Optical Design of Improved Offner Imaging Spectrometer

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Abstract. An improved Offner imaging spectrometer was proposed based on the optical system characteristics of Offner imaging spectrometer, which can ensure perfect imaging quality in a wider annular region. The operating wavelength of the improved Offner imaging spectrometer ranges from 900nm to 1700nm, and the magnification is 1. Improved Offner imaging spectrometer can be obtained by changing the meniscus lens position and further optimizing the design. The results indicate that the improved Offner imaging spectrometer can effectively improve compactness and lightweight, and reduce the difficulty of optical adjustment, which is conducive to the stability of practical application.

Keywords. Offner imaging spectrometer; Improved Offner imaging spectrometer; Optical design;

1. Introduction
Dispersion element is the core part of imaging spectrometer. The difference of dispersion element will directly affect the spectral resolution, optical system structure and volume of the whole system, so it is very important to design and select a suitable dispersion element according to the application requirements. At present, the traditional dispersive prism or diffraction grating is often used as the dispersion element, but both will cause imaging defects [1]. The dispersive prism can introduce aberration, non-linear dispersion, which will greatly increase the complexity of later data processing. The diffraction grating has defects such as lower utilization rate of light energy, overlap of different levels of spectrum, optical distortion, especially when the aperture of optical system increases.

In order to improve the imaging quality of spectral imaging system, double Amici prism is commonly used, it can improve the aberration and non-linear dispersion to a certain extent. However, in practical application, double Amici prism must be in the collimating light path, so it is usually used with the collimating lens and imaging lens, which will lead to more complex optical system and not conducive to the compact design of the optical system[2].

In this case, Offner imaging spectrometer is used based on the convex reflective grating to improve the compactness of the system, which based on the convex reflective grating. However, the Offner imaging spectrometer has poor aberration correction capability and can only obtain good spectral imaging quality in a narrow annular region [3, 4]. Therefore, we designed the improving Offner imaging spectrometer, which can expand the range of telecentric beam and obtain good spectral imaging quality in a wider annular region [5].

In this paper, we focus on the optical design of the improved Offner imaging spectrometer operating in 900-1700nm band, which can be used in code aperture snapshot spectral imager (CASSI). It should be pointed out that the designed improved Offner imaging spectrometer can improve system compactness and lightweight on the premise of ensuring perfect imaging quality in a wider annular region where the code aperture of the CASSI can be placed perfectly.
2. Principle
The representative schematic of CASSI is realized by an objective lens, a coded aperture, a collimating lens, a dispersive element, an imaging lens and a focal plane array detector [6]. The schematic of CASSI is shown in figure 1.

![Figure 1. Schematic of CASSI.](image)

The 3D source information is imaged on the plane of the coded aperture by the objective lens. The coded aperture performs a spatial modulation over all wavelengths in the spectral cube of the source information [7, 8]. The spatially modulated light is dispersed by the dispersive element after propagation through the collimating lens. Ultimately multiple 2D intensity images of the code-modulated scene at wavelength-dependent are integrated on the plane of the detector by the imaging lens, as shown in figure 2.

![Figure 2. Data flow chart of CASSI.](image)

In order to improve the transmittance, the compactness, and image quality of the optical system, we designed the improved Offner imaging spectrometer instead of the collimating lens, the dispersive element and the imaging lens. The improved Offner imaging spectrometer can be achieved by adding a concentric meniscus lens on the right of the convex reflection grating to the Offner imaging spectrometer. The Offner imaging spectrometer is shown in figure 3.

![Figure 3. The Offner imaging spectrometer.](image)

Due to the addition of the concentric meniscus lens, the spherical aberration and overall Petzval sum can be decreased [9]. Therefore, in this paper, we propose the improved Offner imaging spectrometer, which can apply in CASSI. Based on the application background analysis, the specific
design parameters are shown in Table 1.

