

Exoplanet explorer: Optical design of a single spacecraft nulling interferometer

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ABSTRACT

The optical design layout of a single-spacecraft nulling interferometer is presented here as part of an ESA-initiated study to explore the design parameters and performance of an interferometric concept based on a single spacecraft with multiple sub-apertures. Launch constraints drive the ray-traced model to cover the entire optical chain, from the telescope entrance to the null output after the recombination scheme. A trade-off among several telescope architectures led to the choice of a compact two-mirror solution consisting of four 2.5m diameter telescopes arranged in a linear configuration with an extended baseline. Optical performance at the null output is evaluated, confirming compatibility with starlight suppression targets and establishing the key figures of merit for the interferometer. This work presents the first integrated optical design of the mission concept, laying the groundwork for future iterations that include mechanical, thermal, and control aspects.

Keywords: Optical design, Nulling interferometry, Spacecraft, Exoplanets

1. INTRODUCTION

The detection and characterization of temperate rocky exoplanets constitute one of the most compelling scientific challenges in contemporary astrophysics. This has been identified as a top priority in ESA's Voyage 2050 long-term science program¹.

Among the various techniques developed for exoplanet studies, nulling interferometry stands out as a particularly powerful approach for this scientific motivation. It suppresses stellar light at levels of 10^{-5} to 10^{-6} while preserving the faint mid-infrared thermal emission from Earth-like planets in the habitable zones of nearby stars. Operating in the 3-18 μm wavelength range, such an instrument would provide access to key atmospheric constituents, including CO_2 , H_2O , O_3 , and CH_4 , enabling both habitability assessment and biosignature detection.

This space-based nulling interferometer is not a new idea; it dates to 1978, when Bracewell proposed the original idea². From the late 1990s to the mid-2000s, ESA pursued it through the Darwin program and NASA through the Terrestrial Planet Finder Interferometer (TPF-I). Both programs converged on architecture comprising four collector spacecraft feeding a central beam combiner. Despite laboratory demonstrations of 10^{-6} null depths and major advances in formation-flying technology, both programs were discontinued around 2007 due to programmatic constraints rather than technical limitations.

Since 2017, the Large Interferometer for Exoplanets (LIFE) initiative has revived the concept, combining modern photonic technologies, updated exoplanet demographics, and improved mission-architecture studies^{3,4}. Formation flying, once a major uncertainty, has also progressed significantly, most notably with the launch of PROBA-3 in 2024⁵.

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In late 2022, following the revival of nulling interferometry and the recommendations of the Voyage 2050 report, ESA issued a call for technical proposals titled "Nulling interferometry techniques with a single telescope". The call focuses on the feasibility of nulling interferometry without formation flying, using a single spacecraft that fits within an Ariane 6 fairing. Improved understanding of exoplanet occurrence statistics now allows quantification of the scientific return of such a constrained architecture and determination of whether it is sufficient to justify a dedicated mission.

The consortium (TU Delft, KU Leuven, CSL/ULiège & AMOS) has performed four sequential tasks covering requirements consolidation, technology survey, and architecture trade-offs, preliminary design of selected concepts, and technology road mapping with cost estimation^{6,7}.

Among the architectural trade-offs, one objective was to provide an optical chain design. The goal was to develop comprehensive optical designs spanning the individual telescope assemblies through beam combination, beam control, spectral dispersion, and detection. This includes detailed trade-offs among telescope configurations (siderostat-like, 2-mirror, and 3-mirror designs), pupil transfer systems, achromatic phase shifters, the control and monitoring system, the Modified Mach-Zehnder beam combiners, fiber injection, and spectral analysis via the spectrograph. Critical aspects such as polarization management, wavefront quality control, and radiometric performance are addressed.

This paper presents the resulting optical architecture. A companion overview paper and two additional contributions, one on mechanical and thermal design and one on polarization aberrations, are also available at this conference⁸⁻¹⁰.

We first summarize the spacecraft concept and the architecture tradeoffs, then present the full optical layout and its performance.

2. SPACECRAFT CONCEPT AND GENERAL TRADE-OFF

The mission baseline targets the 3–18 μm wavelength range, employing a multi-aperture body-mounted nulling interferometer configuration compatible with Ariane 6 launch capabilities and designed for operation at the Sun-Earth Lagrange Point L2.

The scientific motivation driving this development is to achieve direct detection of temperate rocky exoplanets and measure their spectra with sufficient resolution ($R > 20$) to identify potential biosignatures. During this project, several requirements were derived, and the instrument must achieve an inner working angle below 300 mas at 10 μm and reach starlight suppression levels of 10^{-5} to 10^{-6} , while maintaining sensitivity below 1 Jy at 10 μm . These demanding requirements necessitate a carefully engineered system capable of unprecedented stability and precision.

