

Exoplanet Explorer: polarization aberrations in nulling interferometry

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ABSTRACT

One of the objectives of modern astronomy is the characterization of terrestrial exoplanets orbiting Sun-like stars in the mid-infrared, where instruments face requirements that can only be overcome by nulling interferometry. Particularly, optical effects such as polarization aberrations require careful attention for they deteriorate the null depth. Using the optical design of the Exoplanet Explorer concept study, we simulate the influence of polarization aberrations over the 3–20 μm band, analyze their impact on the null depth and propose multiple compensation strategies for polarization aberrations. Furthermore, we present our nulling interferometry test bench, where we will experimentally investigate polarization aberrations in the beam combiner and phase shifter to provide more insights into the required polarization errors. These results will be used to implement polarization control subsystems in our 4-beams broadband nulling interferometry test bench CAPIBARA (Combining 4 APertures for mid-Infrared Broadband Analysis of Rocky-exoplanets Atmospheres).

Keywords: Nulling interferometry, polarization aberrations, telescope, exoplanets.

1. INTRODUCTION

Since the discovery of 51 Pegasi b in 1995,¹ a large diversity of exoplanets have been discovered, ranging from Jupiter-like gas giants to Earth-like rocky planets.² This variety of exoplanets results in a growing interest for the characterization of exoplanetary atmospheres. Current instruments such as ESPRESSO³ and SPHERE⁴ on the Very Large Telescope, and space telescopes like the Hubble Space Telescope⁵ and the James Webb Space Telescope⁶ are able to probe the atmospheres of some exoplanets. However, atmospheric analyses are predominantly limited to gas giants since current instruments are not able to reach the angular resolution (100 mas) and contrast (10^6 - 10^{10}) required to characterize terrestrial exoplanets.^{7,8}

Space-based nulling interferometry, first proposed by Bracewell in 1978,⁹ offers the capability to meet the high contrast and angular separation requirements for the characterization of Earth-like exoplanets in the mid-infrared. The light entering the different apertures is recombined such that it produces a dark fringe on the line-of-sight, strongly suppressing the stellar emission, while for an off-axis source, like an exoplanet, the light is transmitted with a transmission efficiency depending on the telescope baseline and the wavelength. Such missions were proposed by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) in the early 2000s, respectively with the Terrestrial Planet Finder Interferometer (TPF-I) and Darwin. However, the missions studies were discontinued in the late 2000s. More recently, ground- and space-based nulling interferometry has been gathering momentum with projects such as the Guided-Light Interferometric Nulling Technology

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(GLINT),¹⁰ Asgard-NOTT,¹¹ the Large Interferometer For Exoplanets (LIFE),¹² the Multiple-spacecraft Exoplanet Aperture sYnthetic Interferometer (MEAYIN),¹³ and the Exoplanet Explorer nulling interferometer.¹⁴ The latter is an ESA-funded project investigating the feasibility of a single-spacecraft nulling interferometer, operating in the mid-infrared between 3–20 μm , aiming to detect and characterize temperate rocky exoplanets around nearby stars. The scope of the project encompasses system architecture development, optical chain design, mechanical architecture and performance assessment. The optical design development spans the individual telescope assemblies, the beam combination and control, the spectral dispersion, and the detection. This includes detailed trade-offs between telescope configurations, pupil transfer systems, achromatic phase shifters, the control and monitoring system, the Modified Mach-Zehnder (MMZ) beam combiners, the fiber injection and the spectral analysis through spectrograph. Furthermore, critical aspects such as polarization management, wavefront quality control, and radiometric performance are addressed. Polarization management is especially important in high contrast instrument, as it has been shown to be a contrast limiter in nulling interferometry by several studies.^{15–17}

1.1 Goal of the Study

The objective of this work is to quantify the effects and the impact of polarization aberrations on the null depth. We focus on the analysis of polarization aberrations in the optical design of the Exoplanet Explorer nulling interferometer and on understanding whether polarization aberrations are negligible to achieve a null-depth of 10^{-6} . The simulated results are compared with the calculated diattenuation and retardance requirements needed to reach a null-depth of $N = 10^{-6}$. Finally, we propose compensation strategies to improve the polarization aberrations in the system and describe future work. The paper is organized as follows, the theoretical overview of polarization aberrations is presented in Sec. 2, the optical design is reviewed in Sec. 3, while Sec. 4 describes the methodology and results of the polarization aberrations simulations, and propose mitigation techniques that can reduce the polarization aberrations. In Sec. 5, we present our nulling interferometry testbench, and finally, results and future work are discussed in Sec. 6.

2. THEORY

2.1 Polarization Aberrations

Polarization aberrations correspond to the spatial variations of the polarization states, both in amplitude (known as diattenuation) and phase (known as retardance). They arise from the response of polarization to the coating, the optical design geometry, and the imperfections of the surfaces and the optical alignment. In most optical systems, polarization aberrations have a marginal influence on the instrumental performance when compared to wavefront aberrations and other sources of error, thus these aberrations are often disregarded. However, in high contrasts instruments like nulling interferometers and coronagraphs, polarization aberrations must be taken into account to achieve the scientific objectives.^{15–17}

2.2 Polarization Ray Tracing, Jones Pupil, Diattenuation and Retardance

Polarization ray trace combines standard ray tracing with the vector properties of polarization to understand the impact of the optical system on the polarization across the beam cross-section and to balance the polarization aberrations introduced by the different optical surfaces. The polarization aberrations in an optical system depend on the pupil coordinates (σ_x, σ_y) and the field coordinates (τ_x, τ_y) . The field corresponding to a Sun-Earth-like system is almost zero, thus we assume that the polarization aberrations are only a function of the pupil coordinates. We use the Jones formalism, which provides the amplitude and the absolute phase of the individual rays, however each ray is fully polarized. Usually, the ideal optical system preserves the input polarization, ensuring that a beam with a uniform polarization entering the optical system exits with the same uniform polarization state. Using the Jones formalism, the resulting polarization function is described by the identity Jones matrix, and any deviation from the identity matrix is referred to as polarization aberrations. Thus we have the following relation between the incoming and exiting electric field,

$$\begin{pmatrix} E_1 \\ E_2 \end{pmatrix}_{out} = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \end{pmatrix}_{in}, \quad (1)$$

where $E_1 = A_1 e^{i\phi_1}$ and $E_2 = A_2 e^{i\phi_2}$ are the vector components of the electric field. In the formalism, each Jones matrix is associated to one ray, therefore by taking all the Jones matrices for all the pupil coordinates, we can create a 2x2 map, representing the Jones matrices evolution with the pupil coordinates i.e., the Jones pupil as can be seen in Fig. 3.

