

Mock Observations for the CSST Mission: CPI-C- Targets for High Contrast Imaging Postprint

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2026-01-28

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Abstract

We present CPISM, a dedicated simulation program developed for the Cool Planet Imaging Coronagraph (CPI-C) onboard the Chinese Space Station Survey Telescope. CPISM supports high-contrast exoplanet imaging by simulating observational conditions and instrumental effects to optimize target selection and observation strategies. The program adopts a modular architecture comprising target modeling, imaging simulation, observational effects, detector response, and data product generation modules, thereby enabling flexible and realistic synthetic observations. Validation using simulations of a bright star demonstrates excellent agreement with theoretical expectations, confirming the accuracy and reliability of the program. Owing to its modular design, CPISM can incorporate diverse stellar and planetary models and is capable of simulating instrumental noise, cosmic rays, and other observational effects. This tool facilitates data processing, signal-to-noise ratio analysis, and high-contrast photometry, thus supporting future efforts in exoplanet detection and characterization. The outputs of CPISM will enhance observation planning and maximize the scientific return of the CPI-C mission by providing critical insights into exoplanetary systems.

Full Text

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Mock Observations for the CSST Mission: CPI-C-Targets for High Contrast Imaging Yi-Ming Zhu^{1,2} aa, Gang Zhao^{1,2} aa, Jiang-Pei Dou^{1,2} aa, Zhong-Hua Lv^{1,2}, Yi-Li Chen^{1,2}, Bo Ma^{3,4}, Zhao-Jun Yan⁵, Jing Tang⁶, and Ran Li^{7,8} Nanjing Institute of Astronomical Optics & Technology, Chinese Academy of Sciences, Nanjing 210042, China; gzhao@niaot.ac.cn, jpdou@niaot.ac.cn CAS Key Laboratory of Astronomical Optics & Technology, Nanjing Institute of Astronomical Optics & Technology, Nanjing 210042, China School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519082, China Center of CSST of the Greater Bay Area, Sun Yat-sen University, Zhuhai 519082, China Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China School of Physics and Astronomy, Beijing Normal University, Beijing 100875, China School of Astronomy and Space Sciences, University of Chinese Academy of Sciences, Beijing 100049, China Received 2025 March 24; revised 2025 August 19; accepted 2025 August 23; published 2026 January 6

Abstract

We introduce CPISM, a simulation program developed for the Cool Planet

Imaging Coronagraph (CPI-C) on the Chinese Space Station Survey Telescope. CPISM supports high-contrast exoplanet imaging by simulating observational conditions and instrumental effects to optimize target selection and observation strategies. The modular design includes target modeling, imaging simulation, observational effects, detector response, and data product generation modules, enabling flexible and realistic synthetic observations. Validation through simulations of a bright star shows strong agreement with theoretical expectations, confirming the program's accuracy. CPISM's modular design allows flexibility, accommodating different stellar and planetary models, and can simulate instrumental noise, cosmic rays, and other observational effects. This tool aids in data processing, signal-to-noise ratio analysis, and high-contrast photometry, contributing to future exoplanet discovery and characterization efforts. The program's outputs will enhance observation planning and scientific return for the CPI-C mission, providing critical insights into exoplanetary systems. Key words: planets and satellites: atmospheres -planets and satellites: detection - instrumentation: adaptive optics

1. Introduction exoplanets in the Milky Way. CPI-C stands out due to its Over the past few decades, the exploration of extrasolar advanced coronagraph technology, which allows it to achieve planets has discovered more than 6200 exoplanets orbiting exceptional contrast levels across both optical and infrared different stars, of which dozens have been discovered by direct wavelengths. This capability is crucial for detecting faint imaging methods (Chauvin 2024). High-contrast imaging has exoplanetary signals near their host stars at separations ranging emerged as a crucial tool for directly observing exoplanets, from 0.19 to 1". By combining these advanced features, CPI-C providing invaluable data on planetary atmospheres, surface opens up new possibilities for studying the atmospheric compositions, and orbital dynamics. Groundbreaking instrumentation of exoplanets and could play a key role in the missions like the Gemini Planet Imager (Macintosh et al. 2014) search for biomarkers and signs of habitability. and Spectro-Polarimetric High-contrast Exoplanet REsearch Before CPI-C officially begins its observations, it is (SPHERE; Beuzit et al. 2019) have already revolutionized our essential to make preliminary preparations through simulation understanding of exoplanet systems by delivering high-resolution images that offer unprecedented contrast between observation targets, as well as the development of the survey stars and their orbiting planets (Marois et al. 2008; Mesa strategy. et al. 2019). Simulations play a critical role in optimizing future The Cool Planet Imaging Coronagraph (CPI-C) aboard the observations by enabling astronomers to refine target selection Chinese Space Station Survey Telescope (CSST) represents a and observation strategies. Furthermore, by simulating instrumental effects and observational environments, simulations With its capability to achieve a contrast ratio of 10–8, CPI-C is help mitigate risks and maximize scien-

tific outcomes. set to make significant contributions to our understanding of Similar approaches have been employed for other exoplanet

detection instruments, such as The Coronagraph Instrument generation—each of which can be developed, tested, and (Poberezhskiy et al. 2022) on the Roman Space Telescope replaced separately. This design facilitates focused develop- (Spergel et al. 2015) and The Pandora SmallSat (Hoffman ment on individual components without compromising the et al. 2022), both of which have developed simulation integrity of the overall system. programs (Douglas et al. 2020; Hedges et al. 2024). Second, the platform is highly extensible. It is designed to In this work, we introduce a program named CPISM (CPI-C incorporate external models with minimal modification. Users Image Simulator) used to simulate the observation of CPI-C. can replace the default planetary atmosphere or stellar CPISM connects multiple stages of the mission workflow—spectrum generators with high-resolution alternatives, intefrom target selection and observation configuration to data grate new noise or stray light models, or adapt the simulation format generation and scientific evaluation—and serves as a to accommodate updates in the CPI-C optical system and unified interface between instrumental models, data processing detector configuration. pipelines, and science planning tools. Third, standardized data interfaces ensure seamless com- The simulation platform supports both engineering valida- munication between internal modules and interoperability with tion and scientific exploration. It provides mock Level 0 data external systems such as observation planning and data process formatted for pipeline development, enables photometric pipelines. Simulation inputs—including target catalogs, instruanalysis of simulated planets, and supports observation mental settings, and observational parameters—are passed strategy optimization through contrast and signal-to-noise through structured dictionaries or configurable class instances.

