# Postprint of Time-Series Photometric Precision Analysis Based on CSST Multicolor Photometry

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## Abstract

The Chinese Survey Space Telescope (CSST) is China' s first large-scale space optical telescope, which will conduct research on numerous scientific objectives including exoplanet detection, and is expected to achieve cutting-edge scientific progress. Time-series photometric precision is an important performance indicator for CSST, affected by physical noise and instrumental noise, and requires analysis and evaluation through numerical simulations. Based on the currently published main technical parameters of CSST, the simulation establishes time-series stellar signal and noise models, and analyzes photometric precision in staring observation mode using CSST' s i-band as an example. Through numerical simulation, the contributions of various noise sources in aperture photometry are demonstrated, particularly the jitter noise caused by pointing jitter and pixel response non-uniformity. The simulation results also provide a recommended range for the photometric aperture. To achieve a higher signal-to-noise ratio, one can reduce the instrument jitter amplitude and pixel non-uniformity, or employ differential photometry using reference stars. The results provide simulation data support for subsequent correlation analysis between CSST' s time-series photometric precision and different index parameters, exoplanet detection capability assessment, and photometric data processing.

## Full Text

## Preamble

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### Analysis of Time-Domain Photometric Precision Based on CSST Multi-Color Photometry

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## Abstract

The Chinese Survey Space Telescope (CSST) is China’ s first large space optical telescope, which will conduct research on numerous scientific objectives including exoplanet detection and is expected to achieve frontier scientific progress. Time-domain photometric precision is a crucial performance indicator for CSST, affected by both physical and instrumental noise, requiring analysis and evaluation through numerical simulation. Based on the currently published main technical parameters of CSST, we establish a time-domain model for stellar signals and noise, and analyze the photometric precision in staring observation mode using the i-band as an example. Through numerical simulation, we demonstrate the contributions of various noise components in aperture photometry, particularly the jitter noise caused by pointing jitter and pixel response inhomogeneity. The simulation results also provide a recommended range for the photometric aperture. To achieve higher signal-to-noise ratio, one can reduce the instrument jitter amplitude and pixel non-uniformity, or employ differential photometry using reference stars. The results provide simulation data support for subsequent correlation analysis between CSST’ s time-domain photometric precision and different technical parameters, evaluation of exoplanet detection capabilities, and photometric data processing.

**Keywords:** telescopes, planets and satellites: detection, techniques: photometric, methods: numerical

## 1 Introduction

Over the past two decades, the field of exoplanets has made tremendous progress. With the help of several space missions such as Kepler[1] and TESS (Transiting Exoplanet Survey Satellite)[2], 5,419 exoplanets have been confirmed as of May 16, 2023. The transit method is currently the most widely used exoplanet detection technique, providing information on planetary orbits and planet-to-star radius ratios. Based on stellar parameters provided by telescopes such as Gaia (Global Astrometric Interferometer for Astrophysics)[3] and LAMOST (Large Sky Area Multi-Object Fiber Spectroscopic Telescope)[4], we can obtain more accurate planetary radii, masses, and other information. As the exoplanet sample expands, characterizing the atmospheric features of exoplanets has become a research hotspot. Current studies of exoplanet atmospheres primarily come from transmission spectroscopy observations of transiting planets—during transit, when the planet passes in front of its host star, a portion of the stellar light passes through the planetary atmosphere, exhibiting wavelength-dependent absorption features. By measuring the transmission spectrum during transit, we can infer planetary atmospheric properties such as chemical composition, temperature-pressure structure, and cloud/haze presence. Both exoplanet detection and atmospheric characterization require extremely high photometric precision.

One of the scientific objectives of the Chinese Survey Space Telescope (CSST) is to conduct multi-band photometric and spectroscopic observations of exoplanets, obtain atmospheric spectra of exoplanet systems, and lay an important foundation for future searches and confirmation of biosignature signals. CSST' s primary optical system is a 2-meter off-axis three-mirror anastigmat (TMA) optical system, with backend instruments including multi-color imaging and slitless spectroscopy survey modules, a multi-channel imager, an integral field spectrograph, an exoplanet imaging coronagraph, and a high-sensitivity terahertz module[5]. This paper will perform simulation analysis of CSST' s photometric precision based on multi-color imaging photometric observations.

Photometric precision is affected by various factors, such as photometric variations caused by stellar surface inhomogeneities like spots and faculae[6]. More importantly, photometric precision is subject to interference from various physical and instrumental noises, such as sky background, instrument pointing jitter, and pixel non-uniformity. The magnitude of noise directly affects the signal-to-noise ratio (SNR) in subsequent photometric or spectroscopic observations, thereby influencing planet detection and atmospheric spectral retrieval[7]. Therefore, accurate noise simulation and correction are essential. Previous works have simulated stellar light curves for scientific instruments such as PLATO (PLAnetary Transits and Oscillations of stars), TESS, and JWST (James Webb Space Telescope)[8-10]. Here, we primarily model stellar signals and noise based on CSST' s basic parameters to calculate photometric SNR.

