

# Mock Observations for the CSST Mission: Main Surveys—The Slitless Spectroscopy Simulation (postprint)

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## Abstract

The Chinese Space Station Survey Telescope (CSST), expected to become China's largest space-based optical telescope in the coming decade, is designed to conduct wide-field sky surveys with high spatial resolution. Among its principal observational modes, slitless spectroscopy enables simultaneous imaging and spectral acquisition over a wide field of view, offering substantial advantages for a broad range of astrophysical investigations. As the CSST is currently in the development phase, real observational data are not yet available. Consequently, the construction of its data processing pipeline and the associated scientific preparatory studies must rely on mock data generated through detailed simulations.

This work focuses on developing a simulation framework for the CSST slitless spectral imaging system, and on analyzing its spectral dispersion characteristics and structural design. In addition, the detection performance of the slitless spectroscopic system is evaluated for different classes of astrophysical targets. Simulation results show that nearly all first-order spectra are accompanied by corresponding zero-order images, which is crucial for robust and accurate source identification. Moreover, the GI spectral band exhibits higher detection efficiency than the GV and GU bands, establishing it as the primary observational band for stellar and galactic studies. Overall, this work successfully develops and validates a simulation framework for the CSST slitless spectroscopic instrument.

## Full Text

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Mock Observations for the CSST Mission: Main Surveys—The Slitless Spectroscopy Simulation Xin Zhang<sup>1 aa</sup>, Yue-Dong Fang<sup>2</sup>, Cheng-Liang Wei<sup>3 aa</sup>, Guo-Liang Li<sup>3</sup>, Feng-Shan Liu<sup>1,4</sup>, Hang-Xin Ji<sup>5</sup>, Hao Tian<sup>1 aa</sup>, Nan Li<sup>1,4</sup>, Xian-Min Meng<sup>1</sup>, Jian-Jun Chen<sup>1 aa</sup>, Xia Wang<sup>1</sup>, Rui Wang<sup>1</sup>, Chao Liu<sup>1,4</sup>, Zhong-Wen Hu<sup>4,5</sup>, Ran Li<sup>6</sup>, Peng Wei<sup>1</sup>, and Jing Tang<sup>1</sup> Key Laboratory of Space Astronomy and Technology, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; zhangx@bao.ac.cn  
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telescope in the coming decade, is designed to conduct wide-field sky surveys with high spatial resolution. Among its key observational modes, slitless spectral observation allows simultaneous imaging and spectral data acquisition over a wide field of view, offering significant advantages for astrophysical studies. Currently, the CSST is in the development phase and lacks real observational data. As a result, the development of its data processing pipeline and scientific pre-research must rely on the mock data generated through simulations. This work focuses on developing a simulation framework for the CSST slitless spectral imaging system, analyzing its spectral dispersing properties and structural design. Additionally, the detection performance of the slitless spectral system is assessed for various astrophysical targets. Simulation results demonstrate that nearly all 1st order spectra are accompanied by corresponding 0th order images, facilitating accurate source identification. Furthermore, the GI spectral band exhibits superior detection efficiency compared to the GV and GU bands, establishing it as the primary observational band for stellar and galactic studies. This work successfully develops a simulation framework for the CSST slitless spectroscopic equipment. Key words: methods: numerical -methods: data analysis -techniques: imaging spectroscopy -space vehicles: instruments

1. Introduction complicates the extraction and interpretation of individual Slitless spectroscopy is a highly efficient method for spectral spectra, making the detection and analysis of slitless spectra detection in survey missions, offering unique advantages over inherently more complex than direct imaging observations. traditional slit spectroscopy. Unlike slit-based observations, Slitless spectroscopic surveys were initially implemented in slitless spectroscopy removes the spatial constraints imposed ground-based astronomical observation projects, such as the by a slit, allowing all optical targets within the field of view to Hamburg/ESO Quasar Survey (Wisotzki et al. 1996) and the be dispersed onto a single detector using optical elements such Quasars near Quasars Survey (Worseck et al. 2008). However, as gratings, grisms, or prisms. This approach allows simultaneous ground-based telescopes face limitations due to atmospheric neous spectral acquisition for all detected targets without prior interference, which affects image quality, and stronger stray source selection, significantly improving survey efficiency. light from sources such as the Moon and other terrestrial However, due to this observation method and purpose, factors. In contrast, space-based observations benefit from the slitless spectroscopic observations are not well-suited for high- absence of an atmosphere and significantly reduced stray light, resolution spectral observations. High-resolution spectra enabling higher-quality data acquisition. As a result, large require more area on the detector, and the absence of slits astronomical telescopes have increasingly been deployed in increases

