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Establishment and correction of an Echelle cross-prism spectrogram reduction model

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ABSTRACT

The accuracy of an echelle cross-prism spectrometer depends on the matching degree between the spectrum reduction model and the actual state of the spectrometer. However, the error of adjustment can change the actual state of the spectrometer and result in a reduction model that does not match. This produces an inaccurate wavelength calibration. Therefore, the calibration of a spectrogram reduction model is important for the analysis of any echelle cross-prism spectrometer. In this study, the spectrogram reduction model of an echelle cross-prism spectrometer was established. The image position laws of a spectrometer that varies with the system parameters were simulated to the influence of the changes in prism refractive index, focal length and so on, on the calculation results. The model was divided into different wavebands. The iterative method, least squares principle and element lamps with known characteristic wavelength were used to calibrate the spectral model in different wavebands to obtain the actual values of the system parameters. After correction, the deviation of actual x- and y-coordinates and the coordinates calculated by the model are less than one pixel. The model corrected by this method thus reflects the system parameters in the current spectrometer state and can assist in accurate wavelength extraction. The instrument installation and adjustment would be guided in model-repeated correction, reducing difficulty of equipment, respectively.

1. Introduction

Recently, spectrometers have been widely used in many fields, including agriculture, medicine, and astronomy [1–6]. Among them, the echelle cross-prism spectrometer has the advantages of small volumes and high resolution and has thus become a research hotspot [4,7–10]. The main dispersion element (echelle grating) of the echelle cross-prism spectrometer has a high diffraction order and large blazing angle [11], which produces a high dispersion rate and resolution. However, the high diffraction order leads to overlapping diffraction that makes the spectrometer unusable. To solve this problem, a cross-dispersion element is added after the echelle grating [12,13] to acquire two-dimensional spectrum without overlapping spectral lines. In this two-dimensional spectrogram, the intensity of the target light spot and its image plane position is known. The two-dimensional spectrum has to be transformed into a one-dimensional spectrum. This means that the relationship between the light spot intensity and its image plane position has to be turned into the relationship between the light spot intensity and its wavelength.

In general, a spectrogram reduction model is used to transform a two-dimensional spectrum into a one-dimensional spectrum [14–16]. This model constructs the relationship between the image coordinates and the wavelength values. The relationship between coordinates and the characteristic spot intensity can be acquired by the echelle cross-prism spectrometer. So the relationship between the characteristic spot intensity and wavelength can be deduced, the wavelength can be calculated.

However, this model does not always accurately compute the position of the image plane. This is because the changes in the actual state of the spectrometer will result in changes in the actual parameter values (prism incidence angle, grating incidence angle, grating offset angle, focal length, etc.). If the model with the fixed system parameter values is used to calculate the entire optical system, the spectrogram reduction model may not match the actual state of the spectrometer. This means that the results calculated by the spectral reduction model will be inaccurate, as will the wavelength calculation. Keling [17] has studied the effects of temperature and humidity changes on wavelength calculation

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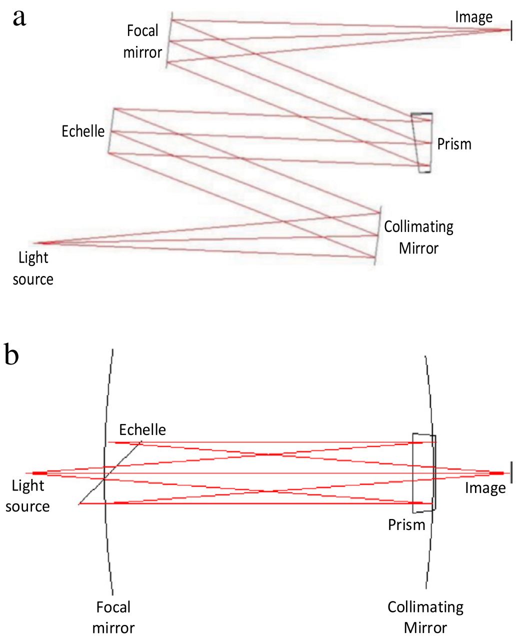

Fig. 1. Structure of the echelle cross-prism spectrometer used in this study (a) XZ plane (b) YZ plane.

accuracy. It can change the optical element status in the spectrometer through transportation, vibration and error of adjustment. This will then change the imaging position and the previously established spectral reduction model will not match the actual situation of the spectrometer and result in an inaccurate wavelength calculation.

Therefore, this paper established spectrogram reduction model. Then, the effect of model parameters on the accuracy of model calculation is simulated when the input parameters in the model are in error with the actual parameters of the spectrometer. The simulation results show that the deviation between the input parameters and the actual parameters will have a great influence on the final model calculation results. Therefore, this paper corrects the model. The iterative method is used to change the value of input parameters in a certain range, and then obtain a number of spectral reduction model. The image plane coordinates of these models are compared with the actual coordinates according to the least square principle (Minimize the sum of squared errors of the computations). Finally, the model with the least residual error is the corrected model, whose input parameters are the parameters after correction.