This simulation method is equally applicable to spectral SNR calculations and can be used in spectral SNR estimation. In this work, we simulate CSST' s stellar signals and various noise components, with particular discussion on the impact of instrument jitter and pixel non-uniformity on photometric observation precision, in preparation for subsequent CSST parameter design, data processing modes, and CCD selection. Section 2 describes the computational model for signal and noise simulation; Section 3 presents the parameters used and test results; Section 4 summarizes this work and discusses future research directions.

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## 2 Photometric Precision Calculation Methods

This section primarily describes the computational framework and algorithms for CSST photometric precision simulation. The simulation is divided into three parts. First, we calculate the stellar radiation flux from the stellar spectrum and apparent magnitude (AB magnitude), obtain the point spread function (PSF) from CSST simulation data, consider the effects of pixel response function (PRF) and instrument jitter, and obtain the simulated stellar signal through convolution. Subsequently, we model and calculate various noise terms including Poisson noise, sky background, dark current, readout noise, and stability errors. Finally, we calculate the aperture photometric signal-to-noise ratio (SNR).

### 2.1.1 Stellar Radiation Flux

At the telescope entrance pupil, the flux density $F_{\text{obs}}(\lambda)$ (in units of $\text{erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-2} \cdot \text{nm}^{-1}$) radiated by a star at wavelength $\lambda$ can be calculated from the AB magnitude $m_s$ in that band using:

$$F_{\text{obs}}(\lambda) = 10^{-0.4 m_s} F_0,$$

where $F_0$ is the zero-point flux of that band. Alternatively, $F_{\text{obs}}(\lambda)$ can be calculated from the stellar model flux density spectrum $F_s(\lambda)$ using:

$$F_{\text{obs}}(\lambda) = F_s(\lambda) \left( \frac{R_s}{d} \right)^2,$$

where $R_s$ is the stellar radius and $d$ is the distance from the star to the telescope. Assuming stellar photons are incident on a telescope with effective area $A_{\text{tel}}$ and modulated by a module efficiency $\eta_\lambda$ (including optical elements and detector), the number of electrons received per unit time by the CCD (charge-coupled device) (in units of $\text{e}^- \cdot \text{s}^{-1}$) is:

$$n_{\lambda,s} = \frac{F_{\text{obs}}(\lambda) A_{\text{tel}} \eta_\lambda \Delta\lambda}{hc/\lambda_c},$$

where $h$ is Planck' s constant, $c$ is the speed of light, $hc/\lambda_c$ is the photon energy at the central wavelength $\lambda_c$, and $\Delta\lambda$ is the bandwidth of the observation band.

### 2.1.2 PSF Model

The profile of a star image formed on the focal plane after passing through the telescope optics can be characterized by its PSF, which is related to both field position and wavelength. The CSST project team has released static PSF simulation data from the Cycle 5 data products of the main survey module. Based on the optical design model, this data incorporates error factors such as mirror fabrication, alignment, CCD non-flatness, gravity variations, and thermal deformation, providing static PSF data for various field positions across different bands. To study the effects of different jitter parameters, this work adopts the static PSF data as the basis for subsequent simulation of dynamic PSF (incorporating pixel response inhomogeneity and jitter effects).

The static PSF simulation data provided by CSST samples 30$×$30 uniformly distributed field positions on each detector of the focal plane to ensure PSF interpolation accuracy. Additionally, within each band of the multi-color imaging system, samples at four typical wavelengths are provided to demonstrate the wavelength dependence of the PSF.

For a given wavelength, the PSF at any position within the field of view can be obtained through interpolation from PSF samples at different field positions. CSST' s PSF simulation employs the IDW (inverse-distance weighting) interpolation method[11], where the PSF field varies continuously, and the PSF at any position is interpolated from its four neighboring PSF samples, with interpolation weights inversely proportional to the square of the distance. [Figure 1: see original paper] shows the PSF interpolated at position (0, 0) for a typical wavelength (706.1 nm) in the i-band. Each PSF provides the energy distribution over a 256$×$256 pixel space, with a sampling pixel size of 5 μm. The horizontal and vertical axes represent the positional coordinates of the PSF on the x-y pixel plane. To improve computational efficiency, we do not perform interpolation and accumulation across different wavelengths; when the observation band is relatively narrow, a typical wavelength can be selected to approximate the PSF for the entire band (see Section 3 for details).

