

Exoplanet explorer: single spacecraft nulling interferometer

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ABSTRACT

One of the most ambitious goals of modern astronomy is to uncover signs of extraterrestrial biological activity. This can be primarily achieved through spectroscopic analysis of mid-infrared light emitted by exoplanets to identify specific atmospheric molecules. Most exoplanets are indirectly detected through techniques like transit and radial velocity methods. Long-term surveys have yielded statistical insights into the occurrence rates of different planet types based on factors such as radius/mass, orbital period, and the spectral type of the host star. First estimations of terrestrial planets within the habitable zone have also emerged. However, the lack of detected light from these exoplanets leaves many unknowns about their nature, formation, and evolution. Following the “ESA Voyage 2050” call, the senior committee recommended the “characterisation of temperate exoplanets” for a possible future L-Class mission: “Answering the question of the existence and distribution of life elsewhere in the Universe has been an important driver for the exploration of other worlds, both in and outside of our Solar System.” As the number of detected rocky exoplanets around nearby stars rises, questions about their atmospheric composition, evolutionary trajectory, and habitability increase. Measuring the infrared spectrum of these exo-planets poses significant challenges due to the star/planets contrast and very small angular separation from their host stars.

In this context, the Exoplanet Explorer concept (studied in the frame of the ESA-funded R&D activity “nulling interferometry techniques with a single telescope”) investigates a single-spacecraft mid-infrared nulling interferometer operating over 3–20 μm for the detection and characterization of temperate rocky exoplanets around nearby stars. In our study, we propose a preliminary end-to-end design for the payload and spacecraft, providing a more realistic assessment of the scientific yield, evaluated in terms of the number of detected exoplanets. The payload now consists of four 2.5 m class telescopes supported by a single spacecraft deployable structure. We study linear and X-array configuration with a baselines up to 32 m and remaining compatible with Ariane 6, inserted into an L2 orbit. The optical chain has been consolidated from the telescopes to the detectors, including an optimised two-mirror telescope with a cat’s-eye relay, a broadband Modified Mach-Zehnder beam combiner, single-mode fiber spatial filtering, and a three-band spectrograph with resolving powers of $R \approx 20$ for detection phase of the mission and $R \approx 50\text{--}100$ for atmospheric characterization phase.

We will present the consolidated system design, highlighting the evolution, including mechanical/thermal architectures for ultra-stable operation, the mechatronic control layer for deep nulling, the polarization aberration, and updated yield simulations that quantify the impact of aperture size and baseline on the detection and characterization of temperate rocky exoplanets. The paper will also identify the most critical technologies and breadboard activities required to bring a single-spacecraft nulling interferometer to mission maturity.

keywords Exoplanets, interferometry, single-spacecraft, Habitable zone

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1. INTRODUCTION

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The detection and characterization of temperate rocky exoplanets represents one of the most compelling scientific challenges in contemporary astrophysics. Among the various techniques developed for exoplanet studies, nulling interferometry stands out as a particularly powerful approach for direct observation of Earth-like planets in the habitable zones of nearby stars. This technique enables the suppression of bright stellar light while revealing the faint planetary signatures, making it possible to detect and characterize the thermal emission from rocky exoplanets in the mid-infrared wavelength range.

The present paper summarises the work conducted under the current ESA contract, specifically addressing the study of the capabilities of a single spacecraft nulling interferometer. While formation flying has been claimed to be the best configuration to realise an interferometric nuller, especially for angular resolution purposes, this work intends to investigate the capabilities of a single-spacecraft with a limited baseline. This work is subdivided into four main tasks: the high-level requirement consolidation, a the technology survey and configuration trade-offs, the preliminary design and a development roadmap. The current proceeding will focus mainly on the requirements, the configuration, the scientific output and the trade-off between configuration. Following the ESA requirements provided for this study, the mission baseline targets the 3–20 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 constraint given by the launcher can be overcome by some deployment mechanisms that increase the distance between the apertures to a reasonable distance for the detection of exoplanets.

The scientific motivation driving this development is to achieve direct detection of temperate rocky exoplanets and measure their spectra with sufficient spectral resolution ($R \geq 20$ during the search phase and 50 to 100 during the characterisation phase) to identify potential biosignatures. The instrument must achieve an inner working angle below 300 mas at 10 μm and reach starlight suppression levels lower than 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.

As a side note, this study addresses a gap not covered by mission concepts based on formation flying. It is intentionally designed to remain agnostic with respect to any predetermined architectural preference. Each concept entails inherent advantages and limitations, which must be carefully weighed to enable an informed selection for future L-class mission concepts within ESA's Voyage 2050 roadmap.

1.1 Objectives

In this paper, we present the preliminary design and detailed performance assessment of selected nulling interferometry implementations compatible with a single spacecraft. The work encompasses multiple interconnected engineering domains, each critical to achieving the mission's scientific objectives. Specifically, this involves:

Performance Assessment: Conducting detailed performance evaluations including exoplanet yield estimates, instrumental error budgets, and sensitivity analyses. This objective encompasses both the search phase (planet detection) and characterization phase (spectral measurement) performance, accounting for realistic instrumental limitations and systematic errors.

System Architecture Development: Establishing a preliminary system engineering frameworks including configuration item trees, functional breakdowns, and requirements derivation. This encompasses orbit selection, technical budgets (mass, volume, thermal, optical), and strategies for achieving the ultra-stability required for effective nulling interferometry.

Optical Chain Design: Developing comprehensive optical designs spanning from the individual telescope assemblies through beam combination, beam control, spectral dispersion, and detection. This includes detailed trade-offs between 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, the fibre injection and the spectral analysis through spectrograph. Critical aspects such as polarization management, wavefront quality control, and radiometric performance are addressed.

Mechanical Architecture: The spacecraft architecture encompasses both deployable structures and comprehensive thermal design to achieve the required stability. For most configurations, the large interferometric baselines necessitate deployable structures capable of maintaining precise alignment and to achieve interferometric baselines ranging from 8 to 32 meters while respecting the volume constraints of the Ariane 6 long fairing. This includes trade-offs between deployment mechanisms (telescopic booms, articulated systems, deployable trusses), structural dynamics analysis, and thermal stability considerations.

1.2 Configuration Trade-offs

The main payload support structure (PL-MSST) provides the structural interface between the four individual telescopes and the central unit. Except for the Lin8 configuration, this structure must be deployed to overcome the dimensions of the Ariane-6 launch fairing. In this section, the trade-offs and design for the main structure are presented. It is based on the master's thesis work of Felix Wiltig, which provides a more detailed description of the background and analysis (1). The six payload configurations specified in TN2 are further elaborated.

