

Assessing nulling performance based on ray-traced optical design

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ABSTRACT

High-contrast imaging of nearby exoplanets remains a major technological challenge, with nulling interferometry identified as one of the most promising approaches for detecting and characterizing Earth-like planets in the mid-infrared. This objective is a key element of the ESA Voyage 2050 roadmap.

While nulling interferometry has been extensively studied in the context of past concepts such as Darwin and TPF-I, renewed interest in space-based architecture has emerged in recent years (e.g., the LIFE consortium). A critical challenge lies in accurately assessing nulling performance. Current approaches are predominantly based on analytical models that introduce small perturbations (e.g., amplitude mismatch, phase errors, polarization effects) but remain largely agnostic to the actual optical chain.

In this work, we present a modeling tool that evaluates nulling performance directly from ray-traced optical systems developed in Code V. The method enables performance estimation upstream of beam combination, allowing the propagation of realistic optical aberrations and misalignments (e.g., decentering, surface figure errors, Zernike modes), thereby overcoming some of the limitations of purely analytical approaches.

The model is first validated against classical analytical formulations using a simplified optical configuration. It is then applied within the framework of an ESA study to assess performance and derive requirements for a single-spacecraft nulling interferometer. The considered architecture consists of four 2.5 m apertures, each feeding a two-mirror afocal telescope followed by a delay line and a cat's-eye system. The resulting null depth is evaluated under various perturbation scenarios.

This work represents a first step toward more integrated and flexible modeling frameworks, enabling parametric analyses and supporting the design of robust nulling interferometers capable of meeting the requirements for detecting and characterizing Earth-like exoplanets.

Keywords: Nulling interferometry, ray-traced software, performance, null ratio

1. INTRODUCTION

The detection and atmospheric characterization of temperate, rocky exoplanets have been identified as a top scientific priority in ESA's Voyage 2050 long-term program¹. Achieving this objective requires overcoming the extreme contrast between a Sun-like star and an Earth-like planet in the mid-infrared, typically on the order of 10^{-5} to 10^{-6} .

Among the proposed techniques, nulling interferometry stands out as one of the few capable of achieving such contrast levels while preserving the planet's thermal emission, making it a leading candidate for future space missions dedicated to exo-Earth detection.

The concept traces to Bracewell in 1978², who proposed combining beams from separate telescopes with a π phase shift to suppress on-axis starlight. From the late 1990s to the mid-2000s, the technique matured significantly through ESA's Darwin program and NASA's Terrestrial Planet Finder Interferometer (TPF-I)^{3,4}. Both initiatives converged on multi-aperture architectures comprising four collector spacecraft feeding a central beam combiner. During this period, major technological advances were achieved: laboratory nulls at the 10^{-6} level, cryogenic mid-IR beam combination, formation-flying demonstrations, and detailed mission architecture studies. Despite this progress, both programs were discontinued around 2007 due to budgetary and programmatic constraints rather than technical limitations.

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Over the past decade, nulling interferometry has experienced renewed momentum. The LIFE (Large Interferometer For Exoplanets) initiative, launched in 2017, has revitalized the field by combining updated exoplanet demographics, modern photonic technologies, improved detector performance, and refined mission architecture studies⁵. LIFE has also produced detailed yield simulations showing that a space-based mid-IR nuller could characterize dozens of temperate terrestrial planets around nearby stars^{6,7}.

Meanwhile, ground-based developments have continued. Instruments such as the Keck Interferometer Nuller, LBTI, and, more recently, NOTT have demonstrated the maturity of nulling techniques under realistic observing conditions. NOTT, built by KU Leuven, is expected to become operational in 2027 and will provide a unique testbed for future space missions⁸.

Following the recommendations of the Voyage 2050 report, ESA issued in late 2022 an Invitation to Tender titled “*Nulling interferometry techniques with a single telescope*”. The objective is to assess whether high-performance nulling can be achieved without formation flying, using a single spacecraft compatible with an Ariane 6 fairing. A consortium comprising TU Delft, KU Leuven, CSL/ULiège, and AMOS has conducted requirements consolidation, technology surveys, architectural trade-offs, preliminary optical and mechanical designs, and technology roadmapping with cost assessment⁹.

Beyond Europe, China has initiated studies of space-based nulling architectures and missions, for instance, through the Multiple-spacecraft Exoplanet Aperture sYnthetic INterferometer (MEAYIN) program¹⁰, illustrating the global interest in this technique.

Despite this renewed activity, a key challenge remains: how to accurately predict nulling performance for real optical designs? Most existing studies rely on analytical models that assume small perturbations (e.g., amplitude mismatch, phase errors, polarization effects) and idealized optical chains^{11,12}. These models are invaluable for conceptual studies but cannot capture realistic aberrations, misalignments, manufacturing defects, or the cumulative impact of multiple optical subsystems.

To address this gap, several master's student projects at CSL/ULiège have developed a modeling tool that evaluates nulling performance directly from ray-traced optical systems^{13–16}. The tool extracts optical path differences, phase distributions, and intensity maps from Code V, propagates realistic perturbations (e.g., decentering, tilts, Zernike surface errors), and computes the resulting null depth through dedicated MATLAB post-processing. This approach bridges the gap between analytical theory and real instrument design, enabling early performance assessment and requirement derivation for future nulling interferometers.

In this paper, we present the current status of this modeling effort and its application to a Bracewell configuration and the ESA single-spacecraft study.