Two distinct spacecraft configurations have been analyzed, representing different approaches to achieve the required interferometric baselines: a linear configuration and an X-array configuration. In the linear configuration, four telescopes are arranged in a quasi-linear array, whereas in the X-array configuration, the telescopes are arranged in an X-shaped array, which is closer to the LIFE configuration and the Emma X-array developed in the Darwin project^{3,4}. Each configuration implements a double Bracewell scheme. For both configurations, three nulling baseline lengths have been identified: 8, 16, and 32 m. Each presents distinct advantages. The trade-off has been made among scientific performance (exoplanet yield, inner working angle, sensitivity), technical complexity (deployability, thermal control, active correction requirements), and feasibility (mass budget, structural stability, integration complexity). Below are the general conclusions; the trade-off is described in more detail in dedicated proceedings, as well as the impact on the mechanics and thermal aspects^{8,9}. This trade-off suggests that a linear configuration with a baseline of 16 m is the best baseline design according to current insights.

For all configurations, the spacecraft comprises four apertures, all encapsulated within the Ariane 6 fairing during launch. A trade-off between aperture sizes was performed, and due to mass and volume budgets, the aperture size was set to 2.5 m. The linear configuration, with an 8-m baseline, is the only non-deployable option, whereas all other configurations and baseline lengths require sophisticated deployment mechanisms to meet launch vehicle constraints. The optical trade-off for the telescope assembly, described in the next section, shows how a 2-mirror approach was selected. Volumetric constraints require deploying the second mirror, M2. Figure 2-1 shows the spacecraft in the linear configuration with a 16 m-long nulling baseline.

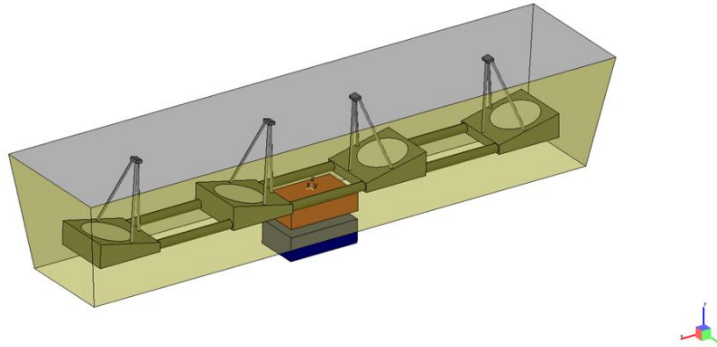


Figure 2-1: Linear configuration, inside the Ariane 6 fairing, with a 16 m nulling baseline.

A large sunshield, inspired by the one on the JWST, covering the bottom and the side of the satellite, is needed to insulate the payload. The beam combiner (orange box in the figure) achieves a temperature of around 125 K in this configuration. Active thermal control is needed to homogenize the temperature, bringing it below 50 K.

For overall performance, a modified version of LIFESim was used. Developed by the LIFE initiative, it assesses the number of detections (e.g., detection yield) over a given mission duration and across a given stellar catalog^{3,4}. It was modified to simulate several nulling configurations at a fixed baseline¹¹.

Within the LIFESim framework, planets were generated around stars within 20 pc (542 in total), and detections were considered successful if an $\text{SNR} > 7$ was reached. As in LIFE, two mission phases were considered: a search phase and a characterization phase. With a linear array featuring a 16 m nulling baseline, about 400 planets can be detected during a four-year search. Of these exoplanets, 90 are rocky ($< 1 R_{\text{Earth}}$), and 17 of those are in their star's habitable zone. During the characterization phase, which also lasts 4 years, 160 exoplanets can be characterized ($\text{SNR} > 10$ and $R = 50$), of which 44 are rocky. Of these, 20 are in the habitable zone. This phase is optimized for this specific type of planet.

Note that instrumental errors are not considered in LIFESim, and, within this project, a parallel study was conducted to improve understanding and modeling of those errors¹². To retain the capability to detect Earth-analogs at 10 pc, piston stability must remain at the order of 1 to 2 nm RMS, with an amplitude error of around 0.1 % RMS.

3. OPTICAL CHAIN

This section focuses on the chosen optical design. Figure 2-1Figure 3-1 represents a diagram block of the optical chain. The structure of this section follows the diagram, presenting each subsystem in more detail and with trade-off information.

General description of the optical design

The interferometer consists of four individual telescopes and their relay optics. They can be arranged in a linear or X-array configuration. This choice does affect the optical design. To create a complete ray-traced model, the linear array was taken as the standard configuration for this chapter. After a trade-off, a two-mirror telescope solution is selected and presented below.

After the telescopes, the transfer optics send the light down to the beam combiner assembly. The beam combination is realized by means of two modified Mach-Zehnder interferometers, as a nulling combiner and a Michelson-like cross-combiner (double Bracewell nulling configuration).

Following the optical chain, the injection system and the spectrometer are positioned and are described below. Polarization effects and mitigation strategies regarding the telescopes and relay optics are presented in a dedicated paper in this conference¹⁰.