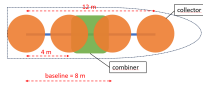


Figure 1. Lin8: non-deployable linear array with 8 m nulling baseline

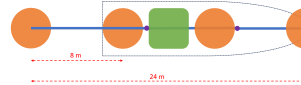


Figure 2. Lin16: linear array with 16 m nulling baseline

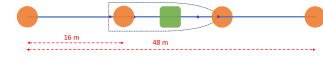


Figure 3. Lin32: linear array with 32 m nulling baseline

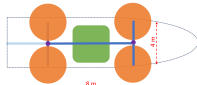


Figure 4. X8: X-array with 8 m nulling baseline

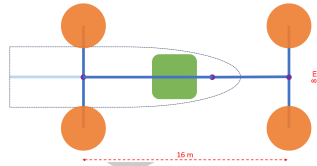


Figure 5. X16: X-array with 16 m nulling baselines

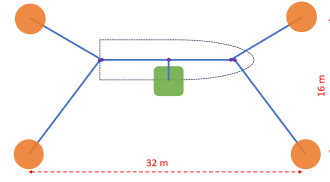


Figure 6. X32: X-array with 32 m nulling baseline

Six distinct spacecraft configurations have been analyzed, representing different approaches to achieving the required interferometric baselines:

- Linear configurations (LIN8, LIN16, LIN32): Four telescopes arranged in a quasi-linear array with nulling baselines of 8, 16, and 32 meters respectively
- X-array configurations (X8, X16, X32): Four telescopes arranged in an X-shaped array with corresponding nulling baselines

Each configuration presents distinct advantages. The trade off has to be made between scientific performance (exoplanet yield, inner working angle, sensitivity), technical complexity (deployability, thermal control, active correction requirements), and feasibility (mass budget, structural stability, integration complexity). The LIN8 configuration is unique as the only non-deployable option, while all others require sophisticated deployment mechanisms to fit within launch vehicle constraints (Ariane 6).

The work presented in this paper employs systematic engineering methods combining analytical modelling, numerical simulation, and comparison with heritage missions. The optical design utilizes ray-tracing software (CODEV, ASAP) for detailed performance analysis. Mechanical structures are analyzed using finite element

methods to evaluate structural dynamics and thermal deformation. Performance assessments employ established tools such as the P-pop exoplanet population synthesis, LIFESim and the PHRINGE simulator for realistic observation scenarios.

2. ORBIT SELECTION AND CONSEQUENCES

The best orbit for a nulling interferometer is the Sun-Earth Lagrange Point (SE-L2). It provides a stable thermal environment, with the Sun and Earth on one side and relatively low infrared flux from Earth due to distance. This also maximizes available sky coverage. Attitude disturbances and orbit maintenance requirements are also lower than for orbits closer to Earth. For these reasons, it is also the orbit selected for the James Webb Telescope (JWST) and the Gaia mission. For thermal stability, an L2 halo orbit is favored due to its constant solar illumination geometry and reduced thermal cycling. The launch mass of the Ariane 6, more specifically the Ariane 64 configuration, to a highly elliptical orbit with L2 at its apogee is 8000kg (2). From a mission perspective, full-sky coverage is preferred, even if the zodiacal disk can limit the detectability of exoplanets (absorption and scattering). By nature of the SE-L2 orbit, a 360° rotation in the ecliptic plane is performed within a year. To point towards a given star of interest, it is best to wait until the star approaches its minimum angle from the Sun-Earth vector. For a given observation time to detect or characterize exoplanet(s), the nulling interferometer must be continuously rotated in the ecliptic plane relative to the Sun-Earth vector to maintain pointing.

The interferometric array needs to be rotated around the line of sight during the observation time to modulate the signal from the exoplanet(s) and to discriminate it from static noise sources. This rotation, in combination with the declination, requires a Sun-shield that covers the entire nulling interferometer, approaching semi-spherical coverage for $\pm 90^\circ$.

3. SCIENCE CASE

The focus of the project is on a space-based mission which shall be tailored for the characterization of earth-like (size, mass, temperature...) exoplanets in the habitable zone (temperate region) of main-sequence stars. An exoplanet will be considered rocky if it has a radius smaller than 2.0 Earth-radii, which corresponds to the approximate theoretical and empirical separation between solid planets and those with significant gaseous envelopes. An exoplanet will be considered temperate if it orbits in the habitable zone of its host star, where the habitable zone is defined as the circumstellar region where a rocky planet with a CO₂-H₂O-N₂ atmosphere can sustain liquid water on its surface [RD4]. The inner habitable zone is delimited by water loss, while the outer habitable zone is delimited by the maximum greenhouse provided by a CO₂ atmosphere. For a Sun-like star, this corresponds to a star-planet distance between 0.99 to 1.7 AU.

While the mission shall be focused on characterisation, it also has the capability to detect new temperate rocky exoplanets around nearby main-sequence stars with the same mission design. A search phase might be required if long-term radial velocity and transit surveys have not yielded a sufficient number of exoplanet candidates. Due to the low probability of transit, high-precision transit survey missions such as PLATO are bound to miss most temperate rocky exoplanets around nearby main-sequence stars. While it is likely that the sample of known temperate rocky exoplanets will continue to increase, a search phase would provide a high detection completeness level around nearby main-sequence stars, without relying on specific geometric configurations such as transit. The search phase would also be executed much faster than the characterization phase, which requires longer integration times to detect the spectral signatures of interesting molecules. In that regard, exoplanet candidates that would be discovered by NASA's Habitable Worlds Observatory (HWO) would be prime targets for the mission. Observations in the mid-infrared are key to better understanding the nature of exoplanets

3.1 Simulation tools

Two elements are needed to estimate the yield in detected exoplanets: a performance simulator of the instrument/spacecraft and a catalog of stars and planets to examine.

For the performance simulator, LIFESim, the software developed by ETH Zurich for the LIFE initiative (see Sec. ?? for more information about the mission), was selected. This tool is available online and is used extensively

by the LIFE consortium in various peer-review papers about the mission*. A second tool, SCIFYsim, is used to assess the influence of instrumental errors, which are not implemented in LIFEsim. This tool was developed by KULeuven for the Asgard/NOTT project (see Sec. ?? for more information about the mission) and was adapted for this project.

Concerning the catalog of targets, several possibilities exist: real stars and already detected planets, real stars and putative planets based on statistics, and real stars and putative planets based on formation models. The second solution was selected with the tool called P-pop. Also developed by ETH Zurich, it has already been implemented in LIFEsim. It is based on the *Kepler* mission statistics. Since *Kepler* is a transit mission, it introduced some biases towards massive and fast-orbiting planets. Nevertheless, it provides valuable information about potential planet populations. To overcome this issue, we also looked at the habitable zone of each star in the catalog and how it is resolved (see Sec. 4.7).

With the catalog, one can introduce these targets in the simulator to derive and sort the detected exoplanets. Since the simulator is modular, a parametric study is performed, allowing the use of the results in the trade-off (see Chapt. ??).