predictions. A companion paper (Zhao et al. 2026) presents the Output products include both a structured image array and detailed modeling of CPI-C' s optical system and detector Flexible Image Transport System (FITS) files conforming to physics. Here, we focus on the system-level design, archi- CSST Level 0 data conventions. tecture, and end-user applications of the CPISM platform. Fourth, CPISM is developed for dual-purpose usability, The paper is structured as follows: Section 2 introduces the serving both scientific and engineering needs. On one hand, it simulation program' s module composition and operational generates Level 0 FITS data products that mimic the raw steps. Section 3 describes the process of simulating CPI-C output of CPI-C and enable realistic testing of the data observation targets using the program. In Section 4, we verify reduction pipeline. On the other hand, the simulator supports the simulation program' s performance for observing targets science-driven applications such as SNR estimation, contrast through an example. Finally, Section 5 presents a summary curve evaluation, and target prioritization, thereby bridging and discussion. technical verification with scientific optimization. Finally, CPISM is designed for interoperability with 2. System Architecture detailed physical models. The architecture accommodates precomputed PSFs, EMCCD response

functions, and other 2.1. Design Overview high-fidelity outputs from physical modeling as drop-in To support both engineering and scientific preparation for components. This capability allows CPISM to serve as a CPI-C operations, we have developed a simulation Python- system-level wrapper that combines realistic hardware behabased software package named CPISM. This tool serves two vior with customizable science scenarios. major purposes: Overall, CPISM provides a flexible framework for generating synthetic observations with instrument- and detector- 1. To generate realistic Level 0 data that mimics raw CPI-C specific characteristics. It supports image-based SNR analysis, observations, including detector and instrumental arithigh-contrast photometry, astrometric measurement, and facts, which can be used to develop and validate the optimization of survey strategies for CPI-C. The CPISM mission' s data processing pipeline; simulation software is publicly available at the official CSST 2. To provide synthetic observations for scientific research, simulation website: <https://csst-tb.bao.ac.cn/simulation/> including target detectability studies, signal-to-noise epic/installation.html, where users can access installation ratio (SNR) analysis, photometric precision tests, and instructions, usage documentation, and example datasets. observation strategy optimization. The architecture is designed with flexibility and clarity in 2.2. Modular Structure mind, featuring modular components, well-defined interfaces, and seamless integration with both scientific workflows and The performance of the CPI-C depends on advanced optical instrument-level simulations. components, including a deformable mirror (DM), apodizing First, modularity is fundamental to CPISM' s structure. The filter, and focal plane mask, which together achieve a contrast simulation framework is composed of functionally indepen- of 10–8. These components collectively suppress starlight and dent modules—including target modeling, optical imaging, enhance the visibility of faint planetary companions. A key detector response, observational effects, and data product performance metric is the Point-Spread Function (PSF), which

Observational Effects Module Imaging Instrument Point spread Simulation Cosmic rays and photoelectric background light function model Module efficiency Camera Module Stellar Stellar Focus plane Stellar SED Stellar image image information spectrum Bias, flat, dark current, readout noise, electron multiplication, saturation overflow, etc.

Planetary Planetary Planetary reflection Planetary SED image information spectrum Data Product Generation Module

Planetary Generate CPI-C level 0 data position according to data definition Target Simulation Module

Figure 1. The working flowchart of the CPISM program.

defines the image quality. Careful optimization ensures that the 2. Imaging Simulation Module. This component models the simulated PSF closely matches the performance expected from instrument' s optical system, including the apodizing the satellite (Zhao et al. 2026). CPI-C uses an Electron pupil filter, wave

front corrector, and focal plane mask.

Multiplying Charge-Coupled Device (EMCCD) camera for Using Fourier optics methods, it computes the system optical imaging, which amplifies faint signals for improved PSF and convolves it with the target scene to produce a sensitivity. These technologies collectively enable the detection and detailed study of exoplanets and their atmospheres. Dark zone regions with high-contrast suppression are constructed to emulate the selection of CPI-C observation bands is guided by the late CPI-C's expected performance. Although CPI-C characteristics of the planetary spectrum. Based on the operations in space and therefore does not need an absorption and platform characteristics derived from planetary conventional ground-based adaptive optics system to spectrum simulations, four optical observation bands were designed, with central wavelengths of 520, 662, 720, and contain an internal DM that runs in a closed-loop wave 850 nm, as well as four infrared observation bands, with front-control mode with an on-board wave front sensor. central wavelengths of 940, 1265, 1425, and 1542 nm. This active control suppresses quasi-static aberrations To support such a complex observational system, CPISM and sustains a dark-hole region required for high-contrast adopts a modular design that mirrors the structure of the actual imaging. In addition, the simulator includes a wave-CPI-C instrument and its operational pipeline. The simulation length-dependent PSF generation module that models the framework is organized into five major components: the Target imaging system's spectral response across each CPI-C Simulation Module, Imaging Simulation Module, Observational Effects Module, Camera Simulation Module, and Data 3. Observational Effects Module. To achieve realism, this Product Generation Module. Each module is responsible for module simulates background light and cosmic ray (CR) simulating a distinct aspect, and the modules communicate via contamination. A CR model tailored to the CPI-C standardized internal data structures. As shown in Figure 1, the imaging camera was developed by referencing CR framework simulates the full observational sequence of CPI-C, energy, frequency, and characteristics from tests contranforming astrophysical target parameters into realistic ducted on the Hubble Space Telescope (HST; Miles Level 0 data products. A brief overview of the module et al. 2021; Hathi 2024). The methods are described in responsibilities is summarized as follows: detail in Section 3.4. For background light, the solar 1. Target Simulation Module. This module is responsible spectrum was used to describe the background's spectral for generating the spectral and spatial characteristics of characteristics, resulting in a uniform background light astrophysical sources. It models stellar spectral energy model. distributions (SEDs) based on the grid from Castelli & 4. Camera Simulation Module. This module simulates the Kurucz (2004) and incorporates a planetary reflection response of CPI-C's EMCCD detector, modeling the full spectrum model from Batalha et al. (2018) parameterized readout chain from photon collection to final digital by metallicity and cloud properties. By incorporating the output. It incorporates key instrumental effects, including Lambertian phase model, contrast model,