In order to compute the diattenuation and retardance from the Jones pupils, we use the polar decomposition method. This method and the formalism of polarization aberrations has been developed by McGuire and Chipman *Polarized Light and Optical Systems*.^{18–21} Here, we shortly describe how to obtain the diattenuation and the retardance from the Jones matrix. Using the polar decomposition theorem, we can write the Jones matrix J as the product of a unitary and a Hermitian matrix.

$$J = UH = H'U, \quad (2)$$

where the Hermitian matrix H corresponds to the diattenuation of the Jones matrix J , and the unitary matrix U corresponds to the retardance of the Jones matrix J . We compute U and H as follow,

$$JJ^\dagger = H^2 \quad \text{and} \quad U = JH^{-1}. \quad (3)$$

Then, we can get the normalized eigenvectors $\hat{v}_\pm$ and eigenvalues $\lambda_\pm$ of H and U , and calculate the diattenuation, the retardance, as well as their orientation and ellipticity. For the diattenuation matrix H , the eigenvalue λ_+ is the maximum diattenuation transmittance and the eigenvalue λ_- is the minimum diattenuation transmittance. The normalized eigenvectors represent the maximum and minimum diattenuation transmission direction of the system. In other words, they correspond to the polarization states that are the most and least transmitted by the system. The diattenuation intensity is given by

$$D = \frac{\lambda_+^2 - \lambda_-^2}{\lambda_+^2 + \lambda_-^2}. \quad (4)$$

The eigenvalues of the retardance matrix U represent the phase accumulated on the fast and slow axes, and the eigenvectors represent the fast and slow axes of the system. The eigenvalues of the retardance matrix U have a magnitude equal to 1, meaning that the eigenvalues can be written as

$$\lambda_\pm = e^{-i\phi_\pm}. \quad (5)$$

The retardance is given by the magnitude of the difference between the angle of the two eigenvalues

$$\delta = |\phi_+ - \phi_-|. \quad (6)$$

2.3 Null-Depth

Before the beam combination, the beams of each telescope subsystem have their own optical path, as shown in Fig 1. For each telescope, the electric field associated with a ray at the pupil coordinates (σ_x, σ_y) is given by $\vec{E}_{\sigma_x, \sigma_y} = (E_{\hat{x}}, E_{\hat{y}})_{\sigma_x, \sigma_y}$, where $E_{\hat{x}}$ and $E_{\hat{y}}$ are the electric field components in the $(\hat{x}, \hat{y})$ base. Thus, the electric field of the telescope system T_i at the pupil coordinates (σ_x, σ_y) is denoted by $\vec{E}_{\sigma_x, \sigma_y}^{T_i}$. The vector representing the polarization state in the telescope system T_i at the pupil coordinates (σ_x, σ_y) is denoted by $\hat{e}_{\sigma_x, \sigma_y}^{T_i}$. For readability in the following equation, we will denote the electric field $\vec{E}_{\sigma_x, \sigma_y}^{T_i}$ by $\vec{E}_i$, and the polarization state $\hat{e}_{\sigma_x, \sigma_y}^{T_i}$ by $\hat{e}_i$. The maximum and minimum intensity resulting from the interference of two beams is given by I_{max} and I_{min} , respectively.

$$I_{max} = |\vec{E}_1|^2 + |\vec{E}_2|^2 + 2\sqrt{|\vec{E}_1|^2 |\vec{E}_2|^2} (\hat{e}_1 \cdot \hat{e}_2), \quad (7)$$

$$I_{min} = |\vec{E}_1|^2 + |\vec{E}_2|^2 - 2\sqrt{|\vec{E}_1|^2 |\vec{E}_2|^2} (\hat{e}_1 \cdot \hat{e}_2). \quad (8)$$

From these we can obtain the null depth N ,

$$N = \frac{I_{min}}{I_{max}}. \quad (9)$$

In Eq. 7, if the polarization state in the telescope systems $\hat{e}_1$ and $\hat{e}_2$ are not identical, we will not maximize I_{max} nor minimize I_{min} due to the dot product between the two polarization states. This directly shows the dependence of the null depth on the phase and the orientation of the polarization between the two interfering beams. Moreover, any imbalance between the intensities of the beams will lead to a degradation of the null depth. In Tab 1, we show the maximal diattenuation difference ΔD , in normalized amplitude, and retardance difference $\Delta\delta$, in degrees, that permit to reach the required null depth of $N = 10^{-6}$. For this calculation, we take identical initial polarization state between the beams, and introduce either retardance or diattenuation on one of the beam such that the null depth equals $N = 10^{-6}$.

Table 1. Required diattenuation and retardance difference between two beams to reach a null depth of 10^{-6} .

Parameter	Units	
Required N	10^{-6}	
ΔD	3×10^{-3}	[-]
$\Delta\delta$	0.16	[deg]

3. OPTICAL DESIGN

3.1 Telescope Design

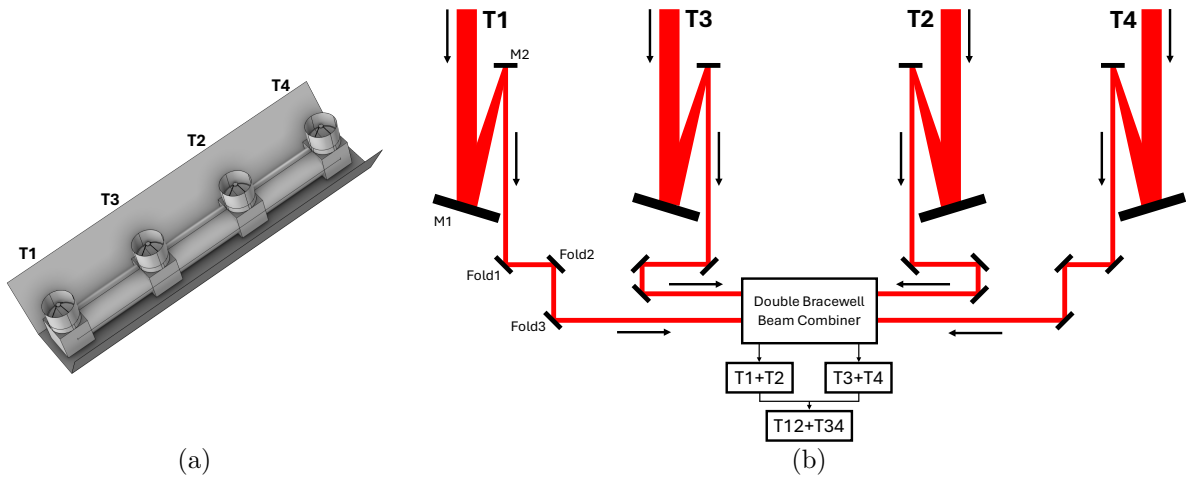


Figure 1. (a) Artistic view of the linear array version of single spacecraft nulling interferometer. (b) Optical chain of the single spacecraft nulling interferometer until the beam combiner entrance. It features 2 identical pairs of telescopes T₁-T₂ and T₃-T₄. Each individual telescope has the same number of reflective surfaces.