3.2 LIFEsim

LIFEsim was developed for the LIFE space mission and is used by the LIFE consortium for their yield estimate (3; 4). In LIFEsim, it assumed an X-array architecture, which is a limited factor for this current project. The simulator was modified to enable simulation of different configurations. In fact, the mathematical formalism was already introduced in (4) but only the mathematical solution for the X-array architecture was kept in the production code of LIFEsim. For recall, the principal steps are introduced below. All of this discussion and code improvement are based on the work of Rogier Norbruis, who did its master thesis on the subject at TuDelft (5), and was improved by the consortium.

Figure 7 represents a schematic view of an interferometric architecture. The apertures of the interferometer are distributed in the x-y plane. Each aperture is represented by its position and radius (x_k, y_k, r_k) , where k represents the k th aperture. The complex field amplitude generated by this aperture by a point source with projected angular offset (α, β) from the line of sight is given by

$$V_k = r_k e^{i2\pi(x_k\alpha + y_k\beta)/\lambda} \quad (1)$$

where λ is the wavelength (4). All the aperture form a vector $\mathbf{v}$ of complex field amplitude. The linear mapping from this input amplitude vector $\mathbf{v}$ to the output amplitude vector $\mathbf{w}$ is represented by the matrix, $\mathbf{U}$. In other words, this matrix $\mathbf{U}$ represents the interferometric combination. It leads to

$$\mathbf{w} = \mathbf{U}\mathbf{v}. \quad (2)$$

The transmission of each output beam is the square modulus of the output beam amplitude, $t = \|\mathbf{w}\|^2$.

The light that enters the instrument is recombined following Equation 2. The combiner is a double Bracewell, as presented in ???. Therefore, the metric used is the differential map, t_{dif} , which is the difference between the two nulled outputs.

However, a Bracewell or even a double Bracewell configuration provides limited coverage of the uv-plane. A solution is to rotate the instrument continuously. The projected fringe pattern will rotate, and the planetary signal will be modulated by it, leading to easier detections.

Figure 8 shows the differential map of a typical double chopped Bracewell. If the map is rotated, the planetary signal will be modulated at a given angular separation, as the figure represents. Depending on the configuration, the modulation is different, and it can impact the detectability of a planetary signal. The modulation efficiency,

*<https://github.com/fdannert/LIFEsim>

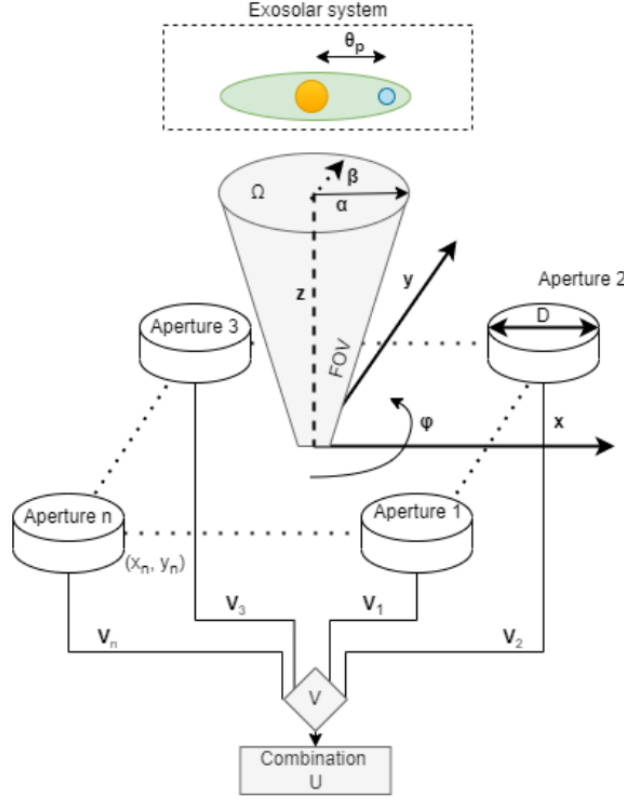


Figure 7. Architecture representation of a nulling interferometer (5).

ξ , is therefore introduced to compare different configurations. This metric is described in ???. It is the root-mean-square (rms) of the differential map upon a complete array rotation (6). For a complete array rotation, it is equal to

$$\xi(\theta) = \sqrt{\langle t_{\text{dif}}(\theta, \phi)^2 \rangle_{\phi}} \quad (3)$$

where θ is the angular separation in the differential map. This metric multiply the flux of the planetary signal as explained in (4).

Compared to LIFEsim, the configuration is the only difference. The flux computation is identical. It considers the primary astrophysical sources, the host star and the exoplanet (Planck law), the stellar leakage, and the local and exozodiacal dust. No instrumental noise terms are considered in the current version of LIFEsim, assuming that the instrument is photo noise-dominated. With the incoming flux and related noises, LIFEsim computes the Signal-to-Ratio (S/N) over the whole wavelength range. As demonstrated by (6), this S/N scales with the square root of integration time, area, and detection efficiency. One can then select a detection threshold per default $S/N = 7$ and then compute the number of detected exoplanets. **LIFEsim is in fact computing the S/N for 1 h and then compute the time to have a S/N of 7. Long integration time (several hours) can impact the platform stability. One may note that the detector is not collecting data without interruption. It is a sum of several integration samples.**

3.2.1 Configurations

All the above equations are general for any recombination scheme. In this project, we consider two configurations: a rectangular one, a.k.a. X-array, and a linear array, a.k.a. Angel Woolf DCB. Equation 3.2.1 and Figure 9 represent the X-array, the linear configurations, and how nulling is performed. The most extended baseline is the nulling one, b . The imaging baseline, qb , is the shortest, contrary to LIFEsim default measurement. For both configurations, the matrix combiner is given by