2. NULLING TOLERANCING MODELING TOOL

Motivation and limitations of analytical approaches

Predicting the nulling performance of a space-based interferometer remains one of the most challenging aspects of instrument design. Yield estimates are typically obtained using ideal-instrument assumptions. For LIFE, for instance, a photon-noise-dominated regime is assumed, meaning that instrumental noise is treated as nondominant^{6,7}. When perturbations are included, they are usually handled through classical analytical models, such as those of Serabyn et al. (2003) or Lay (2005)^{11,12,17}. This approach is also used to assess the impact of perturbations on space-based demonstrators for future large interferometric missions¹⁸. Analytical and numerical instrumental-noise simulations are currently performed both within the LIFE consortium and for the ESA single-spacecraft design^{19–21}.

These perturbations typically include piston, amplitude mismatch, polarization leakage, or tip/tilt errors, and the optical chain is generally treated as idealized or agnostic. While such models are invaluable for conceptual trade-offs, they cannot capture the cumulative impact of realistic aberrations, misalignments, manufacturing defects, or interactions among subsystems.

For future missions targeting null depths of 10^{-5} – 10^{-6} , this limitation becomes critical. The performance of a nuller depends not only on the beam combiner but also on the entire upstream optical train: telescope optics, afocal relays, delay lines, cat's-eye systems, and alignment tolerances. A modeling tool capable of propagating realistic optical errors throughout a full design is therefore essential for deriving meaningful requirements and guiding architectural choices.

As pointed out by Lay (2005)¹² and illustrated in Figure 2-2, an ideal interferometer, in this case a typical Bracewell interferometer, will provide a deep null, only limited by the stellar leakage (enclosed area under the curve). First-order fluctuations (dashed line) in phase, amplitude, or collector separations can preserve the on-axis null but lead to perturbations in the geometric leakage (b). Second-order fluctuations give rise to perturbations in the null floor (c). The goal of the tool is to model these situations directly from ray-traced information.

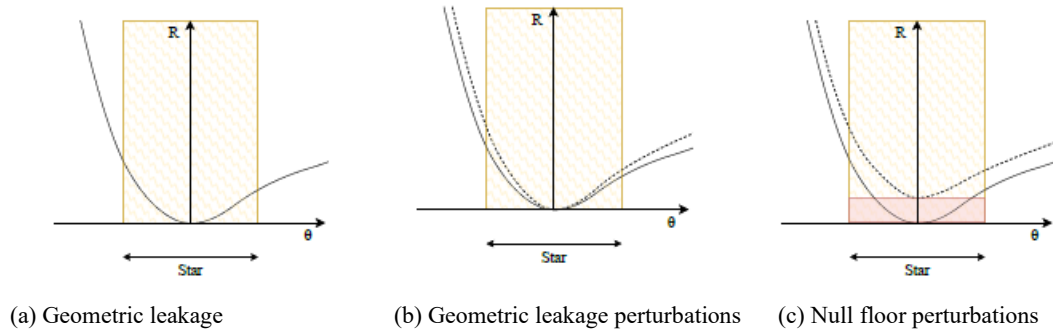


Figure 2-1: Contributions to noise. Adapted from Lay (2005)¹².

The goal of the present work is to present the numerical tool.

Architecture of the modeling tool

The modeling tool developed at CSL/ULiège combines ray tracing, compensation, and numerical post-processing into a single workflow. It is designed to evaluate nulling performance before beam combination, enabling early tolerancing of candidate designs. This tool was first developed for a two-telescope interferometer and then improved for a four-telescope array, with a classical double-Bracewell recombination.

Figure 2-2 shows the general concept of the nulling tolerancing modeling tool. It is a four-step process. The first step is to develop the optical design in Code V, from the telescope entrance pupil to the output of each interferometer arm. For each configuration, the tool extracts the optical path difference (OPD), the phase distribution, the intensity distribution, and wavefront error maps. Realistic perturbations can be injected at any surface or subsystem, such as decentering and tilts, surface figure errors (Zernike modes), piston offsets, or mechanical misalignments. This allows the propagation of physically meaningful aberrations through the entire optical chain. As explained below, compensation is usually necessary to ensure interference. At the end, post-processing is performed in MATLAB to derive figures of merit.

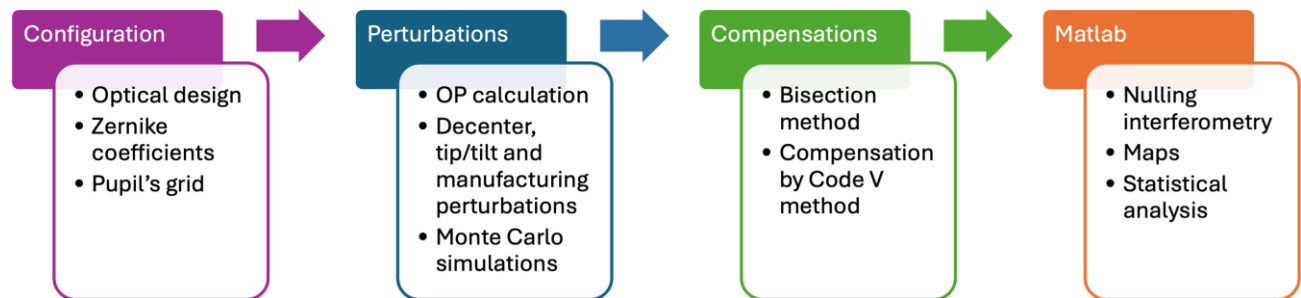


Figure 2-2: General concept of the nulling tolerancing modeling tool.

