Mock Observations for the CSST Mission: Main Surveys–the Stray Light Postprint

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2026-01-28

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Abstract

Stray light has a significant impact on the detection performance of astronomical telescopes. The actual stray-light level during observations depends not only on the telescope' s intrinsic stray-light suppression capability, but also on its operational orbital environment. Accurately estimating stray-light levels is essential for evaluating image quality and conducting realistic scientific simulations.

To enable rapid estimation of stray-light levels under realistic and complex operating conditions, we have developed an analytical model specifically tailored to the Chinese Space Station Survey Telescope. This model simulates stray-light backgrounds produced by off-field sources such as moonlight, starlight, and earthshine, and also incorporates the effects of zodiacal light, as well as scattering and ghost images induced by bright in-field stars. The proposed approach enables fast and accurate assessment of stray-light conditions, thereby supporting both image simulation and the optimization of observational scheduling.

Full Text

Research in Astronomy and Astrophysics, 26:024005 (12pp), 2026 February https://doi.org/10.1088/1674-4527/ae20fc © 2026. National Astronomical Observatories, CAS and IOP Publishing Ltd. All rights, including for text and data CSTR: 32081.14.RAA.ae20fc mining, AI training, and similar technologies, are reserved. Printed in China. aaaaaaa

Mock Observations for the CSST Mission: Main Surveys—the Stray Light Jing-Tian Xian1,2, Lin Lin3, Yue-Dong Fang4, Xin Zhang5, You-Hua Xu5, Xian-Min Meng5, Hao Tian5 aa, Tian-Yi Zhang1, Zhang Ban1, Guo-Liang Li6, Shu-Yan Xu1,2, and Wei Wang1,2 Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China; wangwei123@ciomp.ac.cn University of Chinese Academy of Sciences, Beijing 100049, China Shanghai Astronomical Observatory, Shanghai 200030, China Universitäts-Sternwarte München, Fakultät für Physik, Ludwig-Maximilians-Universität München, 81679 München, Germany National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, China Received 2025 May 28; revised 2025 July 16; accepted 2025 August 5; published 2026 January 6

Abstract Stray light significantly influences the detection capabilities of astronomical telescopes. The actual stray-light level during observations depends not only on the telescope' s inherent stray-light suppression capability but also on its operational orbit conditions. Accurate estimation of stray-light levels is crucial for assessing image quality

and performing realistic scientific simulations. To rapidly estimate stray-light levels under realistic, complex operational conditions, we developed an analytical model tailored to the Chinese Space Station Survey Telescope. Our model simulates stray-light backgrounds generated by off-field sources such as moonlight, starlight, and earthshine, incorporating the effects of zodiacal light, as well as scattering and ghost images induced by bright infield stars. The proposed method allows quick and accurate evaluation of stray-light conditions, facilitating both image simulation and observational scheduling. Key words: Astronomical Instrumentation, Methods and Techniques -methods: analytical -telescopes

1. Introduction established preliminary conservative constraints to mitigate Stray light refers to unwanted radiation reaching a telescope' s stray-light contamination, maintaining minimum avoidance detector (Fest 2013) from various sources, including sunlight, angles of 50° from the Sun, 40° from the Moon, 80° from moonlight, zodiacal light, and earthshine (Boyd et al. 2022; Earth' s bright limb, and 30° from Earth' s dark limb. Clermont & Michel 2024). Such undesired illumination can These constraints, however, require further refinement. For significantly degrade image quality by increasing background instance, the lunar avoidance angle currently relies on the noise, reducing contrast, blurring celestial targets, and introducing brightness of the full Moon, yet the brightness difference between spurious signals. Consequently, faint astronomical objects can new and full Moon can reach 8–10 mag. Earthshine conditions become obscured, potentially causing incorrect detections or are similarly complex, influenced by both the solar position and classifications (Smith 2000). Earth' s bright limb angle. When the angle between the line-of- For space telescopes conducting survey missions, precise sight and the Sun ranges approximately between 50° and 65°, estimation of stray light, particularly from off-field sources, is adjustments to the aperture door orientation are necessary, essential for optimizing observational efficiency given their potentially altering earthshine levels. Furthermore, celestial limited operational lifetimes. The Chinese Space Station bodies within the solar system—such as Venus, Mars, and Survey Telescope (CSST), with its wide 1.1 square-degree Jupiter—as well as bright stars, also serve as secondary strayfield of view (FOV; Zhan 2021), inevitably includes bright light sources. At viewing angles between approximately 50° and stars during observations (Chabot et al. 2023; Krist et al. 80° from Earth' s bright limb, extending exposure time can 2023). These stars can induce blurring and ghost images improve the signal-to-noise ratio, although the specific duration through scattering by optical surfaces and reflections between must be carefully chosen based on real-time stray-light levels. the filters and detectors (Peterson 2004). Therefore, accurate Currently, the mainstream stray-light analysis methods for modeling of both off-field and in-field stray light distributions astronomical telescopes are the ray-tracing method and is crucial for ensuring high-quality observational data. experimental method. The ray-tracing method involves The stray light irradiance and its spatial distribution vary detailed modeling of internal optical structures and external significantly