**Table 1.** Specific design parameters of the improved Offner imaging spectrometer.

| Parameters                        | Value                  |
|-----------------------------------|------------------------|
| Wavelength range                  | 900nm–1700 nm          |
| Optical magnification             | 1                      |
| F-number                          | 5                      |
| Spectral resolution               | 20 nm                  |
| Size of code aperture             | 10.24mm*10.24mm        |
| Grating groove density            | 50lp/mm                |
| Spectral smile                    | <half a pixel          |
| Keystone                          | <half a pixel          |

3. Optical Design
The improved Offner imaging spectrometer is designed in the form of telecentricity in object space and image space. Object space telecentricity can ensure a better parameter matching with the objective lens. Image space telecentricity can ensure the chief ray in each field vertically incident on the shortwave infrared detector. Taking into account the code aperture of 20μm microcomponent size with 512×512 microcomponents, we used short-wave infrared focal plane detector of 20μm pixel size with 640×512 pixels considering the number of spectral bands.

Firstly, we used the Offner imaging spectrometer as the initial structure, and then in combination with the constraint conditions: such as telecentricity in object space and image space, the reduction ratio and the object size, to take further optimization. The design result shown in Figure 4.

![Figure 4. The improved Offner imaging spectrometer.](image)

The performance of the improved Offner imaging spectrometer is evaluated by spot diagrams and the modulation transfer function (MTF). Figure 5 shows the MTF curves for the wavelength 1300nm, wavelength 1700nm and wavelength 900nm. The curve indicates that the MTF is greater than 0.7 in each field at the Nyquist frequency of 25lp/mm.
Figure 5. MTF of the improved Offner imaging spectrometer.

The spot diagrams indicate how a dispersed light images on the focal plane and the spots at each wavelength are given in figure 6. Squares represent each pixel of 20µm at each wavelength and the spots in each field are all focused within one pixel.

Figure 6. The spot diagrams of improved Offner imaging spectrometer.

In addition, the values of the spectral smile and the spectral keystone are also an essential measurement index for spectral imaging system. This paper obtains the spectral smile and spectral keystone values of the system via real ray tracing, as shown in table 2. It indicates that the spectral smile in the 900–1700 nm wavelength range are less than 5.9µm. The spectral keystone of the system is less than 7.8µm throughout the entire wavelength band. Hence, the spectral smile and the spectral keystone are less than half a pixel, signifying there is no need for data processing correction.

Table 2. Spectral smile (µm) of the Offner imaging spectrometer with wavelength (λ) and normalized field (ω).

| ω  | λ(nm)  | 900 | 1000 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|----|--------|-----|------|------|------|------|------|------|------|------|
| 0.7| 4.5    | 3.2 | 3.0  | 2.8  | 2.7  | 2.3  | 2.2  | 2.0  | 1.9  |
| 1  | 5.9    | 5.3 | 4.9  | 4.6  | 4.2  | 4.0  | 3.8  | 3.6  | 3.4  |

Finally, we used the MTF tolerance analysis for the central wavelength of 1300nm to analyze the tolerance sensitivity of the optical system as shown in figure 7. It is generally recognized that the tolerance analysis indicates the feasibility of practical application of optical systems. The results show that the MTF of the optical system has a probability of 99% above a value of 0.787 under the default
tolerance allocation conditions. In other words, the optical system meets the requirements for practical application.

![MTF tolerance analysis](image)

**Figure 7.** MTF tolerance analysis of improved Offner imaging spectrometer with central wavelength 1300nm

### 4. Conclusion

In this paper, the improved Offner imaging spectrometer is designed based on Offner imaging spectrometer. Simulation results indicate that the spot sizes at each field are far less than 20μm, the MTFs at each wavelength are all greater than 0.65, and the spectral smile of the system is less than 9μm. In short, the presented design results illustrate that the performance of the improved Offner imaging spectrometer is excellent and meets the practical application requirements, having the advantages of lightweight, good compactness and easy optical adjustment.

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