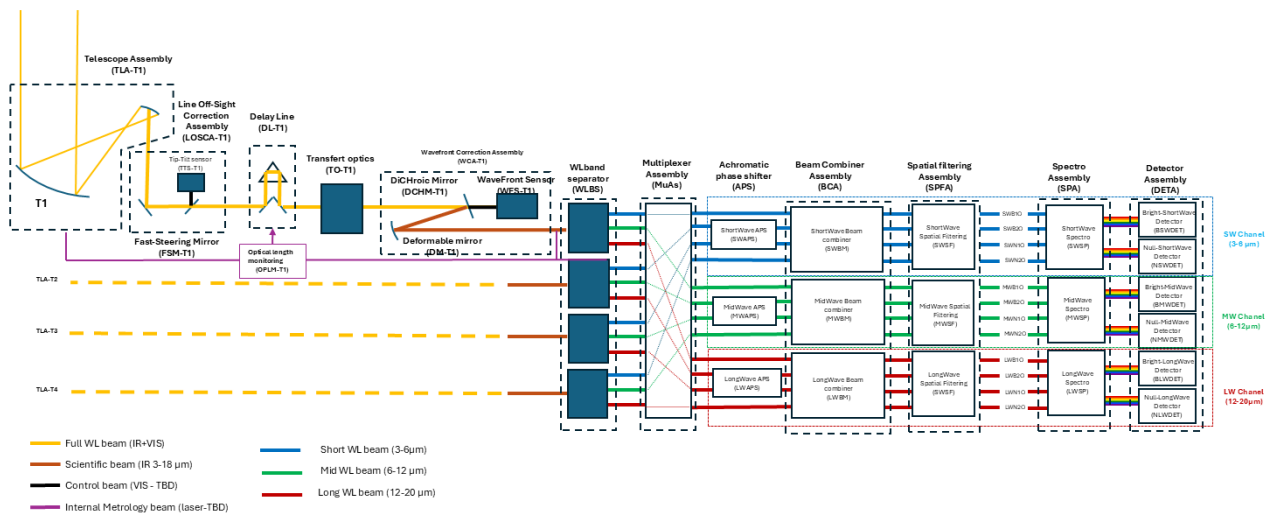


Figure 3-1: Diagram block of the proposed optical chain, from telescopes to the detectors.

Waveband

The science waveband spans 3–18 μm, posing technical challenges across the optical chain, including dielectric coating performance on the beam splitters, broadband spatial filtering, achromatic phase shifter efficiency, single-mode performances, phase correction, ...

To address this, the proposed baseline splits the waveband into three sub-bands, with boundaries currently dictated by the single-mode fiber injection capabilities and the intrinsic limitations of such broad ranges.

The baseline design in this technical note thus incorporates waveband separation to meet the full science requirements. At the current state of technology, no single solution achieves the necessary performance across this entire span, justifying the conservative multi-band approach.

The three sub-bands are:

- SW-band: 3–6 μm (short wavelength)
- MW-band: 6–12 μm (medium wavelength)
- LW-band: 12–18 μm (long wavelength)

Waveband separation affects the entire optical chain by scaling subsystems with the number of bands, thereby increasing overall instrument complexity. The optimal configuration (number of bands) will emerge from trade-offs among technological capabilities, nulling performance, and system complexity.

This approach requires two additional subsystems: (1) a waveband separator on each telescope arm to divide the incoming light into the three bands, and (2) a waveband multiplexer to route each band to its corresponding instrument.

We further note that this trade-off should aim to split the wavelength as far down the chain as possible, with the goal of limiting the non-common path as much as possible, possibly all the way to the spatial filter, or even to the detector, thanks to new technologies in spatial filtering. This push would have the double effect of limiting duplication of components and subsystems and preserving correlations among instrumental systematic errors, thereby facilitating the recovery of the signal in post-processing¹³.

Telescope design

Three telescope configurations have been studied: 1-mirror (siderostat-like), 2-mirror, and 3-mirror. After the trade-off, the 2-mirror configuration was selected.

The design consists of two off-axis parabolic mirrors. To fit the full telescope into the Ariane 6 fairing, the aperture diameter is set to 2.5 m. Figure 3-2 shows the optical design and presents the WFE of the output beam. Its PV amplitude is well below one nanometer. The collimated beam has a diameter of 100 mm at the telescope's output.

The optical properties of the two mirrors are presented in Table 3-1.

