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Study on imaging spectrometer with smile and keystone eliminated

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ABSTRACT

The formulas of image height in two-dimensional field about Gaussian and tilted imaging system of grating-based imaging spectrometer instrument (GISI) are deduced firstly, and the determined expressions of smile and keystone of GISI are obtained. It is proposed to correct the smile with off-axis lens, and the elimination effect of the smile is studied by means of spatial ray tracing. By controlling the degree of off-axis and the distribution of focal power of the off-axis lens, the long-wave infrared imaging spectrometer with well-eliminated smile and keystone is designed. The maximum of smile and keystone at working wavelengths in all fields of view are less than 8.57 μm and 13.33 μm, respectively.

1. Introduction

Hyperspectral imaging technology has been developed since the 1980s on the basis of the multi-spectral imaging technology, and is now widely applied in various fields such as military, marine and geological exploration. Recently, great attention has been paid to the elimination of the smile and keystone of the hyperspectral imaging system with either Offner structure or Dyson concentric optical configuration [1–7]. For both types, the system with simple construction and low distortion can be optimized, however, the design of the cold aperture is difficult and the refrigeration system is bulky, especially for the Offner structure [8]. With Dyson concentric optical configuration, adopting concave grating, there maybe exist serious ghost image due to the detector reflection. In addition, the manufacture technology of curved grating is not mature enough.

Currently, the spectral imaging system with plane grating has been applied in wide fields. However, plane grating brings about a large smile and keystone. Smile is the deviation of the curved image of the slit from the ideal straight-line image at different working wavelengths, which results in spectral aliasing. Keystone is introduced by the magnification difference of the slit for different working wavelengths, which causes the image location of an object point at different columns of the detector for different wavelengths [9].

To correct the smile and keystone, an off-axis optical system should be adopted [10]. However, the use of tilted surface changes the equivalent focal length and the magnification. In this paper, the formulas of the image height of two-dimensional field in tilted imaging system are deduced, based on the formula of image height in coaxial optical system. The expressions of the smile and keystone of grating-based imaging spectrometer instrument (GISI) are obtained with the vector theory of diffraction. Then we deduce the image height formulas in the directions of silt length and dispersion in tilted imaging system of GISI. Finally a long-wave infrared imaging spectrometer, meeting the requirement of hyperspectral imaging system, is designed by adding an off-axis lens behind the grating to eliminate the smile and keystone.

2. The parameter calculation of the imaging system

The imaging spectrometer system is composed of fore-telescope system and spectral imaging system. The fore-telescope forms an image of the Earth strip scene onto the entrance slit, which is then collimated, dispersed and imaged by the spectral imaging system. Finally, the hyperspectral image of the target is displayed on the area-array detector [11]. To get the expressions of the image height, smile and keystone of the imaging system of GISI, the formulas of the image height of two-dimensional field in no-raster tilted imaging system and in Gaussian imaging system are analyzed.

For simplicity, we call the image height in the directions of silt length and dispersion, the smile and the keystone as the imaging system parameters. Fig. 1(a) shows the Gaussian imaging system of GISI where the grating, the imaging lens and the imaging plane are in coaxial. Fig. 1(b) shows the tilted imaging system of GISI where the imaging lens and the imaging plane have the same incline with respect to the grating.

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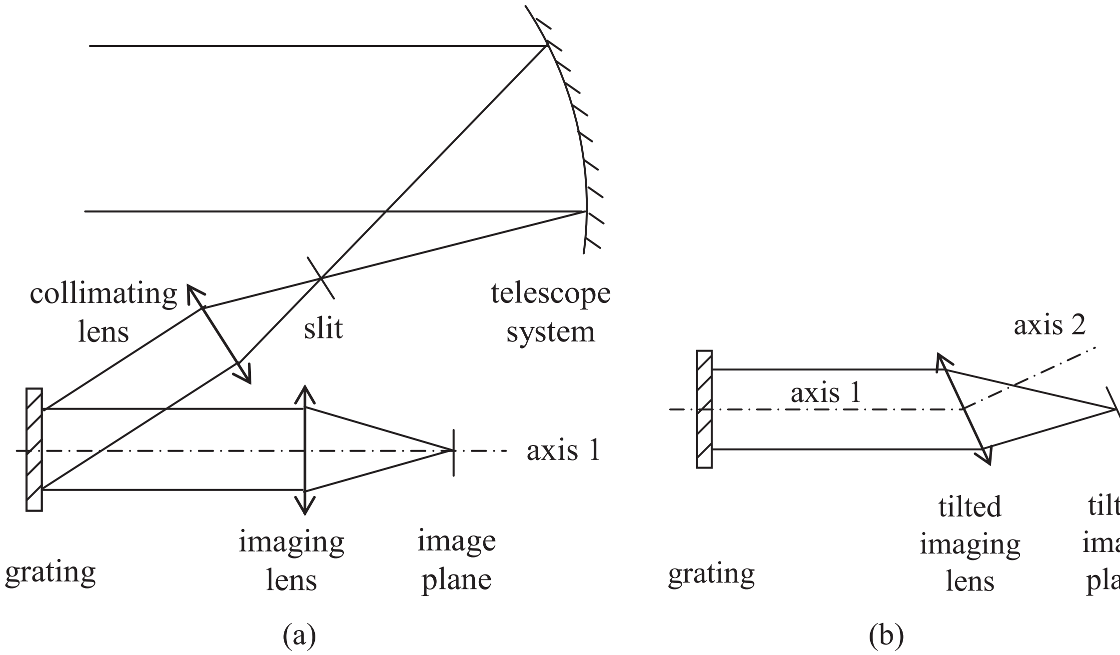

Fig. 1. The imaging system of GISI. (a) Gaussian imaging system. (b) Tilted imaging system.

