Postprint of Ground Testing of CSST Slitless Spectroscopy Using the 80-cm Telescope at Xinglong Observatory

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Date: 2023-11-24T00:00:00+00:00

Abstract

The Chinese Space Station Telescope (CSST), scheduled for launch in 2025, is primarily intended for large-scale multicolor imaging and slitless spectroscopic surveys. Prior to launch, ground-based telescopes must be employed to conduct ground testing of the space telescope's optical imaging system, detector, and long-term operational stability. A slitless spectroscopy ground test has been designed for the 80cm telescope at Xinglong Observatory, utilizing the strong absorption and emission line features of A-type stars, B-type stars, and the Wolf-Rayet star HD4004 to fit dispersion equations, revealing that the dispersion equations possess spatial distribution characteristics. Quadratic surface fitting was performed on the zero-order spectrum position information and dispersion equation coefficients from 53 datasets of HR3173, and this surface was applied to wavelength calibration of HR718 data within the zero-order image position range of HR3173, yielding an average radial velocity precision of 51 km/s within an 8$×$13 pixel range on the CCD.

Full Text

Ground-Based Slitless Spectroscopy Testing with the 80 cm Telescope at Xinglong Observatory

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Abstract

The Chinese Space Station Telescope (CSST), scheduled for launch in 2025, will conduct large-scale multicolor imaging and slitless spectroscopic surveys. Prior to launch, ground-based testing of the space telescope's optical imaging system, detectors, and long-term operational stability is required using ground-based telescopes. This paper presents the design of a slitless spectroscopy ground test for the 80 cm telescope at Xinglong Observatory. By utilizing the strong absorption and emission line features of A-type stars, B-type stars, and the Wolf-Rayet star HD 4004, we fit dispersion equations and find that these equations exhibit spatial distribution characteristics. We performed quadratic surface fitting on the zero-order spectral position information and dispersion equation coefficients from 53 datasets of HR 3173, and used this surface to calibrate wavelengths for HR 718 data within the zero-order image position range of HR 3173. The resulting average radial velocity accuracy was 51 km/s.

Keywords: slitless spectroscopy; CSST; wavelength calibration

1. Introduction

Traditional long-slit spectroscopy aligns a single target with a slit, and the target's light passes through this slit to obtain the target's spectrum dispersed perpendicular to the slit direction. In contrast, slitless spectroscopy has no slit—light passes directly through a prism or grism to produce a dispersed image containing spectra of all objects in the field of view. Since a single exposure yields spectral information for all objects in the field, slitless spectroscopy offers extremely high spectral acquisition efficiency, with each pixel receiving radiation of any wavelength, making it ideal for large-area surveys. However, slitless spectroscopy is susceptible to stray light contamination.

Slitless spectroscopy was initially developed for ground-based observations. M. G. Smith et al. added a thin objective prism to a 60 cm Schmidt telescope at Cerro Tololo Inter-American Observatory to discover quasars, and this method led to a dramatic increase in quasar discoveries. While slitless spectroscopy has value in ground-based observations, it is far more efficient in space-based observations due to the sky background being many orders of magnitude lower than on the ground, and the absence of bright and variable atmospheric absorption and emission components.

The Hubble Space Telescope (HST) has conducted slitless spectroscopy with the Wide Field Planetary Camera 1 (WFPC1), the Advanced Camera for Surveys

(ACS), and the Wide Field Camera 3 (WFC3), covering wavelengths from ultraviolet to near-infrared, primarily for studying quasars and supernovae. The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) on HST is equipped with three grisms (G096, G141, G206) covering 0.8–2.5 m, mainly for galaxy evolution studies. The James Webb Space Telescope (JWST) Near Infrared Imager and Slitless Spectrograph (NIRISS) can achieve wide-field slitless spectroscopy between 0.8–2.2 m with low resolution (R 150) over a 2.2 $×$2.2 field, primarily investigating galaxy formation and evolution. Characterized by low sky background and high spatial resolution, slitless spectroscopy has become the preferred tool for studying galaxy evolution from space and will play a major role in future missions such as CSST and Euclid.