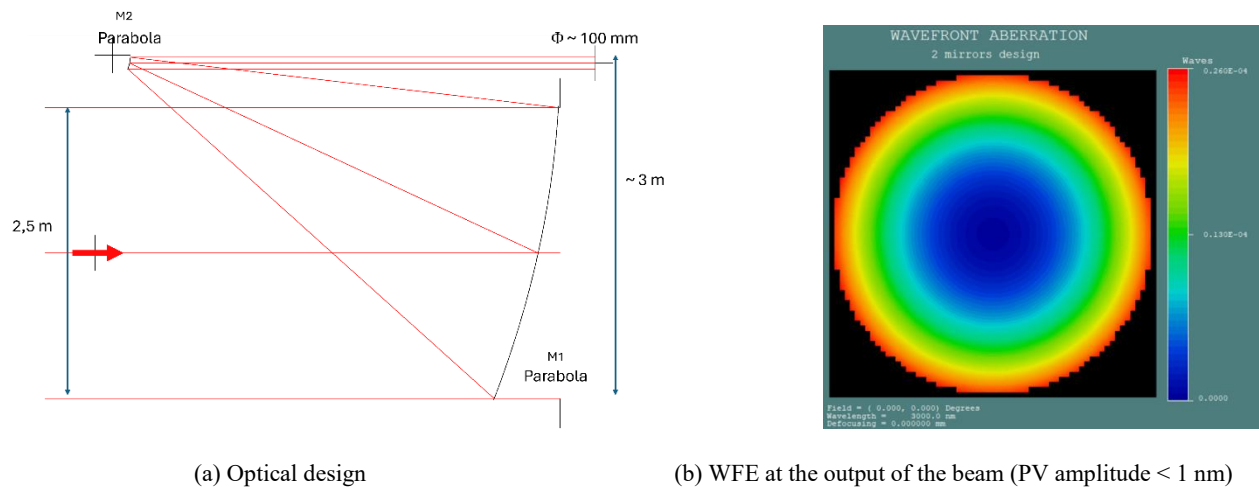


Figure 3-2: Two mirror design with the collimation of the beam (100 mm)

Table 3-1: Design optical properties

Mirror	Radius of curvature	Conic constant	Off-axis	Diameter
M1	7700 mm	-1	1700 mm	2500 mm
M2	310 mm	-1	68.47 mm	102 mm

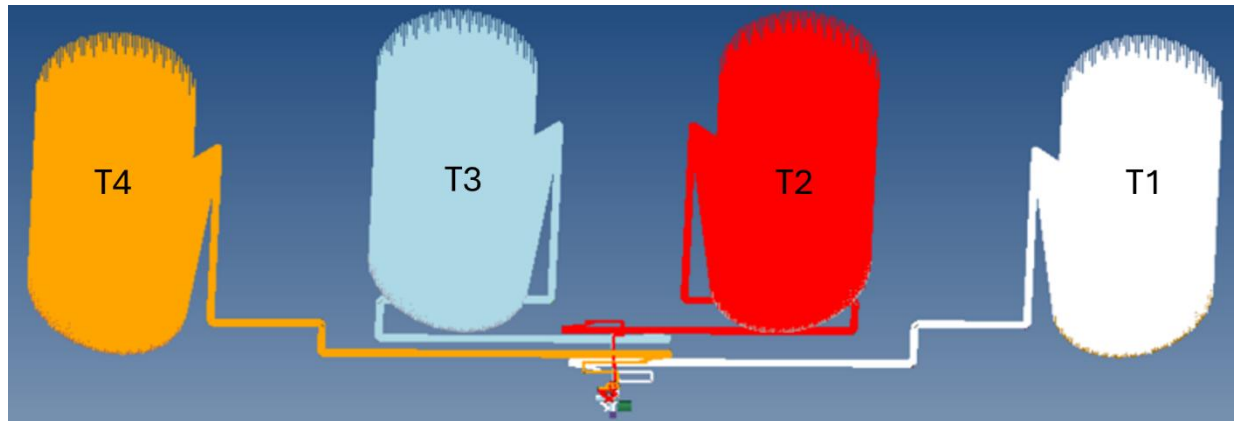
The complete interferometer consists of four copies of this design, with their relative positions shown in Figure 3-3. For the analysis, when the system is fully deployed, the distance between the pupil centers of the two extreme telescopes is 16 meters. Three fold mirrors are added to each telescope to create adjustable delay lines that ensure the same optical path length for all telescopes and the same number of reflections for polarization reasons.

The exit pupil of the two-mirror design is virtual and located behind the secondary mirror. A pupil transfer is required to bring it closer to the beam combiner. A retro-reflective cat's-eye system is used for this purpose. The system consists of two parabolic mirrors (M1 and M3) and one spherical mirror (M2). The ratio of the parabolas' focal lengths determines the ratio of the input and output beam diameters. This ratio is chosen to reduce the beam diameter from 100 mm to 25 mm (with parabolas' focal lengths of 500 mm and 125 mm, respectively). The spherical mirror surface is positioned at the focus of the parabolas, and its radius of curvature determines the position of the output pupil.

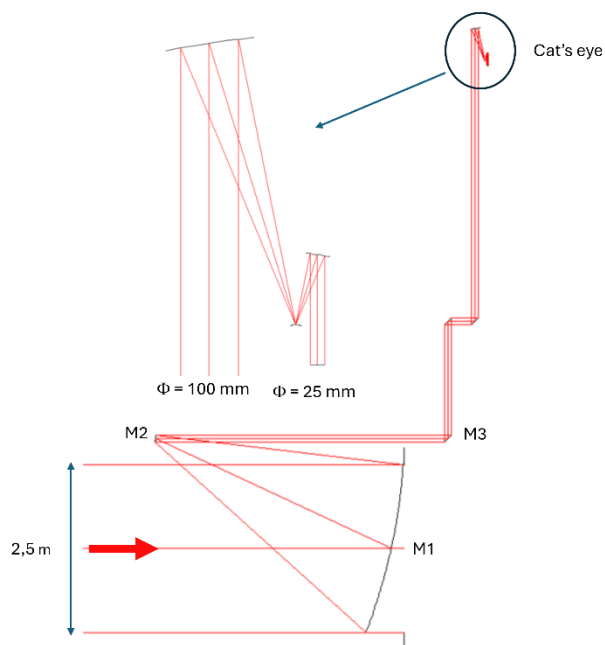
Typically, a cat's-eye setup for large interferometers like the VLT is built around a Variable Curvature Mirror (VCM). In long delay lines, the beam travels through a large vacuum pipe and encounters multiple optics. To keep the beam collimated and to match the interferometer's optical conjugates, the relay optics must adjust as the delay line carriage moves. As the carriage shifts, the beam's effective optical path length, conjugation distance between pupils, and beam divergence or

convergence change. A VCM addresses this by changing its radius of curvature in real time. In our case, there is no VCM because the delay line length is very limited (~cm to ~nm). M2 is therefore not a VCM but a fixed curved mirror, since the pupil's new location is constant.