with operating conditions. Critical factors include sources using commercial optical design software (e.g., the telescope's pointing direction relative to the Sun, lunar Zemax, Code V, FRED). It traces the propagation paths of phases, and angles to Earth' s bright limb. CSST has rays within the system to analyze the mechanisms, intensities,

Table 1 Characteristics of Stray Light Sources

Source Sun Moon Planet Bright Star Space Background Earthshine (Jupiter) (Zodiacal Light) Spectral 5700 K Blackbody Similar to Sun Similar to Sun Various Similar to Sun Similar to Sun Distribution Point Source Point Source Point Source Point Source Diffuse Background Non-uniform Surface Source Temporal Sunlit Area Visible Time Visible Time Visible Time All Time Earth bright edge Magnitude −26 mag −12 mag −2.9 mag −1.5 mag 3 × 10−18 erg s−1 cm−2 A−1 arcsec−2 On Working Condition (Full Moon)

and spatial distributions of stray light. It is capable of In this work, we present a computational approach designed accurately modeling complex optical structures providing specifically for the CSST mission. By inputting the telescope' s intuitive visualization of stray-light propagation paths. The orbital position, observational time, pointing direction, satellite experimental method involves building actual optical systems attitude, relevant star catalogs, and parameters of mechanical

or scaled models in a laboratory environment, using light and optical components, our model calculates the resulting sources and detectors to directly measure the stray-light levels stray-light background across the focal plane. Additionally, the and distributions. It is capable of directly obtaining actual distribution patterns of scattering and ghost images caused by measured data with high reliability revealing practical issues bright in-field stars are derived. overlooked by theoretical or simulation models. Nevertheless, The remainder of this paper is structured as follows: under real complex conditions, the ray-tracing method cannot Section 2 describes the sources and propagation paths of stray handle the computational burden of simultaneously consider- light. Section 3 presents the computational methods for offing numerous sources in the actual sky, while the experimental field point sources and earthshine. Section 4 elaborates on the method is constrained by equipment and facility limitations, computational methods for in-field zodiacal light, scattering, making it impractical to fully replicate the intricate environ- and ghost images. Finally, Section 5 summarizes our findings ment of real space observations (Clermont et al. 2020; Zhang and discusses their implications for scientific image simulation et al. 2023). Thus, we propose a strategy that separates the and observational scheduling. telescope' s inherent stray-light suppression performance from external illumination conditions. Specifically, we employ the 2. Stray Light Sources and Their Propagation Point Source Transmission (PST) to characterize CSST's Mechanisms stray-light suppression capability as a function of incident angle. PST is defined as the ratio of irradiance at the image 2.1. Primary Sources plane from an off-axis point source to that from the same In stray light analysis, most external sources—such as the source positioned on-axis. Validated through simulations and Sun, Moon, major planets in the solar system, and bright stars laboratory experiments, out-of-field (OOF) radiation entering −can effectively be approximated as point sources. Additionthe telescope is scattered by internal baffles and optical ally, extended sources, including earthshine (Sun and Moon components, forming an approximately uniform stray-light reflections from Earth' s surface) and zodiacal light, also background across the image plane (Wang et al. 2021). Due to contribute significantly to stray light. The typical spectral CSST' s asymmetrical structure, its PST is inherently a two- characteristics and intensities of these sources are summarized dimensional function. We obtained the corresponding PST in Table 1. matrix through a combination of experimental measurements According to the observational strategy, the Sun, Moon, and and simulations. By integrating external illumination data earthshine are not permitted to appear within the FOV, so they (obtained from star catalogs) with the PST values at exert influence from OOF. Planets within the solar system and corresponding incident angles, we efficiently calculate off- bright stars generate stray light both from OOF and FOV, field stray-light irradiance. while their paths and mechanisms differ. Zodiacal light, as a In-field stray-light sources, such as zodiacal light and bright full-sky background source, can enter the telescope simultastars, are treated independently and then combined to form the neously from both OOF and FOV. However, the portion of total stray-light background. Among these, scattering and zodiacal light entering from OOF is greatly reduced by the ghost images due to bright stars significantly impact imaging telescope' s inherent stray-light suppression structure, making quality and exhibit relatively stable distribution patterns. Thus, its intensity significantly lower compared to the portion evaluating their relative contributions is essential. entering from within the FOV, typically 4–6 orders at small