The proposed optical design of the single spacecraft nulling interferometer, as shown in Fig. 1, consists of a linear array of 4 telescopes and a double Bracewell beam combiner configuration. In this work, we only consider the telescopes T₁ and T₂, as shown in Fig. 2. The telescopes T₃ and T₄ are the mirrored design of T₁ and T₂, respectively, and will be taken into account in the next phase of our simulation work. Each telescope subsystem has a 2.5 m unobscured off-axis parabolic primary mirror (M1) and an off-axis parabolic secondary mirror (M2). The M1-M2 system compresses the beam to 100 mm. Then, we use three fold mirrors to create a delay line ensuring that the 4 telescopes have the same optical path length. Since the exit pupil of the M1-M2 system is virtual, a transfer of the exit pupil closer to the beam combiner entrance is necessary for wavefront correction. To this end, we add a retro-reflective cat's eye system. The system consists of two parabolic mirrors (parab1 and parab2) and one spherical mirror (spher1). The spherical mirror surface is positioned at the focus of the parabolas, and its radius of curvature defines the position of the output pupil. The beam is shrunk to 25 mm by the cat's eye system as is shown in Fig. 2). Typically, a cat's eye setup is built around a Variable Curvature Mirror (VCM) for large interferometers like the VLT because the beam undergoes changes in effective optical

path length, conjugation distance between pupils, and beam divergence or convergence. However, we do not need a VCM as the delay line length is very limited ($\sim\text{cm}$ to $\sim\text{nm}$). Spher1 is therefore not a VCM but a fixed curved mirror, since the pupil's new location is constant. The optical design is detailed by Mazzoli et al.²²

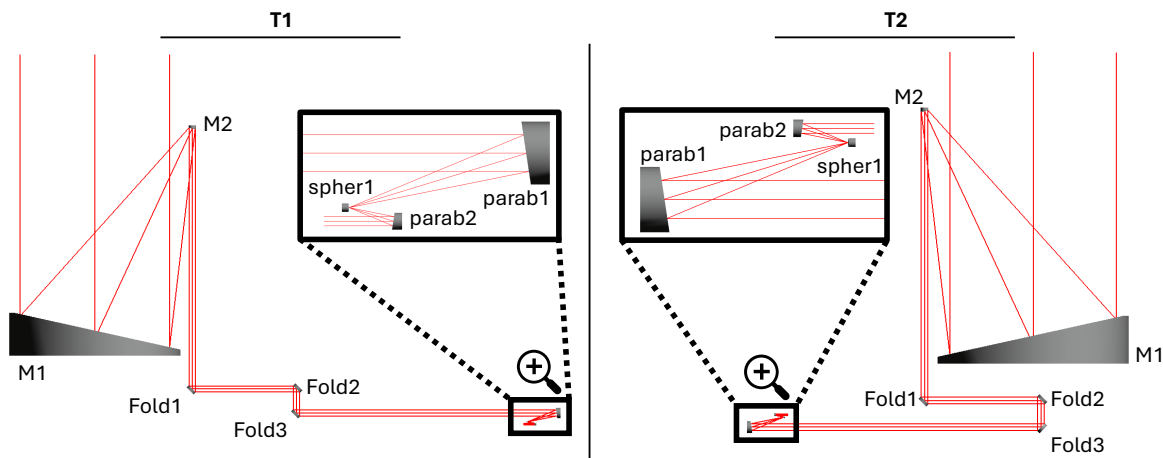


Figure 2. (Left) Telescope T_1 on the left side. (Right) Telescope T_2 on the right side. It features a 2.5 m diameter off-axis parabolic primary mirror. The system is afocal and features a fold mirror system to ensure the same the optical path length for the 4 telescope systems. A cat's eye system transfers the exit pupil of the M1-M2 system closer to the beam combiner entrance.

4. RESULTS AND DISCUSSION

In this work, we are focusing on the diattenuation and the retardance arising from the telescopes subsystems and the effect of these polarization aberrations on the null-depth. Furthermore, we focus our analysis on the telescope systems T_1 and T_2 before the beam combiner entrance, until the exit of the cat's eye system, and we do not use any physical beam combiner to perform our beam combination. Instead, we simulate the interference by overlapping the two counter-propagating beams along the z -axis. We generate the Jones pupil ($\mathbf{J}$) for each surface at wavelengths of $3\ \mu\text{m}$ and $20\ \mu\text{m}$ by performing polarization ray trace with CODE V. The Jones amplitude are normalized between 0 and 1, 1 being the value at the input of the system, and the phase is in radians. Fig. 3 show the Jones pupil amplitudes (a) and the phase (b) variations at the beam combiner entrance of the telescope chain T_1 as shown in Fig. 2 for gold coated surfaces at $\lambda = 3\ \mu\text{m}$. The results for the telescope T_2 can be found in Fig. 8 in App. A.

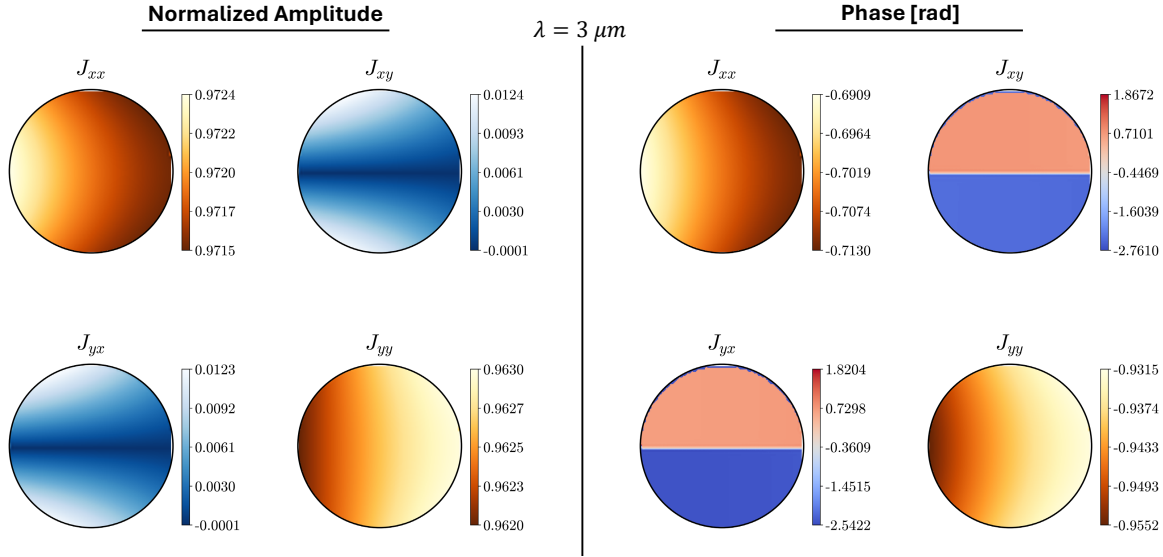


Figure 3. Amplitude and phase of the Jones pupil at $3 \mu\text{m}$, at the beam combiner entrance of the telescope system T_1 . The colorbars do not have the same scale. The $|J_{xx}|$ and $|J_{yy}|$ diagonal terms are about a 100 times larger than the crosstalk terms $|J_{xy}|$ and $|J_{yx}|$, therefore dominating the polarization aberrations. One can observe that across the $|J_{xy}|$ and $|J_{yx}|$ pupils, the variations in amplitude are of the order of 10^{-3} , and the amplitude difference between $|J_{xy}|$ and $|J_{yx}|$ are of the order of 10^{-2} . This introduces small amplitude variations of the polarization state. The phases of the diagonal terms ϕ_{xx} and ϕ_{yy} show variations across their pupil and between each other. These differences introduce ellipticity. Furthermore, the ϕ_{xy} and ϕ_{yx} terms have a discontinuity due to the phase wrapping of the $\arctan 2$ function.