### 2.1.4 Instrument Jitter Effects

The stellar flux value on the CCD is affected by the PRF. The PRF differs at different positions within a pixel and between different pixels, referred to as intra-pixel non-uniformity and inter-pixel non-uniformity, respectively. Therefore, after calculating the flux and PSF for a target star, it is necessary to convolve them with the PRF to obtain the final detector readout. If the telescope pointing is stable, we can correct for inter-pixel response non-uniformity through flat-field measurements. However, as described below, instrument jitter effects couple with pixel non-uniform response, introducing photometric noise.

The performance of CSST' s detector has not yet been finalized. This work adopts the pixel model from the Kepler detector in the corresponding band[12], dividing each pixel into 45$×$45 sub-pixel samples to calculate the response at different pixel positions on the detector. [Figure 2: see original paper] shows the intra-pixel response function (IPRF) at 700 nm wavelength on the left panel, and on the right panel adds 1% random differences between different pixels based on the left panel' s response function.

During CSST' s on-orbit observations, micro-vibration environments and fine guidance residuals cause the instrument to generate small-amplitude jitter at certain frequencies, shifting the star image position on the CCD and thereby changing both the PSF and PRF corresponding to the target source, which affects the stellar signal. To analyze the time-domain variations of stellar signals caused by jitter, this work employs numerical simulation to analyze the photometric errors introduced by jitter combined with PRF effects.

First, jitter sequences are generated using the two-dimensional random walk principle. Starting from a point with initial coordinates $(x_0, y_0)$ on a plane, a random walk step is taken every $\Delta t$ time interval. The components $\Delta x_i, \Delta y_i$ of each step in the $x$ and $y$ directions follow a Gaussian distribution with mean 0 and variance $\sigma_0^2$. According to the central limit theorem, after $n$ steps $(n \gg 1)$, i.e., at time $t = n\Delta t$, the total components in the $x$ and $y$ directions both follow Gaussian distributions. Letting $\Delta x_t, \Delta y_t$ be the $x$ and $y$ components of the jitter sequence at time $t$, then $\Delta x_t = \sum(\Delta x_i)$ and $\Delta y_t = \sum(\Delta y_i)$ both $\sim N(0, n\sigma_0^2)$. The displacement $R = \sqrt{(\Delta x_t)^2 + (\Delta y_t)^2}$ then follows a Rayleigh distribution with probability density function:

$$P(R) = \frac{R}{\sigma^2} \exp\left(-\frac{R^2}{2\sigma^2}\right).$$

[Figure 3: see original paper] shows a sample random jitter sequence generated within 300 s based on CSST' s jitter specification (0.05 @300 s). We take a time step of $\Delta t = 0.05$ s, so the $x$ and $y$ components of a single jitter follow a Gaussian distribution with mean 0 and standard deviation $\sigma_0 \approx 0.007$ pixel.

At each time $t$, the point spread function of the target source is the PSF corresponding to position $(x_t, y_t)$, and because the star image falls on different pixels, the corresponding PRF also differs. After a long exposure time $t_{\text{obs}}$, the total number of electrons received at pixel $(x, y)$ (in units of $\mathrm{e}^-$) is:

$$N_{\lambda,s} = \int_0^{t_{\text{obs}}} n_{\lambda,s} * \text{PSF}(x, y) * \text{PRF}(x, y)\, dt, \quad (5)$$

where $*$ denotes convolution, $n_{\lambda,s}$ is the electron flux corresponding to stellar radiation given by Equation (3), and the point spread function $\text{PSF}(x, y)$ and pixel response function $\text{PRF}(x, y)$ are given in Sections 2.1.2 and 2.1.3, respectively.

### 2.2.1 Shot Noise

The light intensity measured at the telescope gives the average number of received photons. The number of photons received by the telescope at any given moment follows a Poisson distribution; therefore, shot noise is also called Poisson noise. Poisson noise tends toward a normal distribution when the particle number is sufficiently large, with its standard deviation equal to the square root of the photon number. For a specific observation system and wavelength, the number of electrons generated by the detector is proportional to the number of photons it receives, thus:

$$\sigma_{\text{PS}} = \sqrt{N_{\lambda,s}},$$

where $N_{\lambda,s}$ is given by Equation (5).

### 2.2.2 Sky Background Noise

The primary sky background affecting CSST photometric observations originates from zodiacal light. Pascale et al.[13] simulate the sum of reflected and emitted components of zodiacal light (in units of $\mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mu\mathrm{m}^{-1} \cdot \mathrm{sr}^{-1}$) using:

$$I_{\mathrm{Zodi}}(\lambda) = \beta[3.5 \times 10^{-14} B_\lambda(5500\mathrm{K}) + 3.58 \times 10^{-8} B_\lambda(270\mathrm{K})],$$

where $B_\lambda(5500\ \mathrm{K})$ and $B_\lambda(270\ \mathrm{K})$ are the Planck blackbody radiation intensities at temperatures of 5500 K and 270 K, respectively, and $\beta$ is a parameter related to ecliptic latitude. Sarkar et al.[10] propose the following polynomial for $\beta$:

$$\beta = -0.22968868\zeta^7 + 1.12162927\zeta^6 - 1.72338015\zeta^5 + 1.13119022\zeta^4 - 0.95684987\zeta^3 + 0.2199208\zeta^2 - 0.05989941\zeta + 2.$$

where $\zeta = \log_{10}(l_{\mathrm{ecl}} + 1)$, and $l_{\mathrm{ecl}}$ is the ecliptic latitude (in degrees).

