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System analysis of the Segmented Pupil Experiment for Exoplanet Detection - SPEED - in view of the ELTs

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ABSTRACT

SPEED is a new experiment in progress at the Lagrange laboratory to study some critical aspects to succeed in very deep high-contrast imaging at close angular separations with the next generation of ELTs. The SPEED bench will investigate optical, system, and algorithmic approaches to minimize the ELT primary mirror discontinuities and achieve the required contrast for targeting low mass exoplanets. The SPEED project combines high precision co-phasing architectures, wavefront control and shaping using two sequential high order deformable mirrors, and advanced coronagraphy (PIAACMC). In this paper, we describe the overall system architecture and discuss some characteristics to reach 10^{-7} contrast at roughly $1\lambda/D$.

Keywords: Co-phasing, Wavefront control, Deformable mirror, Coronagraphy, High-contrast imaging.

INTRODUCTION

Giant telescopes are expected to tackle the major challenges of contemporary astrophysics. Searching for nearby exoplanets is one of the important scientific drivers, and segmented telescopes offer a practical path towards dramatically enlarging telescope diameter from the ground. However, translating current technological advances in the domain of high contrast imaging for monolithic apertures to the case of segmented apertures is far from trivial. Because of the primary mirror segmentation and the increased mechanical structures of the telescope such as the secondary mirror supports, the resulting pupil is geometrically complex. The pupil exhibits amplitude discontinuities created by the space between the segments and the presence of the secondary supports, and phase discontinuities resulting from imperfect alignment (phasing) between segments. These effects significantly limit high contrast imaging capabilities (speckles and diffraction), especially for exoplanet direct detection.
SPEED - the segmented pupil experiment for exoplanet detection – initiated in early 2013 at the Lagrange laboratory, aims at preparing strategies and technologies for high-contrast instrumentation with segmented telescopes. SPEED will offer an ideal environment to make progress in the domain of ELTs with complex/irregular apertures. It involves efforts in (i) science-grounded instrument conception and design: optical, mechanical, and thermal engineering, (ii) development of novel techniques for tackling high-contrast imaging limitations such as coronagraphy, wavefront control and shaping, and phasing.

SPEED CONCEPT OVERVIEW

We can describe the SPEED experiment as the association of various independent instrumental modules with two optical paths: the visible path dedicated to segment phasing analysis, and the scientific path in the near infrared (H-band). Figure 1 and Figure 2 show the SPEED system overview and the general layout. Briefly, a common path includes a star/planet and E-ELT pupil simulators. The star/planet simulator is inherited from the PERSEE bench [1]. The angular separation and the contrast between star and planet are adjustable. A secondary mirror (M2) mask, a tip/tilt mirror and a segmented deformable mirror compose the ELT simulator. A beam splitter separates the beam into two different optical paths. A visible path in direction of the phasing unit that