Then, we calculate the diattenuation and retardance aberration maps using the methodology described in Sec. 2.2. We plot the diattenuation across the beam cross section at the exit of the telescope system T_1 in Fig. 4 and the retardance in Fig. 5 for the telescope system T_1 . The plots for the telescope system T_2 can be found in App. A. The diattenuation differs at different wavelengths but the overall amplitude of the variations remains similar. The changes of diattenuation with pupil coordinates is caused by the varying angle of incidence of the curved surfaces and the effect is amplified by the fold mirrors at 45° . In addition, we can see a change in the orientation of the diattenuation with the pupil coordinates. These variations are introduced by the non-constant angle of incidences of the parabolic mirrors. The retardance values change with wavelength, same for the variations across the pupil. The retardance shows the same intensity variation pattern as the diattenuation, however the difference of retardance between the two wavelengths is almost of an order of magnitude. It is to be noted further, that both the diattenuation and retardance are slightly elliptical. From these plots, we can understand that the telescope favors different polarization states at different pupil coordinates locations and at different wavelengths. The variation with pupil coordinates implies that we need a polarization compensating strategy that can compensate for different aberrations at the same time across a beam, such as metasurfaces,²³ spatial light modulators (SLMs), or multilayer coatings.²⁴ On the other hand, the variation of diattenuation and retardance with wavelength indicates that we might need to split the system in several wavebands to provide nominal performance across the whole $3\text{--}20 \mu\text{m}$ waveband. In particular, the dependence of the retardance on wavelength could lead to different phase shifts at different wavelengths if not compensated in the phase shifter. Furthermore, the polarization aberrations are stronger at shorter wavelengths, thus we need a stringent polarization management at the shorter wavelengths.

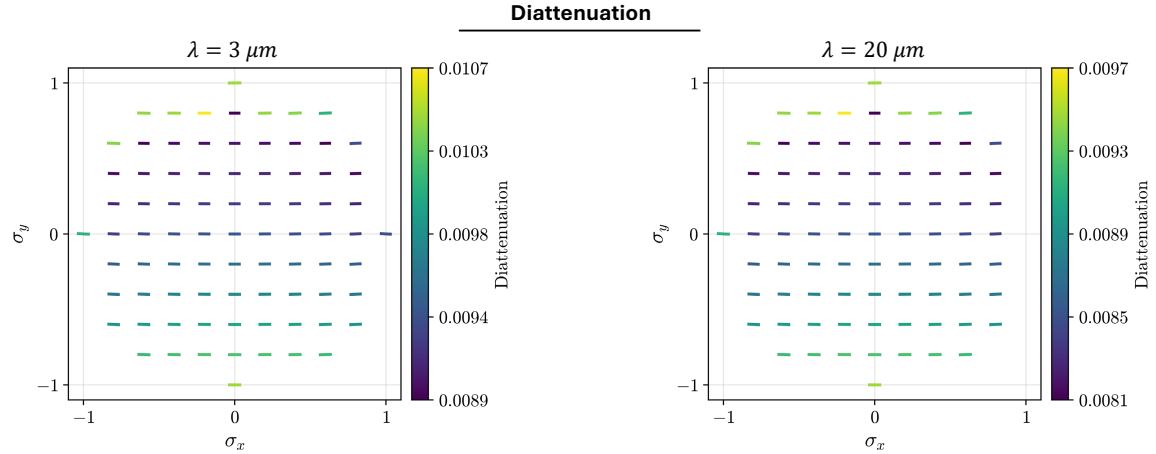


Figure 4. (Left) Diattenuation map at $\lambda = 3 \mu\text{m}$ and (Right) diattenuation map at $\lambda = 20 \mu\text{m}$ at the beam combiner entrance of T_1 . The length and the color of the dashes depict the value of the diattenuation (cf. Eq. 4), while the orientation and ellipticity represent the maximum diattenuation transmission direction of the system. In other words, it corresponds to the polarization states that are the best transmitted by the system. We can see the variations in diattenuation at different position across the beam. The intensity of the diattenuation depends on the wavelength but the order of magnitude of the variations is the same at the different wavelengths.

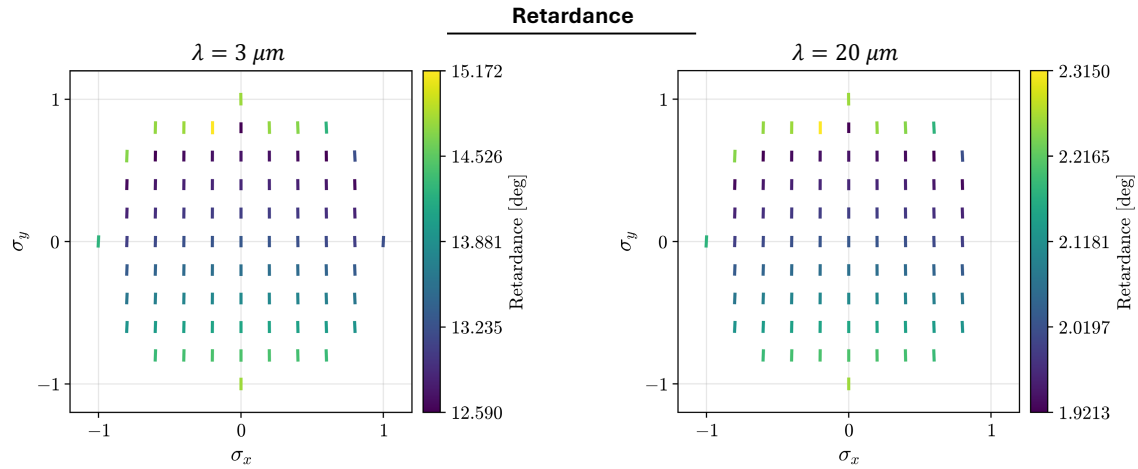


Figure 5. (Left) Retardance map at $\lambda = 3 \mu\text{m}$ and (Right) retardance map at $\lambda = 20 \mu\text{m}$ at the beam combiner entrance of T_1 . The length and the color of the dashes depict the value of the retardance (see equation Eq. 6), while the orientation and ellipticity represent the fast axis of the system at a given pupil coordinate. The variations of retardance across the pupil are located at the same location than the diattenuation ones. We can see a change in retardance with wavelength, both in term of values and variation intensity across the pupil.

Using the Jones pupils of the 2 telescopes system from Figure 2, we simulate the effect of the polarization aberrations on the null depth by recombining the two telescopes outputs using the method described in Sec. 2.3. In the current state of the study, we do not use a specific design for the beam combiner. Instead, we simulate the interference by overlapping the two counter-propagating beams along the z -axis. We calculate the system's null depth for each ray using their associated Jones matrices. At $3 \mu\text{m}$, the center of the pupil, the area limited by the white dotted circle, has an average null depth of $N = 1.70 \times 10^{-6}$, while the whole pupil shows an

average null-depth of $N = 2.05 \times 10^{-5}$. At $20 \mu\text{m}$, the center of the pupil, the area limited by the white dotted circle, has an average null depth of $N = 4.15 \times 10^{-8}$, while the whole pupil shows an average null-depth of $N = 5.66 \times 10^{-7}$. It is important to note that this maximal null-depth is only a result of the polarization aberrations, the optical surfaces and the alignment are considered to be perfect. An optimized layout of the setup and the use of mitigation strategies would allow to reach a deeper null depth. In order to reach a null depth of $N = 10^{-6}$, the polarization aberrations (diattenuation and retardance) must be below values listed in Tab. 1. Figure 6 shows the null depth at (a) $\lambda = 3 \mu\text{m}$ and (b) at $\lambda = 20 \mu\text{m}$.

