A Fresnel propagation analysis for SPEED (Segmented Pupil Experiment for Exoplanet Detection)

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ABSTRACT

Direct detection and characterization of exoplanets is a major scientific driver of the next decade. Direct imaging requires challenging techniques to observe faint companions around bright stars. The development of future large telescopes will increase the capability to directly image and characterize exoplanets thanks to their high resolution and photon collecting power. The E-ELT will be composed of a segmented ~40 m-diameter primary mirror. High contrast imaging techniques for E-ELT will thus need to deal with amplitude errors due to segmentation (pupil discontinuities between the segments). A promising technique is the wavefront shaping. It consists in the use of deformable(s) mirror(s) to cancel the intensity inside the focal plane region. Algorithm improvements and laboratory demonstrations have been developed since the last 20 years. The use of 2 deformable mirrors (DM) in non-conjugated planes will allow correcting not only for phase aberrations but also for the amplitude errors. Lagrange laboratory has begun in 2013 the development of an instrumental project called SPEED (Segmented Pupil Experiment for Exo-planet Detection). Its goal is to develop and test high-contrast imaging techniques optimized for segmented pupil. In this paper we present a detailed end-to-end simulation for the optimization of the SPEED experiment optical design. In particular, we pay attention to the optimal separation between the two DMs necessary for phase and amplitude correction. The trade-off between various parameters (field of correction, field of view, size constraints,...) is presented and discussed.

Keywords: Instrumentation, High-contrast imaging, Wavefront correction, Fresnel propagation, Deformable mirror

INTRODUCTION

Future large telescopes will open a unique niche in the detection of faint exoplanet close to their sun. However, such large telescopes require segmented primary mirror that creates gaps between the mirror segments. Those pupil-plane discontinuities, combined with the secondary mirror obstruction and spiders are a major concern for the high-contrast imaging. SPEED (Segmented Pupil Experiment for Exoplanet Detection) is an experiment, started at Lagrange Laboratory in 2013, to probe high contrast capabilities with segmented pupil. The context of this study is the observation of planets around M-stars with the E-ELT. The goal of this project is to achieve high contrast at small separations in H-band (10^{-7} at 1 λ/D, TBC) and will use for that, a phasing unit for the correction of the segment misalignments and active optics that will correct the amplitude errors due to various discontinuities in the pupil and due to the Fresnel propagation of phase errors. The active optics will include a coronagraph and a wavefront control for high-contrast imaging at the focal plane. Recent numerical solutions have been developed to correct for segments gaps and secondary support with adapted coronagraphs ([1], [2], [3], [4]) and wavefront correction [5]. SPEED will study in details the propagation errors (amplitude and phase) and their impact in high contrast capabilities. This project will help to understand the fundamental limitations of high contrast imaging when dealing with the effects of various discontinuities and missing segments in the pupil but also when dealing with the fact that ELT will partially resolve stars. Indeed, most coronagraphs have been designed assuming the star as a perfect point source. Guyon et al [1] had shown that the coronagraphs useful throughputs drop significantly when taking into account a stellar radius of 0.1 λ/D (note that a Sun at 10 parcsec observed at the E-ELT will be ~0.05 λ/D in H band). He showed that coronagraphs with highest throughput and smallest inner working angle are the most sensitive to stellar angular diameter, which prevent detection of faint exoplanet near their host star.

SPEED will need to study and test the impact of a resolved on-axis object. In this paper, we will present an overview of the SPEED project, the simulation tools in development at Lagrange laboratory and first simulation results on the optical layout optimization.

SPEED CONCEPT OVERVIEW

The SPEED concept overview is detailed in [7] and is illustrated in Figure 1. SPEED will be composed of different instrumental modules that will be briefly described in this section. A common path will include a star/planet system simulator and a E-ELT segmented pupil simulator. A dichroïc will then split the beam into two: the visible path (from 450 to 750 nm) for the phasing and a NIR path for the high-contrast imaging (active optics, coronagraph and IR camera).

