The SPEED Project: SPEEDing up Research and Development towards High-contrast Imaging Instruments for the E-ELT

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An overview is presented of the Segmented Pupil Experiment for Exoplanet Detection (SPEED) testbench. This is an advanced facility in development at the Lagrange Laboratory that will address several of the most critical issues affecting high-contrast imaging for the next generation of optical/near-infrared telescopes. The SPEED testbed can be used to investigate practical solutions for broadband coronography on asymmetric, unfriendly apertures, enabling algorithmic or optical approaches to be developed to minimise segment effects and pupil discontinuity.

In June of last year, a major step towards for the European Extremely Large Telescope (E-ELT) was achieved through the blasting of part of the peak of Cerro Armazones, opening the path towards the construction of the telescope. After completion, the E-ELT will be the world's largest optical/near-infrared telescope, opening up new parameter space in both spatial resolution and photon sensitivity. The E-ELT will provide significant advances over the Very Large Telescope (VLT), with a gain of a factor of five in spatial resolution, 25 in signal to noise, and 625 in exposure time to reach a given signal to noise. Such a giant telescope is expected to tackle the major challenges of contemporary astrophysics. Among the numerous open questions for which it is designed, hunting down low-mass exoplanets in the habitable zones where life could exist is probably its more exciting ambition.

Nevertheless, there is a catch to being the "world's biggest eye on the sky": the unavoidable run for spatial resolution and photon sensitivity leads to a telescope that by design is not optimal for the exoplanet search problem. While segmented telescopes offer dramatically enlarged telescope diameters from the ground, translating current technological advances into the domain of high-contrast imaging for monolithic apertures (e.g., SPHERE at the VLT; Beuzit et al., 2006) to the case of segmented apertures is far from trivial. On account of the segmented primary mirror and the increase in the number of mechanical structures making up the telescope, the resulting pupil is geometrically fairly complex: the pupil exhibits amplitude discontinuities created by the space between the segments, a large central obscuration, various secondary supports, unavoidable missing segments, and phase discontinuities resulting from imperfect alignment (phasing) between the segments. These effects significantly limit high-contrast imaging capabilities (speckles and diffraction), especially for the direct detection of exoplanets. In the area of high-contrast imaging, the only advantage offered by the ELTs is their gain in diameter, but this is accompanied by a large set of drawbacks that demands strong research and development (R&D) efforts on the optical effects. The complexity of the telescope pupil and the high-contrast imaging strategies are bound up with one another.

SPEED — the segmented pupil experiment for exoplanet detection — in development at the Lagrange Laboratory, aims at preparing strategies and technologies for high-contrast instrumentation with segmented telescopes. SPEED will offer an ideal environment in which to make progress in the domain of ELTs with complex/irregular apertures. SPEED combines wavefront control, including precision segment-phasing architectures, wavefront shaping for both phase and amplitude control, and advanced coronagraphy that is relevant to very close angular separation imaging.

Rationale

Different requirements exist for the various science programmes, but the telescope must comply with them all. This is very difficult to achieve, and the situation can be well paraphrased by the idiom "too many irons in the fire". In a high-contrast imaging instrument, the match between the scientific requirements (performance) and the instrumental requirements is generally quite complicated. While the E-ELT aims at gaining a spectacular factor of 100 to 1000 in contrast compared to SPHERE on the VLT for instance, its optical and mechanical characteristics impose severe hurdles that contribute a large part of the error budget of static or quasi-static aberrations, and set the ultimate limit regardless of the integration time. In particular, segmentation is an essential characteristic of the E-ELT that strongly complicates the telescope pupil structure and degrades coronagraphic contrast.

The E-ELT exoplanet imaging camera EPICS (Kasper et al., 2010) phase A conceptual study highlighted the complexity of the error budget affecting the propagation of light in such a new class of instrument. As a result the technological limitations must be addressed through various development programmes (for high-order deformable mirrors, real-time systems, wavefront sensors, etc.). Notwithstanding these obstacles — some of which will probably require technological breakthroughs to surmount — several additional concerns affecting exoplanet detection require that brand new challenges must be tackled in the area of high-contrast imaging. In particular:
- ELTs will start to resolve stellar discs (0.5 milliarcseconds [mas] apparent radius for nearby stars) with a 39-metre telescope at 1.6 µm. The result is degradation of the coronagraphic contrast, in particular for small inner-working angle coronagraphy, since coronagraphic leakage is proportional to the square of stellar radii.
- The pupil of an ELT is made up of various discontinuities in both phase and amplitude: the primary (M1) large central obscuration, inter-segment spacing, island effect from the secondary (M2) support structures, imperfect phasing, etc. All these aspects are detrimental for high-contrast imaging.