and stellar dark current, flat-field nonuniformity, nonlinearity, spectrum model, the program generates the reflected clock-induced charge (CIC), bad columns, vertical spectra of planets based on varying distances, radii, star-blooming, and electron multiplication (EM). The EM planet relative positions, and planetary physical gain is calculated as a function of voltage and properties. temperature using calibration-based models. Bias

stars, across various bands. These images are unprocessed at this stage and serve as raw inputs for further analysis. The naming convention for the Level 0 data files follows a 800 structured format to ensure clear identification of the observation and data type: 300 -File format: CSST_CPIC_CAMERA_TYPE_

Pixel Value (ADU) YYYYMMDDhhmmss_YYYYMMDDhhmmss_OBSID_Y [pixel] 275 X_L0_VER.fits -CAMERA: Denoting whether the data was collected 400 250 by the visible light (VIS) or near-infrared (NIR) camera. 200 -TYPE: Indicating the target type, with a total of eight types: five calibration modes—BIAS (background), DARK (dark field), FLAT (flat field), BKG (sky 0 background calibration), LASER (internal laser cali- 0 200 400 600 800 1000 X [pixel] bration)—and three scientific target modes—SCI

Figure 2. An image of CPI-C Level 0 data simulated by the CPISM program. (scientific observation), DSF (dense star field observa- The frame contains 1080 \times 1050 pixels. With the adopted pixel scale of tion), CALS (calibration star observation). 0. 016153 pix 1, this corresponds to an on-sky footprint of 17. 45 \times 16. 96. The -YYYYMMDD: The observation date in year-monthcolor bar indicates the pixel value (analog-to-digital units, ADU) on a linear scale. day format. -hhmmss: The UTC observation time in hour-minutestructures such as striping, interference, and drift are also second format. -OBSID: A unique observation identifier. included. The output is a 2D image array consistent with -X: A supplementary file name that includes no specific the expected raw telemetry format. information; it is used for formatting purposes. 5. Data Product Generation Module. The final module -L0: Indicating that the file contains Level 0 (raw) data. assembles the outputs of the upstream modules into -VER: Version number of the data file. structured Level 0 data products. These products include FITS images formatted according to CSST conventions, Level 0 data files are organized in a hierarchical directory with appropriate headers, metadata, and version control. structure designed for easy access and categorization. The The output hierarchy supports calibration, engineering, structure is divided into folders based on the type of data and scientific modes, and is compatible with downstream stored. The SCI folder contains the scientific observation data, pipelines for data processing. including raw images from the telescope' s cameras. The CAL folder holds calibration data, such as dark frames, flat field By organizing the simulation pipeline into clearly defined images, and background calibration, which are critical for modules, CPISM ensures maintainability, extensibility, and removing instrumental effects and enhancing the quality of the compatibility with both upstream physical models and down-scientific data. The Params folder contains engineering stream analysis tools.

Detailed operational logic for each telemetry and instrumental parameters, providing the necessary context for accurately interpreting the observations. The folder naming hierarchy is shown in Figure 3. This organizational structure facilitates the efficient retrieval of specific data. Level 0 Data Products types, whether for scientific analysis or for monitoring. The simulation program generates CPI-C Level 0 data files, instrument performance, which consist of raw observational data captured by the optical. When CPISM is executed for an observing sequence, it and near-infrared cameras. These data are stored in the FITS format and include images, auxiliary data, calibration or directory (e.g., SCI/ format and include images, auxiliary data, calibration or CAL/). All frames (N images) acquired in information, and engineering telemetry—all essential for that sequence are written to a single multi-extension FITS subsequent data analysis and processing (see Figure 2 for an Level 0 file: a primary HDU followed by one IMAGE extension per frame (HDU 1 ...HDU N). Separate observing Each exposure in the CPI-C module produces one or more sequences, each identified by a distinct OBSID, are saved as images containing pixel data that represents the light collected additional files and are placed automatically in the same from observed targets, such as exoplanets and background directory tree.

Figure 3. Schematic diagram of CPI-C Level 0 data storage folder structure.

By generating these Level 0 data files, the simulation development and operations. Beyond its engineering role, program supplies the essential raw material for subsequent CPISM can also serve as a scientific simulation engine for stages of data processing, ensuring that high-quality scientific generating observation catalogs and testing observation data can be derived from the simulated CPI-C observations. strategies in batch mode.

2.4. Extensibility and Integration 3. Simulation Workflow CPISM is architected with extensibility as a core design. The simulation workflow integrates several key modules to principle, enabling users to adapt, upgrade, or replace key produce the final output (see Figure 1). The process begins by physical models as the instrument evolves or new scientific inputting the necessary parameters for stars and planets, requirements emerge. Its modular Python implementation, including their physical properties and observational settings. coupled with structured configuration interfaces, allows for Using models for stellar spectra, planetary reflection spectra, seamless integration of external components and high-fidelity and contrast, the target simulation module calculates the simulations. corresponding spectral outputs. In the target simulation module, stellar spectra are generated Next, the imaging simulation module processes these inputs using the model grid from Castelli & Kurucz (2004, to simulate the focal plane image. It accounts for system hereafter CK04) by default. However, the spectrum interpola- characteristics such as the PSF, optical aberrations, and the tion framework—implemented via indexed lookup and tri- modulation of the DM. By convolving the spectral information linear interpolation—is decoupled from the model source, of the star and planet with these system parameters,