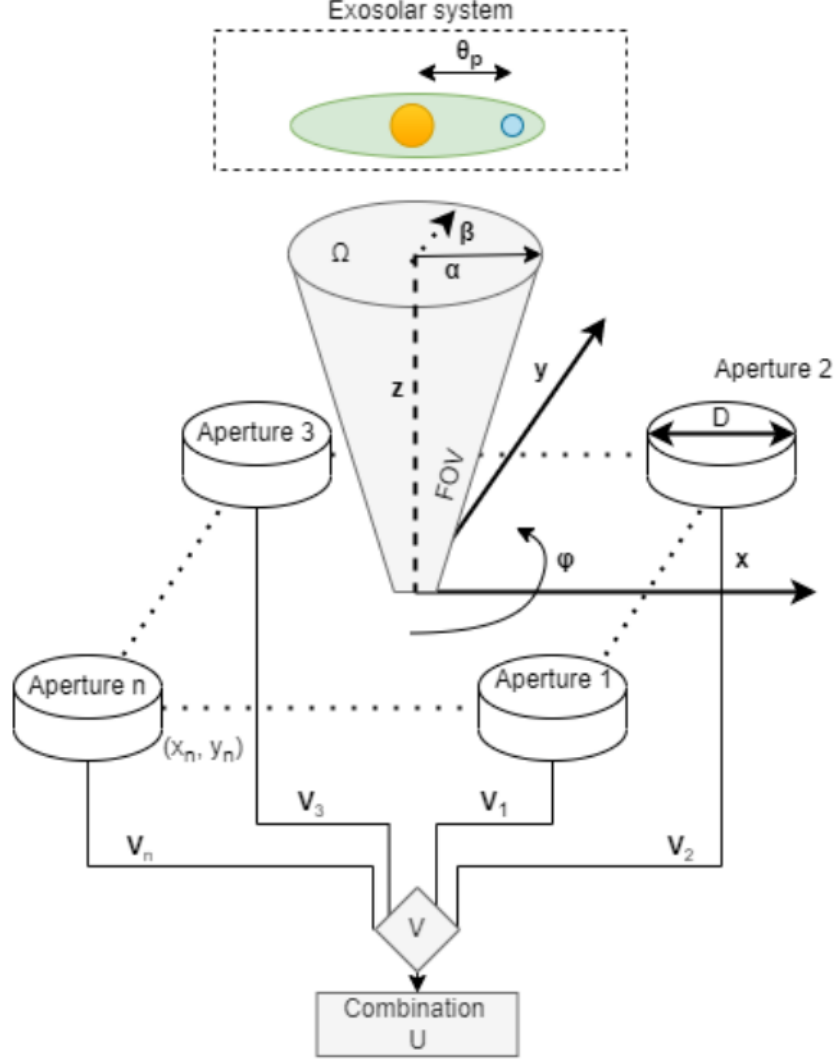


Figure 8. Modulation of 6x36 X-array of planets at 100 mas separation from the line of sight. The three points highlight some positions on the rotation. Top: Transmission maps 3 and 4. Bottom: the modulated map (chopped) and the modulated curves with the modulation efficiency.[verify where this figure comes from](#)

$$U = \frac{1}{\sqrt{4}} \begin{pmatrix} 0 & 0 & \sqrt{2} & \sqrt{2} \\ \sqrt{2} & \sqrt{2} & 0 & 0 \\ 1 & -1 & -e^{i\frac{\pi}{2}} & e^{i\frac{\pi}{2}} \\ 1 & -1 & e^{i\frac{\pi}{2}} & -e^{i\frac{\pi}{2}} \end{pmatrix} \quad (4)$$

which is unitary and orthonormal. One can notice that the first two rows, which correspond to the bright outputs, add up to 1, while the nulling rows add up to 0. The output amplitude vector, and the transmission, according to [Equation 2](#), can be computed from this matrix. As described above, LIFEsim then computes the S/N and indicates whether a planet is detected.

3.3 P-pop

P-pop is a publicly distributed Python tool developed by J. Kammerer. This code generates exoplanet populations based on the *Kepler* mission, a NASA transit space mission that discovered thousands of exoplanets in the

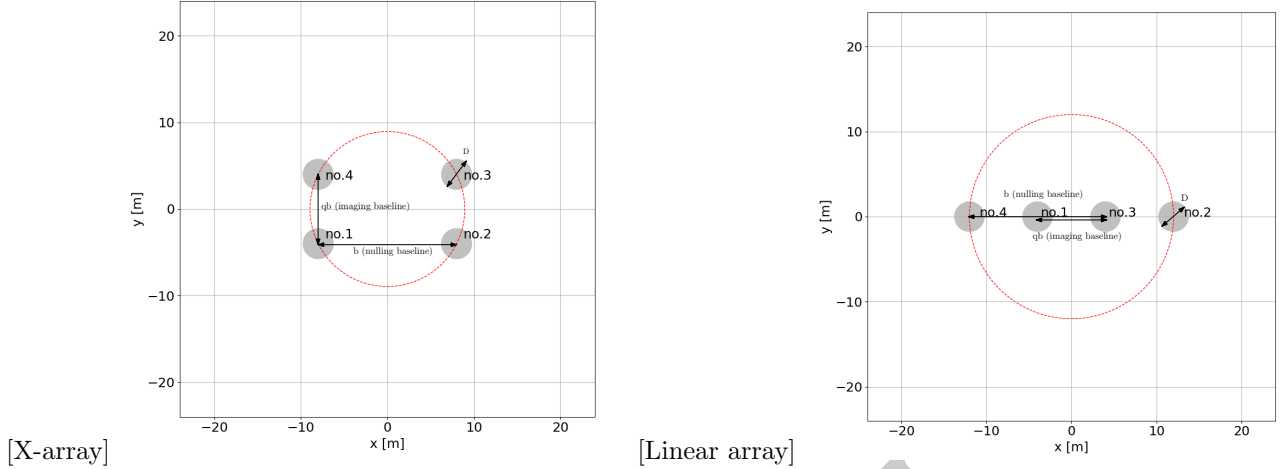


Figure 9. Two configurations used in this work. The nulling baseline is B , and the imaging baseline qb .

2010s. Model distributions were derived from the statistics of discoveries and are applied to generate putative planets around main-sequence stars via Monte Carlo simulations. This tool is already fully compatible with LIFEsim (7).

For our simulations, the tool generates exoplanetary populations around nearby stars (< 20 pc). We limit ourselves to 542 stars for computational reasons, as this WP aims to compare configuration and not derive a total exoplanet yield. M-type stars beyond 10 pc were discarded as their habitable zone are not be resolved. Ten simulations are performed, meaning 10 "universes" are generated, providing a small subset of possibilities.

Figure 10 represents the planets generated by P-POP around the 542 selected stars. P-pop will generate planets of all kinds, but the primary targets are Earth-like planets in the habitable zone of their host stars. Figure 11 is a histogram of all planets, with the main categories. The analysis is limited to planets with radii, R_p , in the range $0.5 R_{\oplus} \leq R_p \leq 6 R_{\oplus}$ for FGK stars and $0.5 R_{\oplus} \leq R_p \leq 4 R_{\oplus}$ for M stars. Orbital periods, PP , in the range $0.5 d \leq Pp \leq 500 d$ and $0.5 d \leq Pp \leq 200 d$ are considered for FGK and M stars, respectively (3).

Following what is done in (3), we use the exoplanet classification available in Table 1.

