divided into two imaging modules by the intermediate image plane. The VNIR spectrum and SWIR spectrum share a set of optical system to realize the integrated design, and the two spectrums are separated through a certain field of view interval in Y direction to image respectively.

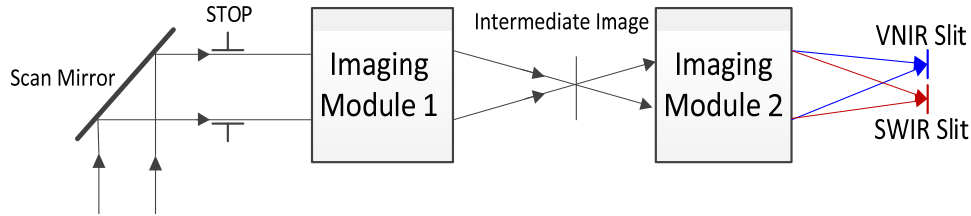


Fig.1 Scheme of optical system design

4. OPTICAL SYSTEM DESIGN

4.1 Design result of the whole system

According to the optical system design scheme, the optical system finally adopts a novel off-axis six-mirror configuration, which has good off-axis aberration correction ability and can realize the telecentric design. The whole optical system is divided into two imaging modules. Each imaging module contains three off-axis mirrors and the intermediate image plane is located between the two modules. The aperture stop is located in front of the primary mirror, and the scanning mirror is placed close to the aperture. After the design, the optical system layout is shown in Figure 2 below. The fourth mirror is a Zernike fringe polynomial freeform surface. Compared with spherical and aspheric surfaces, the freeform surface can advance the image performance, especially reduce the distortion.

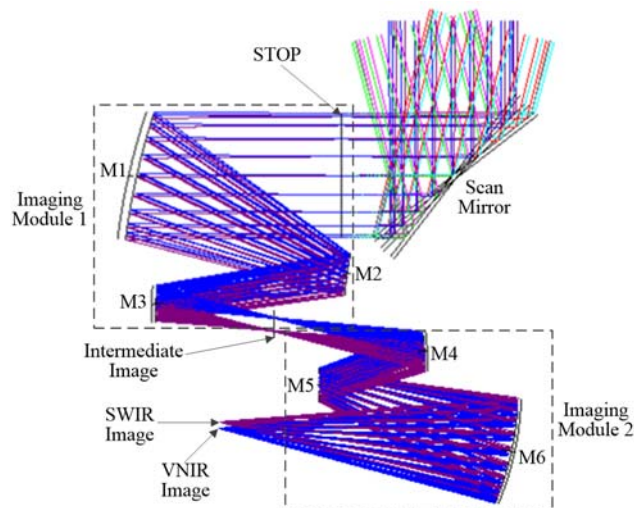


Fig.2 Schematic of off-axis six-mirror anastigmat (6MA) freeform system

The MTF curves of the whole optical system in VNIR and SWIR spectrums are shown in Figure 3 below. The minimum MTF value of different field of view is better than 0.87 and 0.76 in VNIR and SWIR spectrum respectively.

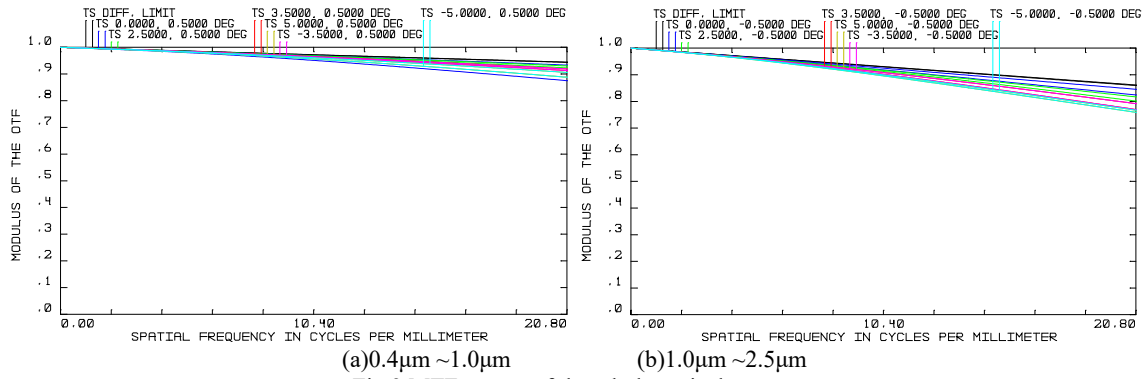


Fig.3 MTF curves of the whole optical system

The spot diagram in VNIR and SWIR spectrums is shown in Figure 4. The RMS radius is small than 1/3 pixel ($8\mu\text{m}$), which can satisfy the imaging requirement.