the module allowing for replacement with alternative spectral libraries generates a realistic focal plane image, incorporating the dark such as PHOENIX (Husser et al. 2013) or empirical SEDs. hole contrast (Zhao et al. 2026). Similarly, the planetary reflection model, currently based on a Subsequent modules introduce observational effects, includ- Batalha et al. (2018) parameterization, can be replaced with ing background light and CR artifacts, and simulate the more sophisticated atmosphere simulators such as PICASO, response of the CPI-C EMCCD detector. The result is a enabling the simulation of high-resolution albedo spectra and comprehensive simulation that produces Level 0 data products, phase-dependent features. fully integrating observational effects into the final image. The CR model within the camera module is initialized from empirical maps derived from HST data (Miles et al. 2021; Hathi 2024). The design supports substituting this model with 3.1. Input Configuration alternative particle energy spectra and morphological tem- CPISM adopts a structured and configurable input interface plates, including those adapted to CPI-C' s specific orbit and to accommodate a wide range of observational scenarios and shielding conditions. model customizations. Simulation parameters are provided On the instrument side, the camera module supports external through Python dictionaries or YAML-based configuration calibration inputs for dark current, CIC maps, flat fields, and files, which define the properties of stellar and planetary bad columns. Users may supply their own calibration products targets, observational settings, and instrument parameters. via configuration. The PSF kernels, EM gain response, dark The instrument configuration file defines camera-level current evolution, and optical aberration maps can be directly parameters such as exposure time, electron multiplication incorporated into CPISM as external data products. settings, readout noise, full-well capacities, and a comprehensive This tight coupling between system-level simulation and sive set of effect toggles grouped under the switch dictionary. physical modeling ensures that CPISM remains a consistent Each camera effect can be individually enabled or disabled. and up-to-date proxy for CPI-C' s performance throughout its These flags allow users to simulate either idealized or fully

Figure 4. The stellar spectra of different spectral types (F5V, G5V, K5V) and their corresponding blackbody spectra across varying V-band magnitudes are generated by the program.

realistic detector responses. Optional reference files for flat- spectral type, and either R.A. and decl. or their separation and field maps, dark frames, CIC maps, and bad columns are position angle relative to the host star must be provided. For automatically loaded based on the default paths or user the planet, the required inputs include radius, albedo model

definitions. parameters, phase angle, and either R.A. and decl. or The observation parameter file defines the physical and separation and position angle relative to the host star. observational properties of the simulated scene. It specifies the After inputting these parameters, the program will generate central star' s coordinates, spectral type, magnitude, and the target' s position

and spectrum based on the provided data. distance, as well as parameters for planetary and background The output is a table containing the positions and spectra of objects, including radius, albedo model, phase angle, angular each target. separation, and spectral model. Each object can utilize either a The function `star_photlam` in the program is used to blackbody or an atmospheric spectrum. Default stellar and generate stellar spectra. When utilizing this function, the planetary reflection spectra are provided, but users may target' s apparent magnitude, spectral type, and choice between override these with custom data or analytical models to test a blackbody spectrum or a more realistic model spectrum alternative physical assumptions. Additionally, observational (CK04) must be specified. settings such as bandpass, frame number, sky background The spectral interpolation function of this code is designed brightness, and spacecraft attitude can be configured. to generate high-fidelity stellar spectra based on three fundamental stellar parameters: effective temperature (T_{eff}), metallicity (metallicity), and surface gravity (\log_g).

3.2. Target and Spectrum Modeling

The process begins with reading a pre-compiled CK04 catalog The target' s position in the program can be given in two stored in FITS format, which contains indexed stellar spectra ways: (1) by using the target' s equatorial coordinates, or (2) by characterized by different parameter combinations. To optimize specifying the position relative to the host star. ize computational efficiency, the catalog is cached to prevent When using equatorial coordinates to assign the target' s redundant I/O operations. Given a specific set of input position, the equatorial coordinates of the host star must also parameters, the code identifies the eight closest spectra in the be provided. When specifying the target' s position relative to parameter space by iteratively filtering the catalog based on the primary star, both the angular separation (in arcseconds) T_{eff} , metallicity, and \log_g . and the position angle (in degrees) must be provided. In the Once the relevant spectra are selected, trilinear interpolation program, the position angle is defined as increasing east of is performed in three sequential steps. The final spectrum is celestial north: 0° corresponds to celestial north and increases derived through successive interpolation along \log_g , counter-clockwise on the detector. metallicity, and T_{eff} , ensuring smooth transitions The program uses the `spectrum_generator` function to across parameter space. The resulting wavelength and flux read the parameters of the targets and generate the positions data are stored in the `pysynphot` spectrum class, with and spectra of all targets. wavelengths in angstroms (\AA), and the flux in photlam The input parameters are provided as a dictionary. The keys (`ph s-1 cm-2 \text{\AA}-1`). Figure 4 presents example spectral plots include name for specifying the target name, `cstar` for various star types and V-band magnitudes. specifying the central star, stars for the background star list, The simulation program includes a built-in planetary and planet for the planet list. reflected model from Batalha et al. (2018). The primary For the host star, the required inputs are magnitude, spectral factors influencing planetary spectra include methane and type, R.A., and decl. For background stars, the magnitude, cloud formations. Two key parameters affecting the brightness

fsed : 2.00 fsed : 0.00 1.0 Z : 0.00 Z : 1.33 Z : 0.00 Z : 1.33 Z : 0.67 Z : 2.00 Z : 0.67 Z : 2.00

geometric albedo 0.8 0.6 0.4 0.2 0.0 Z : 0.00 Z : 2.00 1.0 fsed: 0.00 fsed: 1.33 fsed: 0.00 fsed: 1.33 fsed: 0.67 fsed: 2.00 fsed: 0.67 fsed: 2.00

geometric albedo 0.8 0.6 0.4 0.2 0.0 3200 4000 4800 5600 6400 7200 8000 8800 9600 3200 4000 4800 5600 6400 7200 8000 8800 9600

wavelength (Å) wavelength (Å) Figure 5. The geometric albedo spectra of planets with difference atmosphere parameters. Top: spectra of different metallicity parameters when the sedimentation efficiency parameter is constant. Right: spectra of different sedimentation efficiency parameters when the metallicity parameter is constant.