Figure 1. CSST and its aperture door (Zhan 2021). Figure 2. The main sources and propagations of stray light.

incident angles. From another point of view, the zodiacal light based on Earth-object distances is also much fainter than the OOF stars, even if we consider the total flux. Therefore, only the zodiacal light entering from d0 Ei = E0 ·Ph ·. (1) within the FOV needs to be considered. d

As the CSST' s main survey avoids the Galactic plane and the bright stars are involved in the star catalog, Galactic light Here Ei is the irradiance of the celestial body at the telescope, contributions are excluded from this study. Additionally, E0 is the irradiance of the celestial body at a reference distance airglow intensity across most CSST bands closely matches d0, Ph is the phase coefficient of the celestial body, and d is the zodiacal light levels (Leinert et al. 1998). Given that CSST's actual object-telescope distance. (4) Bright Stars. Positions of bright extrasolar system stars pointing directions maintain at least a 30° separation from change minimally over observational timeframes and thus are Earth' s limb—where the PST value is approximately considered fixed. The bright stars considered in our model are 10−6—stray light from airglow is negligible and thus taken from Gaia Data Release 2. Their corresponding Gaia omitted. magnitudes G, Bp, and Rp are first converted to Sloan Digital Sky Survey (SDSS) magnitude systems (refer to Section 5.3.7 of the Gaia Data Release 2 Documentation) (Katz et al. 2019). 2.2. Out-of-field Stray Light Propagation Mechanisms We also use the Galaxia code (Sharma et al. 2011) to generate Internal structures of CSST, including lens hoods, blocking a mock star sample with stellar properties (such as effective rings, and an aperture door (Figure 1) coated with space-grade temperature, surface gravity, and metallicity) along with SDSS black paint, strongly suppress off-field stray light. Despite magnitudes. Stellar properties from the Galaxia sample are these measures, certain angles or conditions still permit stray then assigned to the Gaia stars by matching their SDSS light entry. Primary stray light sources and their propagation magnitudes. Using these stellar properties, a spectral energy paths are detailed below (see also Figure 2): distribution (SED) for each Gaia star is retrieved from a (1) Sunlight. The Sun, as the brightest source, is typically spectral template library based on the BT-Settl model (Allard blocked by the aperture door, which opens to 135° aligned et al. 2011; Allard 2014). Given the SEDs, the SDSS with the solar azimuth, effectively blocking sunlight at angles magnitudes, and response curves of CSST and SDSS filters, beyond 65° from the optical axis. Under special circumstances, we can then calculate the CSST magnitudes of these bright the door opens only to 105°, restricting sunlight entry at angles Gaia stars via synthetic photometry. between 50° and 65°. Observations with the Sun within 50° of Off-field stellar radiation enters the telescope aperture, the optical axis are strictly prohibited. subsequently scattering from baffles, diaphragms, and mirrors, (2) Moonlight. The intensity of the moonlight significantly finally contributing to stray light irradiance at the image plane. varies with lunar phases. Ignoring slight deviations during (5) Earthshine. Earthshine originates from Earth’ s bright lunar eclipses, lunar phases are quantified by the angular regions illuminated by the Sun and dark regions illuminated by separation between the Moon-Earth and Sun-Earth lines within the Moon. Bright-region radiance depends on solar altitude the ecliptic plane, being 180° at full moon. For intermediate angle and terrestrial reflectivity, whereas dark-region brightphases, brightness ratios relative to the full moon condition are ness mainly correlates with lunar phases. Thus, earthshine intensity significantly varies with orbital position. estimated proportionally. Earthshine enters via two pathways: (3) Planets. Mercury’ s and Venus’ s phases are calculated similarly to lunar phases. Magnitudes for superior planets—1. When the angle between the telescope’ s optical axis and Mars, Jupiter, Saturn, Uranus, Neptune, Pluto—are computed zenith is less than 30° (optical axis oriented upward),

Figure 3. Scattering caused by CSST’ s main system optical components (primary mirror, secondary mirror, tertiary mirror and fast steering mirror). We assume single-direction parallel rays entering the system, which under ideal conditions would form a point image on the focal plane. However, due to scattering from the mirrors, stray light is distributed everywhere on the focal plane.

earthshine predominantly enters from the bottom, reflecting first from the aperture door' s interior surface, subsequently scattering into the aperture. 2. Conversely, at optical axis-zenith angles greater than 20°, terrestrial reflections may directly enter the aperture. After entering the telescope, these OOF rays are scattered by internal baffles and optical components, forming a uniform stray-light background on the image plane.