Compensation stage

As highlighted in this study, deep null depths cannot be achieved without compensating for mechanical mounting or manufacturing variability. These effects typically generate differential optical path errors larger than $\lambda/2$ (after recombination), preventing interference altogether. Nulling interferometers therefore require an active alignment or compensation procedure to reduce these errors.

Both approaches aim to emulate the behavior of delay lines or fine-steering mechanisms, thereby minimizing the OPD before beam combination.

Post-processing in MATLAB

The extracted optical quantities are processed to compute the null depth (via coherent combination of the two arms), the rejection ratio, the OPD RMS and statistical distributions, the phase maps and OPD maps, and the sensitivity curves for selected perturbations.

This post-processing layer enables parametric studies, Monte Carlo analyses, and requirements derivation.

Validation

Before applying the tool to complex optical designs, its outputs were compared with classical analytical formulations for simplified systems (e.g., a single mirror and a two-arm interferometer with ideal optics). The tool reproduces the expected trends for piston, tilt, and low-order aberrations, confirming consistency with theory. This validation is shown in §3.

These tests also highlight the limitations of analytical models: when realistic aberrations or asymmetric optical paths are introduced, analytical predictions diverge, whereas the ray-traced approach remains valid. This confirms the need for a modeling tool grounded in actual optical designs.

Current capabilities and limitations

The tool currently supports the propagation of realistic optical aberrations, the compensation of OPD errors, the estimation of null depth upstream of beam combination, sensitivity analyses, and the derivation of requirements. However, several aspects remain outside the present scope: polarization effects, thermal and structural time-dependent drifts, detector modeling and noise propagation, vibration and pointing stability.

These elements will be addressed in future work, with the long-term goal of providing a fully integrated modeling framework for space-based nulling interferometers.

3. VALIDATION ON SIMPLIFIED CONFIGURATIONS

Before applying the modeling tool to complex interferometric architectures, a series of simplified validation cases were performed. The objective was to verify that the tool reproduces the expected physical trends for basic perturbations (piston, tilt, low-order aberrations) and that the extracted OPD, phase, and null depth behave consistently with analytical formulations. These tests are not intended to certify absolute accuracy, but rather to establish first-order confidence in the modeling approach.

The tool was validated against two idealized configurations for which the null depth can also be estimated analytically: a single perturbed mirror, and an ideal two-telescope nuller.

A minimal optical layout, consisting of a single plane mirror at 45° and a detector, shown in Figure 3-1, was used to verify the extraction and post-processing of the optical path (OP) computed by Code V. For each ray sampled over the pupil, the OPD with respect to the unperturbed configuration is obtained as $\Delta\text{OPD} = \text{OP}_{\text{perturbed}} - \text{OP}_{\text{nominal}}$ and converted into a phase error $\varphi = 2\pi \cdot \Delta\text{OPD} / \lambda$.

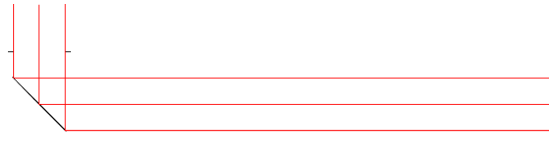


Figure 3-1: Optical design of the basic test with a plane mirror at 45° and 1100 mm between the STOP and the image plane. Designed in Code V.

Two independent definitions of the null depth are then evaluated from this phase map. The first is a geometric, stellar-leakage formulation

$$N = \frac{N_a}{\sum_j A_j^2} \quad (3-1)$$

where the astronomical leakage is $N_a = \sum_j \sum_k A_j A_k \cos(\phi_j - \phi_k) B_{jk}$. A_j is the amplitude collected by aperture j , and B_{jk} accounts for the finite angular diameter θ_* of the star through the first-order Bessel function J_1 , $B_{jk} = 2 \frac{J_1\left(\frac{2\pi b_{jk}\theta}{\lambda}\right)}{\frac{2\pi b_{jk}\theta}{\lambda}}$, with b_{jk} the baseline between aperture j and k . This is the equation driving the modeling tool.

The second is an intensity-based formulation, in which the perturbed fields are coherently recombined pixel-by-pixel over the pupil, before their destructive (I-) and constructive (I+) combinations are integrated over the aperture,

$$N_{int} = \frac{\langle I_- \rangle}{\langle I_+ \rangle}. \quad (3-2)$$

Both estimates are also cross-checked against the classical small-perturbation approximation of Serabyn et al. (2000)¹¹, when only phase contributions are considered,

$$N \approx \frac{1}{4} \langle \Delta\phi^2 \rangle. \quad (3-3)$$

A piston of 3 nm, shown in Figure 3-2, and a tilt of $1^\circ \times 10^{-7}$ (0.36 mas), shown in Figure 3-3, were applied in turn to the mirror. As expected from the nature of a piston aberration, the OPD map remains spatially uniform over the pupil. The mean OPD is therefore equal to 3 nm, with RMS 3 nm, corresponding directly to the applied displacement. The phase map exhibits the same uniform behavior, with a phase variation of approximately $6\pi \times 10^{-3}$ rad for each beam. For the tilt case, the OPD is no longer uniform over the pupil. Instead, a clear gradient is observed across the aperture, resulting from the linear variation of the OP introduced by the tilted mirror. The corresponding phase map exhibits the same spatial gradient, confirming the direct relationship between the OPD and phase distributions. This spatially varying phase directly affects the interference between the beams. In this last case, only a small tilt angle was set. Beyond this value, interference (at 1 μ m) was no longer possible, showing very stringent requirements. Compensation is therefore essential.