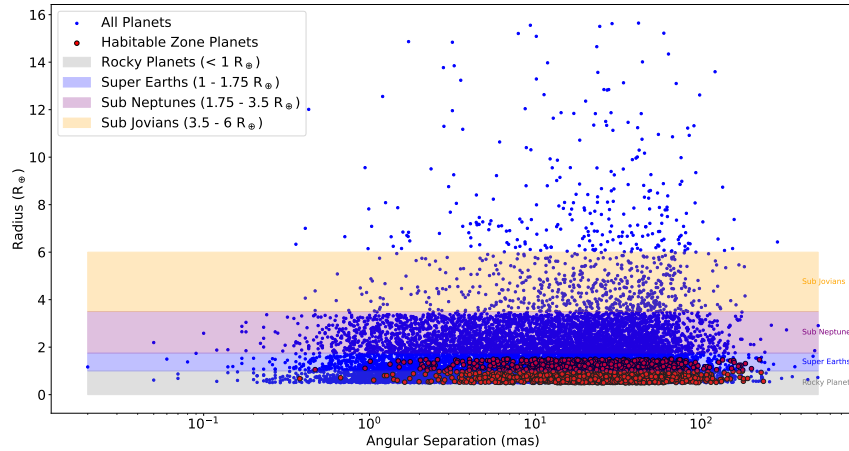


Figure 10. Planets generated by Ppop around 542 stars (< 20 pc). Planets in the habitable zone of their home star are highlighted with red dots.

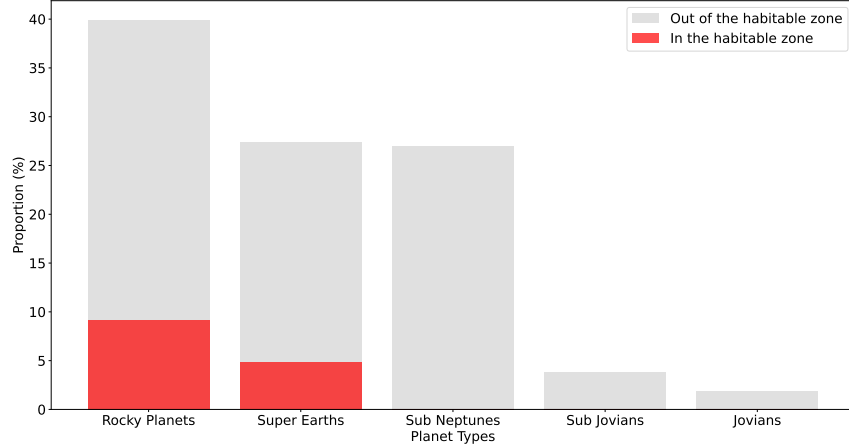


Figure 11. Proportion of the planet types (see Tab. 1) generated by Ppop (542 stars). Planets in the habitable zone are highlighted in red.

Table 1. Exoplanet classification scheme

Planet type	R_p ($R_{\oplus}$)
Rocky	0.5 - 1.0
Super-Earths	1-1.75
Sub-Neptunes	1.75-3.5
Sub-Jovians	3.5-6

4. PARAMETRIC STUDY

With the adapted LIFESim code and Ppop, several simulations can be performed with different entrance parameters. The main parameters are logically the diameter and the baseline of the interferometer, but other parameters, such as the ratio, the throughput, or the targetted S/N, can be exploited. These parameters are described in the next section.

4.1 Hypothesis

LIFESim has many parameters. The idea is to select the most impacting one to converge in the trade-off. Here is a list of the main parameters, with a short description.

- **Diameter:** Diameter of a single aperture. This parameter is varied in [subsection 4.5](#). For the trade-off between different configurations, it is fixed to 3.5 m.
- **Baseline:** Length of the nulling baseline. This parameter is varied in [subsection 4.4](#).
- **Ratio:** This parameter is directly related to the nulling baseline. It is the ratio between the imaging and the nulling baseline. In our simulations, it is fixed to 0.5, meaning that the nulling baseline is twice longer than the imaging baseline. This parameter is only valid for x-array and linear configurations.
- **Wavelength range:** Mid-infrared is the best regime to detect and characterize exoplanets with nulling interferometry. In our simulations, it is [3.0, 20.0]
- **Search time:** The code detects or characterizes exoplanets during a certain amount of time. It can be either a search phase for new discoveries or a characterization for atmospherical retrieval. The search duration is discussed in [subsection 4.3](#) and the characterization phase in [subsection 4.6](#).

Table 2. List of parameters to consider in the simulations

Parameter	Range	Fixed/variable	Related TREQ	Comments
Detection phase duration	0.5 to 10 years	Variable	N/A	For one representative configuration
Slew time	5 hours	Fixed	N/A	
Overheads	25 %	Fixed	N/A	
Nulling baseline length	8 to 32 m	Variable	TREQ8	Input to WP4100 (Payload design)
Telescope diameter	1 to 3.5 m	Variable	TREQ10	Input to WP4100 (Payload design)
Wavelength	3-20 microns	Fixed	TREQ5	
Spectral resolution	20	Fixed	TREQ12	
Optical throughput	10 %	Fixed	TREQ10	To be verified by design (WP120, optical)
Quantum efficiency	70 %	Fixed	TREQ10	
Optics temperature	40 K	Fixed	TREQ10	To be verified by design (WP4140, thermal)
Detector temperature	8 K	Fixed	TREQ10	To be verified by design (WP4140, optical)

- Slew time: The array must rotate between each star to point to the next star. The LIFE consortium estimates this value to be 10 h. However, in our case, the array is monolithic, leading to the assumption that it is quicker than with a formation flying and several satellites to realign. This value was therefore reduced to 5 h. This duration intervenes in the previous parameter.
- Targeted S/N: As explained above, LIFEsim determines if a planet is detected thanks to the computation of an S/N, compared with a threshold. Per default, it is set to 7 during the search phase.
- Spectral resolution: It is the spectral resolution of the spectrometer. Per default, it is set to 20 during the search time. During the characterizing phase, it is increased to 50 combined with a higher S/N to achieve atmospheric retrieval.
- Throughput: This instrument has no defined optical layout at this stage. It is assumed that the whole optical throughput is 10 %. This value is relatively high for a nulling interferometer, but with a monolithic design, performance can be increased with fewer relay optics between the beams.
- Quantum efficiency: The detector in this application still needs to be defined, and the technology is evolving quickly on the subject. The hypothesis is to have a quantum efficiency of 70 %.

Table 2 regroups all these parameters and their related TREQ. The optics and detector temperatures are not considered in LIFEsim. (4) verify that the measurement is dominated by photon noise. It will be verified by design in the WP4140.

4.2 Figures of merit

To compare configurations and perform a trade-off, some figures of merit need to be extracted from the simulator. The obvious one is the total number of detected exoplanets. However, this number can be divided into categories, leading to a more specific yield and the computation of the number of rocky exoplanets.

Table 3 regroups the six figures of merit derived from the simulations and used to compare the configuration. Since the mission duration is not infinite, the targets must be sorted to recover as much data as possible in such a short time. Two scenarios can be performed: maximizing the total number of detected exoplanets over the detection phase or maximizing the number of rocky exoplanets orbiting within the eHZ of their host star. Per default, we use the first scenario.