the likelihood of spectral overlap, making it more space. Following the success of the Hubble Space Telescope challenging to achieve high resolution without significant (HST), slitless spectroscopic observations have transitioned contamination. Despite its efficiency, the absence of a slit into space-based platforms. The HST is equipped with introduces challenges, particularly spectral trace overlap in multiple slitless spectrometers designed to address diverse two-dimensional spectroscopic images. This overlap scientific objectives. For example, the NICMOS/Hubble

emission line galaxies at  $1 < z < 2$  and [O III] emission line galaxies at  $2 < z < 3$ . The James Webb Space Telescope (JWST), previously known as the “Next Generation Space Telescope” (NGST, Gardner et al. 2006), is equipped with state-of-the-art instruments, including the Near-Infrared Imager and Slitless Spectrograph (NIRISS, R. Doyon et al. 2012; Ravindranath & Team 2020). NIRISS enables single-object, cross-dispersed slitless spectroscopy, providing simultaneous wavelength coverage from 0.7 to 2.5  $\mu\text{m}$ . The Chinese Space Station Survey Telescope (CSST, Zhan 2011, 2018, 2021) is a major initiative featuring a 2 m aperture off-axis optical telescope system, scheduled to begin operations around 2027. The project offers wavelength coverage ranging from the near-ultraviolet to near-infrared bands (250–1000 nm). In addition to imaging capabilities, CSST is equipped with three bands to enable slitless spectral sky surveys. The slitless spectroscopic survey and imaging survey

Figure 1. CSST focal plane layout. The L-shaped regions on both sides serve as the spectroscopic imaging areas, incorporating a total of 12 detectors, are designed to cover the same 40% of the sky, with whereas the central region is allocated for integral imaging, comprising 18 overlapping fields. The telescope’s field of view spans detectors. approximately 1.1 square degrees, with the slitless spectroscopic observation area accounting for 40% of this coverage. Space Telescope Grism Parallel Survey (McCarthy et al. 1999) A single observation with the CSST can capture a large aimed to identify high-redshift galaxies by detecting their number of celestial objects. However, the design of the CSST emission lines using the G141 grism ( $\lambda_c=1.5 \mu\text{m}$ , spectral imaging system is highly complex, necessitating the  $\Delta\lambda=0.8 \mu\text{m}$ ). The GRAPES (Pirzkal et al. 2004) focuses on simulation data for its slitless spectra. This simulation data is investigating high-redshift galaxies ( $4 < z < 7$ ) within the critical for supporting the development and iterative refine- Hubble Ultra Deep Field (UDF) using the grism spectrometer ment of the slitless spectral data processing pipeline. of the Advanced Camera for Surveys (ACS). Similarly, the Additionally, analyzing the simulation data allows for a PEARS survey (Straughn et al. 2009; Pirzkal et al. 2013) comprehensive evaluation of the scientific capabilities and employs the ACS G800L grism spectrometer to search for effectiveness of the CSST slitless spectral sky surveys. emission-line galaxies in the GOODS-N and GOODS-S fields This paper mainly introduces the CSST slitless spectral by detecting key emission lines such as  $H\alpha$ , [O III], and [O II]. simulation system. Section 2 provides an overview of CSST 3D-HST (Brammer et al. 2012) is a slitless spectroscopic slitless spectrum. Section 3 presents the methods of slitless sur-