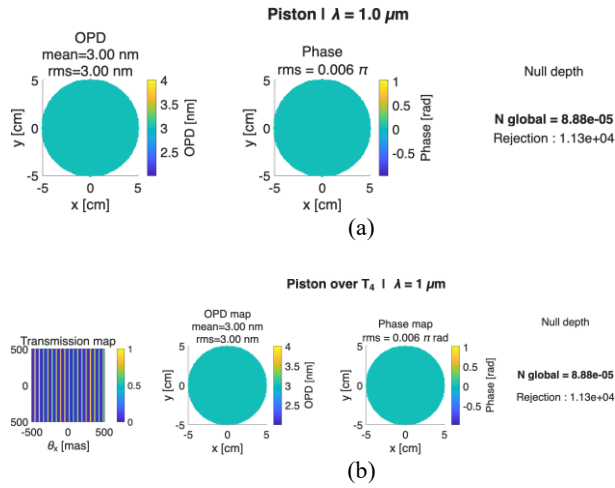


Figure 3-2: Piston of 3 nm. Results (a) with the intensity-based formulation and (b) with the modeling tool.

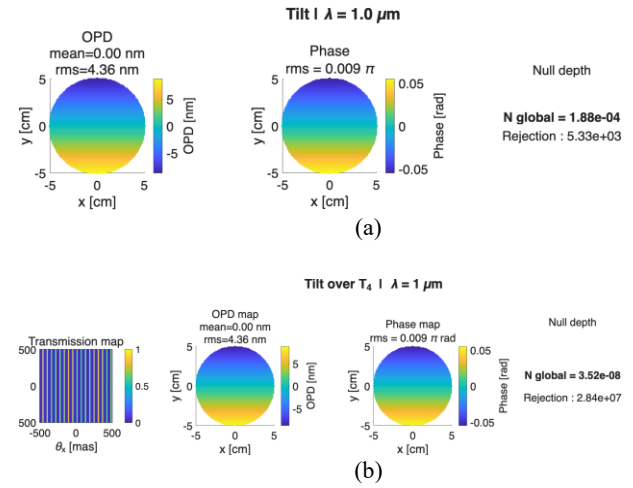


Figure 3-3: Tilt of 0.36 mas. Results (a) with the intensity-based formulation and (b) with the modeling tool.

For the piston, which produces a spatially uniform OPD and phase, the three formulations (Eqs. 3.1, 3.2 and 3.3) agree. For the tilt, which introduces a linear phase gradient across the pupil, the geometric and intensity-based estimates (Eqs. 3.2 and 3.3) diverge by several orders of magnitude, since Eq. 3.1 accounts for the finite angular size of the star while Eq.

3.3 reflects the RMS phase error alone. This confirms that a single scalar phase value is not sufficient to describe the null depth beyond a purely uniform (piston-type) error, and that the spatial distribution of the aberration over the pupil must be considered. This limitation motivates the ray-traced approach of this work.

4. BRACEWELL NULLING PERFORMANCE AND SENSITIVITY

If the modeling tool is designed to work up to a four-aperture interferometer, it can be useful to examine the basic behavior of a nulling interferometer, a classical two-aperture Bracewell configuration. This configuration provides an intermediate step between the analytical validation presented in the previous section and the tolerancing of the ESA single-spacecraft design presented in the next section. It demonstrates how the developed modeling framework translates realistic optical perturbations into a degradation of the interferometric response and highlights the extreme sensitivity of a nulling interferometer to alignment and wavefront errors.

For two beams of equal amplitude and a baseline, the ideal monochromatic response of the destructive output can be written as

$$R(\theta) = 2 \sin^2 \left(\frac{\pi B \theta}{\lambda} \right) \quad (4-1)$$

where θ is the angular separation from the optical axis. More generally, for a two-dimensional angular position, the argument of the sine depends on the projection of the baseline onto the source direction. The response therefore exhibits a central null surrounded by constructive interference fringes.

This ideal response was also recovered analytically in the modeling work, where the response function was derived directly from the coherent combination of the two beams. This response provides a useful reference, but it is an idealization. In a real optical system, manufacturing errors, surface aberrations and alignment errors introduce differential optical path and phase errors between the two beams. The perfect destructive interference is then degraded, and the on-axis response becomes non-zero. Importantly, the effect is not restricted to the center of the interferogram: spatially varying phase errors modify the response function over the entire angular field.

This behavior was investigated through Monte Carlo simulations of a Bracewell-type optical configuration. This design is depicted in Figure 4-1. It has an aperture diameter of $D = 50$ cm and a magnification $M = 20$, following the former FKSI concept as an initial approach²². FKSI was a demonstrator for a large space-based nulling interferometer, and it is still used to demonstrate interest in such demonstrators¹⁸.