will use various technics, among them: the Self-coherent camera phasing sensor [2, 3] and the Asymmetric pupil Fourier wavefront sensor [4]. A near infrared path begins with the wavefront control and shaping, by using two deformable mirrors, followed by a PIAACMC [8] and a low order wavefront sensor. Finally the scientific images will be obtained by a NIR camera.
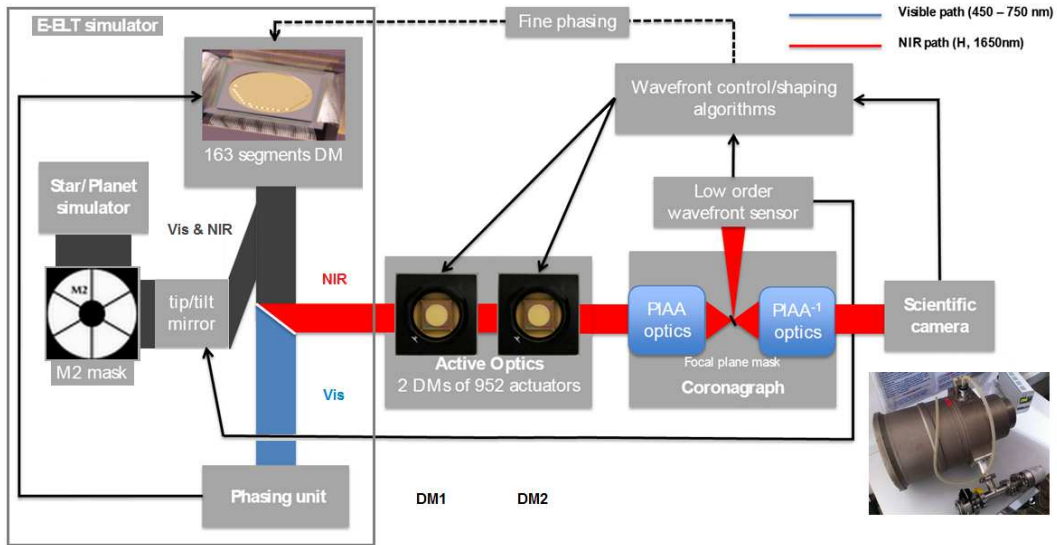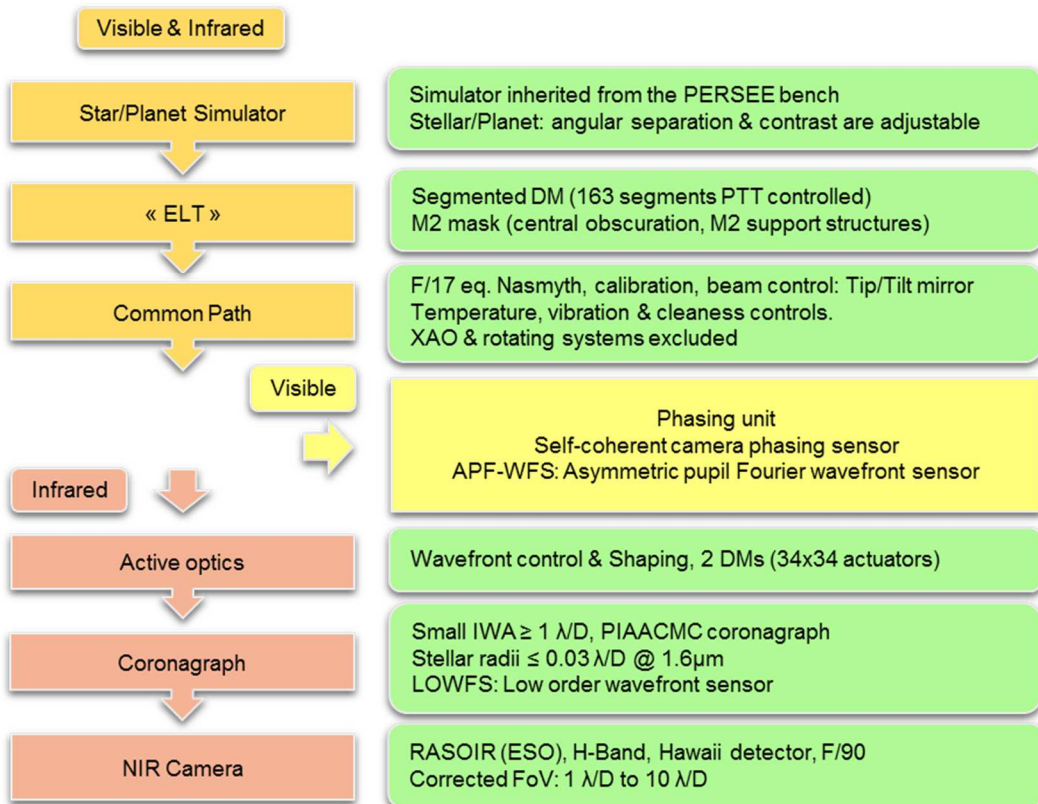

Figure 1. SPEED system overview.

Figure 2. General layout.