2.1. The formula of image height in tilted imaging system

In coaxial optical system, the formulas of image height in two-dimensional field denoted by x and y field are described by

$$\begin{cases} h_x = f\cdot \tan\theta_x \\ h_y = f\cdot \tan\theta_y \end{cases}. \tag{1}$$

For tilted imaging system, the image height will change with the tilted angle and field direction. Suppose the imaging lens and the imaging plane rotate an angle of Tx with respect to x axis, and the y field of view to be considered is θ_y as shown in Fig. 2. The sign convention is as follows. Tx is positive if the rotation is clockwise, and θ_y is positive if the angle is counter-clockwise from the optical axis.

As $\theta_y = 0$, the equivalent focal length of the imaging lens is $f/\cos Tx$ in the x field. In this case we have $h_x = f\cdot\tan\theta_x/\cos Tx$. As $\theta_y \neq 0$, however, the equivalent focal length is $f\cos\theta_y/\cos(\theta_y + Tx)$. Correspondingly we have:

$$h_x = \frac{f\cdot\cos\theta_y\cdot\tan\theta_x}{\cos(\theta_y + Tx)}. \tag{2}$$

In the y field, as Tx and θ_y have the same sign as shown in Fig. 2(a), we have:

$$h_y = f\cdot[\tan(T_x + \theta_y) - \tan T_x] = \frac{f\cdot\sin\theta_y}{\cos T_x\cdot\cos(T_x + \theta_y)}. \tag{3}$$

As Tx and θ_y have opposite sign, taking $0 < -Tx < \theta_y$ as shown in Fig. 2(b) for instance, we have:

$$h_y = f\cdot[\tan(T_x + \theta_y) + \tan(-T_x)] = \frac{f\cdot\sin\theta_y}{\cos T_x\cdot\cos(T_x + \theta_y)}. \tag{4}$$

It is clear that the variations of the image height in x and y fields are different, and it is necessary to change the object field and the focal length to keep the image height constant.

2.2. The parameter calculation of the imaging system of GISI

Typically, a virtual coordinate break surface is used in the spectral imaging system with a reflective diffraction plane grating. To ensure the emergent light paralleled to the optical axis of the collimating system, a certain deflection between the grating and the collimating lens is needed. The deflection angle should be equal to the incidence angle of the slit center ray. As shown in Fig. 3, point 1 and 2 are the entrance slit center and the endpoint of slit respectively. We denote half of the slit length as h. In order to analyze expediently, we move the entrance slit to the collimating lens along the line jointing the points 1 and O. Moreover, the exit slit is moved to the imaging lens along the

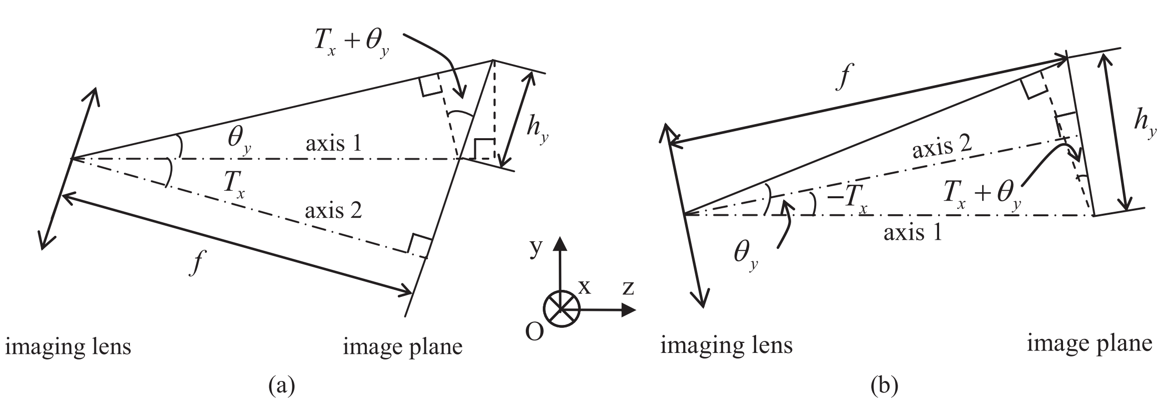

Fig. 2. Sketch map for image height calculation. (a) The sign of Tx and θ_y is the same. (b) The sign of Tx and θ_y is opposite.