Slitless Spectrometer Spectral Efficiency Testing and Error Analysis Postprint

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Abstract

The slitless spectroscopy component of the Chinese Space Survey Telescope (CSST) will be installed in front of the prime focal plane detector of the survey module to conduct wide-field, broad-band slitless spectroscopic observations. As a critical dispersive element of the survey module, the slitless spectroscopy component is assembled from 24 gratings and 12 filters. Spectral efficiency represents one of the key technical specifications of the slitless spectroscopy component, necessitating its measurement during the development process. Owing to the large physical envelope of the slitless spectroscopy component, commercial spectral efficiency measurement equipment cannot be employed for testing. To address the challenge of spectral efficiency testing for the slitless spectroscopy component, this work first introduces the basic structure and measurement principle of the laboratory-established spectral efficiency testing apparatus for the slitless spectroscopy component, subsequently presents the measurement procedures and results for the qualification model of the slitless spectroscopy component, and finally analyzes and calculates the precision of the measurement results using error synthesis theory. The measurement and calculation results demonstrate that the average spectral efficiencies of the slitless spectroscopy component qualification model are 51.9% for the GU band, 67.9% for the GV band, and 71.6% for the GI band (67.7% for the 900-1000;nm band), which satisfy the technical specification requirements.

Full Text

Preamble

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Title and Authors

Spectral Efficiency Testing and Error Analysis of Space Slitless Spectrograph

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Abstract

The slitless spectroscopy assembly of the Chinese Space Survey Telescope (CSST) will be installed in front of the main focal plane detector of the sky survey module to conduct wide-field, wide-band slitless spectral observations. As an important dispersion element of the sky survey module, the slitless spectroscopy assembly is composed of 24 gratings and 12 filters. Spectral efficiency is one of the important technical indicators of the slitless spectroscopy assembly, and it needs to be tested during the development process. Due to the large envelope of the slitless spectroscopy assembly, commercial spectral efficiency measurement equipment cannot be used for testing. This paper addresses the issue of spectral efficiency testing for the slitless spectroscopy assembly. Firstly, the basic structure and measurement principles of the slitless spectroscopy assembly spectral efficiency testing system built in the laboratory are introduced. Then, the steps and results of the spectral efficiency measurement for the initial sample of the slitless spectroscopy assembly are given. Finally, the accuracy of the measurement results is analyzed and calculated using error synthesis theory. The measurement and calculation results show that the average spectral efficiency of the initial sample for the slitless spectroscopy assembly is 51.9% in the GU band, 67.9% in the GV band, and 71.6% in the GI band (67.7% in the 900-1000 nm band), meeting the technical requirements.

Key words: space vehicles: instruments, instrumentation: spectrographs, telescopes, methods: analytical

1. Introduction

The Chinese Space Survey Telescope (CSST) is a space-based survey telescope with a 2-meter aperture and 28-meter focal length, designed primarily for large-scale multi-color imaging and slitless spectroscopic surveys [1-4]. The space slitless spectroscopy assembly consists of 24 gratings and 12 filters tiled together, positioned in front of the detector array of the sky survey module, with the gratings located approximately 70 mm from the detector surface. As a critical component of the sky survey module, the slitless spectroscopy assembly will work in conjunction with the main focal plane to conduct slitless spectral observations in three bands: GU (255-400 nm), GV (400-620 nm), and GI (620-1000 nm) [5]. According to the development plan, the slitless spectroscopy assembly will be installed together with the filter assembly in front of the detector array of the sky survey module. Figure 1 [Figure 1: see original paper] shows the configuration of the slitless spectroscopy assembly and filter assembly installed together (referred to in this paper as the united assembly). The slitless spectroscopy assembly is divided into two parts, I and II, based on installation position, located on opposite sides of the filter assembly.

