Optical Simulation Analysis of a Geometrical-phase-based Nulling Interferometer

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Abstract

The optical performance and limitations of a nulling interferometer operated with geometric phase (Berry’s phase or Pancharatnam phase) are investigated by optical simulation. We first numerically verify the current geometrical-phase-based nulling interferometer [e.g. Baba et al., Opt. Lett. 26, 1167 (2001)]. Next, we evaluate the performance and find that in the direct detection of planetary systems circling a sun-like star, the ratio of the luminosity of the planet to that of the star is shown to depend on not only the achromatically deep null depth of the starlight but also the ratio of the illuminance of the planet to that of the star on the detector. The ratio of the size of the planet to that of the star is a crucial factor, but it is also the one that is unknown in advance. The tolerance of optical component (for example, the beam-splitter) on nulling interferometer is also considered.

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I. Introduction

Nulling interferometry was proposed two decades ago for directly observing gloomy planets around sun-like stars [1]. It is a technique based on a dual-aperture stellar interferometer, in which on-axis starlight is suppressed by destructive interference to increase the luminosity ratio between the planet and the star. However, achromatism is an important issue in nulling interferometry. Several ways to utilize the relative field flip between two arms in a rotational shearing interferometer have been proposed to achieve achromatically deep nulling [2-6]. Hinz et al. reported interferometric observation using multiple mirror telescopes [7], while Mieremet et al. elucidated the theory of adjustable dispersive elements in which the dispersion-induced residual phase shift error can be improved by increasing the number of elements [8]. Serabyn et al. [9] suggested nulling beam combiners with full symmetry to promote the equality of two-arm intensities. Recently, Baba et al. [10] demonstrated a laboratory experiment that used a geometrical-phase-based nulling interferometer, in which a null depth of order $10^{-5}$ was achieved in white light (400 – 700 nm). Nulling interferometry based on geometrical phase is conceptually attractive. Hence, further exploring this kind of interferometry is valuable.

Here, simulation using a commercial optical software package, ASAP [11], was used to examine the performance of a geometrical-phase-based nulling interferometer under ideal conditions. One of the advantages of such an interferometer is that neither two arms nor therefore, precision alignment are required. However, a beam-splitter is required; that is a beam combiner that combines the sources from the optical paths via two telescopes into one optical path. Consequently, the variation in coating properties of such a beam-splitter reduces the null depth. Hence, clarifying the affect of a real 50/50 beamsplitter on the performance of a nulling interferometer
is crucial. Moreover, previous literature has considered mainly null depth, which is the intensity rejection ratio of starlight after to that before nulling. In reality, however, a successful direct observation of a dim source depends not only on the achromatically deep nulling of the starlight but also on the ratio of sizes of the planet and the star as we demonstrated below.

II. General setting of simulation

Figure 1 schematically depicts a geometric-phase-based nulling interferometer, essentially following Baba et al. [10]. ASAP code is developed here to simulate such an interferometer. The direction of the light from the star (solid line) is chosen to coincide with the optical axis of the telescopes, while the light from the planet (dot-dashed line) is somewhat away from the star. Thus, initially, no optical path difference (OPD) exists between the starlight in two arms, but an OPD will be produced between the paths of the light from the planet in two arms. With reference to Fig. 1, by passing through the linear polarizers (LPs), the beams from the star and the planet along the optical paths in two telescopes are mutually orthogonal and polarized, that is, the light from the star and the planet in one path is p-polarized and that in the other path is s-polarized.

A combination of two quarter-wave plates, QWP-1 and QWP-2, where the azimuth angles of QWP-1 and QWP-2 are set to be 45° and one half-wave plate, HWP, is used to change cyclically the polarization state of linearly polarized light. The state changes from the circular, though oppositely circular, and then back to linear polarization, as the light passes through QWP-1, HWP and QWP-2 respectively. In this combination, a rotation of HWP through an angle $\Omega$ that is the angle between the optical axis of HWP and that of QWP, causes a phase delay of $2\Omega$ for one
polarized beam, and a phase delay of $-2\,\Omega$ for the other orthogonally polarized beam. Therefore, the total phase delay, or geometric phase shift between the two beams is $4\,\Omega$. Broadband destructive interference of the starlight can be achieved by rotating the optical axis of HWP because of the geometric phase’s independence of the wavelength.

A real situation of the star and the planet is simulated. The bright and the faint objects are assumed to be thermal sources with surface temperatures of $8000\,\text{K}$ and $1000\,\text{K}$, respectively. These temperatures are such that the wavelength distributions follow different intensity curves. Differently choosing temperature of the faint source does not affect the conclusions reported below.

The number of rays is typically set to 80 and 21 per wavelength, for the bright and faint sources, respectively. Notably in ASAP, more rays imply more energy of the source. But, computer time increases with the number of rays. Thus, in simulation, the intensity of the source is usually assigned directly, without adjusting the numbers of rays. For example, the intensity is 1 watt for the bright source and $10^{-9}$ watts for the faint one. Meanwhile, wavelength range of 400-700 nm with increment of 3 nm is typically simulated.