Figure 4. Reflections between filter and detector. 2.3. In-field Stray Light Propagation Mechanisms Aside from external sources, zodiacal light and bright stars entering the telescope would form a perfect focal point, but within the FOV also contribute to stray light. Zodiacal light surface scattering disperses stray light broadly across the focal induces a nearly uniform stray-light background across the plane, concentrating more strongly near image points focal plane, dependent on ecliptic coordinates relative to the (Figure 3). solar position. Bright in-field stars produce scattered and ghost CSST employs seven spectral bands for multi-band images via optical surface irregularities and internal imaging, implemented using bandpass filters placed in front reflections. of the detectors. Despite anti-reflective coatings, filters cannot The main optical components of CSST include the primary achieve 100% transmission. Additionally, the detector surface, mirror, secondary mirror, tertiary mirror, and fast steering functioning effectively as a mirror, exhibits 20% reflectivity. mirror. Surface imperfections (irregularities, roughness) on Multiple reflections between filters and detector surfaces these optical elements cause scattering. Ideally, parallel rays consequently generate ghost images (Figure 4).

Figure 5. The calculation process of stray light from OOF sources.

3. Calculation Methods for Stray Light from Out-of- Conversely, purely experimental measurements provide high field Sources accuracy but entail significant workloads. Therefore, we employ a hybrid methodology combining both approaches. Off-field radiation entering the telescope is scattered by First, we simulate PST values at various incident angles and internal baffles and optical components, forming an approxiazimuths using a detailed structural model of CSST. Subsemately uniform stray-light background across the image plane quently, laboratory measurements are conducted on the actual (Wang et al. 2021). This behavior has been validated through CSST structure at representative angles using a collimated simulations and laboratory experiments. We adopt PST to light source from a 2 m aperture tube. By calibrating simulated quantitatively characterize the stray light transmission effiresults against these measured data points, we construct a ciency from the telescope entrance aperture to the image plane. reliable PST look-up matrix. By multiplying the irradiance of an OOF source at the entrance aperture by its corresponding PST value, the resultant stray light contribution can be accurately estimated. Figure 5 3.1. Calculation Method for Out-of-field Point Sources illustrates the detailed calculation workflow. Due to CSST' s asymmetrical structure, PST depends not Stray-light irradiance from off-field point sources on the only on the angle θ between the incoming light source and

the image plane is calculated by multiplying each source' s optical axis, but also on the azimuth angle f relative to CSST' s incident irradiance by its corresponding PST value and orientation. Thus, the PST is inherently a two-dimensional considering obstruction factors (whether the source is blocked function defined as by Earth or the aperture door). Ed (,) Positions of the Sun, Moon, and solar system planets vary over PST(,) = , (2) time. In our calculations, these positions are obtained from the Jet Ei (,) Propulsion Laboratory' s (JPL' s) DE405 ephemeris (Standwhere Ed is the stray light irradiance on the image plane and Ei ish 1998). By inputting the observation' s Julian date, we is the incident irradiance at the telescope' s aperture. interpolate accurate celestial positions from this ephemeris. To accurately derive the PST matrix for CSST, ray-tracing For bright stars outside the solar system, relative positions simulations alone are convenient but lack sufficient accuracy. remain nearly constant over typical observational periods. Star

positions and magnitudes are thus directly obtained from the Gaia star catalog. Matching these Gaia stars with CSST' s simulation star catalog provides magnitudes in all seven CSST spectral bands: NUV(255 320 nm), u(320 400 nm), g(400 550 nm), r(550 690 nm), i(690 820 nm), z(820 1000 nm), and y(940 1000 nm). Next, each source' s visibility (potential obstruction by Earth) is assessed. Two conditions must be simultaneously satisfied for a source to be obstructed by Earth: (1) The angle between the source vector and telescope orbital-position vector (line connecting Earth' s center and telescope location) exceeds 90°. (2) The shortest distance between Earth' s center and the source-directed vector originating at the telescope Figure 6. Comparison of earthshine between CSST and HST in bright region. position is less than Earth' s radius. aperture-door scattered earthshine is