profile are examined: the abundance of absorbing gases, response. Each astrophysical source—whether a central star, represented by metallicity (Z^*) within the range of (0, 2), and planet, or background object—is represented by its spectral cloud height and scattering properties, represented by flux within the selected observation band and its angular sedimentation efficiency (fsed) in the range of (-2, 2). A position relative to the field center. These sources are projected higher fsed indicates more efficient sedimentation, leading to into a spatial flux map according to their brightness and sky thinner clouds. Figure 5 demonstrates the functionality of this location. model. To generate the final image, the simulator performs a convolution between the flux map and the PSF kernel 3.3. Imaging and Contrast Simulation associated with the current band-pass. In practice, due to The optical path of CPI-C is modeled using Fourier optics. computational efficiency considerations and because planetary The module first constructs a 2D electric field across the pupil and background sources are faint (making subtle off-axis PSF plane, optionally modified by an apodizing filter. This filter is variations negligible), the simulator adopts a simplified represented as a grayscale transmission map , modulating the convolution-based strategy. Two types of PSFs are generated amplitude of the incident wave front across the telescope for each observing band: an on-axis PSF that includes the aperture. The apodization function is handled using HCIPy- cross-shaped focal-plane mask and represents the central star, compatible arrays. and an off-axis, unmasked PSF representing all other targets. Next, a wave front correction surface—typically derived For off-axis sources, an idealized (delta-function) flux map is from a DM—is optionally applied to the complex field to first created, placing point sources at fractional-pixel positions simulate quasi-static aberration control. Although CPISM does on a finely sampled grid (typically 4×4) to ensure sub-pixel not implement closed-loop wave front optimization internally, positional accuracy. Extended sources are similarly placed via precomputed DM shapes or PSF kernels (from Zhao et al. interpolation. This idealized flux map is then convolved with 2026) can be loaded via the function load_psf() and the off-axis, unmasked PSF. Finally, the central star—injected into the pipeline. represented by the masked PSF—is added. This hybrid The modified electric field is then propagated to the focal treatment balances realism and computational

efficiency, and plane using FFT-based angular spectrum methods. A focal has minimal impact on accuracy, as the faintness of off-axis plane mask may be applied to suppress diffraction structures sources renders minor PSF variations imperceptible. near the star. This combination of optical components This process captures the effects of diffraction, wave front produces a structured PSF, including the dark hole—a region modulation, and focal plane suppression, resulting in a realistic of high suppression, typically from 4 to $15\lambda/D$. intensity distribution across the field. The convolution step Once the wavelength-dependent PSF has been constructed, uses either precomputed kernels or numerically generated the simulator proceeds to synthesize the focal plane image by PSFs, and it accounts for key imaging parameters such as pixel combining the modeled astrophysical scene with the optical scale, oversampling factor, and total field-of-view. The output

is a simulated focal plane image that includes the main stellar For a given exposure time t and image size (in pixels), the PSF, planetary companions with reduced brightness, and other expected number of CR events is estimated as: background sources, all modified by the high-contrast optics of CPI-C. $N = t \cdot A \cdot R_{cr}$, (2) In parallel with image synthesis, CPISM calculates the theoretical contrast of the planet relative to the host star using where A is the effective sensor area in cm^2 and R_{cr} is the the function `planet_contrast`. This function requires the CR rate. input of the planet's radius (in units of Jupiter radii), the Each CR streak is characterized by a random length, width, planet's separation from the host star in the R.A. and decl. deposited charge, and orientation angle. The length is derived directions (in AU), and the planet's phase angle. The phase from a simplified 3D track projection model, considering the angle refers to the angular separation between the line of sight detector depth and pixel pitch. The width is modeled as a to the planet and the line connecting the planet to the host star. Gaussian spread with random variation, and the deposited When the line of sight is aligned with the star-planet line, the charge follows an exponential distribution modulated by a phase angle is 0° . When the line of sight is perpendicular to the power-law tail. star-planet line, the phase angle is 90° . The program calculates To construct the two-dimensional CR artifacts, two models the 3D physical separation between the planet and the star are employed. In the default mode, the CR track image is based on the input projected distance, using the Lambert synthesized using a combination of Gaussian profiles and

function. modulated Fourier-based noise to emulate natural variations in The planetary contrast is then calculated using the equation trail structure. Alternatively, a Monte Carlo-based model is (Madhusudhan & Burrows 2012): adopted, where CR events are generated using a pre-defined set of track templates drawn from real or simulated data. These f planet R_p templates capture the empirical distribution of track sizes and contrast $p = A_g f_{star} r$ morphologies, enabling more physically realistic CR $\sin(\theta) + \cos(\theta)$ simulations. \times , (1) The resulting streak images are randomly positioned on the sensor frame, rotated according to the sampled angle, scaled where A_g is the geometric albedo of