The Chinese Space Station Telescope, expected to launch in 2025, will mainly conduct large-scale multicolor photometric and slitless spectroscopic surveys, with one of its scientific goals being to explore the origin and evolution of galaxies. Since CSST cannot calibrate slitless spectroscopy by switching to direct imaging, we must address the challenge of in-orbit calibration by using appropriate standard stars for calibration rather than calibration lamps. In this work, we utilize the 80 cm telescope at Xinglong Observatory to conduct ground-based slitless spectroscopy observations, using strong absorption and emission lines in one-dimensional spectra to establish a calibration model that provides reference for the in-orbit calibration system.

2. Instrumentation and Observations

2.1 The 80 cm Telescope System The Tsinghua-NAOC 80 cm Telescope (TNT) is located at Xinglong Observatory in Hebei Province, on the southern slope of the main peak of the Yanshan Mountains, at coordinates 117°34 38 E, 40°23 45 N, with an altitude of 830 m. The telescope is an equatorial Cassegrain reflector with a system focal ratio of f/10. It consists of a parabolic primary mirror with an effective diameter of 0.80 m and a hyperbolic secondary mirror with an effective diameter of 0.26 m. The primary mirror has a focal ratio of f/2.6, and after correction at the prime focus, the system focal ratio becomes f/10. The system is fast and accurate, with a maximum slewing speed of 10°/s and pointing accuracy better than 10 . The pointing drift within 15 minutes is less than 1 .

The optical detector is a high-performance full-frame digital camera system manufactured by Princeton Instruments, using a back-illuminated scientific-grade VersArray 1300B LN CCD. The imaging array size is 1340$\times 1300 pixelswithapixelsizeof 20\times 20\mu m. The TNT providesafieldofviewof 11.5'\times$11.2 with a spatial resolution of approximately 0.52 /pixel. Scientific projects conducted with the TNT include multi-color photometric studies of supernovae, active galactic nuclei, and gamma-ray bursts.

2.2 Slitless Spectroscopy Setup For testing the slitless spectroscopy system, we used the TNT at Xinglong Observatory. Considering imaging quality and wavelength coverage, we designed a slitless spectroscopy ground test covering 400–700 nm, consistent with CSST's wavelength range. The experimental setup consists of a bandpass filter, a plane blazed grating, and the detector. The filter and grating are installed before the telescope focal plane to achieve slitless spectroscopy observations. The bandpass filter suppresses out-of-band spectra to avoid second-order spectral overlap.

The physical photos of the equipment are shown in [Figure 1: see original paper] and [Figure 2: see original paper]. The distance between the zero-order image and the blue end of the spectrum is 16.306 mm, while the distance between the zero-order image and the red end is 9.166 mm. The energy concentration radius averages 4 pixels.

2.3 Target Selection and Observation Strategy Since CSST will not carry specific wavelength calibration lamps, our ground testing follows the same strategy. The resolution of the grism greatly limits the selection of appropriate standard stars. Ideal calibration sources should have short required exposure times and spectra containing numerous easily resolvable emission or absorption lines. Additionally, to prevent spectral contamination from nearby objects and avoid introducing additional errors during calibration data processing, we cannot select targets in dense star fields.

Traditional calibration sources include planetary nebulae (PNe) and quasars (QSOs). Planetary nebulae spectra are dominated by narrow, strong emission lines such as [O III], [S III], [N II], and can serve as equivalent to ground-based arc lamps. Quasars have emission features like Lyman-α, C IV, Hβ, [O II], [N II] across virtually any required wavelength range, making them another calibration option. Wolf-Rayet (WR) stars have a series of strong emission lines, while A-type and B-type stars have prominent hydrogen Balmer absorption lines, also making them suitable calibration standards.