The aperture door position is solely determined by the Sun' s location, with a similar procedure used to calculate solar blockage. m k PST (ij, ij) EA2 = MPi ・r ・, (5) Assume n point sources, each with irradiance Ei, incident i= 1 j= 1 dij2 angle θi, azimuth fi, Earth-blockage factor Sei, aperture-door blockage factor Spi, and corresponding PST value PST(θi, fi). where Mpi is the incident irradiance received by each doorblock. Total stray-light irradiance Ep from these sources is Thus, the total earthshine irradiance entering the telescope n aperture is: EA = EA1 + EA2. Ep = Ei Sei Spi PST (,). (3) i=1 3.3. Comparison of Earthshine between CSST and HST To benchmark CSST' s earthshine levels against those 3.2. Calculation Method for Earthshine experienced by the Hubble Space Telescope (HST), we define a common observational scenario: at 00:50 UTC on To model earthshine, Earth' s surface is subdivided into 2026 January 1, both telescopes share identical R.A. and multiple discrete blocks, each approximated as a point source decl. coordinates, situated within the sunlit region. For contributing individually to stray light. For each block, the each telescope, earthshine irradiance is computed across angle and azimuth relative to CSST' s optical axis are denoted an observational grid covering R.A. 0°–345° and decl. by θi and fi, respectively, with corresponding irradiance Ei

−75° to +75°. reaching the telescope aperture. Considering aperture-door Figure 6 illustrates these comparative results, indicating that blockage Spi and Earth blockage Sei, the total irradiance from CSST consistently experiences higher earthshine (combined direct earthshine entering the aperture is calculated as effect of direct earthshine and earthshine scattered by the aperture door) irradiance than HST under identical observan EA1 = Ei Sei Spi PST(,). (4) tional conditions.7 This discrepancy primarily arises from i=1 differences in internal telescope designs and orbital altitudes (CSST at approximately 400 km, versus HST at approximately Additionally, due to the aperture door' s proximity to the 600 km). HST restricts observations within sunlit regions to telescope aperture, some earthshine reflected off the aperture angles greater than 20° from Earth' s bright limb. For CSST to door may directly scatter into the telescope. Hence, it is achieve comparable earthshine conditions, observational necessary to consider the door-to-aperture scattering pathway. angles must be maintained at least 70° from Earth' s bright The aperture door, coated with black paint, is modeled as a limb, a valuable insight informing CSST' s observational Lambertian reflector with reflectance r. Dividing the aperture scheduling strategies. door and telescope aperture into multiple small discrete blocks, we calculate each block pair' s scattering contribution based on The earthshine brightness for HST is determined using the data presented in Figure 6.2 of the STIS Instrument Handbook (https://hst-docs.stsci.edu/ their relative geometrical relationships (incident angles θij, stisihb/chapter-6-exposure-time-calculations/6-5-detector-and-skyazimuth angles fij, and distances dij). The total irradiance from backgrounds).

Considering CSST' s entrance aperture diameter D and focal length f, the resulting irradiance on the focal plane is D2 E=L . (7) 4f 2 Figure 7 shows the calculated zodiacal light distribution in the V-band across the full sky for 2026 January 1, at 00:50 UTC. The red star symbol indicates the solar position at that time. The computed distribution matches closely with observations from HST.

4.2. Scattering by Bright Stars on the Surfaces of Main Figure 7. All-sky zodiacal light distribution in V-band. The red pentagram Optical Components indicates the position of the Sun. The Bidirectional Reflectance Distribution Function (BRDF) characterizes how incident radiation is scattered by 4. Calculation Methods for Stray Light from In-field an optical surface into various outgoing directions. BRDF