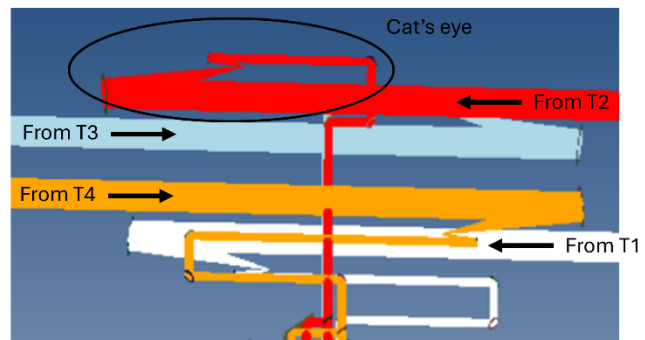
A radius of curvature of 43 mm is selected for the M2, and the exit pupil distance from M3 is approximately 194 mm. The two-mirror telescope cat's eye system is illustrated in Figure 3-3.



(a) General overview of the four telescopes (T1 to T4).



(b) Cat's eye at the telescope level



(c) Closer view on the cat's eye systems for the four beam

Figure 3-3: The four telescopes with their cat's eye system

Wavefront before the beam combiner

The wavefront at the pupil location can also be analyzed before the beam combiner to determine whether it is consistent across all beams. Figure 3-4 shows the wavefront for each arm (T1 to T4). As shown, the wavefronts for T1 & T3 and for T2 & T4 are identical. Note that the variation within the pupil is less than 3 nm PV, and the wavefront is considered uniform.

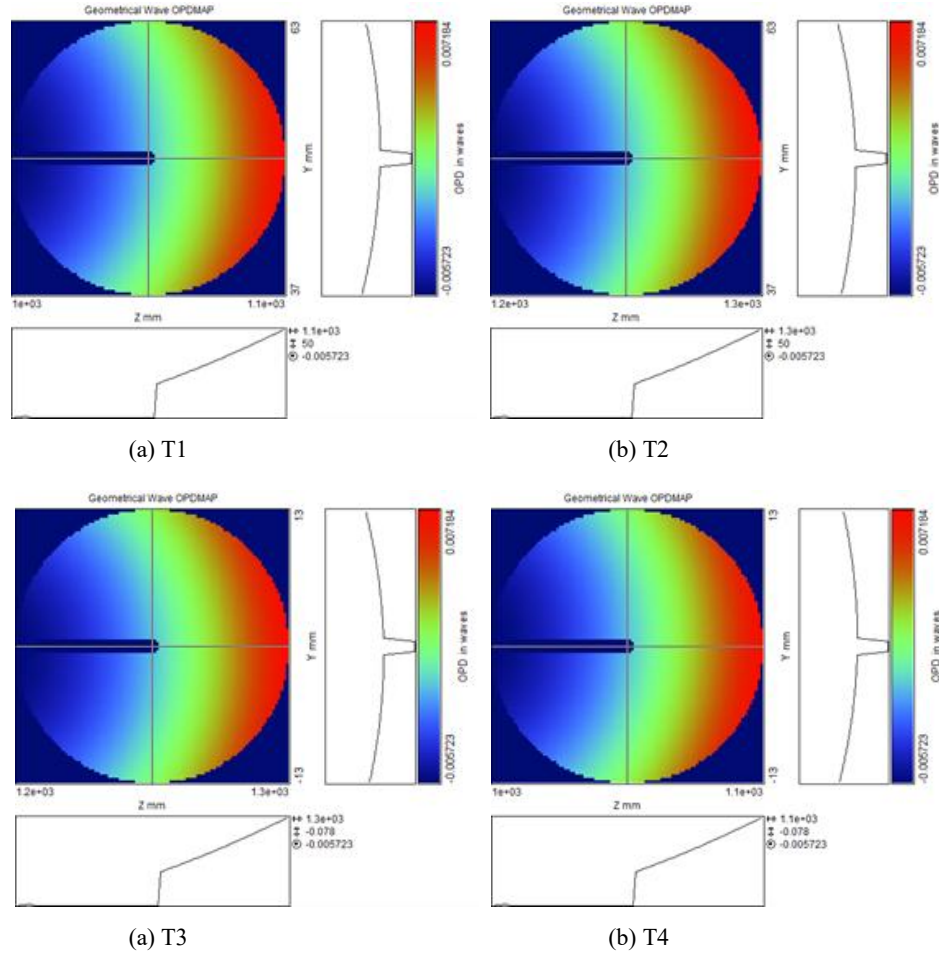


Figure 3-4: WFE before the beam combiner

Waveband separator and multiplexer

The WLBS separates incoming light into the three defined sub-bands (SW: 3–6 μm ; MW: 6–12 μm ; LW: 12–18 μm) and is installed in each telescope arm. A baseline concept employs cascaded dichroic mirrors, each reflecting one sub-band while transmitting the others. This scheme assumes the availability of high-performance IR coatings across these bands but does not account for all current physical limitations that may arise, such as dispersion, absorption, and efficiency roll-off due to aging. A detailed feasibility study is essential to validate this approach, assessing coating performance against system boundary constraints (e.g., angle of incidence, polarization sensitivity, and thermal stability).