We selected the Wolf-Rayet star HD 4004 and several stars from the European Southern Observatory standard star catalog as wavelength calibration standards. Table 1 lists the basic information for these sources, including right ascension (RA), declination (Dec), magnitude, radial velocity, number of datasets, and calibration lines used.

Our observation strategy involves obtaining spectroscopic observations of each target source at least three different positions to capture spatial variations in the dispersion equation. During actual observations, a series of dispersed images containing first-order spectral information can be obtained by moving the target across the CCD. Three ground test observations were conducted: the first on March 20, 2021, the second from January 18–20, 2022, and the third on November 8, 2022. All tests used the PI VersArray 1300B LN CCD detector with 1340\$$\times1300pixels(20\times20\mu mpixelsize),exceptthesecondtestwhichusedtheAndor-$

$DZ936-BEX2-DDdetectorwith2048\times2048pixels$(13.5×$13.5 m pixel size). Before testing, the filter wheel must be removed to install the slitless spectroscopy system.

Xinglong Observatory's atmospheric and dome seeing is approximately 2 . The observed sources are mostly bright standard stars. Exposure times were 150–300 s for standard stars and 10–300 s for the Wolf-Rayet star HD 4004. Table 2 provides an overview of the observations.

3. Data Processing and Spectral Extraction

While the initial observations for slitless spectroscopy are relatively straightforward, the subsequent data processing presents a major challenge. Currently popular software such as aXe cannot meet all the requirements for slitless spectroscopy data processing, as it requires comprehensive instrument calibration parameters that are not yet determined during the testing phase.

We developed a custom pipeline for processing our test data. The primary software used is SExtractor (Source-Extractor) for extracting individual target spectra from slitless images. The basic steps are: (1) subtract the background from the image to obtain a background-subtracted dispersed image; (2) use an elliptical model containing parameters such as centroid coordinates, semi-major axis, semi-minor axis, and position angle to detect candidate target sources in the dispersed image; (3) identify the target source's dispersed image from the detected series of sources; (4) extract the target source's spectrum.

The spectral trace of the target source can be fitted using a polynomial equation. The polynomial takes the form:

$$x = a_0 + a_1 l + a_2 l^2$$

where x and l are image coordinates, and a_0, a_1, and a_2 are the constant, linear, and quadratic terms, respectively. Once the target's spectral trace is determined, we locate the spectral lines belonging to the extraction range and extract the target source's spectrum.

[Figure 4: see original paper] shows the dispersed images of BS 2845 and HD 4004. [Figure 5: see original paper] displays the one-dimensional spectra obtained from processing, with panel (a) showing the standard star BS 2845 and panel (b) showing the Wolf-Rayet star HD 4004.

4. Wavelength Calibration

To convert one-dimensional spectra from pixel space to wavelength space, we perform wavelength calibration using polynomial fitting. Due to the non-linear imaging characteristics of the grating, the dispersion relation can be expressed as:

$$\lambda = a_0 + a_1 \times l + a_2 \times l^2$$

where l is the pixel distance along the trace, and a_0, a_1, and a_2 are the constant, linear, and quadratic coefficients.

Since the slitless spectrograph has no calibration lamps, we use celestial objects with known spectral lines as calibration sources. Our primary targets are standard stars from the European Southern Observatory catalog. Table 1 lists the available calibration lines for each target source. For example, HR 3173 uses H , H , Hδ, Hγ, and Hβ lines; HR 718 uses H , Hδ, Hγ, and Hβ; and BS 2845 uses H , Hδ, Hγ, Hβ, and Hα.

After obtaining the one-dimensional spectral data, we first identify the approximate positions of each spectral line on the CCD. Using Gaussian fitting, we then determine the precise line centers. [Figure 6: see original paper] shows the spectral line center fitting for BS 2845 and HD 4004.