Sources essentially describes the distribution of reflected radiation as a In-field stray light primarily arises from zodiacal light and function of incident and reflected angles, thus providing bright stars within the telescope' s FOV. Zodiacal light crucial data for stray light analysis. generates a nearly uniform background across the focal plane, Surface profiles of optical elements can be obtained using whereas bright stars induce scattering from optical surfaces interferometry measurements, which are subsequently conand create ghost images due to reflections between the filter verted into Power Spectral Density (PSD) data. For optical surfaces with low roughness, PSD data can be reliably and detector. Each of these effects can be treated indepentransformed into BRDF using Rayleigh-Rice perturbation dently, and their combined results yield the total in-field stray theory. In practice, interpolating experimentally measured light irradiance and distribution. PSD data yields more accurate BRDF values for realistic scattering calculations. In principle, the BRDF scattering model should incorporate 4.1. Calculation Method for Zodiacal Light the azimuthal dependence of both incident and scattered rays. Zodiacal light originates from sunlight scattered by inter- However, this comprehensive treatment significantly increases planetary dust particles, predominantly concentrated near the computational complexity. Fortunately, precision-polished ecliptic plane. To estimate its brightness, we reference optical surfaces typically exhibit isotropic scattering behavior, observational brightness data at 0.5 μm wavelength presented meaning the BRDF mainly depends on the angle θs between by Leinert et al. (1998). Given an observational direction' s the scattered ray and the specular reflection direction, and is ecliptic latitude and longitude difference relative to the Sun, nearly independent of azimuthal orientations. zodiacal brightness at 0.5 μm is determined by interpolating For scattering from a single mirror surface, treated tabulated observational data. analogously to an equivalent refractive lens, the scattering CSST' s main survey spectral coverage spans from 0.255 to radiance L, incident irradiance Ei, and BRDF are related as 1 μm, similar to that of the HST. By referencing HST' s follows zodiacal spectral measurements, we calculate relative bright- d s L dA $\cdot$ cos s d s d s /(d (d s2)/f 2) Es f 2 ness ratios between 0.5 μm and other wavelengths. Using these BRDF = = = = , (8) Ei d i d i cos s d i cos s ratios, the brightness at other wavelengths within CSST' s dA spectral range is estimated. Integrating over the wavelength where dΦs and dΦi represent scattered and incident fluxes, interval yields the total brightness for the observational band respectively, Es denotes scattering irradiance, f is the focal n length, and ds is the distance between scattering point and L= V ( )d . (6) image point. In optical systems with long focal lengths 0 ds (s f), the approximation cosθs 1 holds true, simplifying Here, L is the total brightness over the observational spectral the scattered irradiance calculation to range, \$ \$0 and λn are the lower and upper wavelength limits d i BRDF (s) respectively, and V(λ) represents zodiacal brightness at Es = . (9) f2 wavelength λ.

Figure 8. Comparison of simulated and analytical scattering curves.

Given the negligible contribution of higher-order scatterings, described mathematically as (Fest 2013) we limit our calculations to first-order scattering, thus s considering each mirror' s scattering independently and summing their contributions linearly. BRDF(s) = b 0 1 + (sin s l sin) 2 . (12)

We state the BRDF of the four mirrors toward the detector' s We adopted parameters b0 = 139257000, l = 4e − 6, s = −2.7, focal plane is denoted as BRDFt(θs), and their clear aperture representing a typical Total Integrated Scatter (TIS) of about 2% radii as r1, r2, r3, r4. The entrance pupil radius is denoted as R, for regular mirrors. Due to computational limitations, we and the entrance pupil' s scattering angle is θs. The overall compared the logarithm of the relative irradiance between the BRDF of the optical system can be expressed as scattered point and image point within a radius of 50 pixels centered on the image position. Figure 8 shows the simulated and

BRDFt (s) = BRDF ( ) + BRDF( ) R sr R sr analytically computed scattering irradiance curves. The analytical results closely match the simulation, with deviations consistently r12 r22 less than 7%, validating the accuracy and effectiveness of our

- BRDF ( ) + BRDF( ) . R sr R sr

(10) scattering calculation algorithm. In practical CSST imaging calculations, measured mirror r32 r42 surface profiles obtained via interferometry are converted to pupil-plane amplitude and phase distributions. Through Four- Thus, the stray light irradiance distribution on the focal ier transformations, these data yield optical field distributions plane caused by scattering from a bright star is determined by at the image plane. The sampling density of pupil-plane data directly influences the frequency coverage and accuracy of R2 computed results. Typically, computational constraints neces- E (x , y) = Ei BRDFt (s). (11) f2 sitate relatively lower sampling density coupled with a twodimensional Fourier transform to derive accurate point-spread The overall scattering stray-light distribution from multiple function (PSF) data in low-frequency spatial regions. Howbright stars in the field can be computed individually using the ever, increasing sampling density and utilizing one-dimenabove equation and subsequently summed together. sional Fourier transformations can precisely determine the To verify the accuracy of our analytical method, a commercial isotropic scattering distribution in high-frequency regions. optical simulation software (FRED) was employed for compar- Figure 9 illustrates a comparison between computed PSF ison. The simulations utilized the Harvey-Shack scattering model, curves and scattering distributions.