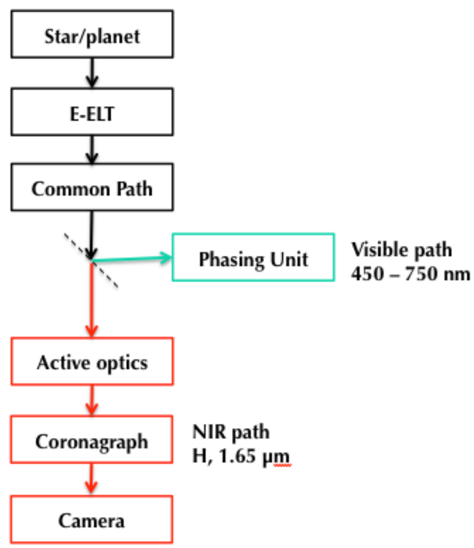

Figure 1. SPEED concept

- **Star/planet simulator**. SPEED will use a simulator inherited from the PERSEE bench [8], the Star and Planet Simulator (SPS). The principle is illustrated in **Figure 2**: the simulator uses the recombination of 2 optical fibers to create a star/planet system from 0.6 to 3.3 µm. The planet separation and the contrast can be adjust (contrast from 10^{-4} to 10^{-6} in H-band). The SPS module will deal with stellar resolution up to 0.5 mas.

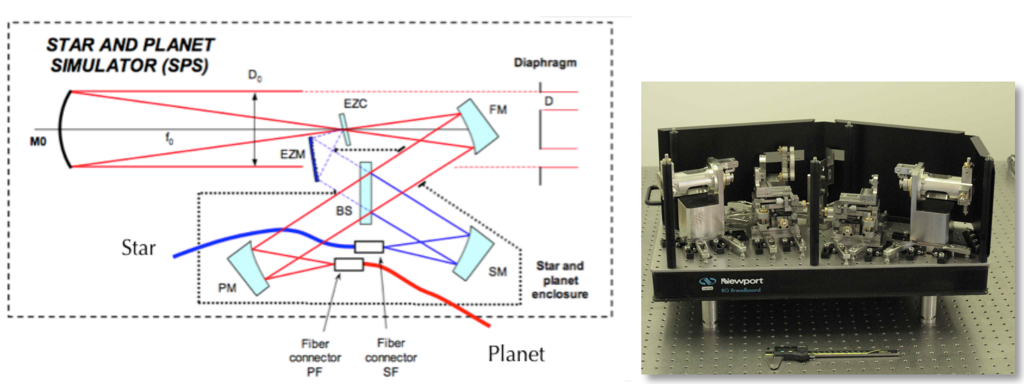

Figure 2. SPS module illustration

- **Telescope simulator**. The segmented pupil will be simulated via a IRIS AO® deformable mirror (DM). It is made with 163 segments that can be adjusted in piston and tip/tilt for a overall pupil diameter of 8 mm (see picture **Figure 3**). The spider and obstruction masks will reproduce the E-ELT obstruction and spiders.

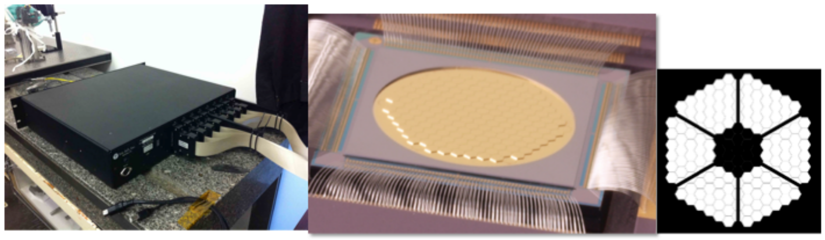

Figure 3. Telescope simulator illustration with DM electronics and mirror (left and middle) and spider and obstruction shape (right).

- **Phasing unit**. Different segments phasing concepts are currently under study at Lagrange laboratory.
  - A new focal plane co-phasing sensor that uses the Self Coherent Camera (SCC) concept, developed by Baudoz et al [9]. The SCC estimates phase and amplitude aberrations upstream of a coronagraph thanks to a pinhole located at the Lyot Stop plane which creates interference pattern at the camera plane (see **Figure 4**). The goal of the current study is to adapt this technique to retrieve the segments piston and tip-tilt for co-phasing [10].