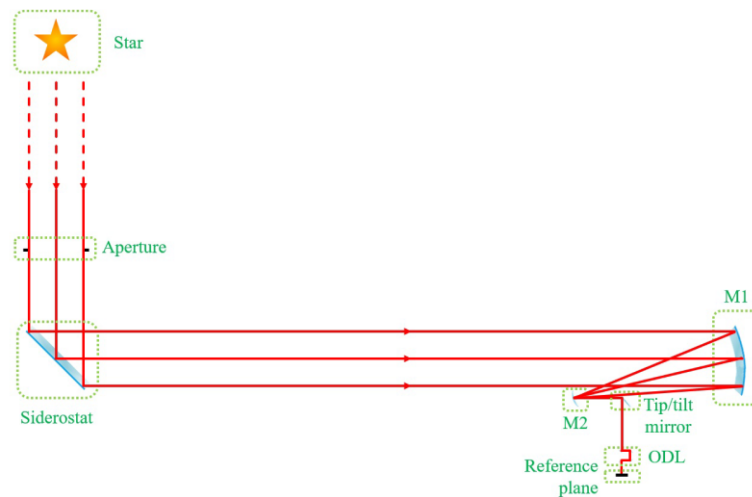


Figure 4-1: Bracewell design implemented in Code V.

In a first case, wavefront errors corresponding to $\lambda/100$ were introduced while no additional misalignment was applied. The resulting response functions, depicted in Figure 4-2, exhibit a non-zero null floor, with an on-axis response of $R(0) = 0.029$ for the considered configuration. The perturbation also increases the stellar leakage at larger angular separations and modify the shape of the response function with respect to the ideal theoretical curve.

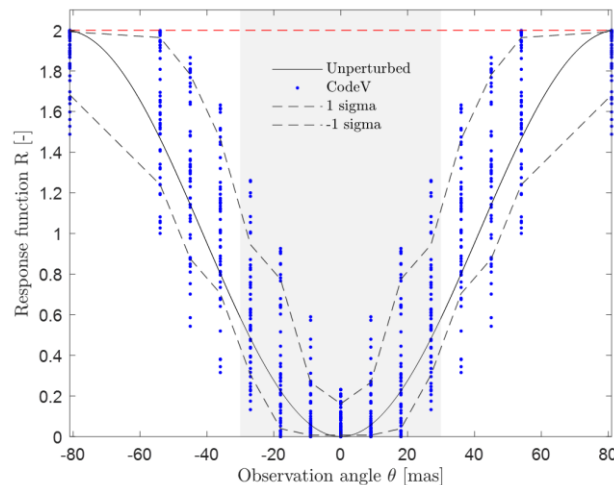


Figure 4-2: Response functions obtained from Monte Carlo simulations in the presence of wavefront and alignment errors, compared with the unperturbed Bracewell response. The perturbations produce a non-zero on-axis response and modify the transmission pattern over the angular field.

The degradation becomes particularly pronounced when alignment errors are introduced. For the case shown in Figure 4-2, a misalignment of up to $1 \mu\text{m}$ was applied to all optical surfaces, in addition to a wavefront error of $\lambda/100$. The Monte Carlo realizations show a much larger dispersion around the nominal response. The central null is no longer reached in any of the perturbed simulations, with $R(0) = 0.162$ for the mean response considered in the study. The large dispersion indicates that different realizations of the same tolerance distribution can substantially affect the interferometric response.

These results illustrate an important characteristic of nulling interferometry: the relevant performance cannot be described solely by the nominal optical design. The quality of the null depends critically on the spatial distribution of the differential optical path between the two beams. This is particularly important for alignment errors such as tip and tilt, which introduce a spatial gradient in the optical path rather than a simple global phase offset.

As for the validation test in §3, sensitivity to angular misalignment was also investigated by varying the tilt applied to the optical system. Figure 4-3 shows the maximum optical path difference obtained as a function of the tilt angle, together with the coherence length of the considered configuration. The OPD increases rapidly with the tilt angle, and the simulations indicate a critical angular range of approximately 0.002° (125 mas) for the investigated configuration, beyond which the OPD becomes incompatible with the coherence requirement.

The spatial nature of this effect can be directly observed in the ray-traced results. A tilt of the optical system produces a gradient in the optical path distribution across the pupil, which is subsequently converted into a spatially varying phase distribution. When this perturbed wavefront is combined with an unperturbed beam, the resulting interference pattern contains regions of constructive interference where the relative phase reaches approximately π . Thus, even a perturbation that may appear small when expressed as an angular error can produce large local phase variations across the pupil and strongly degrade the nulling performance.

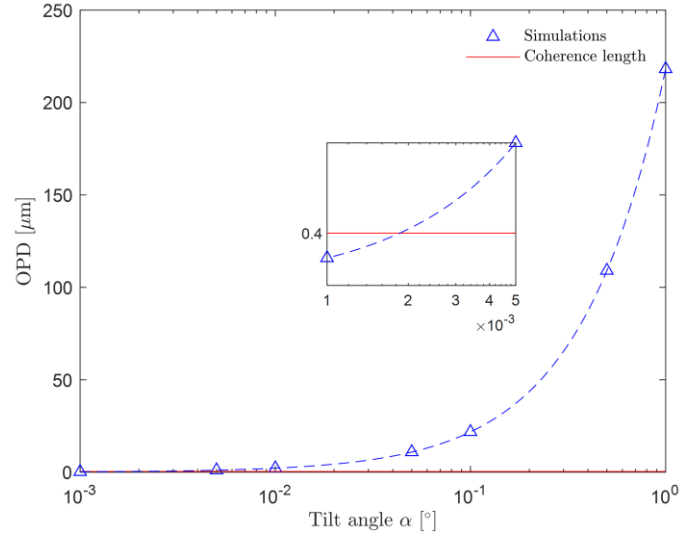


Figure 4-3: Sensitivity analysis of the maximum optical path difference with respect to tilt angles. Discrete data from simulations (blue triangle) and coherence length (red) are represented.

