Full-Field High-Contrast Exoplanet Imaging Design and Numerical Simulation Postprint

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Date: 2019-05-30T00:00:00+00:00

Abstract

Direct imaging detection of terrestrial exoplanets is extremely challenging. In the short-wavelength visible band, the planetary signal primarily originates from starlight reflected by the planetary atmosphere, with the contrast between the two at the order of 10^{-10}, resulting in the faint exoplanet light being overwhelmed. Therefore, effective suppression of intense starlight is crucial for achieving terrestrial exoplanet detection. This paper proposes a technical scheme based on pupil amplitude modulation and phase correction to realize high-contrast imaging across the entire field. Numerical simulation analysis was conducted for the aforementioned scheme to illustrate its feasibility and potential performance. The numerical simulation evaluates the system' s target imaging contrast based on the energy distribution of the point spread function and employs a stochastic parallel gradient descent iterative algorithm for optimization, ultimately achieving an imaging contrast at the order of 10^{-10} across the full 360-degree region. The study demonstrates that this scheme is promising for future space-based direct imaging detection of terrestrial exoplanets.

Full Text

Preamble

High-Contrast Imaging Design and Numerical Simulation for Full-Field Exoplanet Detection

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Abstract: Direct imaging of Earth-like exoplanets presents formidable challenges. In the visible short-wavelength band, planetary signals originate primarily from stellar light reflected by the planetary atmosphere, resulting in an intensity contrast of approximately 10^{1} between planet and star. This extreme contrast causes the faint exoplanet light to be completely overwhelmed by stellar contamination. Consequently, effective suppression of stellar light is the critical enabling technology for Earth-like planet detection. This paper proposes a technical solution based on pupil amplitude modulation combined with phase correction to achieve full-field, high-contrast imaging. Numerical simulations are performed to demonstrate the feasibility and potential performance of this approach. The simulation evaluates system imaging contrast based on the energy distribution of the point spread function (PSF) and employs a stochastic parallel gradient descent (SPGD) iterative algorithm for optimization. The final imaging contrast reaches the 10^{1} level across a full 360-degree working area. These results indicate that the proposed scheme holds promise for future space-based direct imaging missions targeting Earth-like exoplanets.

Keywords: Exoplanet; Terrestrial planet; Direct imaging; High contrast; Numerical simulation; Optimization algorithm

0 Introduction

Exoplanet detection represents a major frontier in contemporary astronomy. As of May 2019, over 4,000 exoplanets have been discovered [?]. Detection methods fall into two categories: indirect techniques and direct imaging. Indirect methods—including radial velocity, transit photometry, astrometry, and microlensing—infer planetary properties through observations of stellar physical parameters, but cannot directly obtain critical information such as effective temperature, atmospheric composition, or surface gravity. Direct imaging, by contrast, enables measurement of planetary mass and orbital parameters, while subsequent spectroscopic analysis reveals atmospheric composition, surface gravity, and effective temperature. This makes direct imaging an essential technology for identifying biosignatures in exoplanet atmospheres [?].

When stellar light passes through a telescope aperture, diffraction occurs, and the stellar intensity far exceeds that of any planetary companion, completely overwhelming the faint planetary signal. The visible short-wavelength band is particularly important for future exoplanet imaging missions because it contains numerous biosignatures and, since spatial resolution scales as /D (where is wavelength and D is telescope aperture), enables equivalent resolution with smaller apertures [?, ?]. However, detecting Earth-like planets in the habitable zones of Sun-like stars at these wavelengths requires imaging contrast of 10^{1} [?]. Coronagraphs can effectively suppress starlight to achieve such ultra-high contrast. In recent years, researchers have proposed various coronagraph designs theoretically capable of 10^{1} contrast [?, ?, ?]. Nevertheless, wavefront aberrations from non-ideal optical elements generate speckle noise that limits achievable contrast. Without wavefront correction, contrast remains around

10 . Therefore, effective wavefront aberration correction to suppress speckle noise is the key to achieving ultra-high contrast imaging of Earth-like planets.

Malbet first proposed an optimization control algorithm using a deformable mirror (DM) to create dark zones [?], achieving contrast up to 10 in localized regions. In recent years, advances in DM technology have improved experimental coronagraph contrast to the 10 level. However, current wavefront correction schemes produce only small high-contrast regions, preventing full-field high-contrast imaging and limiting detection efficiency [?, ?].

To address this limitation, this paper proposes a 360-degree full-field, ultra-high contrast coronagraph technique and presents preliminary numerical simulation results. The simulations employ the SPGD algorithm for iterative optimization, using PSF energy as feedback to control pupil energy distribution and wavefront, thereby maximizing system imaging contrast [?, ?]. The process consists of two steps: first, optimizing a stepped-transmission filter to achieve 10 contrast at 4 /D through amplitude modulation; then applying a 32×32 DM for wavefront correction to obtain 10^{1} contrast in the 4–14 /D region. To further expand the imaging area, we also propose a simultaneous amplitude-phase optimization scheme that achieves 10^{1} contrast across the 4–20 /D region.

1 Optimization Algorithm Principle

The point spread function (PSF) at the focal plane for stellar light passing through an optical system is given by:

$$I_{psf}(x, y) = |\mathcal{F}[P(u, v)e^{i\varphi(u,v)}]|^2 \tag{1}$$

where $\mathcal{F}$ denotes Fourier transform, $P(u, v)$ is the amplitude at the system entrance pupil (here we consider a circular aperture), and $\varphi(u, v)$ is the phase at the entrance pupil. The coronagraph system optimizes these two variables at the pupil plane to achieve high-contrast dark zones using the following merit function:

$$\text{Merit Function} = \frac{\sum I_{out}(x, y)}{\sum I_{in}(x, y)} \tag{2}$$

where $I_{in}(x, y)$ represents intensity in the central region and $I_{out}(x, y)$ represents intensity in the high-contrast imaging region. This merit function seeks to minimize the energy in the imaging region relative to the central region. The high-contrast imaging regions used in this work are illustrated in [Figure 1: see original paper], with optimizations performed for both full and half regions.