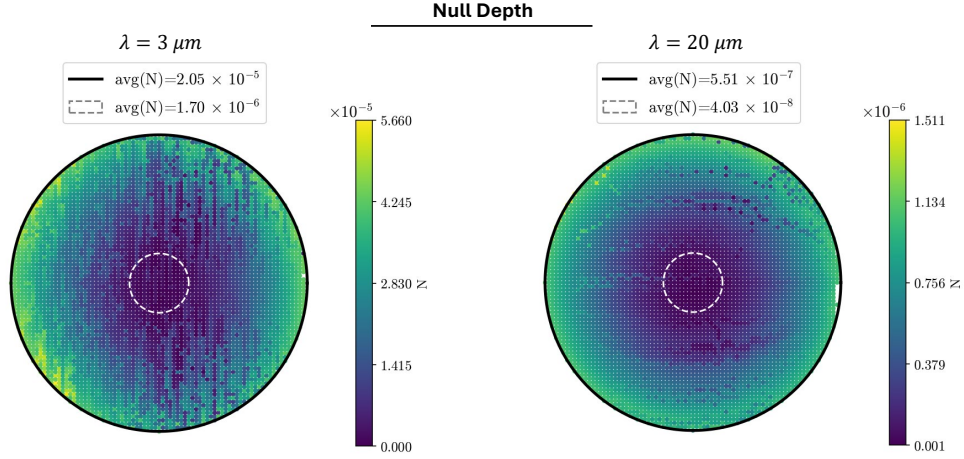


Figure 6. (Left) Null depth at $\lambda = 3 \mu\text{m}$. (Right) Null depth at $\lambda = 20 \mu\text{m}$.

According to the averaged differential diattenuation ΔD and retardance $\Delta\delta$ shown in Tab. 2, the null depth at 3 and $20 \mu\text{m}$ should be lower than 10^{-6} when comparing the results with the requirements presented in Tab 1. However, this is not what is observed in Fig. 6, and it can be explained by several factors. In Tab. 1, we calculate the maximum theoretical null depth using Eq. 7 & 9 in the scenario where we only have diattenuation or retardance, while both are present at the same time in our simulations. Furthermore, in Tab. 2, we take the pupil averaged diattenuation and retardance, which differ from the diattenuation and retardance at the different pupil coordinates. Moreover, the interference not only depends on the values of diattenuation and retardance but also on their orientation and ellipticity, and these can be different for the two telescope exits at overlapping pupil coordinates. Tab. 2 is compiling the results obtained for the simulations of the 2 telescopes system with different beam/system parameters.

Table 2. Averaged diattenuation and retardance for the telescope systems T_1 and T_2 , diattenuation and retardance difference between the two telescopes, and averaged null depth at 3 and $20 \mu\text{m}$.

Parameter	Wavelength		Units
	$3 \mu\text{m}$	$20 \mu\text{m}$	
D_{T_1}	9.58×10^{-3}	8.68×10^{-3}	[-]
δ_{T_1}	13.54	2.07	[deg]
D_{T_2}	9.57×10^{-3}	8.67×10^{-3}	[-]
δ_{T_2}	13.53	2.06	[deg]
ΔD	0.01×10^{-3}	0.01×10^{-3}	[-]
$\Delta\delta$	0.01	0.01	[deg]
$\langle N \rangle$	2.05×10^{-5}	5.66×10^{-7}	[-]
$\langle N_{center} \rangle$	1.70×10^{-6}	4.15×10^{-8}	[-]

4.1 Polarization Aberrations Mitigation

To mitigate the polarization aberrations, we need to consider the aberrations from the telescope system, the transfer optics and the beam combiner. We can reduce the polarization aberrations by optimizing the optical coatings design, lowering the angle of incidence on the mirrors and by using a crossed mirrors configuration for the fold mirrors. Apart from these mitigation techniques, we can compensate polarization aberrations using components that have the opposite amplitude or phase aberration operation, such as metasurfaces, spatial light modulators (SLMs) or phase-masks. Current studies for the next generation of large space observatories also include polarization compensation strategies, such as protective coatings.²⁴ These different mitigation strategies can be used at different levels of the optical chain, before the beam combiner or after the recombination.

5. TESTBENCH

CAPIBARA (Combining 4 APertures for mid-Infrared Broadband Analysis of Rocky-planets Atmospheres) is a nulling interferometry testbench under construction at the TU Delft. The aim is to build a mid-infrared broadband polarization optimized nulling interferometer. We are currently working on the mid-infrared four-beams multispectral beam generator, (see Sigusch et al.²⁵) and on the polarization characterization testbench as shown in Fig. 7. The polarization setup will be capable of generating and measuring any polarization state (full-Stokes) across the beam cross-section. The testbench aims to provide an experimental understanding of the evolution of polarization aberrations in the delay line, achromatic phase shifter and beam combiner, as well as their impact on the null depth.

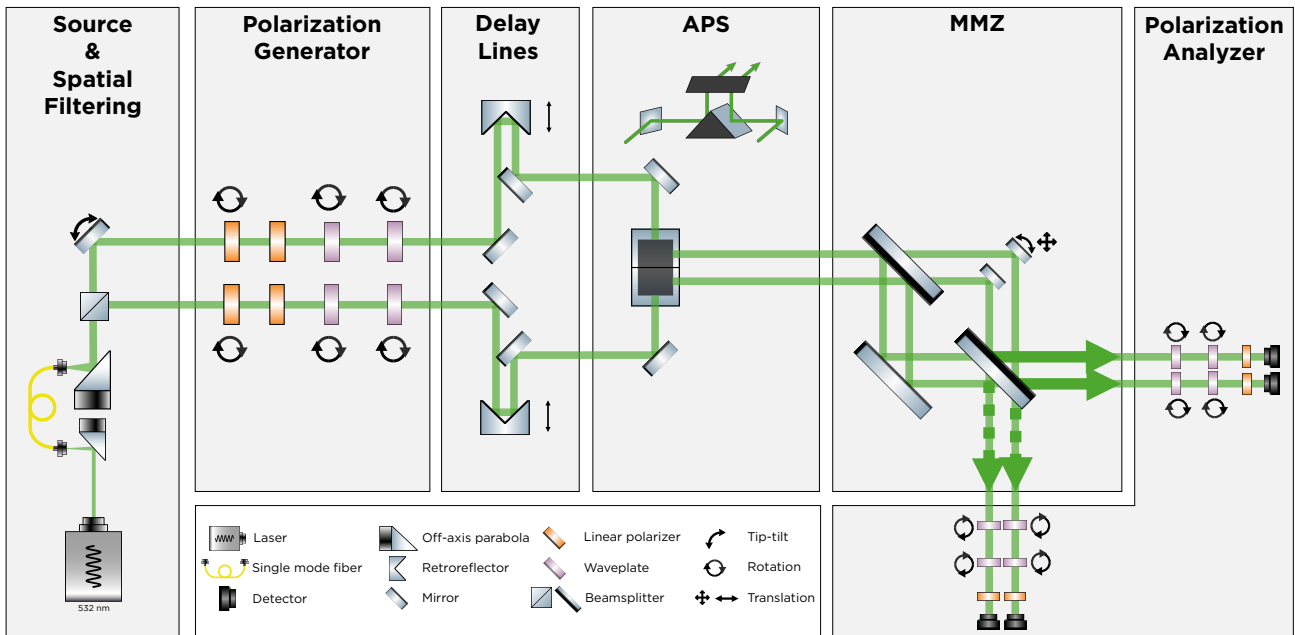


Figure 7. Optical layout of the polarization aberrations characterization testbench. The polarization generator can provide any polarization state and matches the intensities between the two beams. The solid arrows at the output of the MMZ correspond to the null output, and the dashed arrows correspond to the bright output. The MMZ will be mounted on a rotational platform to simulate the angular separation between the planet and the star light. The polarization analyzers measure all polarization states and their variation across the beam.