Preliminary optical design

The preliminary optical design is presented in Figure 3. The entrance F-number is F/17 as for the E-ELT Nasmyth port, and the pupil is defined in the plan where the SDM (segmented mirror) is located with 7.7 mm diameter. Following the up-to-date optical design, DM1 (deformable mirror) is inserted in a conjugated pupil plane, while DM2 is out of pupil plane (see the "End-to-End simulation and DM location optimization" section below, where the final two DMs architecture combination is upon intensive numerical study). The PIAACMC will be entirely developed with reflective optics and the F-number at the focal plane mask is F/90 at the entrance of the NIR camera. The F-number at the visible focus of the phasing unit is F/15. All movable components (filters, neutral densities, phase masks) will be inserted on motorized translation/rotation stages to guaranty for positioning accuracy, stability, and reproducibility. In addition, an integrating sphere will be located at the entrance of the bench for calibration purpose.
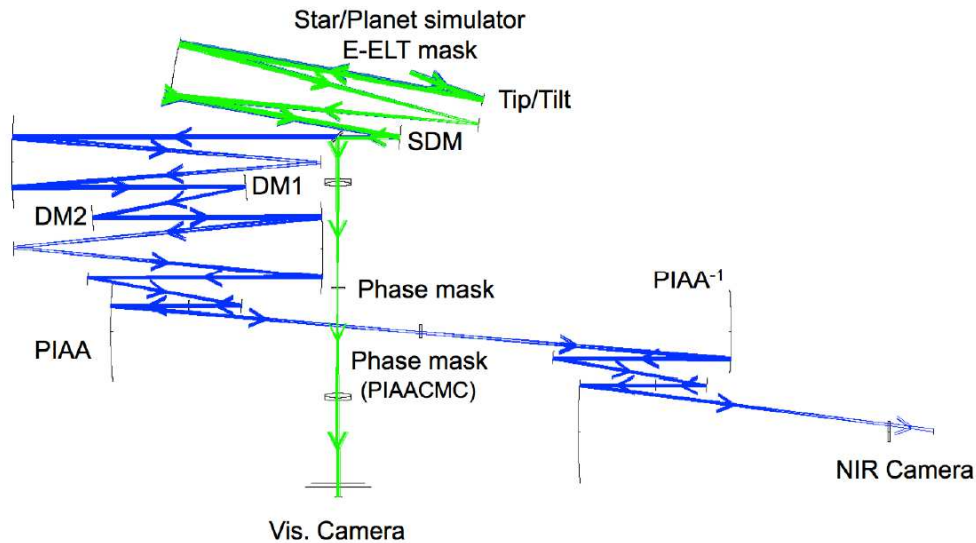

Figure 3. Preliminary optical design. In green color: visible wavelength band, in blue color: NIR H-band.

Star/planet simulator

The SPEED bench will take advantage of an entirely designed and developed star and planet generator source module (called SPS, for "star and planet simulator") inherited from the PERSEE bench. The SPS module, as is showed in Figure 4, allows to simulate a bright and unresolved star radiating in visible band from 0.45 to 0.75μm and in H-band with an exoplanet signal orbiting around it with adjustable angular separation and flux ratio (varying from 10^{-4} to 10^{-6}). In practice, the "star" light is generated with a super-continuum source; while the "planet" light uses a Xenon lamp, and both are optically mixed.

As ELTs will start resolving stars, stellar resolution up to 0.5mas (utmost apparent stellar radii for nearby stars for a 39-m telescope, i.e., 0.03λ/D at 1.6μm) will be considered within the SPS module of SPEED. This aspect is extremely important for high-contrast imaging as small inner working angle (IWA) coronagraphs such as the PIAACMC are sensitive to the stellar angular size (coronagraph leakage due to stellar angular size is proportional to the square of stellar radii).
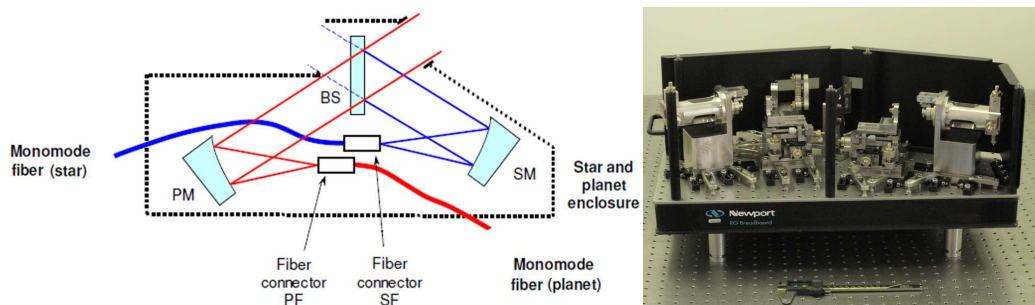

Figure 4. Left: SPS principle diagram, Right: SPS module picture.