We adopt an average value of $\beta = 1.3$, which yields zodiacal light from Equations (7)-(8) consistent with the average zodiacal light value of 22.7 $\mathrm{mag} \cdot \mathrm{arcsec}^{-2}$ given by HST[14].

The number of electrons generated per pixel per unit time on the CCD due to zodiacal light radiation (in units of $\mathrm{e}^- \cdot \mathrm{s}^{-1} \cdot \mathrm{pixel}^{-1}$) is:

$$n_{\mathrm{Zodi}} = \frac{I_{\mathrm{Zodi}} A_{\mathrm{tel}} \Omega_{\mathrm{pix}} \eta_\lambda}{hc/\lambda_c},$$

where $\Omega_{\mathrm{pix}}$ is the pixel solid angle.

After an exposure time $t_{\mathrm{obs}}$, sampling $n_{\mathrm{pix}}$ pixels, the zodiacal light noise can be expressed as:

$$\sigma_{\mathrm{bg}} = \sqrt{n_{\mathrm{Zodi}} n_{\mathrm{pix}} t_{\mathrm{obs}}}.$$

### 2.2.3 Dark Current Noise

The primary thermal noise source in the detector is dark current, which refers to the tiny current generated even when the detector receives no photons. Dark current magnitude is temperature-dependent and accumulates with integration time, also following a Poisson distribution.

Let the average dark current per pixel per unit time be $n_{\mathrm{dc}}$ (in units of $\mathrm{e}^- \cdot \mathrm{s}^{-1} \cdot \mathrm{pixel}^{-1}$). After an exposure time $t_{\mathrm{obs}}$, sampling $n_{\mathrm{pix}}$ pixels, the dark current noise can be expressed as:

$$\sigma_{\mathrm{dc}} = \sqrt{n_{\mathrm{dc}} n_{\mathrm{pix}} t_{\mathrm{obs}}}.$$

### 2.2.4 Readout Noise

When the CCD reads out the signal, converting charge on pixels to numerical values generates readout noise. Readout noise is non-uniform across pixels and is typically characterized by the root mean square (RMS) of electron counts, denoted as $n_{\mathrm{ro}}$ (in units of $\mathrm{e}^-$ RMS/pixel). Sampling $n_{\mathrm{pix}}$ pixels with $n_{\mathrm{exp}}$ readouts, the readout noise can be expressed as:

$$\sigma_{\mathrm{ro}} = \sqrt{n_{\mathrm{pix}} n_{\mathrm{exp}}}\, n_{\mathrm{ro}}.$$

### 2.2.5 Jitter Noise

As described in Section 2.1.4, jitter causes the stellar position on the detector to shift, and different positions correspond to different PSFs and PRFs, thus introducing additional noise into photometry, namely jitter noise. We generate multiple random jitter sequences, perform repeated measurements of the same target source, obtain the sequence of total electrons received by CCD pixels $N_{\lambda,s}^{\mathrm{Array}}$, and calculate its standard deviation (STD) as the jitter noise within an exposure time $t_{\mathrm{obs}}$ and $n_{\mathrm{pix}}$ pixels:

$$\sigma_{\mathrm{jt}} = \mathrm{STD}(N_{\lambda,s}^{\mathrm{Array}}),$$

where $N_{\lambda,s}^{\mathrm{Array}}$ is obtained through multiple calculations using Equation (5).

## 2.3 SNR Calculation Model

According to Sections 2.1 and 2.2, the target source signal is given by Equation (5), and noise is given by Equations (6)-(13). The total noise is:

$$\sigma_{\mathrm{tot}} = \sqrt{\sigma_{\mathrm{PS}}^2 + \sigma_{\mathrm{bg}}^2 + \sigma_{\mathrm{dc}}^2 + \sigma_{\mathrm{ro}}^2 + \sigma_{\mathrm{jt}}^2},$$

where $\sigma_{\mathrm{PS}}$, $\sigma_{\mathrm{bg}}$, $\sigma_{\mathrm{dc}}$, $\sigma_{\mathrm{ro}}$, and $\sigma_{\mathrm{jt}}$ are Poisson noise, sky background noise, dark current noise, readout noise, and jitter noise, respectively.