the planet, θ is the phase by the corresponding flux, and overlaid with attention to edge angle, R_p is the radius of the planet, and r denotes the distance blending and non-negativity. This method ensures both between the planet and the star. Note that the phase angle statistical consistency and structural diversity of the simulated cannot be 0° or 180° . CR artifacts. The effect of CRs in the simulated observation image is 3.4. Observational and Instrumental Effects shown in Figure 6. CRs were observed to have a wide range of morphologies, We also take background light into account in the from point-like to elongated shapes (Fisher-Levine & simulation. Since the actual situation may be very complicated Nomerotski 2015), with an average energy deposition of and the influence of background light is weak, we usually only approximately 2700 electrons per CR. Miles et al. (2021) also add light with a flux density of 21 mag arcsec⁻² uniformly to provided insights into the path lengths of CRs, which were the image. We reserve interfaces for zodiacal light and earthtypically proportional to their angle of incidence, with an atmosphere radiation, which can be modified in the future estimated average path length of about 200 μm . according to actual specific conditions. For stray light, users For the purpose of evaluating the robustness of our image can also pre-calculate the corresponding stray light intensity processing pipeline against high-energy particle interference, data based on the specific characteristics of the optical system, we implemented a synthetic CR frame generator based on and then set it in the program as an input parameter. physical and statistical models in the simulation. CRs Detector effects intrinsic to the EMCCD are modeled interacting with camera sensors produce linear, streak-like comprehensively within the camera module. The simulation artifacts that can corrupt scientific measurements, especially in covers the entire EMCCD readout process, from photon space-based observations. conversion to final digital output. The photon collection phase In order to simulate the real CR situation as much as converts photon flux into electrons, considering non-uniform possible, the energy distribution of the CRs in the program pixel response and adding dark current according to predefined adopts the detected results of the HST (Heyer et al. 2004). The reference frames. Nonlinear response to illumination is incident particle rate is based on the results of Miles et al. modeled uniformly across the sensor array. When collected (2021), the peak of which is about 1 particle s⁻¹ cm⁻². This electrons exceed the pixel full-well capacity, vertical saturrate was modulated by solar activity, with variations corresp- ation and blooming occur, simulating the overflow behavior onding to the 11 yr solar cycle. typical of EMCCDs.

Figure 6. Simulated 3000 s exposure with EM gain of 1 (left) and 300 (right) for cosmic ray observation effect. When EMCCD uses high electron multiplication, cosmic rays may cause saturated overflow, resulting in a “tailing” phenomenon in the image.

The electron multiplication stage, characteristic of EMCCD Figure 7 presents the PSF maps (top row) and the technology, significantly amplifies incoming signals. EM gain corresponding normalized intensity profiles. Two imaging is implemented through a calibrated voltage-dependent configurations are com-

pared: one employing only pupil relationship that also accounts for detector temperature, apodization, and the other incorporating the dark hole Effects specific to EMCCD operation, including CIC, readout structure. The contrast curves are plotted on a logarithmic noise, and charge transfer inefficiency, are explicitly simulated as a function of angular separation from the central star. Additional image artifacts, such as vertical striping, The simulation results show that the random horizontal interference patterns, and bias level drift, coronagraph consistently suppresses stellar light within the are included based on empirical detector characterization. dark hole region (0.19 to 1") to below 10–8 in all four bands, These effects are parameterized in the camera configuration, with slight wavelength-dependent variations. The suppression allowing the simulator to flexibly represent idealized or is most effective near 662 nm, consistent with the optimized realistic instrument behaviors. The culmination of these steps design of CPI-C. The dark hole region appears as a wellproduces raw observational data formatted as Level 0 FITS defined area of reduced intensity, clearly visible in both the files, closely aligned with anticipated real detector outputs. PSF images and contrast curves. These results demonstrate that CPISM can reproduce the expected high-contrast imaging performance of CPI-C across multiple bands and provide a 4. Example Verification useful tool for validating the optical design and informing In the following section, we demonstrate the use of the scientific analysis. CPISM simulation program through an example of simulating a CPI-C target and verifying its accuracy. 4.2. Simulation of a Hypothetical Exoplanet CPI-C targets FGK-type stars within 40 pc of the Sun's neighborhood for high-contrast imaging observations of 4.1. PSF Chromaticity potential exoplanets. The program uses multi-band photometry To evaluate the imaging performance of CPI-C across its and spectral fitting to derive the atmospheric properties of designated observation bands, we simulate the system's PSF detected exoplanets, laying the groundwork for future and corresponding contrast curves at four representative biosignature identification in exoplanetary systems. Based on wavelengths: 520, 662, 720, and 850 nm. These simulations the engineering specifications of CPI-C, there are nearly seven are generated using the `single_band_psf()` function in hundreds nearby stars selected as observation targets, most of the CPISM framework, which constructs the optical field which have V-band magnitudes between 0 and 7. Information through Fourier optics and includes the effects of the about these stars, including spectral type, V-band magnitude, apodizing pupil mask, wave front correction, and focal plane and ecliptic coordinates (for observation planning), was mask. The dark zone is defined within a specific angular range obtained from the SIMBAD database (<https://simbad.cds.unistra.fr/simbad/>), where starlight suppression is optimized.

Wavelength = 520 nm Wavelength = 662 nm Wavelength = 720 nm Wavelength = 850 nm

400 600 400 600 400 600 400 600

Normalized Intensity 10 1 Pupil Apodize Pupil Apodize Pupil Apodize Pupil

Apodize Dark Hole Dark Hole Dark Hole Dark Hole 10 5 10 9 0 1 2 3 0 1
 2 3 0 1 2 3 0 1 2 3 x-distance (arcsec) x-distance (arcsec) x-distance (arcsec)
 x-distance (arcsec) Figure 7. The PSF maps (top row) and the normalized
 contrast intensity profiles along the diagonal direction (bottom row) for each
 wavelength. The orange and blue curves represent the intensity passing through
 or not passing through the dark hole, respectively.

Figure 8. Left: the image contains the central star, planet, and reference star.
 Middle: the image contains only the central star. Right: the image after subtraction,
 where the planet and the reference star can be clearly seen. The simulated
 band is F520. The two crosses mark the positions of the planet and the reference
 star, which are located in different dark holes with position angles of 45° and
 135° respectively.