vey designed to collect galaxy spectra across three-quarters spectral simulation. Section 4 shows the simulation results and of the CANDELS fields (Grogin et al. 2011; Koekemoer et al. related analyses of slitless spectra. Section 5 discusses the 2011) using the WFC3/G141 and ACS/G800L grisms. This slitless spectral simulation in future. project aims to refine measurements of the cosmos and uncover evidence of galaxy formation and evolution. Furthermore, all major on-going space-based optical tele- 2. The Overview of CSST Slitless Spectroscopic scope missions plan to incorporate slitless spectrometers to Instrument advance astronomical research. The Euclid (Laureijs et al. The CSST survey initiative is designed with two primary 2011) is a mission featuring a 1.2 m space-based Korsch observational modes: multi-color imaging and slitless telescope equipped with optical and infrared wide-field spectroscopy. These modes operate concurrently, with multiimagers and slitless spectroscopy. It aims to measure the color filters dedicated to imaging observations and diffraction shapes and redshifts of galaxies and galaxy clusters up to gratings for slitless spectroscopy, both strategically positioned redshifts of 2. The Wide Field Infrared Survey Telescope at distinct locations across the focal plane. Figure 1 illustrates (WFIRST, Green et al. 2012), now known as the Nancy Grace the schematic layout of the CSST focal plane, which consists Roman Space Telescope, is the most sensitive infrared space- of 30 detector imaging areas. Of these, 18 central detectors are based telescope, featuring a 2.4 m aperture for imaging and allocated for the multi-color imaging survey, while the slitless spectroscopic observations. One of its primary remaining 12 detectors, arranged in L-shape configuration on missions, the Galaxy Redshift Survey (GRS, Spergel et al. either side, are designated for spectroscopic imaging. 2015), utilizes a grism to measure the angular diameter The CSST slitless spectrograph uses diffraction gratings as distance,  $DA(z)$ , and the expansion rate,  $H(z)$ , by studying  $H\alpha$  the dispersive elements because of their simple design and

(a) (b)

Figure 2. CSST grating structure. The two gratings disperse toward the center avoid the lost of 1st order spectrum. (a) illustrates a schematic diagram of a slitless spectroscopic imaging region, which consists of a single detector and two opposing diffraction gratings designed for spectral dispersion. Solid lines indicate the propagation direction of light altered by the grating, while dashed lines indicate the propagation direction of light without the grating. (b) depicts the layout of the slitless spectroscopic imaging region on the focal plane. Each detector is divided into two segments due to the presence of the two opposing diffraction gratings positioned above it.

high resolution capability. Table 1 shows CSST slitless Table 1 Design Parameters of CSST Slitless Spectrograph spectrograph design parameters. In the design, the primary working order of the slitless spectrograph is the 1st order Band Centrala Minb Maxb Rc (nm) (nm) (nm) spectrum. The gratings for the slitless spectrograph are positioned approximately 70 millimeters above the detectors. GU 337 255 410 287

Based on the characteristics of the gratings and their dispersive GV 525 400 640 232 properties, the entire grating disperses the 1st order spectrum GI 810 620 1000 207 in a single direction. This results in some of the 1st order spectrum being dispersed outside the detector area. To ensure Notes. a that the 1st order spectrum is dispersed within the detector as Central wavelength of the spectral band. b Designed maximum and minimum wavelengths within each spectral band. much as possible, the CSST slitless spectrograph grating c R denotes the spectral resolution at the central wavelength. structure features an innovative design. Each grating assembly above the detectors consists of two gratings, with each grating dispersing toward the center of the detector. This design grating diffraction efficiency and the quantum efficiency (QE) of the CCD. guarantees that all 1st order spectra are imaged within the detector. Figure 2 shows this grating structure. 3. Methods for Slitless Spectroscopic Simulation The primary orders of the slitless spectrograph are the 0th Based on the Optical System order image and the 1st order spectrum. For the 1st-order spectrum, the minimum average efficiency requirements are 3.1. The Principle of Grating Spectroscopy set at 60% for the GU band and 65% for the GV and GI From Section 2 we can know that diffraction gratings with bands. The efficiency of the 0th order image is 5% to 10% of regular patterns is the optical components of the CSST slitless the efficiency of the 1st order spectrum. Note that the above spectrograph. The light diffracted by a grating is found by parameters are design specifications; the actual measured summing the light diffracted from each of the elements, and is efficiency will be subsequently updated in the software of essentially a convolution of diffraction and interference CSST Main Survey Simulator.7 Figure 3 illustrates the patterns. So all gratings have intensity maxima at angles  $\theta_m$  throughput of the CSST gratings for the 0th order and 1st which are given by the grating equation order spectra, including optical transmission, filter throughput,  $m = d (\sin i \pm \sin m)$ , (1) where  $\theta_i$  is the angle at which the light is incident,  $\theta_m$  is the [https://csst-tb.bao.ac.cn/code/csst-sims/csst\\_msc\\_sim](https://csst-tb.bao.ac.cn/code/csst-sims/csst_msc_sim) diffraction angles,  $d$  is the separation of grating constant, and