Other wavelength-separation processes might be explored, such as gratings or grisms. After separation, the sub-band beams route to the waveband multiplexer, which directs each to its dedicated beam combiner and downstream instrument.

The waveband multiplexer collects the SW, MW, and LW beams emerging from the waveband separators and directs each one to the entrance pupil of its dedicated beam combiner. The baseline architecture uses reflective optics (flat mirrors and

periscope-like folding assemblies), which minimizes chromatic effects and maintains common optical paths across the full infrared range. For each wavelength band, the mirrors are arranged so that the geometric path length from any telescope to the corresponding beam combiner is equalized within the allocated OPD budget.

Achromatic phase shifter

The Achromatic Phase Shifter (APS) is inserted upstream of the beam combiner to introduce the required π -phase shift while preserving amplitude balance and wavefront quality. Multiple technical approaches have been demonstrated and reviewed in the literature^{14,15}, but the current state of the project does not yet justify down-selecting a single baseline solution. Dedicated technological development and breadboarding are therefore required before a final choice can be made. In past studies, it has been proposed to combine the APS with the Adaptive nuller (see below) to accurately monitor and correct phase chromatically.

The main drivers for the choice of APS are:

- Phase accuracy and achromaticity over the full 3–18 μm band (or within each sub-band).
- Polarization behavior, including induced polarization effects and polarization-dependent aberrations, and the stability of the phase response with respect to polarization state.
- Throughput and stray-light behavior, including reflection losses, absorption, and ghost management.
- Sensitivity to alignment, manufacturing tolerances, and thermal drifts, under cryogenic and space conditions.
- Pupil orientation or pupil flip, which may impact the telescope design and the pupil relay through the instrument.
- Overall impact on achievable instrumental null depth.

Several APS concepts are relevant for this instrument:

- Bulk-optic periscope-based APS uses geometric path differences and pupil flips to generate the required phase shift with inherently achromatic behavior. This solution is attractive for its simplicity and broad spectral coverage but requires very careful control of polarization and pupil imaging.
- Achromatic Fresnel rhombs, which generate phase shifts via total internal reflection, offer good achromaticity over a limited band and enable compact packaging. Material availability, coating performance in the mid-IR, and polarization sensitivity are key design drivers.
- Focus-crossing phase shifters are those in which one of the two beams is brought to a focus and re-collimated so that the required π -shift arises from the Gouy phase. They are intrinsically achromatic but place tight constraints on wavefront quality and alignment near the focus.

Adaptive nuller and chromatic phase compensation

Chromatic phase control of the incoming beams is essential for achieving deep nulls over a broad wavelength range. To this end, an active compensation stage that corrects phase errors at (quasi-)individual wavelengths is required. In the adaptive nuller concept proposed by Peters et al. (2004), the beam is first spectrally dispersed, and the resulting wavelength channels are then imaged onto a deformable mirror (DM)¹⁶. Each actuator (or group of actuators) addresses a specific spectral and polarization element, allowing the DM to modify a spatially varying phase that compensates chromatic phase errors across the band. This system enables fine, wavelength-dependent tuning of the null at the expense of increased optical complexity and stringent requirements for the calibration and stability of the dispersion and DM.

Modified Mach-Zehnder Beam Combiner

Modified Mach-Zehnder interferometers are used to coherently combine two beams following a double Bracewell combination. This last employs two stages with pairwise coherent beam combinations.

As shown in Figure 3-5, the two science beams each contribute with one reflection (r) and one transmission (t), i.e., $rt' + tr$. If the chromatic behavior is the same on both beamsplitters, the result is a balanced amplitude contribution. It consists of four beam splitters and two large fold mirrors. Each beam hits a beam splitter (50% transmission, 50% reflection), then a fold, and then a second beam splitter. Four output beams are produced, with two being bright outputs caused by constructive interference, and the other two being dark outputs resulting from destructive interference.