- While the current specification for E-ELT segment phasing can reasonably be considered to be achievable, it is uncertain whether the high-precision phasing requirements deemed appropriate for a high-contrast instrument can be achieved. The solution may require dedicated solutions at the instrument level.
- Missing segments are of the utmost concern. Since the segment reflectivity coating will have a lifetime of about 18 months, up to three segments will need to be re-coated on a daily basis. As for now, three to seven segments in total may be expected to be missing per observing run at the E-ELT. The effect of missing segments is dramatic and can be easily understood from classical Fraunhofer diffraction theory following Babinet's theorem: the far-field pattern of an obscuration is equal to that of an aperture of similar dimensions. Thus the width of the diffraction halo in the image plane is inversely proportional to the missing segment diameter, while its maximum intensity is proportional to the segment surface.
- Both the gain in spatial resolution offered by the E-ELT, and new scientific targets (e.g., M stars) for planet detection, demand an observing mode with a small inner-working angle (IWA), typically 15 mas (!) in the near-infrared. As a result, this mode will be subject to difficulties due to stellar resolution, pointing stability, amplitude error effects, etc.
- The instrument design and control of contrast on such giant telescopes requires careful mastering of Fresnel/Talbot effects, which are an important class of perturbation affecting a high-contrast imager. A pure phase aberration on an optical surface mixes between phase and amplitude aberrations as light propagates, and this oscillation occurs over a distance called the Talbot distance. This distance is proportional to the square of the aberration spatial period and inversely proportional to the wavelength of light, and hence is a chromatic effect. While the E-ELT diameter is increased by a factor of five compared to the VLT, the instrument size is not, and the optical beam compression is crude so that Fresnel diffraction induced by out-of-pupil optics is of the utmost importance.

Following from these points, both specialised and efficient post-coronagraphic wavefront sensing and control solutions, as well as image post-processing, are of major importance. This is especially so for the case of observing modes at small IWAs where standard strategies, such as angular differential imaging, are likely inefficient.

Concept and features

The complications elucidated here require both prudence and pragmatism in translating the current concept (e.g., SPHERE) to the ELTs. In order to provide insights into these issues, the concept of SPEED (Martinez et al., 2014) was proposed in 2013 to study solutions for optimising high-contrast imaging with unfriendly telescope apertures. The SPEED concept is described in Figure 1, while the 3D optical/mechanical view of the SPEED bench is shown in Figure 2.

Star planet simulator

At the entrance of the testbed, a star planet simulator (SPS source; Hénault et al., 2011) will allow a bright and unresolved star with an exoplanet signal to be simulated with adjustable angular separation and flux ratio. Stellar resolution will be possible within the SPS module up to 0.5 mas. Within SPEED it is assumed that the atmospheric turbulence (short-lived and fast-evolving speckles) has already been pre-corrected by an upfront eXtreme Adaptive Optics (XAO) system, and thus we can concentrate on the quasi-static aberrations in the instrument. While the SPEED bench will mainly operate on the assumption that this virtual correction is perfect (i.e., no XAO residuals), it will be possible to generate uncorrected atmospheric residuals using exchangeable phase screens.

Segmented telescope simulator

The next subsystem is the segmented telescope simulator. This consists of the combination of an active segmented mirror (ASM) with 163 segments controlled in piston and tip-tilt (a surrogate of the E-ELT primary mirror) and an optical mask inserted into the beam to simulate the presence of the E-ELT secondary mirror, including the primary central obscuration. The E-ELT M4 residuals and segmentation will be included at a later stage using a dedicated phase screen. Such a telescope simulator will allow several key aspects of the E-ELT architecture and error propagation to be investigated, as well as their impact for high-contrast imaging in the form of missing segments, gaps and the island effect. The island effect consists of the partial, or complete, coverage of the pupil by the dark zones created by the secondary mirror supports (spider arms), thus directly impacting the phasing sensor or wavefront sensor.