As an example, we selected Alpha Centauri (HIP 71681), a the planet and reference
 star. The subtracted frames are K1V-type star with a V-band magnitude
 of 1.35 (ESA 1997), subsequently co-added to further reduce random noise, lo-
 cated at a distance of 1.35 pc (van Leeuwen 2007). A resulting in an image that
 includes only the planet and hypothetical planet is generated with the following
 parameters: reference star, while largely removing the background. position an-
 gle of 315° , phase angle of 90° , radius of 1 RJupiter, Figure 8 shows an example
 of simulated F520-band images and an angular distance of 0. 65 from the host
 star. The before and after subtraction. This simulation and image metallicity is
 set to $Z^* = 1$ and the sedimentation efficiency to processing are conducted across
 all four observation bands $f_{sed} = 1$. Additionally, a background star is added
 for flux of CPI-C. calibration, with a position angle of 225° , a spectral type
 of In real CPI-C observations, dedicated reference star K1V (the same as the
 central star), and an angular separation observations may not be feasible due to
 time and resource of 0. 95. constraints. Instead, flux calibration of the central
 star can be We use the simulation program to generate two sets of achieved by
 offsetting the target slightly from the coronaimages: one containing the central
 star, planet, and reference graphic mask and acquiring a set of short-exposure,
 nonstar, and the other containing only the central star. Other coronagraphic
 images (as shown in Figure 9). These direct parameters, such as exposure time,
 remain the same for observations of the stellar PSF can then be used to esti-
 mate the both sets. stellar flux and calibrate the planet-to-star contrast. This
 After running the simulation, we adopt a Reference strategy allows for robust
 photometric referencing without Differential Imaging (RDI) technique to sup-
 press background requiring a separate reference star or coronagraph-off noise in
 images containing planetary signals. For each science sequence. frame, its dark
 hole is extracted and linearly fitted using a library of background images known
 to be free of planetary 4.3. Photometric Analysis signals. Singular Value De-
 composition is employed to Next, we apply aperture photometry to measure the
 magnitude construct an optimal background model specific to each of sources in
 the image. The sep code (Barbary 2016) is frame (Ren & Chen 2021). Then the
 images containing only used to determine the exact coordinates of the target
 planet. the central star are then subtracted from the images containing Then,

photutils (Bradley et al. 2025) is employed to

shift=[0" ,0"] shift=[0.2" ,0.2"] shift=[0.5" ,0.5"] shift=[1" ,1"] 700 700 700 700
 600 600 600 600 500 500 500 500 400 400 400 400 300 300 300 300 400 600 400
 600 400 600 400 600 Figure 9. Simulated images of the star shifted away from
 the central obstruction. The images from left to right show the stars with no
 shift, a shift of 0. 2, 0. 5, and 1". Because central stars are typically very bright,
 multiple short-exposure images are taken and subsequently combined to avoid
 saturation. The simulation is conducted in the F520 band with the exposure
 time of 0.01 s \times 50 for each situation.

select a circular aperture with an appropriate radius for the Table 1 target,
 and a square aperture for the background area, based The Resulting Contrast
 and Signal-to-noise Ratio of Four Bands on the position and size of the dark
 region. The combined Filter Exposure Contrast SNR flux within the target and
 background apertures, as well as (s) ($\times 10^{-8}$)

the standard deviation within the background aperture, are F520 17 \times 30 5.163
 8.870 calculated separately. The target aperture is used as a mask F662 9 \times 30
 4.737 4.451 when measuring the background aperture to minimize F720 50 \times
 30 3.533 5.480 F850 100 \times 30 2.138 5.488 contamination from the target. The
 following parameters were obtained statistically: the Note. The photometric re-
 sults of the target planet in the simulated image are standard deviation and the
 sum of readings in the background used as an example. area, the signal at the
 target aperture, the number of pixels a0 in the target aperture, and the number
 of pixels as in the background area. Additionally, two known instrument para-
 photometric error of the target planet is obtained through meters were used:
 the GAIN, representing the number of error propagation. photoelectrons per
 analog-to-digital unit (ADU), and the At this stage, the photometry of the im-
 age target is electron multiplication (EMGAIN) occurring inside the complete,
 and the contrast and SNR of the planet have been EMCCD. determined. The
 photometry results for the four bands are The background value is determined
 by averaging the presented in Table 1. readings in the skylight background
 area, i.e., D_s/a_s . There- Figure 10 shows the photometric results of the simu-
 lated fore, the number of photons in the target signal is the total planet in four
 bands alongside the theoretical planetary signal within the aperture minus the
 background signal within spectrum calculated based on the input parameters.
 The the aperture: resemblance between the photometry of the simulated images
 $S_0 = K \cdot (D_0 D_s \cdot (a_0 / a_s))$, (3) and the theoretical models confirms that
 key physical parameters, such as planetary albedo and phase angle, were where
 K is the ratio of GAIN to EMGAIN, it represents the correctly implemented
 and processed. number of photons corresponding to each ADU. By using this
 method to measure the number of photons 4.4. Exposure Time and EM Gain
 Effects from both the planet and a reference star with the same aperture size,
 the magnitude of the planet can be calculated Exposure time and EM gain
 are critical observational based on the known magnitude of the reference star.
 parameters that significantly influence the performance of Subsequently, the ob-

servational contrast of the planet relative EMCCD-based coronagraphic imaging instruments. To evalto the star can be determined. uate and illustrate these effects within our CPISM simulations, To calculate the noise, we account for the noise generated we present simulated CPI-C images generated at different by both the target source and the background, relative to the exposure times (30 s, 300 s) and EM gains (EMGAIN = 1, 20), number of pixels in the chosen apertures: as shown in Figure 11. The simulated results clearly demonstrate distinct trends. At 2 a short exposure time (30 s) with low EM gain (S 0) = $S_0 + s \cdot a_0 \cdot (1 + a_0 / a_s)$. (4) (EMGAIN = 1), the image is dominated by detector noise The measurement error between the target planet and the and shows limited sensitivity, with only the brightest targets reference star is calculated using Equation (4), and the barely detectable. Increasing the exposure time to 300 s at low

Contrast ($\times 10^{-8}$)

5000 6000 7000 8000 9000

Wavelength (Angstrom) Figure 10. Comparison of photometric results and theoretical spectra.

EXPT=30s, EMGAIN=1 EXPT=300s, EMGAIN=1 artifacts become pronounced, demonstrating a trade-off between sensitivity and image fidelity. In the case of a longer exposure (300 s) combined with higher EM gain, severe saturation and blooming effects dominate the image, substantially degrading image quality and making accurate photometric extraction challenging or impossible.