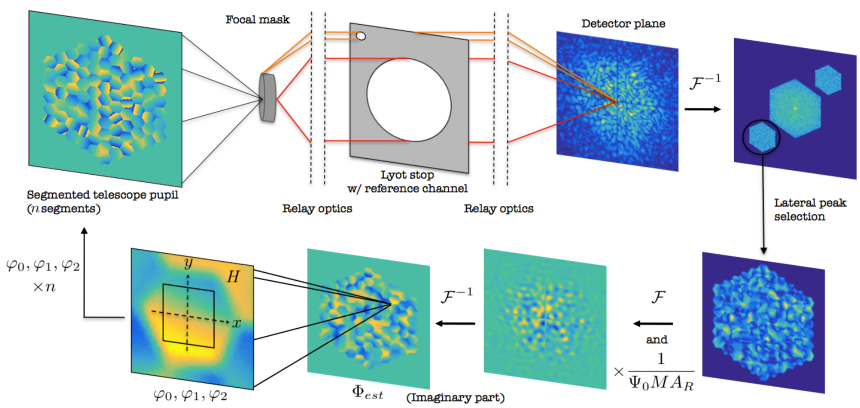

Figure 4. General scheme of the phasing unit using the SCC. The Fourier Transform of the interference pattern at the focal plane allows the recovery of aberrations.

  - A pupil plane analysis called ZEUS (Zernike Unit for Segment phasing) developed by LAM, IAC and ESO [11]. It is based on the Mach-Zender concept but uses a simple phase mask that replaces the Mach-Zender interferometer optics.

- **Coronagraph**. The chosen coronagraph design is PIAACMC (Phase Induced Amplitude Apodization Complex Mask Coronagraph). It uses the combination of 2 out-of-pupil apodized optics and a complex focal mask [12]. It provides very good contrast at very small separation (1 λ/D or sub- λ/D) with high throughput. It can also deal with segmented pupil by correcting some pupil discontinuities. The coronagraph design is currently under study. We also consider the option to use a less complex coronagraph at the very beginning of the integration and test.

- **Wavefront control and shaping with active optics.** It will be made thanks to 2 deformable mirrors (DM) from Boston Micromachine® with 34x34 actuators (see pictures **Figure 5**). The combination of DMs and coronagraph will be optimized for high contrast imaging with segmented pupils.

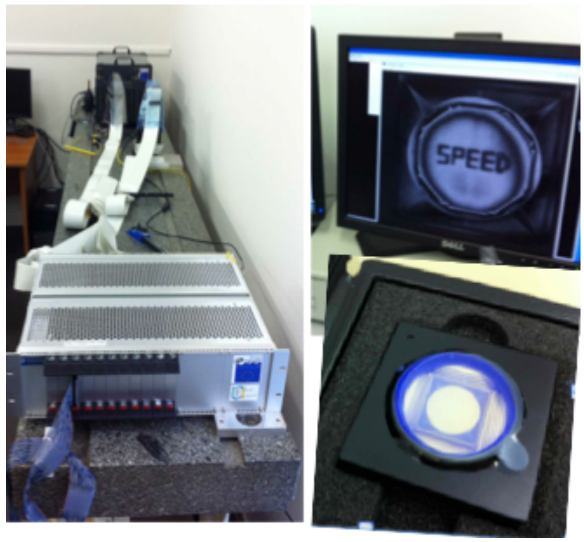

Figure 5. Pitcure of DMs for wavefront control

- **Low order wavefront correction**. The low order correction will be made with a tip-tilt mirror and a Coronagraphic Low Order Wavefront Sensor that uses light rejected by the Lyot Stop of the PIAACMC (currently used in SCExAO at Subaru [13 14]).
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END-TO-END SPEED SIMULATION METHODOLOGY

SPEED combines a coronagraph and active optics to create dark zones at the image plane. An end-to-end simulation has been developed that includes the Fresnel propagation between each ~ 25 optics presents in SPEED (see a preliminary design in **Figure 6**). We have initiated at Lagrange laboratory the development of some simulation tools to help for

- the optimization of the optical layout (DM location, optical sizes…)
- the prediction of the performances and contrast capabilities at small separation with unfriendly pupils
- the optimization of dark hole algorithm that deal with pupil discontinuities