III. Tolerance analysis of the beam-splitter

In the simulation, the luminosity ratio between the planet and the star is first set to $1:10^9$, and the wavelength is in the range, 400-700 nm. These settings are based on what is expected in the case of the Earth and the Sun in the visible regime [6]. Note that the luminosity means the total energy radiated from the surface of a star per second (unit: Watt/sec). Figure 2-(a) presents the result of simulation of direct
detection of planet where the starlight is not nulled, while Fig.2 (b) shows the result that the starlight is nulled. The simulation is under ideal conditions: (1) no energy is lost when the light passes through optical elements, (2) the division of intensity is perfect in the wavelength regime concerned, that is the beamsplitter is an ideal 50/50 beamsplitter, and (3) no alignment errors occur. Clearly, no residual interference of the starlight occurs due to the wavelength-independent geometric phase delay of $\pi$, revealing the power of geometric-phase-based nulling interferometry. (Our simulation shows a null depth of order $10^{-13}$ in simulation limit.)

Tolerance can be critical to achieve the desired performance. For a beamsplitter with a transmission inaccuracy of 1% such that 50.5% of light is transmitted and 49.5% is reflected, for both the p-polarized and s-polarized beams, the performance of a nulling interferometer is considered. Figure 3 (a) shows the simulation result. The null depth of the starlight is in the order of $10^{-5}$. Considering the previous perfect result, the degradation is severe and the luminosity of the planet is too low to be detected. The radiation ratio between the Earth and the Sun in the infrared (IR) regime is $1:10^6$ [6]. However, the planet remains hard to detect as the simulation reveal. Therefore, a good-quality beamsplitter with transmission inaccuracy less than 0.1% is required to support the entire range of wavelengths of the nulling interferometer.

A commercial broadband non-polarizing beamsplitter, produced by Newport (model number: 20BC17MB.1) [12], is considered as a practical example. Figure 3 (b) shows relevant data. Only a null depth of the order of $10^{-3}$ is obtained for the starlight in the visible wavelength range because of very different transmittance and reflectance coefficients for p-polarized and s-polarized lights. Note that this
difference appears typically for commercial components. Thus, the tolerance of commercial component used in a geometrical-phase-based nulling interferometer critically determines the interferometer’s practical effectiveness.

IV. Limit due to the ratio of the dimensions of star and planet

The null depth is defined as the ratio of the nulled intensity to the un-nulled intensity, where intensity refers to the illumination summed over the pixel areas of the detector. For a given intensity, illumination is a function of the radius of the star/planet: a larger radius of the star corresponds to a lower illumination. Hence, the ratio of the radius of the planet to that of the star will also influence the detection of the planet, representing an intrinsic limitation of the geometric-phase-based nulling interferometry. In real situation, the dimension ratio (size ratio) cannot be determined a priori, and clarifying the fundamental limit of the geometric-phase-based nulling interferometer in detecting faint object is difficult.

A simulation, considering of different radius ratios, and hence different illuminance ratios of the planet and the star, is used to clarify the limitation. For comparison, the null depths of the starlight are assumed to be equal for the cases with different radius ratios. Figure 4 shows the simulation results. In Fig. 4 (a), the ratio of the radius of the planet to that of the star is 1:5, while in Fig. 4 (b) the ratio is 1:10. In both cases, the size of the planet is fixed. The signature of the faint source of Fig. 4(b) is more significant than that of Fig. 4(a). Therefore, for a larger size ratio, detecting a faint source becomes more difficult. This conclusion has been verified for the cases with different radius ratios. Different assignment of the number of rays also does not change the conclusion.
IV. Conclusions

The performance and tolerance of a geometric-phase-based nulling interferometer was examined by running a simulation on a commercial optical software package, ASAP. Under ideal conditions, no residual interference was produced by the interferometer within numerical precision. This shows the power of geometric-phase-based nulling interferometry. However, the tolerance of optical components critically governs the performance.

As well as technical issues related to the tolerance, the intrinsic limit determined by the ratio of the dimension of the planet to that of the star could also be critical. This limit makes analyzing the performance of a geometric-phase-based nulling interferometer difficult, because the ratio is normally unknown in advance. This simulation analysis establishes that the direct detection of planet around a sun-like star depends not only on the null depth of the starlight but also on the ratio of the radius of the planet to that of the star. Notably, the influences of the size ratio on the detection and tolerance of optical components (here beam-splitter as a critical demonstration) are not limited to the nulling interferometer examined here.

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References:


11. The detail information of ASAP can be found from Breault Research Organization, Inc., the web site is “www.breault.com”
12. The detail information can be found in Newport Corporation, the web site is

www.newport.com
Figure Captions

Figure 1 Setup of geometric-phase-based nulling interferometer for simulation analysis where LP marks the linear polarizer, BS the beam splitter, QWP the quarter-wave plate, HWP the half-wave plate, and OPD the optical path difference.

Figure 2 Simulation of nulling interferometer, under ideal conditions. (a) Only the star can be seen where the starlight is un-nulled. (b) As the starlight is nulled, the planet appears. The scale is in unit of mm and the energy is in units of watt/mm².

Figure 3 (a) Simulation results for nulling of star, using a beamsplitter with a transmittance error of 1%. In such a case, the planet cannot be detected. (b) Simulation results for nulling of star, using a commercial beam-splitter from Newport.

Figure 4 Influence of the radius ratio, the illuminance ratio, between the planet and the star. (a) The ratio is 1:5. (b) 1:10. The null depth for the starlight is assumed to be the same for (a) and (b).
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