2. Establishment and correction of the spectrogram reduction model

2.1. The establishment of the spectrogram reduction model

The spectrometer has a C-T type structure (Fig. 1).

The dispersion direction of the prism is perpendicular to the dispersion direction of the echelle. Assume that the prism dispersion is in the horizontal (x) direction and the echelle is in the vertical (y) direction. Establishment a spectral reduction model. Firstly, study on the echelle dispersion direction. The echelle grating is placed in the echelle cross-prism spectrometer with a certain offset angle. The diffraction equation can be expressed as:

$$d\left(\sin\alpha + \sin\beta\right)\cos\omega = m\lambda \tag{1}$$

where d is the groove spacing, α is the incidence angle of the echelle grating, β is the diffraction angle of the echelle grating, ω is the grating offset angle, m is the grating diffraction order, and λ is the incident light wavelength.

The light at the blazing angle emitted from the grating is transmitted to the center of the image plane. The angle at the grating between the arbitrary lights and the light on the center of the image plane can be expressed by:

$$\Delta\beta = \beta - \beta_0 \tag{2}$$

where β_0 is the diffraction angle of the light on the center of the image plane, and $\Delta\beta$ is the angle between arbitrary lights and the light incident on the center of the image plane.

The distance between the position of the arbitrary lights on the image plane and the center of the image plane in the y direction can be expressed as:

$$y = \frac{\Delta\beta}{f\cos\omega} \tag{3}$$

where y is the distance between the position of arbitrary lights on the image plane and the center of the image plane in the y direction, and f is the system focal length. Based on Eqs. (1)–(3), the relationship between the wavelength and y-coordinates can be established and the relationship expressed as:

$$\lambda = \frac{d}{m}\left[\sin\alpha + \sin\left(\beta_0 + \frac{y}{f\cos\omega}\right)\right]\cos\omega. \tag{4}$$

For the prism dispersion direction, the prism exit angle corresponding to the light at the center of the image plane can be deduced by the geometric optics theory. The prism exit angle of the arbitrary lights can be calculated using the law of refraction. Thus, the angle on the prism between the arbitrary lights and the light on the center of the image plane can be determined. The distance between the position of arbitrary lights on the image plane and the center of the image plane in the x direction can be expressed as:

$$x = f * \left(\theta - \theta_0\right) \tag{5}$$

where x is the distance between the position of the arbitrary lights on the image plane and the center of the image plane in the x direction, θ is the exit angle of arbitrary lights on the prism, and θ_0 is the prism exit angle corresponding to the light at the center of the image plane. The prism is made of materials that can be transmitted through ultraviolet light (JGS1). Based on the law of refraction, the prism exit angle is related to the prism refractive index with different wavelengths corresponding to different refractive indices [15]:

$$n^2 = 2.1049 + \frac{0.0087}{\lambda^2 - 0.0111} - 0.0103\lambda^2 \tag{6}$$

where n is the refractive index, λ is the wavelength value and the adaptive band range of Eq. (6) is 190–600 nm.

Using Eq. (6), the relationship between a wavelength and its x-coordinates can be established, and then expressed as:

$$\begin{aligned} x = {} & f * \tan\left\{\arcsin\left\{n\left(\lambda_1\right)\sin\left[2\delta - \sin^{-1} i/n\left(\lambda_1\right)\right]\right\}\right. \\ & \left. - \arcsin\left\{n\left(\lambda_0\right)\sin\left[2\delta - \sin^{-1} i/n\left(\lambda_0\right)\right]\right\}\right\} \end{aligned} \tag{7}$$

where λ_1 and λ_0 are the wavelengths with output angles θ and θ_0, respectively, i is the incidence angle of the prism, δ is the apex angle of the prism, and $n(\lambda)$ is the wavelength-dependent refractive index.

Finally, according to the Eqs. (4) and (7), the relationship between the wavelengths and the x- and y-coordinates of the image plane can be confirmed. Put the results into a matrix, the number of rows and columns of the matrix correspond to the X and Y coordinate values, and the value of the matrix corresponding to the wavelength.

$$\lambda_{X,Y} = \begin{bmatrix} \lambda_{X_1Y_1} & \lambda_{X_1Y_2} & \cdots & \lambda_{X_1Y_q} \\ \lambda_{X_2Y_1} & \lambda_{X_2Y_2} & \cdots & \lambda_{X_2Y_q} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \lambda_{X_pY_1} & \lambda_{X_pY_1} & \cdots & \lambda_{X_pY_q} \end{bmatrix} \tag{8}$$

where p and q are the number of pixels in the Charge-coupled Device (CCD) detector.