This analysis provides a useful physical interpretation of the tolerancing problem addressed in the following section. The objective is not simply to minimize an isolated optical error, but to control the differential wavefront between interfering beams so that destructive interference is maintained over the relevant pupil and field. The ray-traced approach is particularly suited to this task because it retains the spatial information of the optical path distribution and allows realistic perturbations to be propagated through the complete optical system.

5. TOLERANCING OF THE ESA DESIGN

The validated modeling tool was also applied to the optical design developed in the framework of the ESA single-spacecraft nulling interferometer study^{9,23}. The objective was to assess the sensitivity of the design to realistic manufacturing and alignment errors and to investigate whether these errors could be compensated within the available optical degrees of freedom.

This optical design consists of four 2.5-m apertures, each feeding a two-mirror afocal telescope, a delay line, and a cat's-eye system, and is represented in Figure 5-1. Early tests focused only on M1 and M2. The “detector” was placed at the position of M3. Other optical surfaces, such as the cat's eye system, were not considered in this first sensitivity analysis.

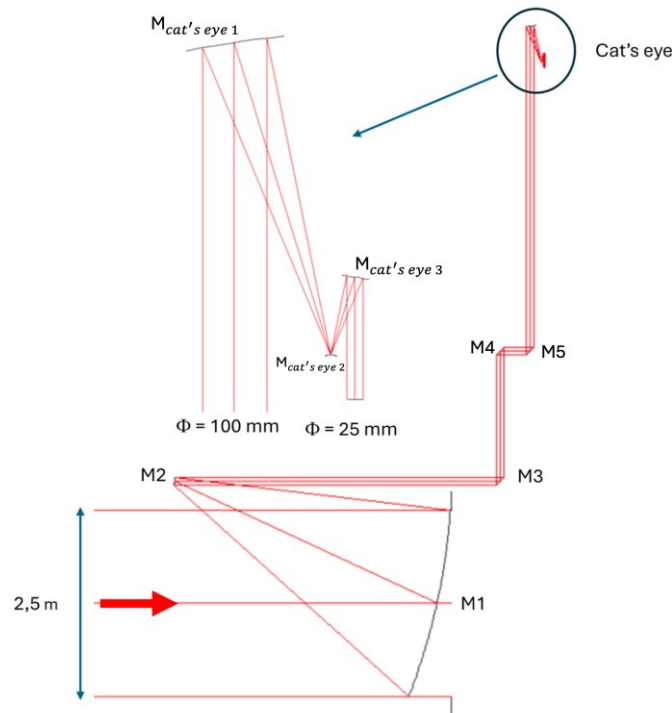


Figure 5-1: ESA single-spacecraft design. Adapted from Mazzoli et al. (2026).

The objective was to assess the sensitivity of the design to realistic manufacturing and alignment errors and to investigate whether these errors could be compensated for using the available optical degrees of freedom.

A Monte Carlo tolerancing approach was adopted. Perturbations were introduced independently and in combination on the optical surfaces, including translations, tip/tilt errors, variations of the radius of curvature and conic constant, as well as surface-figure errors represented by Zernike coefficients. Three perturbation scenarios were considered, with progressively increasing levels of mechanical errors and available compensation ranges. For each realization, the resulting OPD distribution was extracted from the ray-traced model and its RMS value was used as the main performance indicator. The global piston term is removed since delay lines are implemented in the design and perturbations are small. The criterion used to maintain coherent interference was an OPD RMS below $\lambda/2$.

The compensation was applied through the secondary mirror, which provides the available degrees of freedom while avoiding direct perturbation of the highly sensitive primary mirror. Two approaches were investigated. The first is an iterative bisection algorithm in which the compensation degrees of freedom are adjusted sequentially, with successive reductions of the search interval and multiple restarts. The second relies on the native Code V optimizer, which simultaneously adjusts the available parameters. The comparison therefore provides not only a tolerancing assessment of the optical design, but also a test of the suitability of the two optimization strategies for this type of problem.

For all three perturbation scenarios, the bisection method consistently reduced the OPD RMS. Its effectiveness increased as the available compensation range was enlarged. For the smallest perturbations, corresponding to mirror translations of approximately $1 \mu\text{m}$ and tip/tilt errors of 0.1 arcsec , reductions of up to 96.7% were obtained for individual Monte Carlo realizations. With perturbations increased to approximately $100 \mu\text{m}$ and 10 arcsec , most realizations exhibited reductions above 80%, with individual cases reaching approximately 96–97%. Nevertheless, none of the simulated configurations reached the $\lambda/2$ criterion after compensation. The native Code V optimizer showed markedly different behavior. In the first scenario, most simulations exhibited only limited improvements, with several cases even showing an increase in the residual OPD RMS. The bisection approach remained stable and benefited directly from the increased search range.

Figure 5-2 shows the Monte Carlo results for the third simulation (100 μm and 10 arcsec), indicating improvements but not enough to achieve good nulling results.