Figure 5. Schematic diagram of spectral dispersion image. This schematic diagram illustrates the pixel grid of the detector. The red star indicates the directly imaged position on the detector (virtual image), while the colored lines represent the dispersed first-order spectrum across the detector surface. Each pixel integrates photons within a wavelength interval  $\Delta\lambda$ .

this sketch, the definition of  $\theta_m$  and  $\theta_i$  is the same as described Figure 3. The throughput of 0st order and 1st order spectrum of CSST three above,  $D$  represents the average distance between the grating bands, including optical transmission, filter throughput, grating diffraction and the focal plane,  $D_m$  is the distance between the diffraction

efficiency and the quantum efficiency (QE) of the CCD. The throughput of the 0st order spectrum is globally scaled according to the efficiency of the 1st point and the origin,  $\theta_f$  shows the angle between the focal order spectrum, adjusted to 10% of the 1st order spectral efficiency. plane and the grating plane. According

to Equation (1) and the geometric relationship in Figure 4,  $D_m$  can be expressed as:

$$D_m = d \sin(\theta_i) - d \cos(\theta_m) \quad (2)$$

In the equation,  $\theta_i$ ,  $\theta_m$ ,  $\theta_f$ ,  $D$  and  $D_m$  follow Equation (2) definitions, while  $d$  denotes the grating constant. For the CSST grating design, this constant ( $d$ ) is determined by the groove density.  $D_m$  represent the position of the light with wavelength  $\lambda$  in the detector. From Equation (2), we can find that the position  $D_m$  is only related to the wavelength, giving the optical path remains unchanged. Furthermore,  $D_m$  is linearly related to the wavelength. In addition, if the lines of the grating are parallel and uniform, the spectrum obtained by the Figure 4. The Schematic Diagram of CSST Slitless Spectrograph Optical dispersion will also appear as a straight line. In the subsequent Path.  $\theta_i$  is the incident angle, defined as the angle between the incident light simulations, we will also assume that the relationship between ray and the grating normal;  $\theta_m$  is the diffraction angle, defined as the angle  $x$  and  $y$  coordinates on the detector, where the spectrum is between the diffracted light ray and the grating normal;  $\theta_f$  is the grating tilt imaged, is linearly correlated based on this premise. angle, defined as the angle between the grating surface and the focal plane;  $D$  represents the average distance between the grating and the focal plane,  $D_m$  is the distance between the diffraction point and the origin where the grating 3.2. The Representation Methods for Slitless Spectra normal intersects the focal plane. From Section 3.1, we can conclude that the position of the spectrum image along the  $y$ -axis ( $y$ ) in relation to the  $x$ -axis ( $x$ ),  $m$  is the number of spectrum order which is integer. The sign as well as the position  $D_m$  with respect to the wavelength  $\lambda$ , “ $\pm$ ” in the equation depends on the relative positions of the exhibit a linear relationship. Figure 5 provides a schematic incident and diffracted rays relative to the grating normal: the illustration of the spectrum being imaged on the detector. In sign of “ $-$ ” applies when both rays reside on the same side of the diagram, the direct image serves as a virtual image, which the normal, whereas the sign of “ $+$ ” is used when they lie on is utilized as a reference point for wavelength calibration. We opposite sides. can use a polynomial to describe the positional relationship of Based on the optical path design of the CSST, it is evident the spectrum as Equation (3). that the incident light strikes the grating at a specific angle relative to its normal, while the grating itself is oriented at a  $y = a_0 + a_1x + a_2x^2 + \dots + a_nx^k$ . (3) distinct angle relative to the focal plane, resulting in a nonparallel configuration between these components. Figure 4 Based on the above description, the spectrum trace can be shows the sketch of CSST slitless spectrograph optical path. In represented by a 1st order polynomial, so the spectrum trace