Spectral efficiency is one of the key technical specifications of the slitless spectroscopy assembly and must be tested before delivery. Due to the large physical envelope of the united assembly, it is difficult to directly measure its spectral efficiency using commercial equipment. After investigating various structures and principles of spectral efficiency and transmittance measurement devices [6-11] and consulting relevant experts, we augmented our existing laboratory setup for measuring spectral image quality and resolution of the slitless spectroscopy assembly with the capability to measure spectral efficiency. The QHY4040 PRO-BSI camera originally part of this system was used to complete the spectral efficiency measurements of the initial sample of the slitless spectroscopy assembly. This paper describes the composition and working principle of the measurement apparatus, the measurement procedures and results for the initial sample, and analyzes the precision of the measurement results.

2. Test Apparatus and Principle

The acceptance testing of the spectral efficiency of the space slitless spectroscopy assembly is performed using an optical performance testing system. The schematic diagram of this system is shown in Figure 2 [Figure 2: see original paper], consisting primarily of an F14 optical simulator, a high-precision grating assembly positioning platform, a QHY4040 PRO-BSI camera, and a light source. The F14 optical simulator in the system converts light incident from an optical fiber into an F14 beam to simulate the output from the CSST primary optical system. Mounted on a four-dimensional motion platform, the simulator can translate in the Y direction (horizontal in the plane) and Z direction (vertical in the plane) and rotate about the X-axis (perpendicular to the plane) and Y-axis, enabling simulation of the output beam from the CSST primary optical system at different field points. The slitless spectroscopy assembly is installed on a one-dimensional translation stage, movable along the X direction to test image quality and spectral efficiency at different grating positions or different test points on the same grating. The test camera is mounted on a two-dimensional translation stage, capable of moving forward/backward and left/right along the X and Y axes in the horizontal plane to simulate detectors at various positions for receiving spectral images.

The light source for the testing system comprises a laser-driven light source, a monochromator (Acton SP2500i), a silicon photodiode, a beam shaping and coupling system, and a light guide fiber, with its basic structure shown in Figure 3 [Figure 3: see original paper]. The source system is mounted on an optical platform outside the light-shielded environment, using lenses and fiber jumpers to introduce the monochromator output into the entrance port of the F14 optical simulator. To enable spectral efficiency testing, a photodiode is added to the optical path to monitor variations in output light intensity.

Before using this testing system, the relative coordinates of the three translation stages shown in Figure 2 must be experimentally determined and aligned to establish the spatial coordinate system of the entire positioning system. The slitless spectroscopy assembly is then installed on the one-dimensional stage, and the relative position between the assembly and the camera sensor plane is adjusted to match the design specifications. Based on the incident beam angles for different test points in the design, the measurement positions and beam angles are set, and measurements are conducted. The 3D model and physical implementation of the testing system are shown in Figure 4 [Figure 4: see original paper] and Figure 5 [Figure 5: see original paper], respectively.

The spectral efficiency of the slitless spectroscopy assembly is measured by capturing images with the camera and using the summed grayscale values of the spot image to represent the spot energy. The method and procedure for measuring the spectral efficiency of a specific grating at a given measurement point at wavelength λ_0 in the united assembly configuration are as follows: (1) Set the monochromator output wavelength to λ_0; (2) Determine the incident beam angle for the corresponding measurement point from the design documentation and input the measurement point coordinates and beam angle coordinates into the testing system control software; (3) Without the slitless spectroscopy assembly installed, use the camera at the image plane position of the measurement point to capture the spot image formed by the F14 optical simulator output beam at the set angle, record this as the incident light image, and simultaneously record the photodiode output voltage monitoring the light intensity variation; (4) Remove the F14 optical simulator and install the slitless spectroscopy assembly on the one-dimensional translation stage; (5) Move the translation stage and F14 optical simulator to the measurement point position of the grating to be tested and adjust the F14 optical simulator state according to the set output beam angle; (6) Move the camera again to the image plane position of the measurement point, capture the spectral image recorded as the output spectral image, and record the photodiode output voltage; (7) Save the captured images to complete the test.