5. Summary In this paper, we introduce CPISM, the simulation program for CPI-C, one of the backend modules of the CSST. The EXPT=30s, EMGAIN=20 EXPT=300s, EMGAIN=20 program includes modules for generating stellar spectra, planetary albedo models, and contrast calculations. It enables users to input parameters for stars and planets, and to compute expected photometric and spectral outputs. Additionally, the program can calculate the required exposure time for observations or the SNR of the observational results. We also present a methodology for simulating CPI-C observation targets using a stellar spectrum model and a planetary albedo model to measure the contrast. Based on the modular framework, CPISM includes functional components Figure 11. Simulated CPI-C images generated at different exposure times for target modeling, imaging simulation, observational effects, (30 s, 300 s) and EM gains (EMGAIN = 1, 20). A bright source is added in and detector response. The complete simulation workflow is the dark hole on the lower right at a position angle of 135° and an angular then described, from parameter configuration to Level 0 data distance of 0.95. generation, integrating optical propagation, PSF convolution, noise modeling, and EMCCD detector behaviors. EM gain significantly enhances signal detection but also leads We use Alpha Centauri as an example to demonstrate the to saturation

and blooming in the brightest regions, resulting in program's capability to simulate realistic high-contrast imacharacteristic vertical streak artifacts in the image. ging observations. By applying an RDI technique and aperture When employing higher EM gain ($EMGAIN = 20$), even a photometry, we extract contrast and SNR values of a relatively short exposure (30 s) greatly amplifies the photon- hypothetical planet across multiple bands. The photometric generated electrons, improving sensitivity to faint sources. results show good agreement with the theoretical input spectra. However, the amplified noise and bright-source saturation The example demonstrate the end-to-end operability of the

simulator—from parameter input to Level 0 data output—data processing and analysis system of the China Manned under a controlled, simplified observational scenario. Space Project. We acknowledge the National Natural Science This result not only verifies the scientific robustness of our Foundation of China (NSFC) under grant Nos. 11827804, simulation but also provides a solid foundation for applying U2031210 and 11433007, as well as the science research the program to future survey strategy. The close alignment grants CMS-CSST-201906, CMS-CSST-2025-A18, CMSbetween simulated and theoretical results indicates that the CSST-2021-A11, and CMS-CSST-2021-B04 from the China program can reliably predict observational outcomes under Manned Space Project. This research is also funded by the various conditions, highlighting its potential as a tool for “Jiangsu Funding Program for Excellent Postdoctoral Talent.” optimizing high-contrast exoplanet observations. This accuracy is crucial for developing strategies that maximize ORCID iDs observational efficiency and scientific return from instruments like CPI-C. Yi-Ming Zhuaa <https://orcid.org/0000-0002-9106-8718> Further analysis of exposure time and EM gain demonstrates Gang Zhaoaa <https://orcid.org/0000-0001-8544-0280> CPISM's capability to accurately reproduce image artifacts Jiang-Pei Douaa <https://orcid.org/0000-0002-7612-6377> and sensitivity variations. Shorter exposures and lower EM gains result in detector-noise dominated images, whereas References longer exposures and higher gains increase sensitivity but also

cause saturation and blooming artifacts. This analysis high- Bao, C., Ji, J., Zhao, G., et al. 2025, arXiv:2509.16761 Barbary, K. 2016, JOSS, 1, 58 lights CPISM's practical utility in optimizing observational Batalha, N. E., Smith, A. J. R. W., Lewis, N. K., et al. 2018, AJ, 156, 158 parameters. Beuzit, J. L., Vigan, A., Mouillet, D., et al. 2019, A&A, 631, A155 Our simulation program is highly flexible. With the Bradley, L., Sipócz, B., Robitaille, T., et al. 2025, astropy/photutils: v2.3.0 Castelli, F., & Kurucz, R. L. 2004, IAUS, 210, A20 provided interfaces, the stellar spectrum model and planetary Chauvin, G. 2024, CRPhy, 24, 139 albedo model can be easily replaced. In this article, we have Dou, J. P., Zhang, X., Zhao, G., et al. 2026, arXiv:2512.11292 selected a relatively simplified atmospheric model as an Douglas, E. S., Ashcraft, J. N., Belikov, R., et al. 2020, SPIE, 11443, 1144338 ESA 1997, ESA Special Publication, Vol. 1200, The HIPPARCOS and example, but users can substitute it with a more sophisticated TYCHO catalogues. Astrometric and photometric star catalogues

derived model based on their needs. Additionally, the observation band from the ESA HIPPARCOS Space Astrometry Mission, used in the simulation can be changed, provided a corresponding transmittance curve is available. This program will also assist in selecting optimal observation bands for CPI-C. Hedges, C., Holcomb, R. J., Hord, B., et al. 2024, SPIE, 13101, 131010F Looking ahead, this simulation framework will play a crucial role in advancing exoplanetary research, including the characterization of debris disks and planet-disk interactions (Bao et al. 2025). As the CPI-C module is poised for ground-breaking discoveries, the insights provided by our simulations will be instrumental in detecting and characterizing new worlds beyond our solar system. Mesa, D., Keppler, M., Cantalloube, F., et al. 2019, A&A, 632, A25 Miles, N. D., Deustua, S. E., Tancredi, G., et al. 2021, ApJ, 918, 86 Poberezhskiy, I., Heydorff, K., Luchik, T., et al. 2022, SPIE, 12180, 121801X Acknowledgments Ren, D., & Chen, Y. 2021, MNRAS, 502, 2158 Spergel, D., Gehrels, N., Baltay, C., et al. 2015, arXiv:1503.03757 This work is based on the mock data created by the CSST van Leeuwen, F. 2007, A&A, 474, 653 Simulation Team, which is supported by the CSST scientific Zhao, G., Zhu, Y., Dou, J., et al. 2026, RAA, 26, 024010

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

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