Segmented telescope simulator

The telescope simulator module consists in the association of, firstly, an optical mask inserted into the optical beam to simulate the presence of the E-ELT (European-ELT) secondary mirror (secondary mirror M2, including M1 central obscuration and M2 supports). Secondly, a segmented mirror from IRIS AO manufacturer [5] with 163 segments controllable in piston and tip/tilt (PTT489 DM) as a surrogate of the E-ELT primary mirror. The M2 mask showed in Figure 5 consists in six radial arms regularly distributed (60 degrees between arms) and a large central obscuration (30%). Several configurations (i.e., several masks with various configurations) will be possible to be implemented and changed at any time. This mask is placed just front of a 1-inch diameter mirror fixed onto a piezoelectric tip/tilt. The segmented mirror is represented in Figure 5, where the inscribed pupil aperture is 7.7mm diameter. Such a system will allow exploring several key aspects of the E-ELT architecture (missing segments, inter segments spacing, island effect, etc.) regarding segment alignment (phasing), as well as the propagation of such errors and impact for high-contrast imaging.
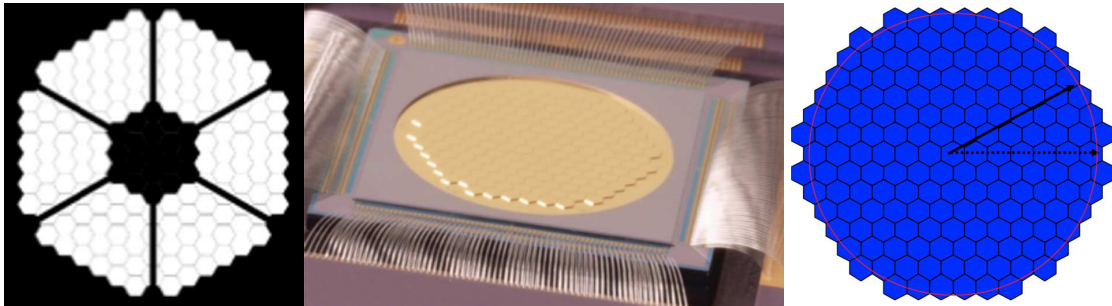

Figure 5. Left: M2 mask with six radial arms, Middle: PTT 489 IRISAO segmented DM, Right: schematic view of the 163 segments distribution over the inscribed aperture of 7.7mm (courtesy IRISAO manufacturer).

Phasing unit

SPEED will use a new co-phasing method directly exploiting the scientific image delivered by the Self-Coherent Camera (SCC) [6], see Figure 6, by adequately combining segment misalignment estimators (piston and tip/tilt) and image processing. The Self Coherent Camera Phasing Sensor (SCC-PS) [3] is shown to be capable of estimating accurately and simultaneously piston and tip/tilt misalignments and to correct them in close-loop operation in a few iterations. For more details and references, see the paper 114: "Self-Coherent Camera as a focal plane phasing sensor - Overview and early comparison with the Zernike Phase Contrast Sensor" by Pierre Janin-Potiron et al., in the same proceedings.
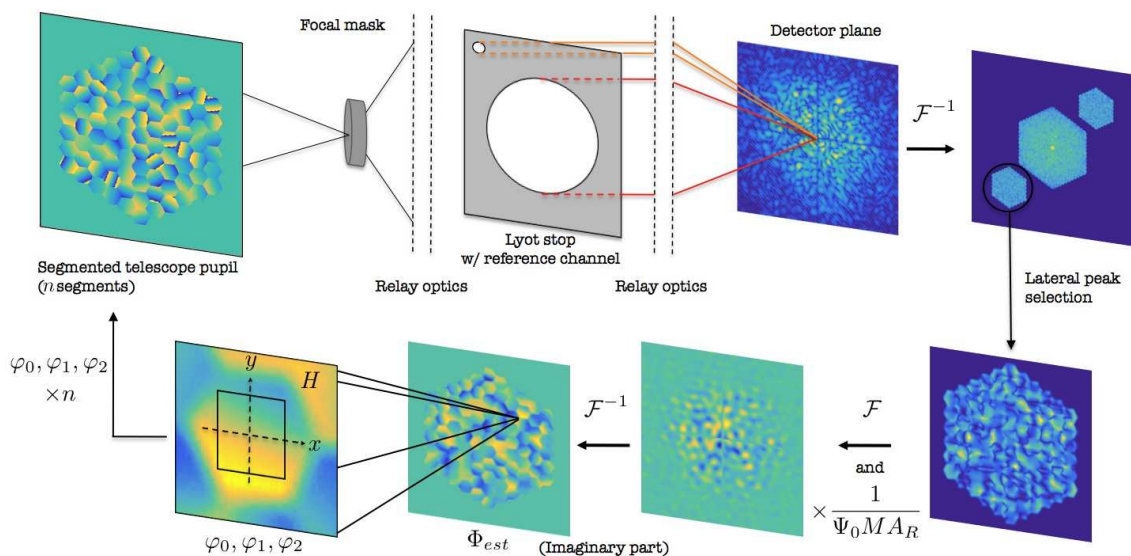