can described by  $y = a_0 + a_1x$ . (4) In addition, the trajectory of the spectrum is also related to the incident position of light. Here, we believe that the trajectory of spectral dispersion is related to the position where light directly falls on the detector (that is, the position of direct imaging). So we can use the direct image position ( $m$ ,  $n$ ) to describe the coefficients of spectrum trajectory  $a_0$  and  $a_1$  as

follows:  $a_k = b_{k,0} + b_{k,1}m + b_{k,2}n + b_{k,3}m^2 + b_{k,4}n^2 + b_{k,5}mn$  (5) so  $y = b_{0,0} + b_{0,1}m + b_{0,2}n + b_{0,3}m^2$  Figure 6. The Points of Optical Simulation. For each grating,  $10 \times 10 + b_{0,4}n^2 + b_{0,5}mn$  positions are selected. The stars in the figure are the positions of direct imaging. The dotted lines are the 1st order spectra. Each direct imaging point  $(b_{1,0} + b_{1,1}m + b_{1,2}n + b_{1,3}m^2 + b_{1,4}n^2 + b_{1,5}mn)$  x. (6) composed of eight points.

From experience, the coefficients of the spectral trajectory are 3.3. Fitting the Trajectory of Spectra well-represented by the aforementioned two-dimensional second-order polynomial. As shown in the previous section, the trajectory of the Similarly, we can use a polynomial to describe the spectrum can be described by Equations (6), (11) which are relationship between the wavelength of the spectrum and the both related to the imaging position (m, n). So we need to spectral position. obtain the spectral trajectory characteristics of imaging at 2 k different positions on the detector. Since there is no measured  $= 0 + 1$  L trace  $+ 2$  L trace  $+ \dots + n$  L trace. (7) observation data, we take the data from optical simulation as Ltrace represents the length of spectral trajectory in the spectral the input for fitting the spectral trajectory. The optical position (x, y), can be described by simulation includes the black box model of the main optical path of the optical system (Ban et al 2026) and the design of X L trace  $= dx^2 + dy^2$ ,  $y = f(x)$ . (8) the CSST slitless spectrometer grating. Here, it is necessary to 0 simulate the changes in imaging spectra at different positions Similarly, we can use a polynomial to describe the relationship on the entire detector for the grating. Therefore, we have between the wavelength of the spectrum and the spectral designed relatively dense sampling. Due to the unique design position. So Equation (7) can be removed the higher-order of the CSST slitless spectrometer, as we can see from Figure 2, terms as two gratings cover one detector. Therefore, we have selected  $10 \times 10$  sampling points within the range of a single grating.  $= 0 + 1$  L trace. (9) Through optical simulation, we obtain the spectral trajectory The coefficients  $\$0$  and  $\$0$  can be described by a position- characteristics of 100 positions. For each spectral trajectory, dependent polynomial like Equation (5) as eight wavelengths are uniformly selected for representation. The working orders of the CSST slitless spectrum are the 0th-  $2 + 2k = k, 0 + k, 1m + k, 2n + k, 3m, k, 4n + k, 5mn$ . order image and the 1st order spectrum. In addition, we have (10) added three non-working order spectra in the simulation—the 2nd, -1st, and +2nd orders. Therefore, the optical simulation By combining Equation (10) and Equation (7), we can perform a total of five order spectral simulations (0th,  $\pm 1$ st, represent lambda with the following equation and  $\pm 2$ nd) for each position. Figure 6 shows the positions of  $= 0, 0 + 0, 1m + 0, 2n + 0, 3m$  the optical simulation sampling points. This figure takes GV as  $n^2 +$  an example. GU and GI are similar to this. The figure only  $+ 0, 4 0, 5mn^2$  shows the positions of the 1st order spectra. The other orders  $+ ( 1, 0 + 1, 1m + 1, 2n + 1, 3m$  are similar to this, except that the dispersion direction and  $+ 1, 4n + 1, 5mn)$  L trace. (11) position are slightly different.