The acceptance testing experiment for the united assembly selected one field point per grating in the initial sample of the slitless spectroscopy assembly for spectral efficiency measurement. To improve measurement accuracy, six additional field points were randomly added during testing across the 20 gratings in three bands, with the layout of selected measurement field points shown in Figure 6 [Figure 6: see original paper]. (Note: Gratings were not installed at positions GV5, GV6, GI7, and GI8 in the initial sample, resulting in a total of 20 gratings.) The slitless spectroscopy assembly operates in three bands, with five wavelengths selected for testing in each band. Since the GI band requires reporting the average spectral efficiency for 900–1000 nm, three additional test wavelengths in this range were included, and one test wavelength at 310 nm was randomly added for the GU band during testing. The final test wavelengths for spectral efficiency measurement of the initial sample are listed in Table 1 .

In the actual measurement process, to ensure the safety of the initial sample of the united assembly, frequent installation and removal were avoided. Therefore, after determining the field points and wavelengths to be measured, all incident spot images were first captured without the slitless spectroscopy assembly installed. The initial sample of the united assembly was then installed, and all first-order spectral images passing through the slitless spectroscopy assembly were captured in a subsequent measurement session. Finally, the measurement results were processed uniformly to calculate the spectral efficiency at different field points.

3. Test Results Processing

The incident spot images and post-grating spectral images captured during spectral efficiency testing of the initial sample are shown in Figure 7 [Figure 7: see original paper]. Since the incident light used for testing is monochromatic (spectral bandwidth less than 0.5 nm), both the incident light images and first-order spectral images appear as single spots. The test results are processed as follows: (1) Extract the spot images and background from both the incident spot images and first-order spectral images, and subtract the background from the spot images; (2) Sum all grayscale values within a radius of approximately 0.6 arcseconds from the spot center; (3) Using the grayscale value I_0 and integration time T_0 of the incident spot image, along with the grayscale value I_1 and integration time T_1 of the first-order spectral image captured after passing through the slitless spectroscopy assembly, the spectral efficiency E at that wavelength can be obtained through the following equation:

(cid:2) where N0 and N1 are the photodiode voltages when acquiring the incident spot and first-order spectral images, respectively, used to correct for light intensity variations during the measurement process.

Tables 2 , 3 , and 4 present the measured grayscale values, integration times, photodiode voltages N (x=0, 1), and calculated spectral efficiencies for the GU, GV, and GI band central wavelengths, respectively.

The spectral efficiencies of all gratings in the initial sample at the test wavelengths are listed in Tables 5 , 6 , and 7 . For gratings with two test points, the values given in the tables represent the average of both points. Based on the test results, the average spectral efficiency is 51.9% for the GU band, 67.9% for the GV band, and 71.6% for the GI band, with an average of 67.7% for the 900–1000 nm sub-band.

4. Measurement Error Analysis and Calculation

By definition, spectral efficiency can be expressed as the ratio of the first-order spectral intensity after passing through the slitless spectroscopy assembly to the incident light intensity, as shown in the equation. Where P = I (x = 0, 1) is called the normalized incident or exit intensity per unit time, I represents the grayscale value of the incident or exit spot, T represents the integration time for incident or exit light, and N corresponds to the diode output voltage monitoring the light source intensity variation, used to correct for the effect of source intensity fluctuations on measurement results. Since the incident intensity P_0 and exit intensity P_1 are independent variables measured separately, according to error synthesis theory [12-13], the measurement error of spectral efficiency E can be expressed as shown in the equation. In the equation, σE, σP_1, and σP_0 are the measurement errors of spectral efficiency, exit intensity, and incident intensity, respectively. Substituting equation (1) into the above equation yields the expression for error propagation. By substituting $P_1 = E\ P_0$, where E is the true value of E, and $\sigma P_1 = E\ \sigma P_0$ into the equation, we obtain the simplified error expression. Furthermore, the relative error of spectral efficiency can be expressed as shown in the equation. The equation shows that the relative error of spectral efficiency is twice the relative error of the incident normalized intensity, i.e., $\sigma E/E = 2\sigma P_0/P_0$. Therefore, the relative error of the spectral efficiency measurement results can be determined by calculating the relative error of the incident normalized intensity. Using the same method, it can be proven that the relative error of spectral efficiency is also $\sqrt{2}$ times the relative error of the exit normalized intensity.