Figure 9. Comparison of PSF and scattering curves.

Figure 10. Ghost images caused by reflections between the filter and the detector.

Practically, results from PSF calculations are adopted in reflections, we consider only second-order ghost reflections regions close to image points, while scattering distributions are for our calculations, balancing accuracy and computational employed for distant regions. Interpolation is used in efficiency with actual measurement constraints. transitional regions to ensure smooth continuity between PSF Each detector' s reflectance Rd was estimated from measured and scattering calculations. Quantum Efficiency (QE) values using the relation Rd 1 − QE, as recommended by standard optical references and technical documents (Fabricius et al. 2006; Howell 2006). 4.3. Ghost Images between the Filter and Detector We define R1, R2 and Rd as reflectances of the filter' s front Based on laboratory measurements, reflectance values of surface, filter' s back surface, and detector surface, respec- CSST filters across the seven imaging bands range from tively. Similarly, T1 and T2 represent the transmittance values approximately 0.5% to 3.8%. Each reflection thus significantly of the filter' s front and back surfaces. attenuates the energy transmitted through the system. Since Considering these parameters, there are three possible ghost images can only form after an even number of second-order ghost image formation paths, illustrated in

Figure 11. Ghost image ray tracing simulation and irradiance distribution.

Figure 10, categorized according to their proximity to the subtended by the entrance pupil rays on the detector, and n is nominal image position: the refractive index of the filter material. Consequently, the irradiances (E1, E2, E3) of these ghost images are given by: (1) Reflection between the filter' s front and back surfaces; (2) Reflection between the filter' s back surface and the T1T2 R1R2 T1T2 Rd R2 1 2 detector surface; E1 = = , E2 = = , r12 u 2 r22 (2D 2 u)2 (3) Reflection between the filter' s front surface and the (2 D1 n) detector surface. T1T23 R1 Rd E3 = = . (15) The total energies associated with these ghost images r32 D 2u (n1 + D2)

($ $1, $ $2, $ $3) are calculated as follows:

1= T1T2 R1R2 , For CSST, the maximum angle between incident rays and the 2 = T1 T2 Rd R2 , detector' s surface normal is typically no greater than 7°. Thus, 3 small-angle approximations (= sin ( ) = tan ( )) are justi- 3 = T1 T2 R1 Rd . (13) fied. Assuming θx and θy represent ray inclination angles with Here, Φ denotes the incident energy from the bright star. respect to the detector' s x-axis and y-axis respectively, the The radii of these ghost images (r1, r2, r3) are calculated central coordinates (xi, yi) of each ghost image relative to the using the geometry of the filter and detector, expressed as: nominal image point (x0, y0) can be expressed as:

u r1 = 2D1 , r 2 = 2D 2 u , x1 = x 0 + 2D1 x y1 = y0 + 2D1 y n n n D x 2 = x 0 + 2D 2 x y2 = y0 + 2D2 y r 3 = 2 u 1 + D2 , (14) n x3 = x 0 + 2D1 x + 2D2 x where D1 represents the distance from the filter' s front surface n y to the filter' s back surface, and D2 represents the distance from y3 = y0 + 2D1 + 2D2 y. (16) the filter' s back surface to the detector, u is the angle n

Figure 12. Scientific Simulation Image with in-field stray light.

Finally, incorporating these positions, radii, and irradiances, the derived equations, accurate determinations of the filter the resulting ghost irradiance distribution function E(x, y) on surfaces' transmittance and reflectance, detector reflectance, the detector can be summarized as and precise filter-detector distances can be achieved. Such experimental validations allow construction of highly accurate E (x , y) = E1circ (x1, y1, r1) ghost image models for rigorous scientific image simulations. + E2 circ (x2 , y2 , r2) + E3 circ (x3, y3, r3). (17) 4.4. Image Simulation with In-field Stray Light Here, circ(x, y, r) denotes a circular function representing the geometric extent of each ghost image. Integrating all in-field stray-light factors, we imported the Taking the NUV band as an illustrative example, we simulated star catalog from the Cycle 9 data product of CSScomputed the ghosting effects caused by an in-field bright star. OS, generating scientific simulation multi-band images on the We adopted an incident ray elevation angle of 3°.9, matching image plane. Figure 12 shows an example from a partial area actual structural parameters, and set geometric parameters as of one NUV-band detector. D1 = 5 mm, D2 = 8mm, T1 = T2 = 0.825, R1 = In this figure, the reddish regions indicate the stellar image R2 = 0.0093, Rd = 0.15. points and their scattering areas, while the cyan-colored To validate these analytical calculations, results were cross- regions represent ghost images. Data analysis reveals that the checked using the optical engineering simulation software ghost images have a relative intensity of approximately 10−6 FRED. Figure 11 shows simulated ghost image positions and compared to the stellar image points. Regarding scattering relative irradiance distributions. Simulation outcomes confirm effects, the relative intensity at a distance of 10 pixels from the that ghost images' relative irradiances typically fall below stellar image points is about 10−4, and at a distance of 10−6 compared to the main stellar image, corroborating our 100 pixels, it drops to approximately 10−6. analytical results. Similar agreement was observed across the other CSST imaging bands. 5. Conclusion In practical experiments using real devices, ghost images This paper addresses the challenge of accurately assessing can be clearly observed by intentionally overexposing the the level and spatial distribution of stray light in space-based sensor. By measuring the energies, positions, and sizes of these astronomical telescopes under complex operational scenarios. ghost images, and substituting these measured parameters into We present a comprehensive calculation model that