Figure 6. Illustration of the self-coherent camera phasing sensor (SCC-PS) principle. The red rays correspond to the path of the light in a classical coronagraph propagation process. The orange rays correspond to the path of light in the reference pupil in the Lyot stop. From the estimated phase map (Φ_{est}), three estimators are evaluated on each segment ($\varphi0$, $\varphi1$, and $\varphi2$).

Wavefront control and shaping

Two sequential DMs separated by free-space propagation can be efficiently used to correct for both phase and amplitude errors on a symmetrical field of view for relatively wide spectral bandwidth. DM1 and DM2 of SPEED, from Boston Micromachines manufacturer, can be used in a configuration optimized together with PIAACMC coronagraph to deliver high contrast level with complex aperture. DM1 and DM2 are Kilo-C-DM with 34x34 actuators across the circular pupil (952 actuators in total) with 1.5μm stroke (300μm pitch).

Figure 7. Left: picture of one of the two deformable mirrors (Kilo-C-DM) from Boston Micromachines manufacturer, Right: picture of a DM taken by a ZYGO interferometer with activation of some actuators.

End-to-End simulation and DM location optimization

SPEED combines a coronagraph and active optics to create dark zones at the image plane. An end-to-end simulation has been developed at Lagrange laboratory that includes the Fresnel propagation between each ~ 25 optics presents in SPEED (see a preliminary optical design in Figure 3). We have initiated the development of some simulation tools to help for (i) the optimization of the optical layout, (ii) the prediction of the performances and contrast capabilities at small separation with unfriendly pupils, (iii) the optimization of dark hole algorithm that deal with pupil discontinuities.

The first step of the optimization is to predict how the optical layout affects the dark hole (DH) performances within some setup constraints: the overall setup length, the optics sizes, the best DM location, etc... To focus on the optimum DM location, we indeed need to analyze the focal plane contrast in different configurations (see Figure 8): the first DM is placed at the pupil plane and the second DM out of the pupil plane, for this illustrative example.
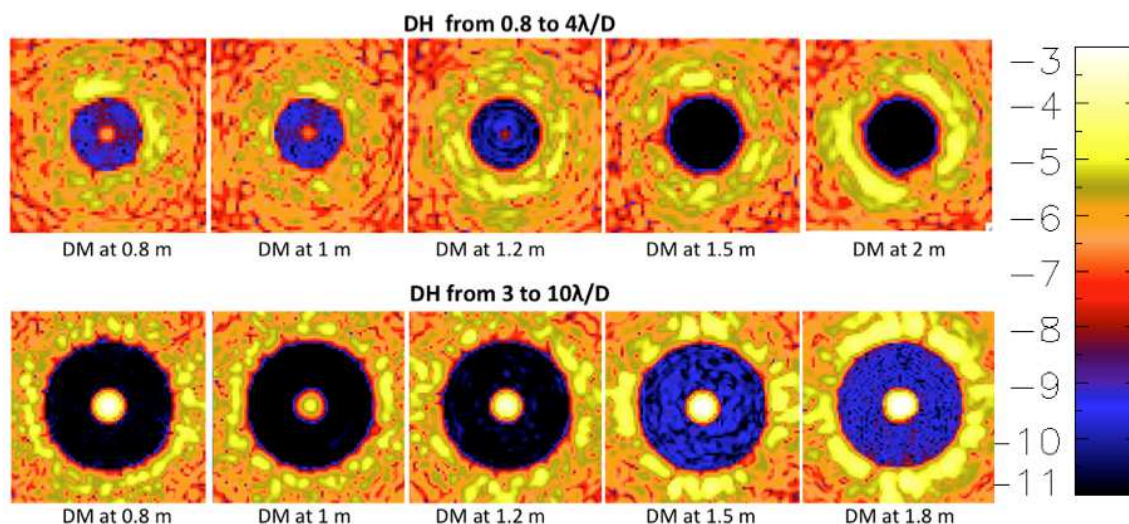