During the spectral efficiency measurement of the initial sample, we measured the incident intensity at each measurement point for different wavelengths and the first-order spectral intensity after passing through the slitless spectroscopy assembly at each point. Theoretically, the incident intensities at different measurement points for the same wavelength should be identical, so the relative error of the measurement results can be calculated using the incident intensities obtained at different measurement points during the measurement process. Based on the measured grayscale values of incident spots, integration times, and diode output voltages at different measurement points, the incident normalized intensities for a given wavelength are calculated, from which the relative measurement error of the incident normalized intensity is determined (using standard deviation to calculate relative error, with a confidence interval of 2σ and confidence probability of 95.45%). From the relative measurement error of the incident normalized intensity, the relative measurement errors of spectral efficiency at different wavelengths are obtained as shown in Table 8 .

Based on the relative measurement errors of spectral efficiency at each wavelength, error synthesis theory can similarly be applied to obtain the measurement error of the average spectral efficiency within each working band. The average spectral efficiency for different bands is calculated using arithmetic mean, as expressed in the formula. According to the measurement results, the average spectral efficiency of the initial sample meets the requirements of >50% for the GU band, >55% for the GV band, and >55% for the GI band (with >54% for the 900-1000 nm sub-band). Where Eij is the spectral efficiency measured for a particular grating at a particular wavelength, n is the number of gratings measured within the same working band, and m represents the number of measurement wavelengths. As described previously, during the measurement process, the incident intensities at different wavelengths for each grating position are first collected, then the slitless spectroscopy assembly is installed, and the exit intensities at different wavelengths for all gratings are collected, from which the spectral efficiencies for different gratings and wavelengths are finally calculated. Since each spectral efficiency is obtained using both incident and exit intensities, these measurement results can be considered to be positively strongly correlated, with a correlation coefficient approximately equal to 1. According to the error propagation formula, the measurement error of the average spectral efficiency $\bar{E}$ can be expressed as follows [14]. After rearrangement, we obtain the expression. In the equation, k and l represent different combinations of (i, j), and σk represents the measurement error of the spectral efficiency for the k-th combination corresponding to the i-th grating and j-th wavelength. We first use the relative errors of each measurement result from Table 8 and the measurement results from Tables 5, 6, and 7 to calculate the absolute measurement errors for each spectral efficiency measurement. Then, using equation (9), the measurement errors of the average spectral efficiency within the GU, GV, GI, and 900-1000 nm bands are determined to be 2.38%, 3.52%, 5.03%, and 6.20%, respectively (confidence probability 95.45%).

Therefore, the average spectral efficiencies of the initial sample are: GU band: (51.9% ± 2.38%), GV band: (67.9% ± 3.52%), GI band: (71.6% ± 5.03%), and 900-1000 nm band: (67.7% ± 6.2%).

5. Conclusion

This paper presents the spectral efficiency testing of the initial sample of the slitless spectroscopy assembly for the sky survey module of the Chinese Space Survey Telescope. The article details the principle, composition, and testing procedures of the spectral efficiency measurement apparatus, and presents the test results for the spectral efficiency of the slitless spectroscopy assembly. Finally, based on error theory and using the incident intensity information obtained during testing, a detailed analysis of the precision of the spectral efficiency test results is conducted. This work provides experience for testing the flight model of the slitless spectroscopy assembly and for measuring the spectral efficiency of large-scale optical spectroscopic equipment. The method used in this paper to calculate the precision of spectral efficiency measurement results can also be applied to evaluate and calculate the precision of similar experimental results.

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Note: Figure translations are in progress. See original paper for figures.