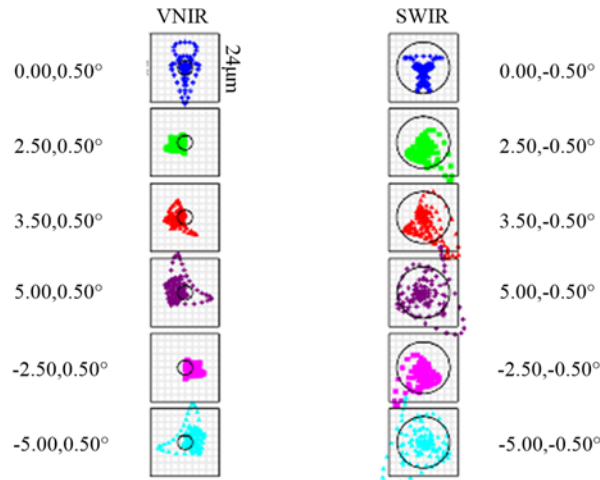


Fig.4 Spot diagrams of the whole optical system

The grid distortion is shown in Figure 5. The maximum relative distortion is below 0.4% within $10^\circ \times 1^\circ$ field of view. The low distortion is benefit for the remote sensing data processing and quick application.

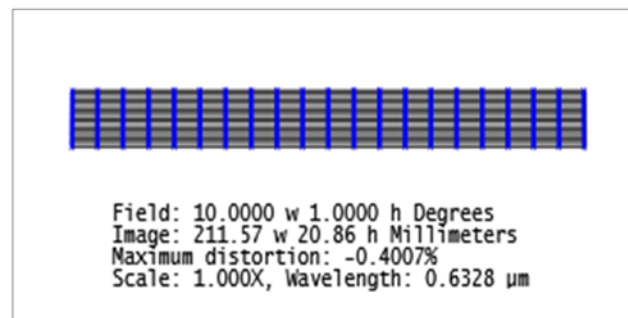


Fig.5 Grid distortion of the whole optical system

4.2 Design result of each imaging module

The more the number of optical elements there are, the greater the difficulty of the installation and adjustment of the optical system is. The off-axial system is more difficult than the coaxial system because the off-axial optical elements have more degree of freedom. In order to reduce the overall alignment difficulty of the off-axis six-mirror freeform system, not only the overall system can meet the design requirements, but also each of the two imaging modules has a certain degree of perfect imaging. Therefore, the assembly and test evaluation of the single imaging module can be carried out firstly, and

then the two imaging modules can be combined to ensure the feasibility of the complex off-axis optical system and improve the alignment effect.

The independent optical system layout of imaging module is shown in Figure 6.

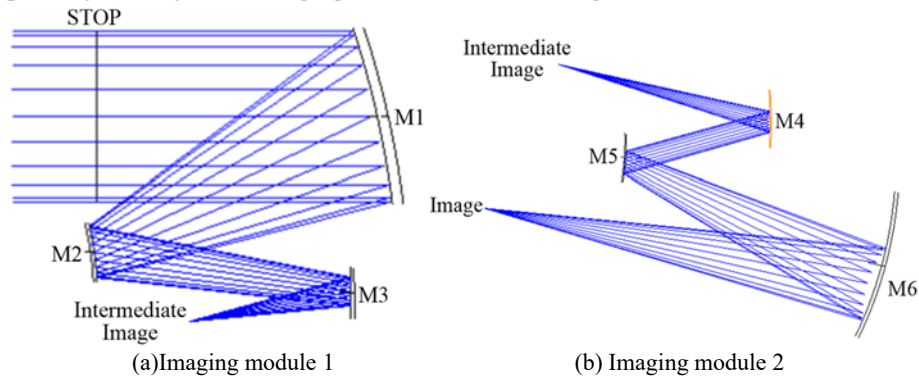


Fig.6 Schematic of two optical system imaging modules

The MTF curves of the two imaging modules are shown in Figure 7 below. The MTF can reach the diffraction limit at the 0° field of view, which benefit the alignment and evaluation.

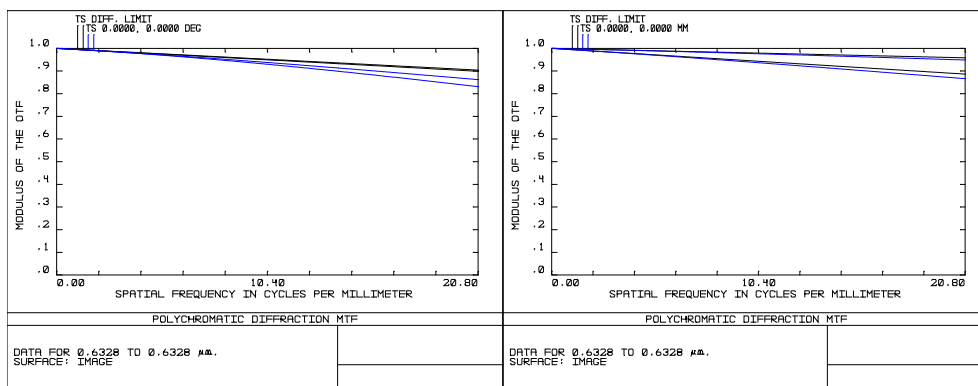


Fig.7 MTF curves of two optical system imaging modules

The wavefront map of the single imaging module is shown in Figure 8. The RMS wavefront error of the imaging module 1 is 0.11λ ($\lambda=0.6328\mu\text{m}$) and the RMS wavefront error of the imaging module 2 is 0.108λ ($\lambda=0.6328\mu\text{m}$), which can be evaluated by the interferometer.