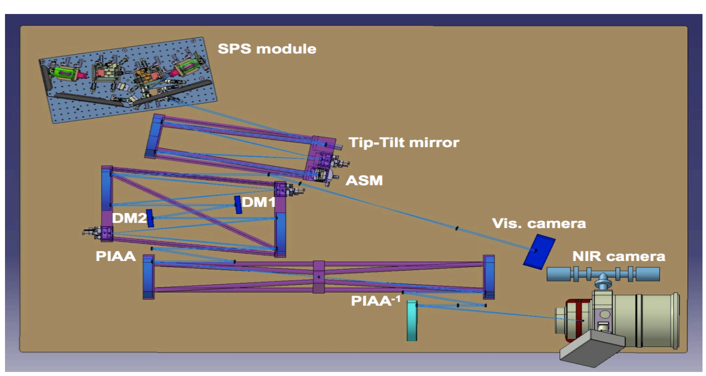

Figure 6. SPEED preliminary design

The first step of the optimization is to predict how the optical layout impacts the dark hole (DH) performances within some setup constraints: the overall setup length, the optics sizes, the best DM location... We first focused on the optimum DM location. We indeed need to analyze the focal plane contrast in different configurations: one DM at the pupil plane and one DM out of the pupil plane, 2 DMs out of the pupil plane and DMs in converging beam.

The methodology used for the optimization is described as follow:

- **Fresnel propagation**. The Fresnel code used to simulate the SPEED optical layout is called PROPER [15]. This IDL code uses the angular spectrum and Fresnel approximation as propagation algorithms; the procedures automatically determine which is the best algorithm to implement. At each propagation plane, phase and amplitude errors can be added.
- **Coronagraph**. We used for this simulation a perfect coronagraph, that removes all light present in the setup without aberrations. As we will be actually limited by a real coronagraph, the use of a perfect coronagraph will assess the ultimate effects of Fresnel propagation on DH performances.
- **Optics amplitude and aberrations**. Each optic can be implemented with different amplitude and aberration shapes. Each optic (except the 2 DMs) is assumed to have amplitudes much larger than the beam diameter and contains 5 nm rms phase aberrations following a power-law distrubution PSD $\propto f^{-3}$ where f is the frequency.
- **Wavefront shape and control: dark hole algorithm**. The interaction matrix, which reflects how each DM actuator impacts the focal plane, is numerically computed. Each DM actuator is poked, then propagated through the optical design without aberration, to the image plane where the complex amplitude is recorded. Note that each poke is small (<<1 rad) to keep the setup in the linear regime. The interaction matrix is then made by computing the overall amplitude inside the desired DH for each DM actuator. The 2 DMs coefficients are finally computed to minimize the intensity inside the DH. The algorithm is also implemented to do stroke minimization [16] to force the algorithm to converge within adequate phase values. As the interaction matrix computation requires large computational time, we use a data centre, “MesoCentre”, available at Observatoire de la Côte d’Azur with ~3k cores shared with all users. The Fresnel propagation code has been adapted in C to be compatible with the data centre. The computation of one setup lasts ~10 minutes compared to previous ~15 hours on a laptop.
- **Pupil shape**. We first computed solely the linear algorithm approach: the discontinuities were not taken into account in the coronagraph nor in the DH algorithm (the pupil is circular). We, as a first step, focused on the Fresnel propagation of smoothed errors.
- **Wavelength**. The simulation is monochromatic at 1.65 μm.

DM LOCATION OPTIMIZATION: FIRST DM AT PUPIL PLANE

This simulation attemps to determine the optimal location of the 2nd DM when the 1st DM is at pupil plane. For this simulation, we used a perfect design as described in previous section, in order to emphasize the impact of DM location on the contrast. The 2nd DM was tested at various locations after the 1st DM plane, from 0.8 to 2 m. Focal plane intensities, in logarithmic scales, are shown in **Figure 7** with a small DH on top (“DH_A”, defined from 0.8 to 4 λ/D) and a larger DH at bottom (“DH_B”, from 3 to 10 λ/D). The best DM location depends on the DH frequencies: it is at 2 m for the smallest DH whereas it is 1 m for the largest one.