Figure 8. SPEED focal plane intensities (logarithmic scale) for different locations of the second DM, from DH: 0.8 to 4λ/D (top) and 3 to 10λ/D (bottom).

For more details and references, see the paper 109: "A Fresnel propagation analysis for SPEED" by Mathilde Beaulieu et al, in the same proceedings.

Coronagraph, low order wavefront sensor and scientific cameras

Several small inner-working angle class coronagraphs are currently subject to vigorous R&D to gear them up to high technological maturity. In particular, the PIAA (Phase Induced Amplitude Apodization) [7] uses beam remapping for lossless apodization and can be combined with opaque masks (PIAAC and PIAALC) or partially transmissive phase shifting (complex) masks (PIAACMC [8]). It theoretically offers complete starlight extinction, with high throughput and sub-λ/D inner working angle, regardless of the aperture shape. The PIAA offers nearly 100% throughput and approaches the fundamental coronagraph performance limits [9]. The goal within SPEED is to develop a PIAACMC that can cope with 1λ/D IWA (inner working angle), stellar angular size up to 0.5mas, and correct for all or part of the telescope pupil discontinuities (secondary support structures), with 10^{-7} raw contrast at IWA. As the PIAACMC development will likely require intensive efforts in term of optimization process, manufacturing and testing, a step 0 coronagraph (conventional pupil apodization [10]) will be considered first on the SPEED testbed to open the path towards PIAACMC at a later stage during the project.

A low order wavefront sensor is critical to ensure that starlight remains centered at the coronagraph plane. Because the PIAACMC is highly sensitive to low-order aberrations, especially tip/tilt errors (pointing errors). SPEED therefore includes a robust and efficient wavefront sensor to measure tip/tilt as well as defocus, namely the Coronagraphic Low- Order Wavefront Sensor (CLOWFS) currently in use in the SCExAO instrument at the Subaru telescope [11, 12].
A dedicated tip/tilt mirror upstream in the optical path (see Figure 1) will be used to correct for the tip tilt estimation from the CLOWFS, though tip/tilt correction could be carried out alternatively by DM1, DM2, or SDM.

At the end of the near-infrared path, the infrared camera is working at 1.65μm with an internal H-band filter. Its read-out-noise is 12 e- rms/pixel and quantum efficiency >60%. The detector pixels (18.5μm) are read in double correlated sampling mode, and is an 1kx1k Hawaii array (engineering grade) from which we select only a quadrant of 512 pixels, enough considering the field of view of 64λ/D (corrected field of view: 1 to 10λ/D). The camera has been kindly lending by the European Southern Observatory.

The visible camera for the phasing unit is an Apogee camera with 1024x1024 pixels (13μm pixel) with 2.2 e- rms/pixel read-out-noise, and 92% quantum efficiency.

CONCLUSION AND FUTURE WORK

The SPEED bench is under extensive development at the Lagrange laboratory, and will be unique in Europe for tackling high-contrast imaging with segmented and complex/irregular telescope aperture. While the SPEED optical design finalization is under way, pending to extensive numerical simulation efforts around the problematic of Fresnel effects, the integration of the visible path is planned to start in early 2016 in a new ISO7 cleanliness room.

ACKNOWLEDGMENTS

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