systematically incorporates all major sources of stray light, CSST-KSC-HTW-00-2023-009. L.L., X.Y.-H. and M.X.-M. including sunlight, moonlight, major planets within the solar acknowledge the science research grant from the China system, bright stars outside the solar system, earthshine, and Manned Space Project with Nos. CMS-CSST-2021-B04 zodiacal light. and CMS-CSST-2025-A17. L.L acknowledges the support Established on a robust logical framework, our model yields from the Youth Innovation Promotion Association CAS representative computational results for earthshine and zodia- (id. 2022260). cal light under various realistic scenarios. By comparing these results with statistical data from the HST, we demonstrate a ORCID iDs consistent trend between the two, thus validating the accuracy of our method. Moreover, the comparative analysis highlights Hao Tianaa https://orcid.org/0000-0003-3347-7596 critical differences between the telescopes, providing valuable insights for astronomical observational scheduling. References Furthermore, the proposed model incorporates precise computational approaches to simulate both the scattering and Allard, F. 2014, IAUS, 299, 271 Allard, F., Homeier, D., & Freytag, B. 2011, ASPC, 448, 91 ghost image distributions arising from bright stars in the FOV, Boyd, P. T., Wilson, E. L., Smale, A. P., et al. 2022, JATIS, 8, 014003 ensuring that all dominant stray-light mechanisms are Chabot, T., Brousseau, D.,

Figure 1

Figure 1: Figure 1

& Thibault, S. 2023, OptEn, 62, 025102 quantitatively accounted for. These simulation results serve Clermont, L., & Michel, C. 2024, JARS, 18, 016508

Clermont, L., Michel, C., Blain, P., Loicq, J., & Stockman, Y. 2020, OptEn, as a critical reference for high-fidelity scientific image 59, 025102 simulation and for understanding the impact of stray light on Fabricius, M., Bebek, C., Groom, D., Karcher, A., & Roe, N. 2006, SPIE, data quality. 6068, 144 Fest, E. 2013, SPIE The model has already been integrated into the CSST Main Howell, S. B. 2006, Handbook of CCD Astronomy (2nd ed.; Cambridge Univ. Survey Simulator. In future work, we will refine and calibrate Press) the model parameters using actual measurement data obtained Katz, D., Sartoretti, P., Cropper, M., et al. 2019, As&A, 622, A205 Krist, J. E., Steeves, J. B., Dube, B. D., et al. 2023, JATIS, 9, 045002 from engineering tests of the telescope, further improving its Leinert, C., Bowyer, S., Haikala, L. K., et al. 1998, A&AS, 127, 1 predictive accuracy and applicability in mission operations. Peterson, G. L. 2004, SPIE, 5178, 184 Sharma, S., Bland-Hawthorn, J., Johnston, K. V., et al. 2011, ApJ, 730, 3 Acknowledgments Smith, B. A. 2000, Stray Light in Optical Systems (SPIE Press) Standish, E. M. 1998, JPL Planetary and Lunar Ephemerides, DE405/LE405, This work was supported by National Astronomical Interoffice Memorandum 312.F-98-048, JPL Wang, W., Lu, L., Zhang, T.-y., et al. 2021, Chinese Optics, 14, 390 Observatories, Chinese Academy of Sciences, The Data Zhan, H. 2021, ChSBu, 66, 1290 Processing and Analysis system for CSST, under grant Zhang, E., Ye, W., Xia, Y., Wang, L., & Zhang, M. 2023, OptEn, 62, 034103

Figures