Table 3. List of yield metrics (YM) considered in the trade-off study.

width=1

Metric number	Definition
YM1	Number of detected rocky exoplanets in the habitable zone during the detection phase
YM2	Number of characterised temperate rocky exoplanets in the habitable zone during the chara
YM3	Number of detected rocky exoplanets during the detection phase
YM4	Number of characterised rocky exoplanets during the characterization phase
YM5	Number of detected exoplanets during the search/detection phase
YM6	Number of characterised exoplanets during the characterization phase

4.3 Detection/characterisation phase

The mission is divided into two phases. The first is the detection phase when the instrument detects new exoplanets. It corresponds to a low spectral resolution and a low required S/N. This phase is then followed by a characterization phase of newly detected or already known exoplanets. It corresponds to a higher spectral resolution to perform atmospheric parameters retrieval. The spectral parameters needed for this phase are described in subsection 4.6.

The main question is to adjust the time spent on each phase. For the detection phase, a way is to plot the total number of detected planets throughout this phase. The simulator sorts the exoplanets from the easiest to the hardest to detect. During the first months of the mission, the instrument will detect “easy” targets and become more costly in mission duration to detect a new exoplanets. We consider an overhead of 25 %, added to consider the slow time.

Figure 12 shows on the left (subsection 4.3) the total number of detections over four years, with a decomposition in spectral type (YM5). It shows that there is no specific predominance for a specific spectral type. As expected, a plateau is reached after a few years. On the right (subsection 4.3), it shows the gain to continue the search phase (first derivative). It shows a peak after only one year, meaning that the gain in detecting new exoplanets is becoming more and more marginal. For the number of detected rocky exoplanets in the habitable zone (YM1), detecting new exoplanets in that range is prohibitive after five years. This curve shows that this metric constrained the duration of this search/detection phase. **The integration time (after 4 years) to detect these exoplanets ranges from a few hours (15) to long integration times (340).**

Let us mention that these metrics are directly dependent on the catalog. The star catalog contains all close stars and should not dramatically evolve. Ppop is providing putative planets close to the real universe, but some discrepancies exist, and models are evolving with more known exoplanets. The mission’s duration should not be an *ad vitam* fixed parameter but should move with the current knowledge of the exoplanet population. Nevertheless, the observing strategy will need to be refined, moving away from search and characterization phases to search and characterization campaigns that can be executed throughout the mission duration. This would help manage risks by starting characterization of already known planets from day one of the mission and prioritizing the characterization of most promising newly detected planets.

4.4 Baseline length

The performance of the system will mainly be dictated by the baseline, which sets the inner working angle, and the collecting diameter, which dictates the sensitivity and the outer working angle.

For a simple Bracewell nuller, the inner working angle can be defined as:

$$\text{IWA}_{\text{Bracewell}} = \frac{\lambda}{4B} \quad (5)$$

where λ is the wavelength and B is the baseline. For more complicated configurations and as outlined in ?? and ?? the practical value is often closer to:

$$\text{IWA}_{\text{Bracewell}} = \frac{\lambda}{2B}. \quad (6)$$

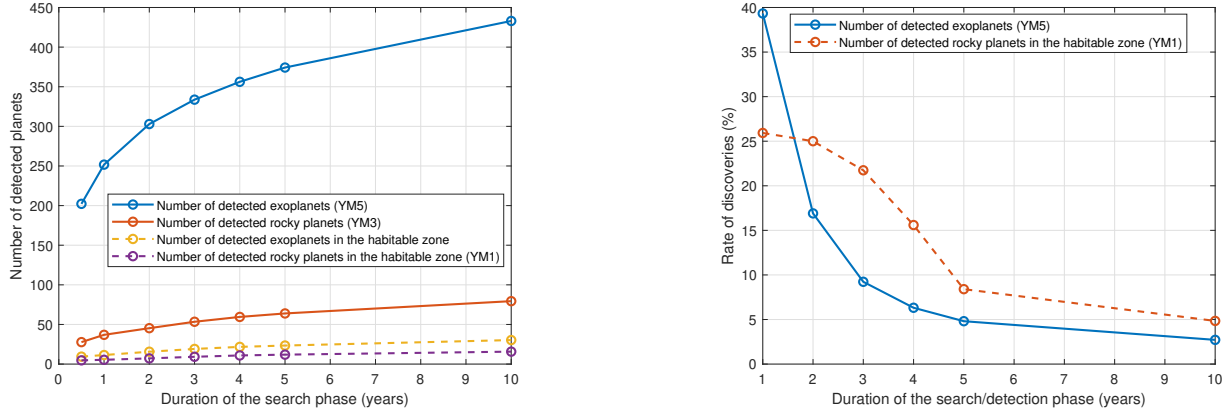


Figure 12. Search phase duration. Configuration: X-array with $B = 16m$ and $D = 3.5m$.

where B is the nulling baseline, which is the longest baseline for four telescopes array as shown in Figure 9. The imaging baseline, the shortest one, is determined by the selected ratio, which is equal to 0.5 for our application.

By increasing the baseline, the angular resolution will increase, permitting the detection of planets closer to their host star, which is highly valuable for planets in the habitable zone of their host star. The empirical habitable zone for a Sun-like star corresponds to an insolation range of $0.32S_{\oplus} \leq S_p \leq 1.76S_{\oplus}$, where $S_{\oplus}$ is the insolation level of the Earth. The habitable zone used is the empirical one (eHZ) defined in (8).

Different baselines can be compared by keeping all parameters identical and with the same stars/planets catalog. On the X-array, baseline is vary from $8m$ to $32m$, as shown by Figure 13. We can also vary the diameter (see subsection 4.5).

Logically, increasing the nulling baseline length increases the detection yield from 100 to 600 detections (YM5) after four years of the search phase (Equation 4.4). Concerning rocky exoplanets in the habitable zone (YM1), it is visible that increasing the nulling baseline length has a significant impact at constant aperture diameter (Equation 4.4).

4.5 Aperture size

Increasing the aperture size improves the S/N since the total collective area increases, and more photons are obtained. It also dictates the outer working angle (OWA), as

$$OWA = \frac{\lambda}{D} \quad (7)$$

where λ is the wavelength.

For a given stellar type and planet, the sensitivity of the instrument depends on the rocky temperate planet flux which depends on the collecting area and the planet solid angle. Therefore the planet flux is proportional to the square of the diameter and the inverse square of the distance to the star: $F_{\text{planet}} \propto D^2/d_{\text{star}}^2$. Therefore, all other things being equal, the volume (and the yield) over which the instrument is sensitive to a given type of planet increases with $V_{\text{sens.}} \propto D^3$. Of course, this distribution is convolved by the distribution of stars in this volume, and the distribution of potential planets around these stars.