The signal-to-noise ratio is calculated as:

$$\mathrm{SNR} = \frac{N_{\lambda,s}}{\sigma_{\mathrm{tot}}} = \frac{N_{\lambda,s}}{\sqrt{N_{\lambda,s} + n_{\mathrm{bg}} n_{\mathrm{pix}} t_{\mathrm{obs}} + n_{\mathrm{dc}} n_{\mathrm{pix}} t_{\mathrm{obs}} + n_{\mathrm{ro}}^2 n_{\mathrm{pix}} n_{\mathrm{exp}} + \sigma_{\mathrm{jt}}^2}},$$

where the parameters have the same meanings as in Sections 2.1 and 2.2.

The stellar photometric SNR calculated above can be used to determine whether exoplanets can be detected in this mode. The typical transit depth of hot Jupiters around Sun-like stars is about 1%. Kepler typically limits the transit signal SNR for planet candidate identification to SNR $> 7.1$[15], although some works have explored the reasonableness of SNR  6[16]. Here we select SNR $> 6$ as the detection threshold for transit signals. By dividing the typical hot Jupiter transit depth value by the transit signal SNR threshold, we consider that when the noise level of stellar observations is $\leq 1/600$, i.e., when the stellar photometric SNR $> 600$, the system has the capability to detect exo-Jovian planets.

## 3 Aperture Photometry Simulation and Test Results

This section presents the test results and analysis of CSST aperture photometric precision simulation in specific bands. First, we introduce the system and target source parameters used in the tests, followed by a description of the photometric aperture selection method. Next, we discuss in detail the effects of different instrument jitter and pixel response parameters on stability errors, and consider the improvement in photometric precision through differential photometry with reference stars. Finally, we compare simulation results from two sub-bands to demonstrate the reasonableness of extrapolating these tests to wide-band photometry.

[Figure 4: see original paper] shows the filter arrangement for multi-color imaging and slitless spectroscopy on the focal plane. The red square indicates the test band in our work.

### 3.2 Photometric Aperture Selection

The focal plane layout of CSST' s multi-color imaging and slitless spectroscopy survey module is shown in Figure 4. The main focal plane covers a central field of view of 1.1° × 1.2°, containing bands such as NUV, u, g, r, i, z and GU, GV, GI (see CSST Science White Paper for details). The fine guidance sensor (FGS) and wavefront sensor (WFS) focal planes are distributed in auxiliary imaging areas on both sides, while the photometric calibration component and near-infrared (NIR) focal plane are distributed in the remaining field of view. We select a detector corresponding to the i-band filter, whose position on the detector focal plane is marked by a red box in Figure 4, and use one of its sub-bands with a central wavelength of 706.1 nm and bandwidth of 32.2 nm as an example for testing. CSST' s survey staring mode has a single exposure time of 300 s. Based on the detector' s full well electron capacity, we select a star with i-band AB magnitude of 16 mag (radiation flux density of 8.69$×10^{-15}$ erg·s$^{-1}$·cm$^{-2}$·nm$^{-1}$) as the target source. The jitter frequency is set to 20 Hz. The main technical parameters of CSST' s primary optical system and multi-color imaging module used in the calculations are shown in Table 1.

The photometric aperture is an important parameter for flux extraction, and determining the optimal aperture value is essential for accurate photometry. If the aperture is too small, it cannot contain enough target source photons, and small offsets in the star image center will introduce large errors into photometry. If the aperture is too large, sky background and other noises will excessively remain within the aperture, significantly reducing photometric precision, especially for faint targets. Additionally, for dense star fields, an overly large aperture may introduce flux from other sources. Typically, the photometric aperture size is selected to be 3–4 times the PSF full width at half maximum (FWHM). [Figure 5: see original paper] shows the relationship between SNR and the ratio of various noise components to signal versus photometric aperture size and shape. Simple tests show that when using square and circular apertures for photometry, if the square side length equals the circular diameter, the photometric precision of the square aperture is similar to $\sqrt{2}$ times that of the circular aperture; if square and circular apertures with similar numbers of pixels are selected, the resulting SNR is comparable. As shown in the left panel of Figure 5, the magenta dot shows the photometric SNR for a circular aperture with diameter of 11 pixels, and the red dot shows the SNR for a circular aperture with diameter of 12.4 pixels. This indicates that photometric precision is related to the number of pixels contained within the photometric aperture and is insensitive to aperture shape. To simplify the problem, this work selects square photometric apertures for simulation. In actual photometry, jitter in each image may cause the star image to elongate in random directions, breaking the symmetry of the star image. Using symmetric aperture photometry may not be optimal, and more accurate photometric apertures need to be determined using PSF fitting methods combined with the star image to improve photometric precision. Additionally, differential photometry using reference stars can partially offset the effects of random jitter offsets (see Section 3.5 for details).