6. CONCLUSION AND FUTURE WORK

With our analysis, we analyzed the behavior of polarization aberrations across the pupil of the optical chain of the Exoplanet Explorer telescope design. We performed the analysis at two different wavelengths and demonstrated the wavelength dependence of polarization aberrations and the corresponding null depth degradation. We

proposed several mitigation techniques to mitigate the polarization aberrations including compensating optics and multilayer coatings.

In future works, we will extend the analysis to the 4 telescopes of the spacecraft, and include the optical chain of complete instrument. We are going to investigate the differential effects between the telescope systems (T_1 , T_2 , T_3 , and T_4) due to their different orientations. Towards this end, we will study the impact on the beam combination of: the pupils rotations, alignment and the polarization aberrations differences between the pupils in order to optimize the optical chain. Moreover, we will simulate the optical chain up to the detector in order to understand the polarization impact in the different subsystems to find the best optical design strategies. The future study will also include several coatings for beamsplitters and mirrors, as well as different beam combiners and achromatic phase shifter designs. The results should provide requirements on polarization aberrations at the subsystem level to reach the desired null depth of 10^{-6} .

Finally, to verify experimentally our simulations, we are building a testbench to study the behavior of polarization in the beam combiner and in the phase shifter.

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APPENDIX A. TELESCOPE SUBSYSTEM 2

In this section, we show the Jones pupils of telescope T_2 on Fig. 8, and its diattenuation and retardance maps on Fig. 9 & 10 for comparison purposes with the same figures shown for T_1 in Sec. 4.

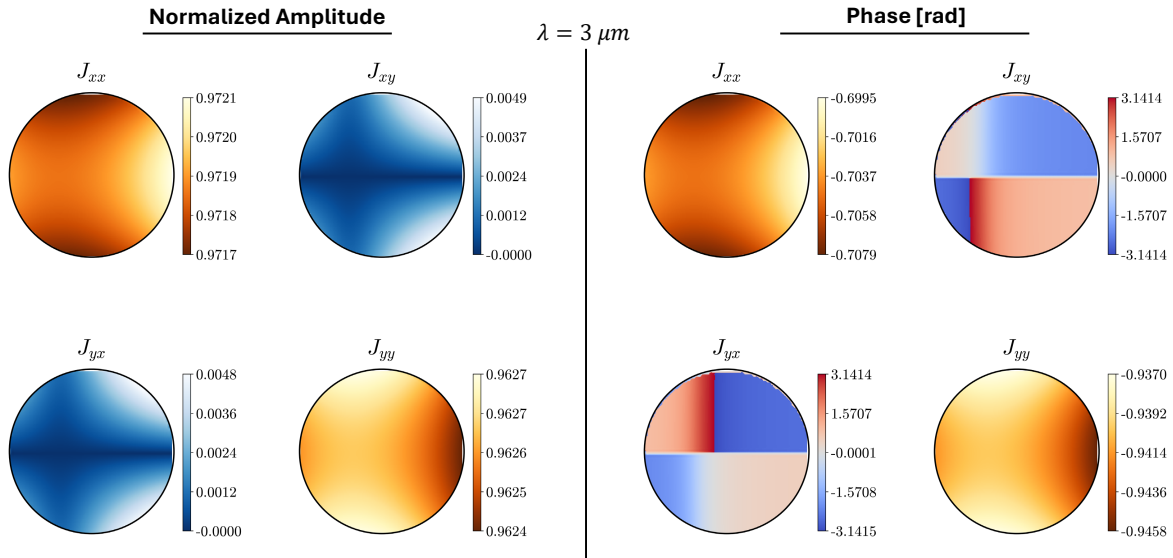


Figure 8. Amplitude and phase of the Jones pupil at $3 \mu\text{m}$ at the beam combiner entrance of the telescope system T_2 . The colorbars do not have the same scale. The $|J_{xx}|$ and $|J_{yy}|$ diagonal terms are about a 100 times larger than the crosstalk terms $|J_{xy}|$ and $|J_{yx}|$, therefore dominating the polarization aberrations. One can observe that across the $|J_{xy}|$ and $|J_{yx}|$ pupils, the variations in amplitude are of the order of 10^{-3} , and the amplitude difference between $|J_{xy}|$ and $|J_{yx}|$ are of the order of 10^{-2} . This introduces small amplitude variations of the polarization state. The phases of the diagonal terms ϕ_{xx} and ϕ_{yy} are showing variations across their pupil and between each other. These differences introduce ellipticity. The ϕ_{xy} and ϕ_{yx} terms have a discontinuity due to phase wrapping of the arctan2 function.

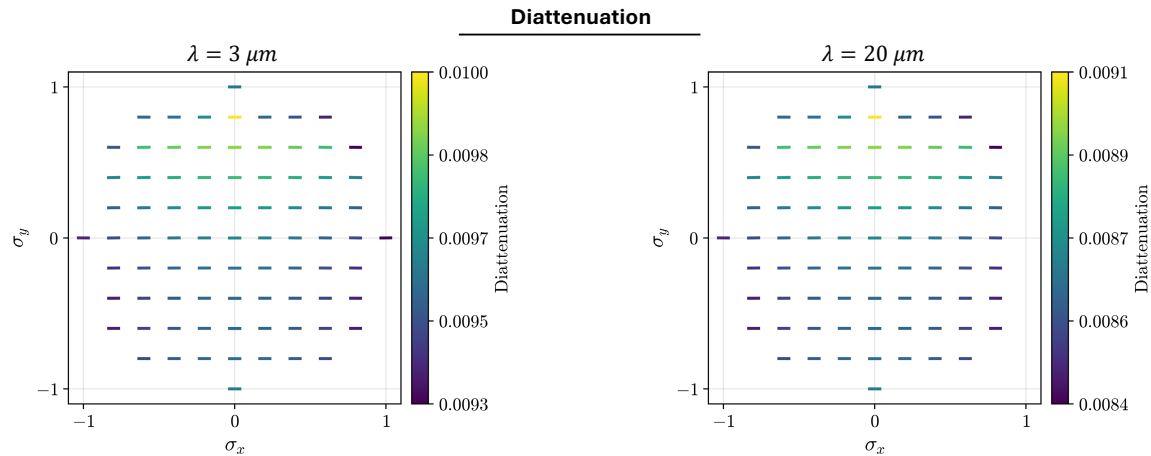


Figure 9. (Left) Diattenuation map at $\lambda = 3 \mu\text{m}$ and (Right) diattenuation map at $\lambda = 20 \mu\text{m}$ at the beam combiner entrance of T₂. We can see the variations in diattenuation at different position across the beam. The intensity of the diattenuation depends on the wavelength but the order of magnitude of the variations is the same at the different wavelengths.