Figure 13 shows how the diameter aperture affects the yield. With a baseline of $16m$, going from a diameter of $3.5m$ to $2.0m$ lead to a yield decrease of 27% (356 to 260 exoplanets) for the total number of detected exoplanets (YM5) and 47% (10.9 to 5.8) for the number of detected rocky exoplanets in the habitable zone (YM1). It shows that a large diameter is necessary to keep a high yield for this specific type of planet.

A side-effect of the increase in diameter is to reduce the field of view from the outside, as the OWA $\alpha_{\text{outer}} \propto \lambda/D$. As D increases some of the outer planets of the nearest systems become unreachable, which would describe an additional exclusion volume V_{outer} . While this has a noticeable effect on the total yield, it does not affect negatively the capabilities in the habitable zone as can be seen in subsection 4.7.

4.6 Spectroscopic parameters for characterization phase

The mission continues with a characterization phase after the search/detection phase (see [subsection 4.3](#)). The main advantage of nulling interferometry is that it is a direct method. It permits the spectroscopy of the atmosphere and molecular retrieval.

(9) determined for the LIFE initiative which parameters are needed for atmospheric retrieval of cloud-free modern Earth-twin planet orbiting a Sun-like star at 10 pc from our Earth.

They conclude that with an S/N of 10 (at 11.2 μ m, the radius (10% of uncertainties), the surface pressure, and the surface temperature ($< \approx 20K$) can be achieved. For recall, the default S/N to detect an exoplanet is 7.

With an S/N of ≈ 10 , abundance of molecules like H_2O , O_3 can be retrieve. For N_2O , NH_3 , only the upper limited is recovered. CO , N_2 and O_2 are unconstrained. To retrieve CH_4 , the minimum S/N is 10 with a spectral resolution equal to 50.

A full recap of these parameters is available in ?? (??) where the tradeoff is performed.

We selected a target S/N of 10 and a spectral resolution equal to 50 for our simulations. For the observation strategy, we optimize the sorting to maximize the number of rocky planets orbiting within the habitable zone. The configuration used is the x-array with a $B = 16m$ and $D = 3.5m$.

[subsection 4.6](#) shows the number of characterized exoplanets as a function of the duration of this phase. As for the detection/search phase, it reached a plateau. [subsection 4.6](#) shows the first derivative of this curve, providing information about the rate of characterizations. After four years, ≈ 30 rocky exoplanets can be characterized, of which 2/3 are in the habitable zone of their host star. Compared to the search phase, the number of new characterizations decreased at the same rate for the total number of exoplanets and the number of rocky exoplanets in the habitable zone.

4.7 Resolution of the habitable zone

All the previous figures of merit are based on instrumental parameters, but their measurements are directly related to the star/planets catalog generated by Ppop. The conclusions are no less interesting, but they are linked to the state of knowledge at a given moment. For a given spectral type, the habitable zone is located at a fixed physical scale of about a [au] around the star. For a given spectral type and its statistical distribution of planets, and all other metrics remaining constant, the yield will be proportional to the number of stars probed, which is proportional to the volume probed. The physical dimension of the array, as measured by its baseline plays an important role in reaching angular resolution and probing the physical scales a in the planetary systems. The angular separation is proportional to the distance of the system, and the search volume over which the scale a is reached increases with the square of the baseline $V_{sep.} \propto kb^3$, where $k \approx [2..4]$ depending on the architecture of the interferometer.

In this abstraction, we consider the habitable zone is resolved if its middle is within the IWA and OWA of the interferometer. [subsection 4.7](#) gives the percentage of stars (542 stars in total) where the habitable is visible. As expected, the aperture diameter has nearly no effect. By increasing the nulling baseline from 8m to 32m, nearly 85 % of habitable zones of the 542 stars are resolved. [subsection 4.7](#) shows the histogram of the angular separation of the middle of the habitable zone. Vertical lines represent the $(\lambda/(4B))$ IWA in blue and the (λ/D) OWA in red. The interferometer can resolve all the habitable zones between the corresponding vertical lines depending on the selected baseline and aperture diameter. However planets themselves may still be unreachable due to sensitivity as discussed in [subsection 4.5](#).

5. EXOPLANET YIELD RESULTS

We follow the option space presented in ?? for the configuration. It means an interferometer with a nulling baseline of 8m, 16m or 32m with an aperture diameter of 3.5m. Two configurations are compared: linear and x-array, as presented in [subsection 3.2.1](#). The yield metrics (YM - see [subsection 4.2](#)) are used to be able to compare both configurations.

The mission is divided into two phases: one for new discoveries, called the detection or search phase, and one for characterization.

5.1 Exoplanet yield (detection phase)

The duration of the detection/search phase is selected to four years, following what was presented in [subsection 4.3](#).

[subsection 5.1](#) shows the absolute yields for general exoplanets (**YM3** and **YM5**) with the varying baseline for both configurations. It also provides information about the number of detected rocky exoplanets in the habitable zone (**YM1**). [subsection 5.2](#) shows the ratio between configuration. The linear array shows better results for each nulling baseline. The ratio between is not constant. At shorter wavelength, the ratio tends to be lower but it is but this influence of B is not preponderant.

One of the main reason of this difference between each configuration is the higher modulation efficiency. It is equal to 0.22 for the X-array and 0.28 for the linear DCB B (6).

Examining the demography of the detected synthetic planets informs us on the performance of the considered architecture. [Figure 17](#) shows the brightness of the detected planets for an X-array double-Bracewell architecture. With the selected mission profile, rocky habitable-zone planets were detected as low 0.1Jy, which is a factor 10 below the sensitivity requirement set in task 1 (TREQ3).

5.2 Exoplanet yield (characterization phase)

The duration of the characterization phase is selected to 4 years, following what was presented in [subsection 4.6](#).

[subsection 5.2](#) shows the absolute yields for general exoplanets (**YM4** and **YM6**) with the different baselines for both configurations. It also provides information about the number of characterized rocky exoplanets in the habitable zone (**YM2**). [subsection 5.2](#) shows the ratio between configurations. As for the search phase, the linear array provides better results than the X-array ($\approx 25\%$).

6. OVERALL ARCHITECTURE

6.1 optical Chain

This chapter focuses on the optical design and trade-offs. [Figure 19](#) represents a diagram block of the optical chain. Each element is related to the configuration item and the function list described in Section ???. The structure of this chapter follows this diagram, presenting each subsystem with more details and trade-off information.

7. GENERAL DESCRIPTION OF THE OPTICAL DESIGN

The interferometer consists of four individual telescopes (PL-Tx) and their relay optics (Delay Lines, or PL-Tx-DL). They can be arranged in a linear or X-array configuration. This choice does affect the optical design. In Section ??, a trade-off between different types of telescopes is discussed, and for example, the siderostat-like telescope is considered to be more advantageous for the X-array than for the linear array. Nevertheless, to create a complete ray-traced model, the linear array was taken as the standard configuration for this chapter. Subsequently, the two-mirror telescope solution is chosen. This design is further developed and analyzed.