**Table 1 Main technical parameters in our simulation**

| Characteristic | CSST Performance |
|---|---|
| Diameter | 2000 mm |
| Focal Length | 28000 mm |
| Field of View | 1.7 $\mathrm{deg}^2$ |
| Wavelengths | 0.69–0.83 μm (i band) |
| Pixel Size | 15 μm |
| Plate Scale | 0.074 |
| Module Efficiency | 0.62 @ i band |
| Accuracy of Image Stabilization | 0.05 @300 s |
| Dark Current | 0.02 $e^- \cdot s^{-1} \cdot \mathrm{pixel}^{-1}$ @ detector temperature |
| Readout Noise | 5 $e^- \cdot \mathrm{pixel}^{-1}$ |
| Full Well | 90 $ke^-$ (average) |

At the wavelength selected in this section, the PSF FWHM is approximately 2.8 pixels without considering jitter effects, and increases to an average of about 3.5 pixels when jitter effects are included. Therefore, we search for the optimal aperture value within the range of 8–15 pixels.

We adopt CSST' s instrument jitter parameters (single jitter standard deviation $\sigma_{\mathrm{CSST}} \approx 0.007$ pixel), use the Kepler pixel model as the intra-pixel response function, and add 1% random differences between different pixels. Ten sets of random tests are performed, with the mean taken as the stellar signal and the RMS as jitter noise. Figure 5 shows the variation of photometric SNR and various noise components with photometric aperture size. It should be noted that the relative error of SNR is below 1%, so error bars are not prominently displayed in the figure.

According to the test results, increasing the aperture can significantly reduce jitter noise, while Poisson noise, sky background, dark current, and readout noise increase slightly. When the aperture value is $< 11$ pixels, instrument jitter noise dominates, while when the aperture value $> 11$ pixels, SNR depends more on Poisson noise. When the aperture value $> 11$ pixels, the photometric SNR $> 600$. With an aperture value of 13 pixels, approximately 92% of the target source flux is contained within the aperture. When the aperture value $> 13$ pixels, increasing the aperture yields only small improvements in SNR, which stabilizes at approximately 700. Considering the ideal photometric SNR, selecting a square aperture side length of 11–13 pixels is reasonable. For computational efficiency, this work uses a square aperture with side length of 11 pixels for subsequent tests.

### 3.3 Impact of Instrument Jitter Amplitude on Jitter Noise

This section tests the impact of instrument jitter amplitude on photometric precision. The STD of CSST' s single jitter is $\sigma_{\mathrm{CSST}} \approx 0.007$ pixel. We select 10×, 5×, 2×, 1×, and 0.5× the CSST jitter variance parameter (denoted as 10×, 5×, 2×, 1×, 0.5×), performing 10 sets of random tests for each case to calculate the noise and SNR produced by different jitter sequences. The results are shown in [Figure 6: see original paper]. To isolate the effect of jitter, we assume uniform pixel response across the CCD. It should be noted that the relative error of SNR is below 1%, so error bars are not displayed in the figure.

According to the test results, as the jitter sequence standard deviation decreases, jitter noise is significantly reduced and photometric precision is substantially improved. This is because when the jitter amplitude is too large, the star image position at each moment experiences large random offsets, and under the integration effect of long exposure times, this accumulates into substantial jitter noise. When the jitter standard deviation is 2–10 times $\sigma_{\mathrm{CSST}}$, reducing the jitter standard deviation can significantly improve SNR. When the jitter standard deviation is $\leq \sigma_{\mathrm{CSST}}$, SNR $> 600$, and further reducing the jitter standard deviation yields only small improvements in SNR.

Therefore, we should minimize jitter amplitude as much as possible so that the resulting jitter noise is significantly smaller than photon noise. This result demonstrates that CSST' s current jitter specification is reasonable. It should be noted that in actual observations, when jitter causes the star image to deviate far from its initial position, the telescope may actively control to pull the star image back near the initial position. This discontinuous sudden change is not considered in this section.

### 3.4 Impact of Pixel Non-Uniformity on Jitter Noise

According to the computational model in Section 2.1.4, the effects caused by jitter and pixel non-uniformity are closely coupled. This section tests the impact of pixel non-uniformity on photometric precision. We select the following six groups of pixel response functions for testing:

(1) Uniform response everywhere, both intra-pixel and inter-pixel, denoted as "uniform" ;

(2) Non-uniform intra-pixel response, with intra-pixel response function (IPRF) following the Kepler pixel model and consistent IPRF across pixels, denoted as "IPRF + 0.00" ;

(3) Non-uniform intra-pixel response with IPRF following the Kepler pixel model, and non-uniform inter-pixel response with 1% random differences added between different pixels based on the Kepler IPRF, denoted as "IPRF + 0.01" ;

(4) Non-uniform intra-pixel response with IPRF following the Kepler pixel model, and non-uniform inter-pixel response with 2% random differences added between different pixels based on the Kepler IPRF, denoted as "IPRF + 0.02" ;

(5) Non-uniform intra-pixel response with IPRF following the Kepler pixel model, and non-uniform inter-pixel response with 5% random differences added between different pixels based on the Kepler IPRF, denoted as "IPRF + 0.05" ;

(6) Non-uniform intra-pixel response with IPRF following the Kepler pixel model, and non-uniform inter-pixel response with 10% random differences added between different pixels based on the Kepler IPRF, denoted as "IPRF + 0.10" .