For each grating, the data of the  $10 \times 10$  positions as each grating. As illustrated in Figure 7, the error was found to be less than 0.2 pixels for both the 0th and 1st order spectra at Equation (6) and Equation (11) need to be fitted respectively. the working level. We use the least squares method to fit the 12 parameters  $b = [b_{0,0}, b_{0,1}, b_{0,2}, b_{0,3}, b_{0,4}, b_{0,5}, b_{1,0}, b_{1,1}, b_{1,2}, b_{1,3}, b_{1,4}, b_{1,5}]$ . Through the description of the above sections, we have shown the method of spectral description. For the spectral representing the spectral position and the 12 parameters —description of different orders, we have adopted the description method of the aXe extraction software (Kümmel et al. 2009). Each grating corresponds to a configuration file, which contains the polynomial parameters of the spectral trajectory of representing the relationship between spectral wavelength and each order and the light transmission efficiency of the position. For the fitting of spectral position parameters, spectrum. For detailed description, see the CSST simulation Equation (12) is constructed. Using the configuration files of different gratings

b

$$\begin{aligned}
 & b_{0,0} X_{m,n} b_{0,1} Y_{m,n} b_{0,2} y_0 b_{0,3} m_{m,n} b_{0,4} n_{m,n} b_{0,5} m_{m,n} n_{m,n} x_0 m_{m,n} x_0 n_{m,n} x_0 m_{m,n} x_0 n_{m,n} x_0 \\
 & y_1 b_{0,3} m_{m,n} m_{m,n} n_{m,n} x_1 m_{m,n} x_1 n_{m,n} x_1 m_{m,n} x_1 n_{m,n} x_1 \dots b_{0,4} \dots \dots b_{0,5} \dots \\
 & (12) = \dots \dots b_{1,0} \dots \dots b_{1,1} y_i m_{m,n} m_{m,n} n_{m,n} x_i m_{m,n} x_i n_{m,n} x_i m_{m,n} x_i n_{m,n} x_i \\
 & m_{m,n} x_i n_{m,n} x_i m_{m,n} x_i n_{m,n} x_i m_{m,n} x_i n_{m,n} x_i m_{m,n} x_i n_{m,n} x_i m_{m,n} x_i n_{m,n} x_i
 \end{aligned}$$

X represents the data matrix, b is the parameter vector and Y and the efficiency files of different spectra orders, we can is the data result related to X. (m, n) is the position where the generate spectral images of different orders of the target source light directly enters the focal plane (or detector), (xi, yi) denotes on the image. By adding the sky light, cosmic rays and CSST the position of spectra whose origin is the position (m, n) instrument effects (including background, dark current, gain of where the light enters the focal plane. The least squares method 16-channel readout, nonlinearity, brighter-fatter effect, photo- Equation (13) is used to fit the parameter vector b. The one response non-uniformity (PRUN), bad pixels, bad pixel with the smallest residual is selected as the fitting result. The columns, blooming, etc.) to this image, we can obtain spectral fitting method for the parameter vector is the same as that images under different gratings. From the image results, it can for b. Refer to the fitting process of b for details. be seen that the image contains the unique bidirectional  $\min ||Xb - Y||_2$ . (13) spectroscopic characteristics of CSST slitless spectra. Figure 8 b presents the results of the CSST slitless spectral simulation images, displaying the simulation outcomes for detectors To verify the fitting results, the following procedure was corresponding to GU, GV, and GI. The results reveal that the adopted. For each grating, the x-coordinates at the  $10 \times 10$  edges of the images exhibit slight darkening, a phenomenon input positions were used as inputs to the fitting polynomial, attributed to dispersion. Specifically, at the image

edges,  $a$  and the corresponding  $y$ -values were calculated. These portion of the light is dispersed beyond the detector's calculated  $y$ -values were then compared with the true  $y$ -values boundaries. In addition, it can also be seen from the image at each position. The statistical error between the 100 calculated  $y$ -values and the true values was computed for [https://csst-tb.bao.ac.cn/code/csst-sims/csst\\_msc\\_sim](https://csst-tb.bao.ac.cn/code/csst-sims/csst_msc_sim)

Figure 7. The fitting results of the spectra positions. The  $x$  of every spectrum of the  $10 \times 10$  positions every grating is used as an input to the fitting polynomial to calculate the result  $y$ , which is compared with the input  $y$ . The error of all  $y$  values on each grating is calculated to obtain the fitting error of each grating.