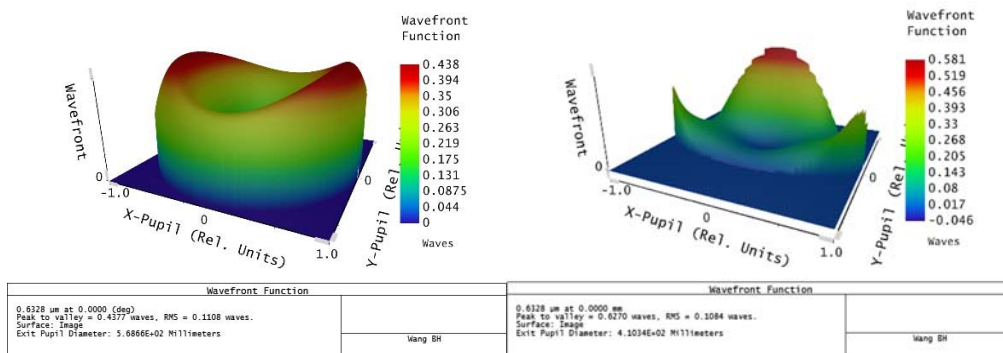


Fig.8 Wavefront error of two optical system imaging modules

5. TOLERANCE ANALYSIS

The optical system tolerances are analyzed to give the manufacture and alignment requirements. The back focal length and distance between two imaging modules are taken as the compensators. 500 Monte Carlo cycles are run and the statistics are given in Fig. 9. The average MTF values can be over 0.735 and 0.647 at the Nyquist frequency in the VNIR and SWIR spectrum respectively, which can also meet the specification.

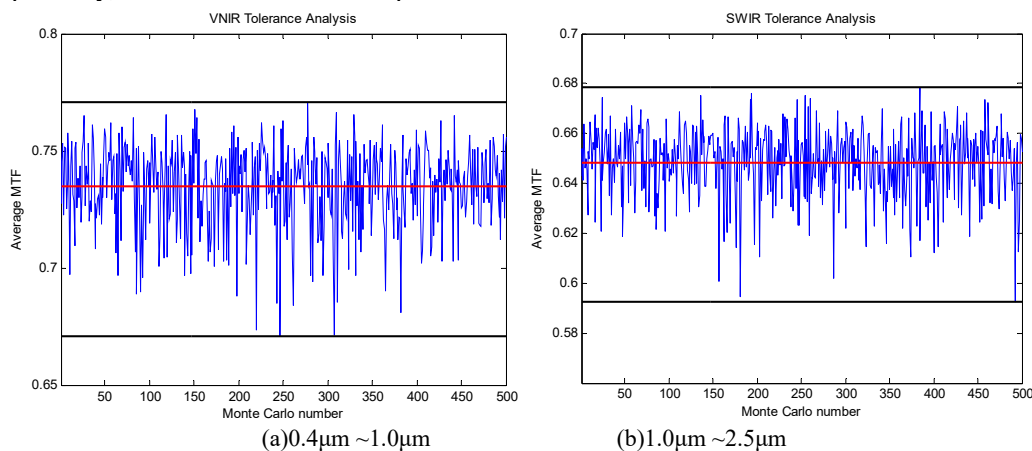


Fig.9 The tolerance analysis result of the whole optical system

6. CONCLUSION

Aiming at the deficiency of spatial resolution and swathing width of imaging spectrometer in orbit and under development and combining with the application requirements in different fields, a telescope optical system with large field of view and large relative aperture is designed. The working spectrum covers $0.4\mu\text{m} \sim 2.5\mu\text{m}$, the focal length is 1200mm, the relative aperture is 1/3, and the field of view angle is $10^\circ \times 1.0^\circ$. The spatial resolution can achieve 14.1m and swathing width is over 120 km at 705km orbit altitude. A new type of off-axis six-mirror optical system configuration is proposed, which has the advantages of small scanning mirror size, high stray light suppression and good image telecentricity. The imaging quality of the whole optical system is close to the diffraction limit and each imaging module has a certain degree of perfect imaging. The alignment difficulty of the whole system is reduced through the modular assembly and test. The optical system tolerance of manufacture and alignment is loose, which is helpful to improve the engineering feasibility.

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