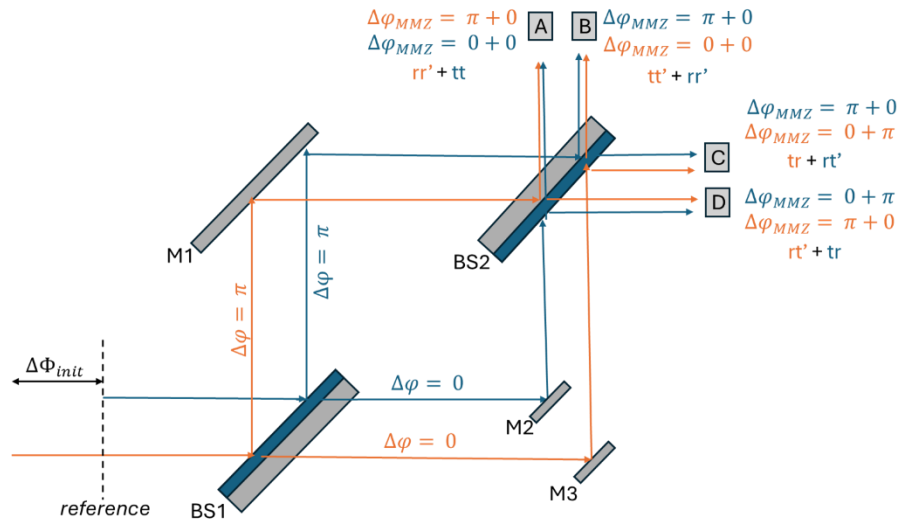


Figure 3-5: Schematic of the working principle of a two-beam input Modified Mach-Zehnder interferometer. The scientific outputs C and D are composed of light coming from both inputs undergoing each one transmission (t or t' depending on direction) and one reflection (r or r') with the beamsplitters.

Two modified Mach-Zehnder interferometers (MMZ) are used: one to combine telescopes 1 and 3, and the other to combine telescopes 2 and 4. They are positioned on top of each other and on the side of the telescopes, as shown in Figure 3-6.

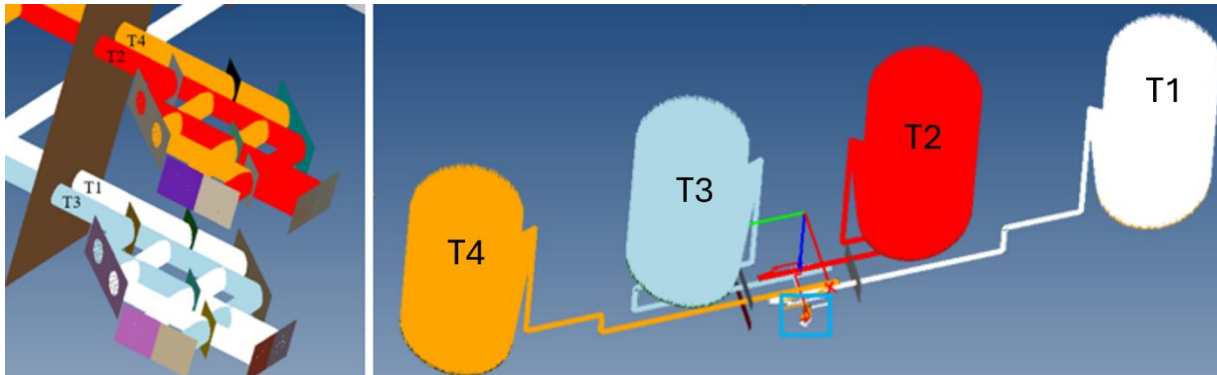
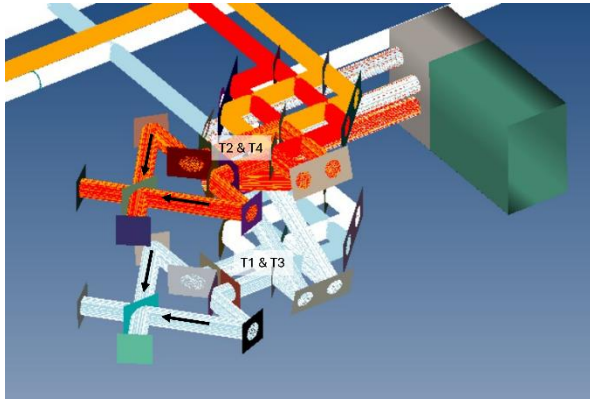


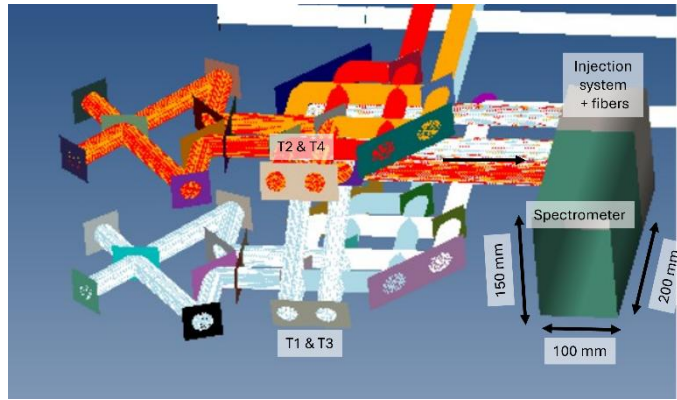
Figure 3-6: Modified Mach-Zehnder (MMZ) interferometers. The left shows a close-up of the two MMZ; the right provides a general overview of the design.

The two dark outputs from each MMZ are combined with a common beam splitter, and the four outputs are directed to an injection system and optical fibers that serve as inputs to the spectrometer. The spectrometer and injection systems are not modeled in detail but are discussed in the following sections. Requirements or component parameters, such as the optical fibers (core diameter, position, numerical aperture, etc.), are not yet defined.