For these six PRFs, we adopt CSST' s instrument jitter parameters and perform 10 sets of random tests for each case, calculating the jitter noise and SNR produced by different PRFs. The results are shown in [Figure 7: see original paper]. It should be noted that the relative error of SNR is below the 1% level, so error bars are not displayed in the figure.

According to the test results, as pixel non-uniformity increases, jitter noise shows an increasing trend and SNR shows a decreasing trend, but the changes are not significant and do not differ by orders of magnitude. When the random differences in inter-pixel IPRF are $< 10\%$, SNR $> 600$ in all cases. Compared with Section 3.3, using CSST' s default instrument jitter amplitude and Kepler IPRF model, the impact of jitter amplitude on jitter noise is far greater than that of pixel non-uniformity, but photometric precision can still be improved to some extent by reducing pixel non-uniformity.

### 3.5 Differential Photometric Precision

Differential photometry using reference stars can significantly improve photometric precision, achieving relative photometric precision of 0.001 or better from the ground[17-18]. We randomly select 5 reference stars within 100 pixels of the target source with magnitude differences within 1 mag, adopt CSST' s instrument jitter parameters (single jitter standard deviation $\sigma_{\mathrm{CSST}} \approx 0.007$ pixel), use the Kepler pixel model as the intra-pixel response function, and add 1% random differences between different pixels. Ten sets of random tests are performed. Subsequently, we perform photometry on both reference stars and the target star, using the average magnitude of reference stars to subtract time-correlated noise.

With a square photometric aperture side length of 11 pixels, the simulation calculations show that the differential method can reduce jitter noise to approximately 66% of its original value. The impact of differential photometry on photometric SNR and the ratio of various noise components to signal is shown in [Figure 8: see original paper]. The left panel of Figure 8 shows the change in SNR before and after differential photometry. It should be noted that the relative error of SNR is below 1%, so error bars are not prominently displayed in the figure.

The right panel of Figure 8 shows the variation of various noise components with aperture size before and after differential photometry, where the main effect is that differential photometry reduces jitter noise. According to the test results, differential photometry can reduce errors caused by instrument jitter to some extent and improve photometric SNR. When the photometric aperture value $>$ 11 pixels, differential photometry can achieve SNR $> 600$. When the aperture value $>$ 13 pixels, differential photometry provides smaller improvements in SNR, which stabilizes at approximately 700. Therefore, in actual photometric observations, differential photometry can be employed to improve photometric precision.

### 3.6 Extension to Wide-Band Scenario

In previous sections, we tested a sub-band with a central wavelength of 706.1 nm and bandwidth of 32.2 nm (denoted as Band1), while CSST' s actual i-band wavelength range is 0.69–0.83 μm. Since stellar PSF and detector PRF parameters differ at different wavelengths, it is necessary to investigate whether Band1 results can be applied to the entire band.

This section tests another sub-band on the same CCD with a central wavelength of 822.6 nm and bandwidth of 14.8 nm (denoted as Band2). Except for the central wavelength and bandwidth, other parameters are set the same as before: CSST' s default instrument jitter parameters, Kepler pixel model as IPRF, and 1% random differences between pixels. Ten sets of tests are performed. To better compare results, we scale Band2 results to Band1' s central wavelength and bandwidth values (denoted as Band2 Normalized). shows the simulated noise components and SNR for the three band groups: Band1, Band2, and Band2 Normalized.

According to Table 2 results, after normalizing for wavelength and bandwidth, the overall results from the two sub-bands Band1 and Band2 are essentially consistent. The main difference appears in the jitter noise term, primarily due to differences in stellar PSF distribution within different sub-bands and differences in detector PRF within different sub-bands. Typically, noise values and photometric precision for the entire band can be estimated by performing similar calculations for multiple sub-bands within the band. Moreover, both sub-bands achieve SNR around 600. Considering that differential photometry can improve photometric precision to some extent, we believe that CSST' s multi-color photometry module has the capability to detect Jupiter-sized exoplanets.