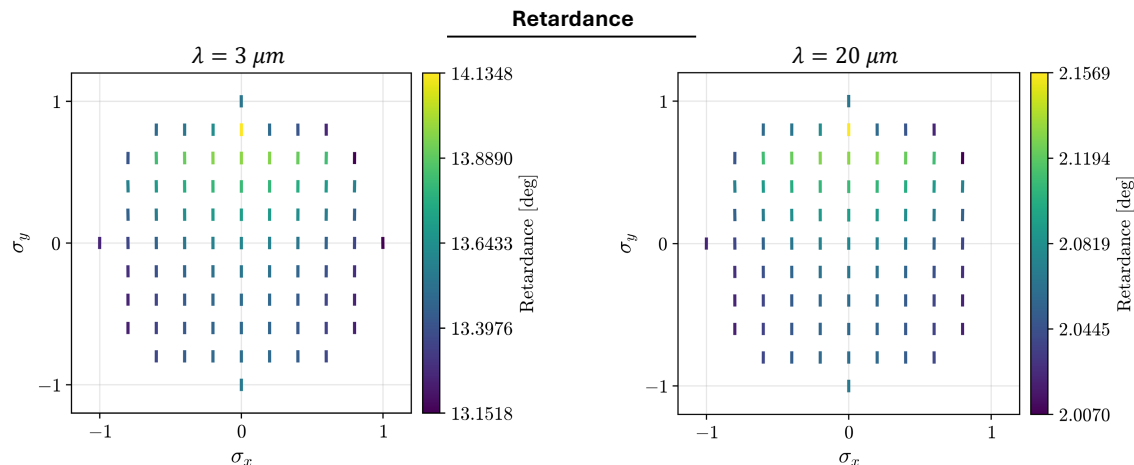


Figure 10. (Left) Retardance map at $\lambda = 3 \mu\text{m}$ and (Right) retardance map at $\lambda = 20 \mu\text{m}$ at the beam combiner entrance of T₂. The variations of retardance across the pupil are located at the same location than the diattenuation ones. We can see a change in retardance with wavelength, both in term of values and variation intensity across the pupil.

REFERENCES

- [1] Mayor, M. and Queloz, D., “A Jupiter-mass companion to a solar-type star,” *Nature* **378**, 355–359 (Nov. 1995). ADS Bibcode: 1995Natur.378..355M.
- [2] Kopparapu, R., Hebrard, E., Belikov, R., Batalha, N. M., Mulders, G. D., Stark, C., Teal, D., Domagal-Goldman, S., Gelino, D., Mandell, A., Roberge, A., Rinehart, S., Kane, S. R., Hasegawa, Y., Henning, W., Hicks, B., Adibekyan, V., Schwieterman, E. W., Kohler, E., Teske, J., Hinkel, N., Nixon, C., France, K., Danchi, W., Haqq-Misra, J., Wolf, E. T., Guzewich, S. D., Charnay, B., Arney, G., Hartnett, H. E., Lopez, E. D., Minniti, D., Renaud, J., Airapetian, V., Dong, C., Del Genio, A. D., Trainer, M., Rau, G., Jensen, A., Way, M., Lisse, C. M., Lyra, W., Marchis, F., Jontof-Hutter, D., Young, P., Pierrehumbert, R., Harman, C. E., Fortney, J., Moore, B., Beckwith, S., Shock, E., Desch, S., Mandt, K. E., Izenberg, N.,

- Ford, E. B., Curry, S., Scharf, C., and Anbar, A., “Exoplanet Diversity in the Era of Space-based Direct Imaging Missions,” (Mar. 2018). arXiv:1803.03812 [astro-ph].
- [3] Casasayas-Barris, N., Palle, E., Stangret, M., Bourrier, V., Tabernero, H. M., Yan, F., Borsa, F., Allart, R., Osorio, M. R. Z., Lovis, C., Sousa, S. G., Chen, G., Oshagh, M., Santos, N. C., Pepe, F., Rebolo, R., Molaro, P., Cristiani, S., Adibekyan, V., Alibert, Y., Prieto, C. A., Bouchy, F., Demangeon, O. D. S., Marcantonio, P. D., D’Odorico, V., Ehrenreich, D., Figueira, P., Santos, R. G., Hernández, J. I. G., Lavie, B., Lillo-Box, J., Curto, G. L., Martins, C. J. a. P., Mehner, A., Micela, G., Nunes, N. J., Poretti, E., Sozzetti, A., Mascareño, A. S., and Udry, S., “The atmosphere of HD 209458b seen with ESPRESSO - No detectable planetary absorptions at high resolution,” *Astronomy & Astrophysics* **647**, A26 (Mar. 2021).
 - [4] Beuzit, J. L., Vigan, A., Mouillet, D., Dohlen, K., Gratton, R., Boccaletti, A., Sauvage, J. F., Schmid, H. M., Langlois, M., Petit, C., Baruffolo, A., Feldt, M., Milli, J., Wahhaj, Z., Abe, L., Anselmi, U., Antichi, J., Barette, R., Baudrand, J., Baudoz, P., Bazzon, A., Bernardi, P., Blanchard, P., Brast, R., Bruno, P., Buey, T., Carillet, M., Carle, M., Cascone, E., Chapron, F., Charton, J., Chauvin, G., Claudi, R., Costille, A., De Caprio, V., de Boer, J., Delboulbé, A., Desidera, S., Dominik, C., Downing, M., Dupuis, O., Fabron, C., Fantinel, D., Farisato, G., Feautrier, P., Fedrigo, E., Fusco, T., Gigan, P., Ginski, C., Girard, J., Giro, E., Gisler, D., Gluck, L., Gry, C., Henning, T., Hubin, N., Hugot, E., Incorvaia, S., Jaquet, M., Kasper, M., Lagadec, E., Lagrange, A. M., Le Coroller, H., Le Mignant, D., Le Ruyet, B., Lessio, G., Lizon, J. L., Llored, M., Lundin, L., Madec, F., Magnard, Y., Marteaud, M., Martinez, P., Maurel, D., Ménard, F., Mesa, D., Möller-Nilsson, O., Moulin, T., Moutou, C., Origné, A., Parisot, J., Pavlov, A., Perret, D., Pragt, J., Puget, P., Rabou, P., Ramos, J., Reess, J. M., Rigal, F., Rochat, S., Roelfsema, R., Rousset, G., Roux, A., Saisse, M., Salasnich, B., Santambrogio, E., Scuderi, S., Segransan, D., Sevin, A., Siebenmorgen, R., Soenke, C., Stadler, E., Suarez, M., Tiphène, D., Turatto, M., Udry, S., Vakili, F., Waters, L. B. F. M., Weber, L., Wildi, F., Zins, G., and Zurlo, A., “SPHERE: the exoplanet imager for the Very Large Telescope,” *Astronomy and Astrophysics* **631**, A155 (Nov. 2019). ADS Bibcode: 2019A&A...631A.155B.
 - [5] Roy, P.-A., Benneke, B., Piaulet, C., Gully-Santiago, M. A., Crossfield, I. J. M., Morley, C. V., Kreidberg, L., Mikal-Evans, T., Brande, J., Delisle, S., Greene, T. P., Hardegree-Ullman, K. K., Barman, T., Christiansen, J. L., Dragomir, D., Fortney, J. J., Howard, A. W., Kosiarek, M. R., and Lothringer, J. D., “Water absorption in the transmission spectrum of the water-world candidate GJ9827d,” *The Astrophysical Journal Letters* **954**, L52 (Sept. 2023). arXiv:2309.10845 [astro-ph].
 - [6] Kulkarni, S., “‘Milestone’ discovery as JWST confirms atmosphere on an Earth-like exoplanet,” *Nature* (May 2024). Bandiera_abtest: a Cg.type: News Subject_term: Planetary science, Astronomy and astrophysics, Astronomical instrumentation.
 - [7] Cavarroc, C., Boccaletti, A., Baudoz, P., Fusco, T., and Rouan, D., “Fundamental limitations on Earth-like planet detection with extremely large telescopes,” *Astronomy & Astrophysics* **447**, 397–403 (Feb. 2006). Number: 1.
 - [8] Guyon, O., “High performance coronagraphy for direct imaging of exoplanets,” *EPJ Web of Conferences* **16**, 03001 (2011).
 - [9] Bracewell, R. N., “Detecting nonsolar planets by spinning infrared interferometer,” *Nature* **274**, 780–781 (Aug. 1978).
 - [10] Spalding, E., Arcadi, E., Douglass, G., Gross, S., Guyon, O., Martinod, M.-A., Norris, B., Rossini-Bryson, S., Taras, A., Tuthill, P., Ahn, K., Deo, V., Morsy, M. E., Lozi, J., Vievard, S., and Withford, M., “The GLINT nulling interferometer: improving nulls for high-contrast imaging,” in [*Optical and Infrared Interferometry and Imaging IX*], **13095**, 59–73, SPIE (Aug. 2024).
 - [11] Defrère, D., Laugier, R., Martinod, M.-A., Garreau, G., Missiaen, K., Salman, M., Raskin, G., Dandumont, C., Ertel, S., Ireland, M. J., Kraus, S., Labadie, L., Mazzoli, A., Medgyesi, G., Sanny, A., Absil, O., Ábráham, P., Berger, J.-P., Bonduelle, M., Biglioli, A., Bouzerand, E., Carter, J., Cvetojevic, N., Courtney-Barrer, B., Glauser, A. M., Gross, S., Haubois, X., James, N., Joo, A. P., Lagarde, S., Léger, A., Leisenring, J., Loicq, J., Martin, G., Martinache, F., Mezo, G., Morel, S., Morren, J., Ollivier, M., Robertson, G., Rousseau, H., Schofield, W., Schuhler, N., Taras, A., Vandenbussche, B., and Woillez, J., “L-band nulling interferometry at the VLTI with Asgard/NOTT: status and plans,” (July 2024). arXiv:2407.08397 [astro-ph].