(a) GU (b) GV (c) GI Figure 8. CSST slitless spectrum image simulation results. Image size is  $9 \text{ k} \times 9 \text{ k}$ .

that there will be a bright strip in the area slightly to the left of dispersion profile used in the simulations is directly applicable. the middle of the image. This phenomenon is particularly These two pieces of information are critical for spectral obvious in the GI band. This is because of the design of extraction, and by avoiding measurement errors in these bidirectional spectroscopy, and the sky light is dispersed to the aspects, we are able to achieve nearly perfect spectral middle. Figure 9 shows the cutout of the two-dimensional extraction results. In practical data processing, the accuracy spectra of three bands of a galaxy. Extract these three spectra of wavelength positioning largely depends on the precision of and compare them with the input spectra. As can be seen from the spectral dispersion profile construction and the centering the figure, the spectra extracted from the simulation data can accuracy of the reference point. Assuming that one resolution be well matched with the input spectra. element of the slitless spectrum spans 4 pixels (with  $R80 = 0.3$  In the aforementioned measurements, we rely on two ideal and a pixel size of  $0.074$ ), and if the combined precision of assumptions: first, the reference point for the measurements these two factors is  $0.5$  pixels, the wavelength deviations for (either the direct imaging position or the position of the 0th the GU, GV, and GI bands, calculated based on the data in order image) is precisely known, and second, the spectral Table 1, would be  $1.47 \text{ \AA}$ ,  $2.83 \text{ \AA}$ , and  $4.89 \text{ \AA}$ , respectively.

(a) single source spectrum image  
 (b) 1d spectrum extracted Figure 9. Presentation of spectrum extracted from simulation data. (a) includes GU, GV, GI and direct image of a galaxy. (b) shows the extracted result.

Figure 10. The corresponding relationship between the brightness and signal-to-noise ratio of the target source of the detected 1st order spectrum.

Taking the central wavelength of the GI band ( $8100 \text{ \AA}$ ) as an Table 2 example, if the rest wavelength is  $5000 \text{ \AA}$  and the measure- Number Density Estimation of Galaxies and Stars under CSST Slitless ment deviation is  $4.89 \text{ \AA}$ , the combined errors from reference Spectrum Imaging point centering and spectral dispersion

profile measurement GU GV GI would lead to an impact on the spectroscopic redshift precision (arcmin<sup>-2</sup>) (arcmin<sup>-2</sup>) (arcmin<sup>-2</sup>) of approximately 1. This estimate does not yet include the 0st Order (total) 1.11 3.56 7.43 more complex instrumental effects, underscoring that precise 1st Order (total) 0.82 1.99 4.32 spectral extraction is crucial for achieving accurate photometric redshift measurements in practical observations. 1st Order (stellar) 0.81 1.68 1.96 Using Galaxia as the input of the stellar catalog and 1st Order (galaxy) 0.01 0.31 2.36 CosmoDC2 as the input of the galaxy catalog, a region of approximately 0.4 square degrees is selected for statistics in the central region with R.A. and decl. of [60, -40]°. In this in Table 2, the results here are all from simulations with a definition, if the signal-to-noise ratio of a single pixel in the single exposure of 150 s. As shown in the table, nearly all observation area of the target source is greater than 1, it is detectable 1st order spectra have corresponding 0th order considered that the target position is an observable source. images detectable, except in cases where the 0th order image From the above definition, we can obtain the results as shown falls outside the detector's field of view. The detection