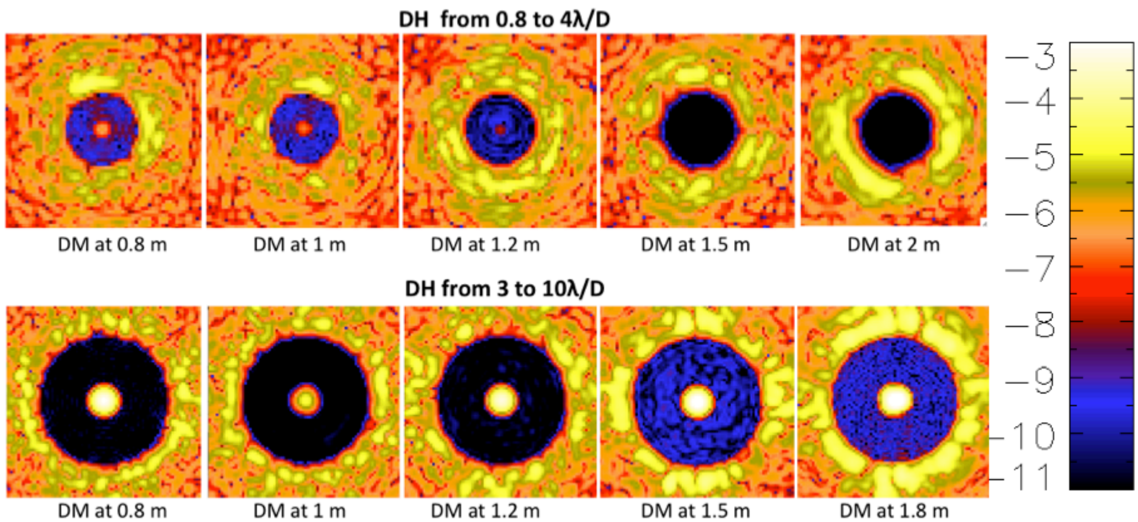

Figure 7. SPEED focal plane intensities (logarithmic scale) for different DM locations for DH_A (top) and DH_B (bottom)

This result can be explained by looking at the impact of an out of pupil plane DM at the focal plane (see **Figure 8**). A DM located after the pupil plane at a distance z will have an impact at the focal plane that can be estimated by first Fresnel propagate the DM to the lens (E_{lens}), add the lens and finally propagate to the focal plane (E_f).

$$E_{lens}(\alpha,\beta) = \frac{e^{i\frac{2\pi}{\lambda}(f-z)}}{i\lambda(f-z)} \iint E_{DM}(u,v)\cdot e^{i\frac{\pi}{\lambda(f-z)}\left((\alpha-u)^2+(\beta-v)^2\right)}\, du\, dv \quad \text{and} \quad E_f(x,y) = \frac{e^{i\frac{2\pi f}{\lambda}}}{i\lambda f} e^{i\frac{\pi z}{\lambda f}\left(x^2+y^2\right)}\cdot TF_{x,y}\left[E_{lens}\right]$$

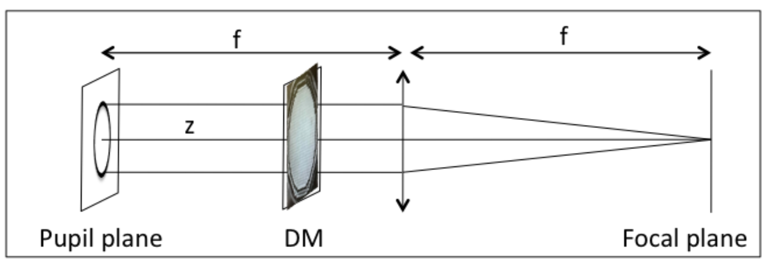

Figure 8. 2nd DM configuration

The complex amplitude $E_f(x,y)$ at the focal plane is thus

$$E_f(x,y) = \frac{e^{i\frac{2\pi}{\lambda}(2f-z)}}{i\lambda f}\cdot e^{i\frac{\pi z}{\lambda f}\left(x^2+y^2\right)}\cdot TF_{x,y}\left[E_{DM}(u,v)\right] = \frac{e^{i\frac{2\pi}{\lambda}(2f-z)}}{i\lambda f}\cdot TF_{x,y}\left[E_{DM}(u,v)\right]\cdot\left(\cos\left[\frac{\pi z}{\lambda f}\left(x^2+y^2\right)\right] + i\sin\left[\frac{\pi z}{\lambda f}\left(x^2+y^2\right)\right]\right)$$