The two bright outputs of the same MMZ are also combined using a beamsplitter. Detectors then monitor the two obtained outputs per MMZ.



(a) The two bright outputs of the same MMZ are recombined



(b) Injection of dark outputs towards the spectrometer

Figure 3-7: Recombination of outputs

WFE at the output of MMZ1 and MMZ2 are identical.

Fiber injection system

The four dark outputs from the cross-combination stage, after the two MMZs, are each injected into a single-mode fiber. The objective is to clean the beam of all possible aberrations. They are then directed to a low-resolution spectrometer ($R = 20$ and $R = 50$), mainly because the reduced flux limits what can be achieved.

Single-mode fibers serve as both spatial and modal filters. While pinholes can act as spatial filters, single-mode fibers are more efficient and reduce the requirements for telescope pointing accuracy¹⁷.

Single-mode fibers transmit only the fundamental mode optimally when the incoming electric field matches the fiber's mode profile, regardless of the wavefront's initial shape. The electric field remains constant during propagation, unaffected by the input light's electric profile, and takes the shape of a Gaussian distribution. However, using SMFs introduces a drawback: energy loss during injection. When light is injected into a single-mode fiber, not all of the input energy is transmitted to the output. Only a portion couples into the fundamental mode, while the rest is lost. It has been shown that the maximum coupling efficiency is limited to 78% for a plane wave focused on the fiber core.

Unfortunately, the coupling is chromatic and depends on the materials. A single fiber can couple light within its critical wavelength, λ_c , and up to twice that wavelength. This means that to cover the full wavelength range (3-18 μm), several bands are necessary. In addition to the chromatic dependence, the coupling efficiency depends on pupil matching, which should be optimized upstream with a proper beam-steering algorithm.

New solutions are emerging, such as the one proposed by Ireland et al. (2024), which suggests that efficient single-mode injection can be achieved across most of the wavelength range of interest by combining a photonic crystal waveguide with phase-induced amplitude apodization¹⁸. Simulations indicate that a 90% injection rate from 8 to 18 μm is theoretically possible, covering a large part of the science band. Experimental validation of this technique has been funded and is expected to yield results in the coming years.

Spectrometer

The spectrograph in the nulling interferometer must deliver an exoplanet spectrum over the full wavelength range from 3 to 18 μm . The required resolving power is $R = 20$ during the detection phase and increases to $R = 50$ during the characterization phase. As presented, the spectral range is provisionally divided into three bands, and the current baseline assumes one dedicated spectrograph per band. A future evolution could be to combine several bands within a single spectrograph, provided this remains compatible with the optical and detector constraints. Each spectrograph is fed by a set of single-mode fibers at the cross-combiner output. At this stage, eight outputs are considered (four nulled and four bright channels). The need to spectrally disperse the bright outputs still needs to be confirmed. These eight fiber outputs are

arranged in a line perpendicular to the dispersion direction, forming the spectrograph's entrance slit. The fiber cores define the physical slit width.

4. CONCLUSION

This paper presents the integrated optical design of a single-spacecraft nulling interferometer developed within the framework of an ESA-initiated study. The design spans the full optical chain, from the four 2.5 m-diameter collecting telescopes through the beam-combination stage to the fiber-injection and spectrograph subsystems, covering the 3–18 μm science waveband.

The two-mirror telescope architecture, combined with a cat's-eye pupil transfer system, was identified as the optimal solution, offering the best balance among compactness, launch compatibility within the Ariane 6 fairing, and optical performance. The wavefront error delivered to the beam combiner is below 3 nm PV across all four telescope arms, confirming the uniformity required for deep nulling.

The waveband is split into three sub-bands (SW: 3–6 μm , MW: 6–12 μm , LW: 12–18 μm) to address the chromatic limitations of current spatial filtering and coating technologies. While this approach increases instrument complexity, it is a necessary and justified trade-off to meet the science requirements.

The two Modified Mach-Zehnder beam combiners produce identical output wavefronts, a critical prerequisite for the cross-combination stage. Their design highlights technological challenges in broadband operation and polarization management, which will require dedicated development of coatings and beam-splitter fabrication.

Injection into single-mode fibers ensures efficient spatial filtering, although chromatic coupling limitations remain an open challenge that emerging photonic technologies, such as photonic crystal waveguides, are beginning to address. The downstream low-resolution spectrographs ($R = 20$ to $R = 50$) are provisionally baselined as one unit per waveband.

This work constitutes the first fully ray-traced optical model of this mission concept and establishes the key figures of merit for the interferometer, confirming compatibility with the target starlight suppression levels of 10^{-5} to 10^{-6} . It lays a solid foundation for future design iterations that will incorporate mechanical and thermal co-design, active wavefront and piston control, and a detailed polarization aberration budget, as addressed in companion contributions at this conference.

ACKNOWLEDGEMENTS

The authors thank the European Space Agency for its valuable contributions and guidance throughout the project.

The authors acknowledge the use of AI-assisted writing tools for improving the clarity and structure of the manuscript. All scientific content, analyses, and conclusions remain the sole responsibility of the authors.

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