efficiency of GU is much lower than that of GV and GI. various wavelengths can be captured on the detector. Using the In addition, due to galaxy spectra, the detection of galaxies in fitting method described in this paper, a configuration file the GI band is much higher than in the other two bands. characterizing the grating's spectral dispersion properties can Figure 10 illustrates the relationship between the brightness be generated. By fitting the measured data, the spectral and signal-to-noise ratio (SNR) of the target source for the 1st characteristics of the CSST slitless spectrometer will be more order spectrum. As evident from the figure, the SNR of the accurately and realistically represented. detected spectrum follows the order GI > GV > GU. Notably, the SNR of GU is significantly lower compared to the other Acknowledgments two bands. Consequently, not only is the number of GU bands This work is supported by the project of the CSST scientific limited, but the measurement accuracy is also reduced due to data processing and analysis system of the China Manned its lower SNR. Space Project. X.Z. acknowledges the support of the National Natural Science Foundation of China (grant No. U2031143). 5. Summary In this study, the simulation of the CSST slitless spectrum ORCID iDs primarily focuses on modeling the spectral dispersion characteristics of the true spectrum. These characteristics are Xin Zhangaa <https://orcid.org/0000-0001-7314-4169> Cheng-Liang Weiaa <https://orcid.org/0000-0001-5912-7522>

influenced by multiple factors, including the groove density of the grating, the Point-Spread Function (PSF) of the optical Hao Tianaa <https://orcid.org/0000-0003-3347-7596> system, the relative position between the grating and the focal Jian-Jun Chenaa <https://orcid.org/0000-0003-4525-1287> plane, and the manufacturing process of the grating. Due to these factors and the large field of view (FoV) of the CSST, the References image quality cannot be guaranteed to be uniform across all Ban, Z., Li, X., Yang, X., Jiang, Y., & Ma, H. 2026, RAA, 26, 024002 positions. Additionally, the large size of the grating makes it Brammer,

G. B., van Dokkum, P. G., Franx, M., et al. 2012, ApJS, 200, 13 challenging to ensure consistent spectral dispersion character- Doyon, R., Hutchings, J. B., Beaulieu, M., et al. 2012, SPIE, 8442, 84422R Gardner, J. P., Mather, J. C., Clampin, M., et al. 2006, SSRv, 123, 485 istics at every position. Therefore, it is necessary to sample Green, J., Schechter, P., Baltay, C., et al. 2012, arXiv:1208.4012 multiple positions on the same grating to accurately fit the Grogin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, ApJS, 197, 35 spectral dispersion characteristics. Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011, ApJS, 197, 36 Kümmel, M., Walsh, J. R., Pirzkal, N., Kuntschner, H., & Pasquali, A. 2009, Currently, there are no measured spectral data available for PASP, 121, 59 the CSST. As a result, this study adopts an optical simulation Laureijs, R., Amiaux, J., Arduini, S., et al. 2011, arXiv:1110.3193 approach, utilizing optical software to generate spectral data at McCarthy, P. J., Yan, L., Freudling, W., et al. 1999, ApJ, 520, 548 Pirzkal, N., Xu, C., Malhotra, S., et al. 2004, ApJS, 154, 501 different positions on the grating based on the design Pirzkal, N., Rothberg, B., Ly, C., et al. 2013, ApJ, 772, 48 parameters of the optical system and the grating. In future Ravindranath, S., & Team, N. 2020, AAS Meeting, 235, 372.11 laboratory tests, a uniformly perforated coronagraphic mask Spergel, D., Gehrels, N., Baltay, C., et al. 2015, arXiv:1503.03757 Straughn, A. N., Pirzkal, N., Meurer, G. R., et al. 2009, AJ, 138, 1022 will be placed over the grating of the detector to be tested. This Wisotzki, L., Koehler, T., Groote, D., & Reimers, D. 1996, A&AS, 115, 227 setup will allow light to pass through the mask, creating Worseck, G., Wisotzki, L., & Selman, F. 2008, A&A, 487, 539 uniformly distributed point sources across the entire grating Zhan, H. 2011, SSPMA, 41, 1441 Zhan, H. 2018, in 42nd COSPAR Scientific Assembly (2018 July 14-22) area. By illuminating the grating with narrowband light (Pasadena, California, USA), E1.16-4-18 sources of different wavelengths, the dispersed positions of Zhan, H. 2021, ChSBu, 66, 1290

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

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