Imaging contrast is defined as:

$$\text{Contrast} = \frac{I(x, y)}{I_{max}} \tag{3}$$

where I_{max} is the maximum energy at the focal plane. Based on the distribution characteristics of a circular aperture PSF, energy concentrates primarily within the central Airy disk of radius 1.22 /D, with I_{max} representing the central Airy disk intensity. Since the circular aperture PSF is axisymmetric, this work evaluates contrast along the diagonal direction.

Various optimization algorithms exist, including genetic algorithms [?] and SPGD. This work employs the SPGD algorithm for iterative amplitude and phase optimization. SPGD simultaneously applies small random perturbations to all variables, evaluates the gradient change in the merit function, and iteratively updates the solution [?]. The variable update equation is:

$$u_{k+1} = u_k - \gamma \delta J_k \delta u_k \tag{4}$$

where k is the iteration number, $u = \{u_1, u_2, ..., u_n\}$ represents the optimization variables, n is the number of parameters, γ is the gain coefficient (positive for minimization), δu is a random perturbation following a Bernoulli distribution, and δJ is the change in the merit function:

$$\delta J = J(u + \delta u) - J(u) = J(u_1 + \delta u_1, ..., u_n + \delta u_n) - J(u_1, ..., u_n) \tag{5}$$

For improved accuracy, we employ bilateral perturbation:

$$\delta J = J^+ - J^- = J(u + \delta u) - J(u - \delta u) \tag{6}$$

To accelerate convergence, the gain coefficient γ adapts to the merit function change:

$$\gamma_{k+1} = \gamma_k \cdot J_k \tag{7}$$

2 Numerical Simulation

2.1 Stepwise Optimization of Amplitude Modulation and Wavefront Correction

The coronagraph configuration is shown in [Figure 2: see original paper]. Starlight passes through the telescope focus and is collimated by lens L1. The parallel beam then passes through an aperture stop and encounters a stepped-transmission filter for amplitude modulation. After passing through imaging lens L2 and collimating lens L3, a DM performs wavefront correction at the pupil plane. Finally, imaging lens L4 forms the image, which is captured by a detector at the focal plane.

The SPGD algorithm optimizes the stepped-transmission filter design by treating each annular zone' s transmittance as an independent variable for simultaneous iteration. After multiple iterations, this achieves 10 contrast in the 4–14 /D region. [Figure 3: see original paper] shows the optimized stepped-transmission filter and its radial transmittance profile. [Figure 4: see original paper] displays the resulting PSF after modulation.

Due to the Nyquist sampling theorem [?], an $N \times N$ DM can theoretically control wavefront aberrations within $N/2 \times \lambda/D$. The achievable contrast can be expressed empirically as:

$$\text{Contrast} = \left(\frac{\pi\sigma}{N}\right)^2 \tag{8}$$

where σ is the mirror RMS surface error and N is the number of DM actuators. Equation (8) indicates that contrast can be improved by increasing DM actuator count or reducing the optimization region.

This scheme simulates a 32×32 DM with a theoretical control range of 16 /D. Simulations use half this range for wavefront correction. Each DM actuator serves as an independent optimization variable. After iterative optimization, the system achieves 3.5×10^{1} contrast across the full 4–8 /D region with 32.04% throughput. [Figure 5: see original paper] shows the DM phase distribution and resulting PSF. [Figure 6: see original paper] presents contrast curves for the 4–8 /D region, comparing unmodulated (black), amplitude-modulated (blue), and phase-corrected (red) performance.

Optimizing over half the 4–14 /D region yields 1.6×10^{1} contrast with 32.04% throughput. [Figure 7: see original paper] shows the DM phase distribution and PSF for this case, while [Figure 8: see original paper] displays the contrast curve with amplitude modulation and wavefront correction.

2.2 Simultaneous Amplitude Modulation and Wavefront Correction

This section considers simultaneous amplitude modulation and wavefront phase correction. Starlight is collimated by L1, then passes through two modulators that perform simultaneous amplitude and phase control before imaging by L2. The system configuration is shown in [Figure 9: see original paper].

Both amplitude and phase are arranged in annular zones, with each zone representing an independent variable. After iterative optimization, this approach achieves 10^{1} contrast across the full 4–20 /D region with 10.5% system transmittance. [Figure 10: see original paper] shows the amplitude mask and its radial profile. [Figure 11: see original paper] displays the phase distribution and resulting PSF. [Figure 12: see original paper] presents the contrast curve for the 4–20 /D region after simultaneous optimization.

3 Conclusion

Both proposed optimization schemes achieve 10^{1} contrast across full working areas, enabling future direct imaging of Earth-like exoplanets. summarizes the numerical simulation results.

Simultaneous amplitude-phase optimization enables higher contrast over larger regions, making it suitable for large-area, full-field exoplanet surveys. However, this scheme suffers from lower transmittance, requiring longer exposure times that impact observation efficiency. Additionally, the large number of control units needed exceeds current DM capabilities; spatial light modulators (SLM) could serve as an alternative. SLM-based amplitude modulation offers greater flexibility than stepped-transmission filters, enabling real-time adaptation to pupil geometry. However, SLMs require two linear polarizers, further reducing system transmittance. Future work will focus on transmittance optimization to improve system throughput, experimental validation, and investigation of broadband high-contrast imaging.

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