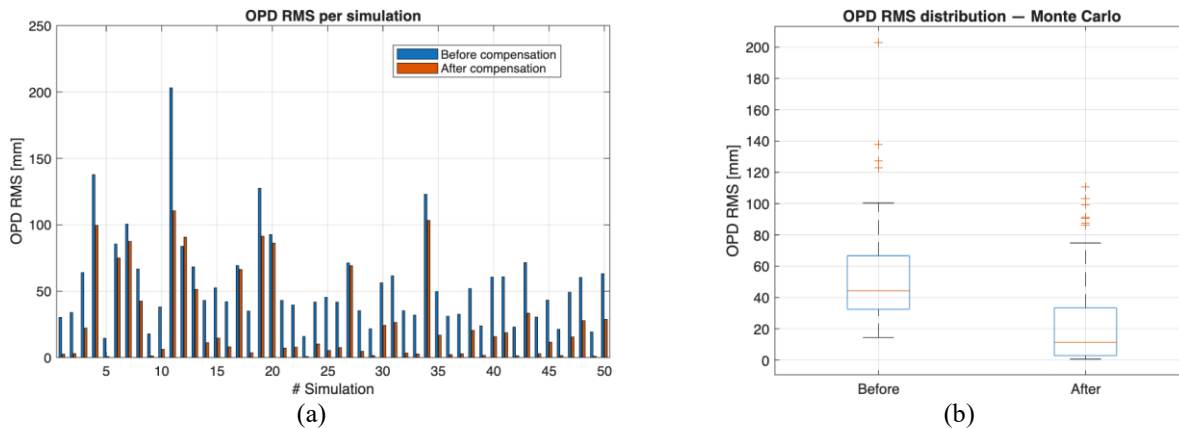


Figure 5-2: Statistical analysis of the 50 simulations for the third scenario, in the case of compensation by the bisection method, through the repartition of the OPD RMS before and after each compensation of the associated simulation and the boxplot.

These results demonstrate that the implemented compensation strategy is effective at reducing the wavefront errors introduced by realistic perturbations, but that the optical design itself remains the dominant limitation. The residual OPD remains well above the $\lambda/2$ criterion in all investigated cases. The results therefore do not indicate that the compensation algorithm alone can bring the present design to the required performance; rather, they point to a need for reducing the intrinsic sensitivity of the optical architecture. In particular, the large primary mirror and the associated sensitivity to angular perturbations appear to be major contributors to the residual OPD. This conclusion is consistent with the earlier single-perturbation analysis described in §3 and applied to this optical design. In this case, a tilt of only 0.36 mas already produced an OPD RMS of 54.9 nm when applied to the secondary mirror, while tilting the primary mirror led to an OPD RMS exceeding the validity range of the phase-based calculation.

Overall, the tolerancing study demonstrates the value of combining ray tracing, numerical compensation, and statistical analysis. Rather than providing a final tolerance budget for the mission, the present analysis identifies the dominant sensitivities of the current optical concept and provides a framework that can be applied iteratively as the design evolves. The results also show that an optimization strategy specifically designed for the tolerancing problem can be substantially more robust than a conventional optical-design optimizer.

6. CONCLUSION

This work presented a ray-traced modeling approach to assess the performance and tolerances of space-based nulling interferometers using realistic optical designs. By combining Code V ray tracing with dedicated numerical post-processing, the framework propagates optical path differences and phase distributions through the optical train, thereby linking analytical nulling models to realistic optical-system tolerancing.

The approach was first validated against analytical formulations for piston and tilt perturbations, confirming the expected behavior and highlighting the importance of preserving the spatial distribution of the phase error over the pupil. Its application to a two-aperture Bracewell configuration further illustrated how realistic wavefront and alignment errors degrade the ideal central null, producing a non-zero null floor and increased stellar leakage. In particular, the strong sensitivity to tip/tilt demonstrates the stringent coherence requirements inherent to nulling interferometry.

The framework was finally applied to the ESA single-spacecraft nulling interferometer design. Monte Carlo simulations showed that active compensation can reduce the OPD RMS by up to approximately 97% for individual realizations. However, none of the investigated configurations reached the criterion after compensation, indicating that the residual

performance is primarily driven by the intrinsic sensitivity of the optical architecture rather than by the compensation strategy alone.

These results demonstrate the potential of ray-traced modeling to identify critical sensitivities and assess mitigation strategies during the development of space-based nulling interferometers. Further developments will extend the framework towards polarization, thermal and structural effects, pointing errors, and detector and noise contributions, with the long-term objective of providing a more complete end-to-end performance model.