where $TF_{x,y}\left[E_{DM}(u,v)\right]$ is the Fourier Transform of the complex amplitude at the DM plane and z is the distance of the DM to the pupil plane. We see that this amplitude is modulated by a sine and a cosine that depends on the distance z, the focal length f and the spatial frequencies x and y. **Figure 9** shows the absolute value of the sine contribution as a function of the spatial frequencies for different z locations (at 0.8, 1, 1.5, 2 and 2.5 m). The DH from 0.8 to 4 λ/D (DH_A) is enlightened in yellow. The coverage inside the DH changes with the DM location; a very low sine value will need a very large stroke to compensate for the poor coverage, which will be out of the linear approximation of the DH algorithm. The contrast inside the DH will be better if there is a good coverage inside the defined DH. The optimum DM location depends thus on the desired DH: it requires very large distances for contrast at small separation (~ 2 m) and smaller distances for high contrast at larger separations.

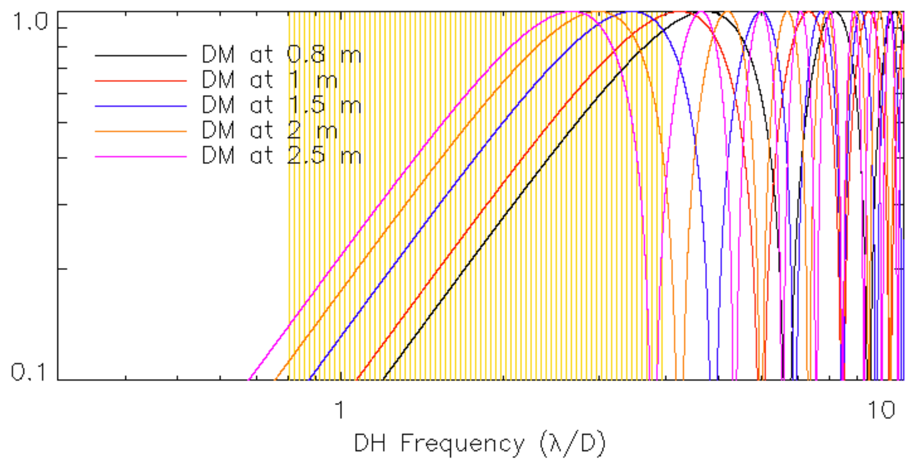

Figure 9. Sine component as a function of the dark hole frequencies for different DM locations (0.8, 1, 1.5, 2 and 2 m from the pupil plane).

Table 1 lists the computed efficiency (mean of the sine) inside each DH (DH_A and DH_B) for different DM locations. The best coverage occurs at 2 m and 1 m respectively for DH_A and DH_B (in bold in the table), which is consistent with our propagation simulation results.

DM location	Mean efficiency (%) in DH from 3 to 10 λ/D	Mean efficiency (%) in DH from 0.8 to 4 λ/D
0.8 m	67	42
1 m	**70**	50
1.2 m	67	56
1.5 m	65	63
2 m	64	**64**
2.5 m	62	59

Table 1. Efficiency inside the small DH (right) and large DH (left) for several

CONCLUSION AND FUTURE WORK

SPEED aims to assess the performances at small separation for segmented pupils. In this context, simulation tools are under development in order to optimize the optical layout, predict the performances and improve the DH contrast when dealing with segmented pupil. We have presented in this paper an optical layout optimization: the optimum DM location for the configuration where the 1st DM is at the pupil plane and the 2nd DM is out of the pupil plane. We have shown that the best layout depends on the desired contrast separations and requires large setup to provide good contrast at small separations. Future work will include the analysis of other configurations (DMs out of the pupil plane, DMs in converging beam…) and the impact of the optical layout (optics sizes, aberrations amounts…) on the performances. We will also include real coronagraph and segmented pupil to find out the best way to tackle the pupil discontinuities impact on contrast. The stellar angular size will also be taken into account in the simulation. We will finally predict the future SPEED performances by using polychromatic simulations and measured aberrations, noise…

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