After the PL-TX, transfer optics (PL-Tx-TO)) are there to send the light down to the Beam Combiner Assembly. The beam combination is realized by means of two modified Mach-Zehnder (PL-CU-BCA), their architecture is analyzed in terms of wavefront errors in Section ??.

Following the optical chain, the injection system (PL-CU-SPFA) and the Spectrometer (PL-CU-SPA) are described in Section ?? and Section ?? respectively. To finalize the analysis of the optical chain, the polarization effects and mitigation strategies regarding the telescopes and relay optics are presented in Section ??.

8. WAVEBANDS

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 dictated presently by the single-mode fibre injection capabilities and their intrinsic limitations over such broad ranges. The baseline design in this technical note thus incorporates waveband separation to cover 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 impacts the entire optical chain by scaling subsystems with the number of bands, which increases overall instrument complexity. The optimal configuration (number of bands) will emerge from trade-offs balancing 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 (WLBS), and (2) a waveband multiplexer to route each band to its corresponding instrument (MuAs).

We further note that this trade-off should aim towards making the wavelength split as far down chain as possible, with the goal to limit 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 mentioned in ?? . This push would have the double effect of limiting the duplication of components and subsystems, but also preserve the correlation of instrumental systematic errors which facilitates the salvaging of signal in post-processing (?).

8.1 preliminary thermal assesement

9. A BIT OF SYSTEM ENGINEERING

10. TRADE-OFF ANALYSIS

11. CONCLUSION

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Performance_Yield/BDYM5-eps-converted-to.pdf

[Number of detected exoplanets (YM5)]

[Number of

Performance_Yield/BDYM3-eps-converted-to.pdf

detected rocky exoplanets (YM3)]

[Number of detected

Performance_Yield/BD-eps-converted-to.pdf

exoplanets in the habitable zone]

[Number of detected

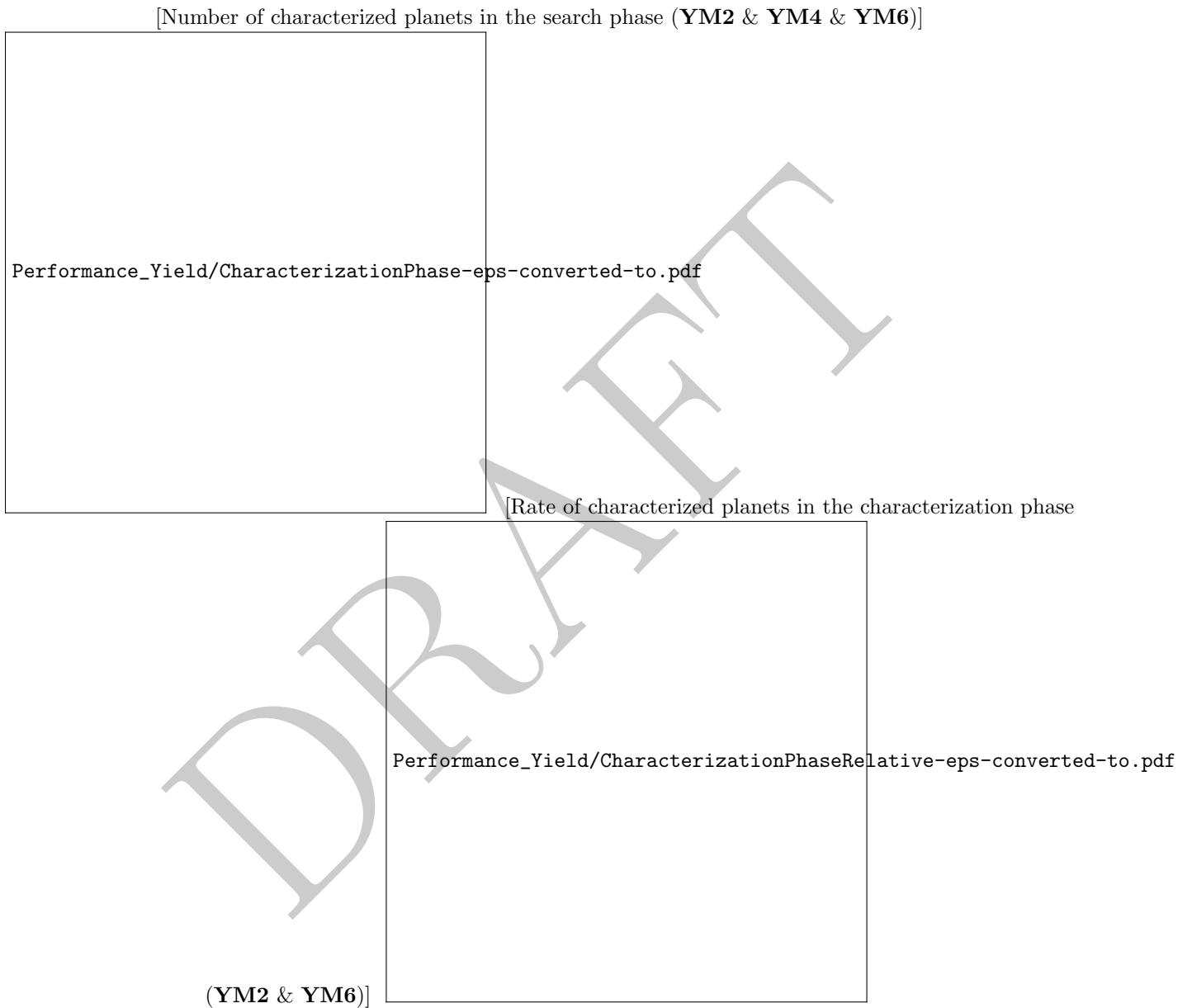


Figure 14. Characterization phase duration. Configuration: X-array with $B = 16m$ and $D = 3.5m$.

Performance_Yield/heatmap-eps-converted-to.pdf

[Heatmap]

Performance_Yield/Hz.pdf

[Absolute yield (search phase). X-array in blue and linear DCB-B in red.]

Performance_Yield/ComparisonAbsolute-eps-converted-to.pdf

between both configurations]

[Ratio of detections

Performance_Yield/ComparisonRelative-eps-converted-to.pdf



Figure 17. A representation of the demography of the synthetic planets detected by a 16m X-array with 2m diameter collectors. The faintest planets detected are as low as 0.1Jy at 10..

[Absolute yield (characterization phase). X-array in blue and linear DCB-B in red.]

Performance_Yield/ComparisonAbsoluteCharacterization-eps-converted-to.pdf

characterizations between both configurations]

[Ratio of

Performance_Yield/ComparisonRelativeCharacterization-eps-converted-to.pdf

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WP4120 - Optical chain/ESA_nulling_optical_chain_v5.png

Figure 19. Diagram block of the proposed optical chain, from telescopes to the detectors.