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REFERENCES

- [1] “Voyage 2050: Final Recommendations from the Voyage 2050 Senior Committee”.
- [2] Bracewell, R. N., “Detecting nonsolar planets by spinning infrared interferometer,” *Nature* **274**(5673), 780–781 (1978).
- [3] Beichman, C. A., Woolf, N. J. and Lindensmith, C. A., “The Terrestrial Planet Finder (TPF) : a NASA Origins Program to search for habitable planets,” (1999).
- [4] Léger, A., Mariotti, J. M., Mennesson, B., Ollivier, M., Puget, J. L., Rouan, D. and Schneider, J., “The DARWIN project: An infrared nulling interferometer in space,” *Astrophys. Space Sci.* **241**(1), 135–146 (1996).
- [5] Glauser, A. M., Quanz, S. P., Hansen, J., Dannert, F., Ireland, M. J., Linz, H., Absil, O., Alei, E., Angerhausen, D., Birbacher, T., Defrère, D., Fortier, A., Huber, P. A., Kammerer, J., Laugier, R., Lichtenberg, T., Noack, L., Ranganathan, M., Rugheimer, S., et al., “The Large Interferometer For Exoplanets (LIFE): a space mission for mid-infrared nulling interferometry,” *Opt. Infrared Interferom. Imaging IX*, S. Sallum, J. Sanchez-Bermudez, and J. Kammerer, Eds., 48, SPIE, Yokohama, Japan (2024).
- [6] Quanz, S. P., Ottiger, M., Fontanet, E., Kammerer, J., Menti, F., Dannert, F., Gheorghe, A., Absil, O., Airapetian, V. S., Alei, E., Allart, R., Angerhausen, D., Blumenthal, S., Buchhave, L. A., Cabrera, J., Carrión-González, Ó., Chauvin, G., Danchi, W. C., Dandumont, C., et al., “Large Interferometer For Exoplanets (LIFE): I. Improved exoplanet detection yield estimates for a large mid-infrared space-interferometer mission,” *Astron. Astrophys.* **664**, A21 (2022).
- [7] Dannert, F. A., Ottiger, M., Quanz, S. P., Laugier, R., Fontanet, E., Gheorghe, A., Absil, O., Dandumont, C., Defrère, D., Gascón, C., Glauser, A. M., Kammerer, J., Lichtenberg, T., Linz, H., Loicq, J., and the LIFE collaboration., “Large Interferometer For Exoplanets (LIFE): II. Signal simulation, signal extraction, and fundamental exoplanet parameters from single-epoch observations,” *Astron. Astrophys.* **664**, A22 (2022).
- [8] Laugier, R., Defrère, D., Woillez, J., Courtney-Barrar, B., Dannert, F. A., Matter, A., Dandumont, C., Gross, S., Absil, O., Bigioli, A., Garreau, G., Labadie, L., Loicq, J., Martinod, M.-A., Mazzoli, A., Raskin, G. and Sanny, A., “Asgard/NOTT: *L* -band nulling interferometry at the VLTI: I. Simulating the expected high-contrast performance,” *Astron. Astrophys.* **671**, A110 (2023).
- [9] Loicq, J., Defrère, D., Laugier, R., Saathof, R., Bouwmeester, J., Piron, P., Dandumont, C., Moreau, V., Borguet, B., Hallibert, P., Alaluf, D., Schifano, L., Escudero, I. and Lueftinger, T., “Exoplanet explorer: a single spacecraft nulling interferometer,” 2026, SPIE.
- [10] 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,” *Appl. Opt.* **65**(2), 433 (2026).
- [11] Serabyn, E., “Nulling interferometry: symmetry requirements and experimental results,” presented at *Astronomical Telescopes and Instrumentation*, 5 July 2000, 328.
- [12] Lay, O. P., “Imaging properties of rotating nulling interferometers,” 13 (2005).
- [13] Carboni, C., “Master thesis: Opto-mechanical design of a four apertures nulling interferometer” (2025).
- [14] De Bortoli, F., “Master thesis: Development of an advanced modelling tool for a four apertures nulling interferometer” (2025).
- [15] Viseur, L., “Master thesis: Development of a performance modeling tool for nulling interferometry” (2024).

- [16] Dubus, J., “Master thesis: Enhancement and Validation of a Tolerancing Modeling Tool for a Space-Based Nulling Interferometer” (2026).
- [17] Lay, O. P., “Systematic errors in nulling interferometers,” 24 (2004).
- [18] Dandumont, C., Defrère, D., Kammerer, J., Absil, O., Quanz, S. P. and Loicq, J., “Exoplanet detection yield of a space-based Bracewell interferometer from small to medium satellites,” *J. Astron. Telesc. Instrum. Syst.* **6**(03) (2020).
- [19] Huber, P. A., Dannert, F. A., Laugier, R., Matsuo, T., Rutten, L. W., Glauser, A. M., Quanz, S. P., and (LIFE Collaboration), “Robust Data Interpretation for Perturbed Nulling Interferometers via Proper Handling of Correlated Errors,” *Astron. J.* **170**(4), 227 (2025).
- [20] Huber, P. A., Dannert, F. A., Laugier, R., Birbacher, T., Glauser, A. M., Hansen, J. T. and Quanz, S. P., “Analytical and numerical instrumental noise simulations for the Large Interferometer For Exoplanets (LIFE),” *Opt. Infrared Interferom. Imaging IX*, S. Sallum, J. Sanchez-Bermudez, and J. Kammerer, Eds., 50, SPIE, Yokohama, Japan (2024).
- [21] Rutten, L. W., Laugier, R., Loicq, J., Sigusch, I., Huber, P. A., Dandumont, C. and Defrère, D., “Flexible versus fixed baselines: A comparison of nulling interferometry exoplanet detection yields in the presence of instrumental noise” (in review).
- [22] Danchi, W. C., Barry, R. K., Lawson, P. R., Traub, W. A. and Unwin, S., “The Fourier-Kelvin Stellar Interferometer (FKSI): a review, progress report, and update,” presented at SPIE Astronomical Telescopes + Instrumentation, 14 July 2008, 70132Q.
- [23] Mazzoli, A., Dandumont, C., Besse, A., Borguet, B., Bouwmeester, J., Defrère, D., Khan, I., Loicq, J., Laugier, R., Moreau, V., Piron, P., Saathof, R., Sigusch, I., Terrasa, G., Hallibert, P., Alaluf, D., Schifano, L. and Lueftinger, T., “Exoplanet explorer: Optical design of a single spacecraft nulling interferometer,” 2026, SPIE.