During ground testing, since we cannot obtain direct images of the target sources and most data lack zero-order images, we select a stable absorption line center as the reference point. By calculating the distance l from each line to this reference point and performing polynomial fitting with the corresponding theoretical wavelengths, we obtain the spectral dispersion equation. The theoretical wavelengths used account for redshift corrections, including Earth's rotation and orbital motion. The dispersion equation is fitted to second order.

[Figure 7: see original paper] shows the dispersion equation for HR 718, and [Figure 8: see original paper] shows the residual histogram for this equation. The residuals represent the difference between fitted and theoretical wavelengths.

5. Analysis of Dispersion Equation Coefficients

Since the dispersion equation uses quadratic polynomial fitting with three coefficients (constant, linear, and quadratic terms), we analyze the spatial distribution of these coefficients using the reference point position coordinates.

5.1 Spatial Distribution of Coefficients Three tests yielded 7, 8, and 8 dispersion equations respectively. [Figure 10: see original paper] shows the coefficient distributions across the CCD, with panels (a), (b), and (c) representing the constant, linear, and quadratic terms. The color scale represents coefficient values.

The first test data show subtle differences at different positions, particularly noticeable near one edge location. The second test data are distributed linearly, related to the movement direction during observations. The third test data show clear color partitioning, indicating significant differences in dispersion equation coefficients across different positions.

5.2 Radial Velocity Accuracy The constant term in the dispersion equation represents the fitted wavelength at the reference point. By substituting the distance l from each absorption line to the reference point into the dispersion equation, we obtain a series of wavelength values. Statistical analysis of the residuals yields the standard deviation, which reflects data stability.

[Figure 11: see original paper] shows histograms of reference point fitting accuracy for the three tests. The third test shows more stable reference points. From the fitting residuals, we derive the radial velocity accuracy.

However, this represents only part of the total radial velocity precision. The impact of dispersion equation variations at different positions on spatial distribution must also be considered. For the first test, we calculated radial velocity precision at 7 different positions using standard star BS 2845 (Table 3). For the third test, we calculated radial velocity precision for data with zero-order images (Table 4).

To validate our method, we randomly divided 53 HR 3173 datasets into two groups: 27 for fitting a quadratic surface and 26 for validation. Using the zero-order image as the wavelength zero point, we applied the dispersion equation from the first group to calibrate the second group, achieving an average radial velocity precision of 51 km/s within an 8$×$13 pixel zero-order image position range (Table 5).

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6. Summary and Outlook

We conducted slitless spectroscopy ground tests on the Xinglong 80 cm telescope using data from three observation runs. By polynomial fitting, we obtained dispersion equations and analyzed the spatial distribution of their coefficients on the detector. We also calculated fitting residuals to evaluate radial velocity precision.

The results demonstrate clear spatial variations in dispersion across the detector. Using quadratic surface fitting on zero-order spectral position information and dispersion equation coefficients from 53 HR 3173 datasets, we calibrated wavelengths for HR 718 data within the HR 3173 zero-order image position range, achieving an average radial velocity accuracy of 51 km/s.

Several limitations remain in this work: (1) flat-field effects were not considered during spectral extraction; (2) target selection did not prioritize sources with rich, clear spectral lines; (3) the two-dimensional surface model can only calibrate partial data since zero-order image data do not cover the entire CCD. Future work requires more zero-order spectral data covering the full CCD range to further calibrate spectra at different field positions, construct flat-field cubes, test system stability, and characterize image distortion for more reliable results.

Acknowledgments

We thank the staff of Xinglong Observatory and the CSST Slitless Spectroscopy Data Team for their support. We are grateful to Xuan Fang, Zhizhong Zhou, Jianjun Chen, Linhua Jiang, Fengshan Liu, and Chao Liu for providing the first observation dataset; to Yang Huang and Zihuang Cao for assisting with the second ground test; and to Yanan Cao, Guangyao Xiao, and Peipei Wang for their selfless help, along with other teachers and classmates for their significant support.

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