- [12] Quanz, S. P., Kammerer, J., Defrère, D., Absil, O., Glauser, A. M., and Kitzmann, D., “Exoplanet science with a space-based mid-infrared nulling interferometer,” **10701**, 107011I (July 2018). Conference Name: Optical and Infrared Interferometry and Imaging VI Place: eprint: arXiv:1807.06088 ADS Bibcode: 2018SPIE10701E..1IQ.
- [13] Jiang, A., Liu, X., Mo, X., Gao, S., Chen, B., Wang, T., and Wang, J., “Dual-mode variable-array imaging interferometer testbed for the MEAYIN program,” *Applied Optics* **65**, 433 (Jan. 2026).
- [14] Loicq, J., Defrère, D., Laugier, R., Saathof, R., Bouwmeester, J., Piron, P., Potin, S., Dandumont, C., Moreau, V., Borguet, B., Hallibert, P., Alaluf, D., Escudero Sanz, I., Lueftinger, T., Mennesson, B., and Danchi, W., “Single spacecraft nulling interferometer for exoplanets: preliminary concept,” in [*Optical and Infrared Interferometry and Imaging IX*], Sallum, S., Sanchez-Bermudez, J., and Kammerer, J., eds., 113, SPIE, Yokohama, Japan (Aug. 2024).
- [15] Chazelas, B., “Contribution à l’étude de l’interférométrie annulante, pour la recherche d’exoplanètes,”
- [16] Buisset, C., “Caracterisation and optimisation of a nulling interferometer,” (Nov. 2007).
- [17] Elias II, N. M., “Modeling polarization effects in nulling interferometers,” in [*Techniques and Instrumentation for Detection of Exoplanets*], **5170**, 91–94, SPIE (Nov. 2003).
- [18] Chipman, R. A., Lam, W.-S. T., and Young, G., [*Polarized Light and Optical Systems*], CRC Press, Boca Raton : Taylor & Francis, CRC Press, 2019. | Series: Optical sciences and applications of light, 1 ed. (July 2018).
- [19] McGuire, J. P. and Chipman, R. A., “Polarization aberrations. 1. Rotationally symmetric optical systems,” *Applied Optics* **33**, 5080–5100 (Aug. 1994).
- [20] McGuire, J. P. and Chipman, R. A., “Polarization aberrations. 2. Tilted and decentered optical systems,” *Applied Optics* **33**, 5101–5107 (Aug. 1994).
- [21] Lu, S.-Y. and Chipman, R. A., “Homogeneous and inhomogeneous Jones matrices,” *Journal of the Optical Society of America A* **11**, 766 (Feb. 1994).
- [22] A. Mazzoli, C. Dandumont, A. Besse, B. Borguet, J. Bouwmeester, D. Defrère, I. Khan, R. Laugier, J. Loicq, P. Piron, R. Saathof, I. Sigusch, G. Terrasa, P. Hallibert, D. Alalufe, Luca Schifano, and T. Rank-Luefing, “Exoplanet explorer: Optical design of a single spacecraft nulling interferometer,” in [*Optical and Infrared Interferometry and Imaging X*], SPIE (2026).
- [23] Khan, A. R., Hamden, E., Kyne, G., Jewell, A. D., Hennessy, J., Nikzad, S., Jones, T., Kerkese, N. I., Parker, B., Picouet, V., Lin, Z., Vider, J., Verma, S., Bradley, H., Beaty, D., Gacon, F., Ford, J., West, G., and Arbo, P., “Comprehensive detector test platform with precision thermal control for noise characterization of charge-coupled devices,” *Journal of Astronomical Telescopes, Instruments, and Systems* **11** (June 2025).
- [24] Balasubramanian, K., Hoppe, D. J., Mouroulis, P. Z., Marchen, L. F., and Shaklan, S. B., “Polarization compensating protective coatings for TPF-Coronagraph optics to control contrast degrading cross polarization leakage,” 59050H (Aug. 2005).
- [25] I. Sigusch, A. Besse, P. Piron, I. Khan, A. Adam, and J. Loicq, “Experimental multiwavelength beam combination for space-based nulling interferometry,” in [*Optical and Infrared Interferometry and Imaging X*], SPIE (2026).