**Table 2 Signal and noise in different sub-waveband.** $N_{\lambda,s}$: the total number of electrons from the object, $\sigma_{\mathrm{PS}}$: Poisson noise, $\sigma_{\mathrm{bg}}$: sky background noise, $\sigma_{\mathrm{dc}}$: dark current noise, $\sigma_{\mathrm{ro}}$: readout noise, $\sigma_{\mathrm{jt}}$: jitter noise.

| Bands | $N_{\lambda,s}$ ($e^-$) | $\sigma_{\mathrm{PS}}$ ($e^-$ RMS) | $\sigma_{\mathrm{bg}}$ ($e^-$ RMS) | $\sigma_{\mathrm{dc}}$ ($e^-$ RMS) | $\sigma_{\mathrm{ro}}$ ($e^-$ RMS) | $\sigma_{\mathrm{jt}}$ ($e^-$ RMS) | $\sigma_{\mathrm{tot}}$ ($e^-$ RMS) |
|---|---|---|---|---|---|---|---|
| Band1 | $5.24\times10^{5}$ | 724 | 100 | 24 | 18 | 456 | 830 |
| Band2 | $2.05\times10^{5}$ | 453 | 68 | 20 | 15 | 234 | 522 |
| Band2 Normalized | $5.20\times10^{5}$ | 721 | 102 | 25 | 18 | 371 | 814 |

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## 4 Summary and Discussion

Based on staring observations with CSST' s main survey multi-color imaging module, this work simulates the expected stellar signals and noise contributions from various sources. We specifically consider the impact of noise caused by instrument jitter and pixel non-uniformity on photometric precision. The main conclusions of this paper are summarized as follows:

(1) Poisson noise and jitter noise are important noise sources in CSST photometry. When the photometric aperture is small (side length $< 11$ pixels), jitter noise magnitude dominates the photometric SNR. Increasing the photometric aperture can effectively reduce jitter noise. Based on the FWHM of the stellar PSF in the test band, we propose that a square photometric aperture side length of 11-13 pixels is appropriate.

(2) Test results for different jitter amplitudes show that the magnitude of jitter sequence standard deviation significantly affects jitter noise. Therefore, it is necessary to control the telescope’ s image stabilization precision specification as much as possible to improve photometric precision. According to simulation tests, under CSST’ s current jitter parameter specification (single jitter standard deviation $\sigma_{\mathrm{CSST}} \approx 0.007$ pixel), time-domain photometric SNR exceeds 600, meeting the precision requirements for exoplanet detection, particularly hot Jupiter detection.

(3) Test results for different pixel response functions show that the impact of pixel non-uniformity on jitter noise is non-negligible but does not affect the order of magnitude of jitter noise. When random differences in inter-pixel IPRF are $\leq 10\%$, SNR $> 600$ in all cases. We need to select detectors with lower pixel non-uniformity to improve photometric precision to some extent.

(4) Test results for differential photometry with reference stars show that selecting 5 reference stars with similar magnitudes can reduce jitter noise to approximately 66% of its original level, thereby achieving photometric SNR $> 600$. This differential photometry approach is commonly applied in actual observations and data processing.

(5) Test results for two different sub-bands in CSST’ s i-band show that the noise levels of the two bands exhibit good consistency after normalization, with photometric SNR approaching 600. Considering the improvement in photometric precision from differential photometry, we believe that the current photometric mode can detect exoplanets within this band. Subsequently, similar estimates can be performed for multiple sub-bands within the band, combined with stellar spectral stacking to estimate photometric precision across the entire band.

Although this paper primarily discusses the impact of pixel non-uniformity and pointing stability on time-domain photometric precision, it can also be applied to spectrograph detection. In the noise analysis, the estimation of sky background noise focuses on zodiacal light, ignoring other background sources such as Earth and Moon radiation. According to HST sky background measurement data[14], this work may underestimate the sky background by 2-3 times, but it remains far lower than Poisson noise and jitter noise, thus not affecting the final conclusions. In jitter noise simulations, the selected target source position is relatively close to the central region of the CCD, with reference stars within 100 pixels of the target source. The impact of target sources at different initial positions on results has not yet been considered. The pixel response functions selected are based on Kepler pixels with added random errors, which may differ from the final performance of CSST' s detectors. The photometric band studied is currently limited to CSST' s i-band, and similar methods can be used to estimate other bands in the future.

Due to limitations in detector full well electron capacity, the target source selected has an i-band magnitude of approximately 16 mag (AB magnitude). Considering future observations targeting exoplanet atmospheres, host stars suitable for atmospheric observations typically have V magnitudes in the range of 7–12 mag, and planetary atmospheric transmission spectral features are extremely weak relative to the host star signal, requiring at least $10^{-3}$–$10^{-4}$ precision. This demands very high photometric precision that staring mode observations cannot satisfy. To address this issue, CSST may employ drift mode for long-duration imaging and slitless spectroscopic observations. We will conduct simulation calculations for this approach in future work to better assist CSST in achieving its scientific goals of exoplanet detection and exoplanet atmospheric observation.

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