As part of the telescope simulator, a phasing system based on the Zernike contrast sensor principle (Dohlen et al., 2006) will be implemented, while alternative solutions, such as the asymmetric pupil Fourier wavefront sensor (Martinache et al., 2013), or the self coherent camera phasing sensor (Janin-Potiron et al., in preparation), will be compared. In this context, the purpose of the former ESO Active Phasing Experiment (APE) project (Gonté et al., 2009) was to explore, integrate and validate non-adaptive segment phasing schemes and technologies at the telescope level for an ELT. While the current specifications of the E-ELT segment phasing is assumed to be achievable by such means, high-contrast imaging might be much more demanding in terms of phasing requirements. Fine phasing at the instrument level will be treated within SPEED.

Wavefront-shaping module

Two sequential deformable mirrors of 952 actuators (DM1 and DM2), separated by free-space propagation, constitute the wavefront control and shaping module of SPEED, enabling efficient correction for both phase and amplitude errors, and/or remapping of the pupil discontinuities. The upfront correction of aperture irregularities by optical remapping in the geometric, and thus achromatic, regime is feasible for subsequent feeding into a coronagraphic stage. The difficulty is driven by the demand to derive mirror shapes (Pueyo et al., 2013) suitable to remove the structures introduced by spiders and gaps, without losing photons.

Coronagraphic module

Several small IWA-class coronagraphs are currently the subject of vigorous R&D to bring them to high technological

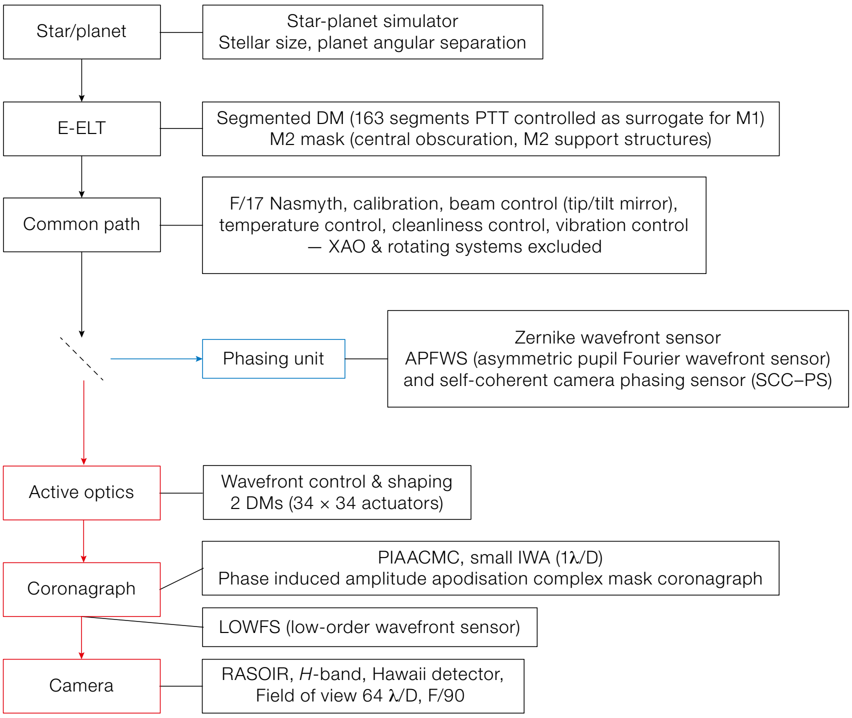

Figure 1. The general layout of SPEED is shown with optical/near-infrared paths differentiated by blue and red colours respectively.

maturity. In particular, PIAA (phase induced amplitude apodisation) uses beam remapping for lossless apodisation (Guyon et al., 2014), and can be combined with opaque masks (PIAAC and PIAALC), or partially transmissive phase-shifting (complex) masks (PIAACMC). PIAA theoretically offers complete starlight extinction, with high throughput and sub-λ/D inner working angle, regardless of the aperture shape. PIAA offers nearly 100% throughput and approaches the fundamental coronagraph performance limits.

The technological maturity of PIAA benefits from ten years of R&D activities, from scratch to on-sky demonstration, and actual raw contrast reaches levels up to 10^{-8} at 2 λ/D and is expected to deliver 10^{-6} in *H*-band at 1 λ/D at the Subaru Telescope. The goal within SPEED is to develop a PIAACMC that can cope with 1 λ/D IWA, stellar angular size up to 0.5 mas, and correct for all or part of the telescope pupil discontinuities (secondary support structures) with raw contrast of 10^{-7} at the IWA. The PIAACMC is shown in Figure 2 and is composed of three elements: the PIAA module (to create pupil apodisation by optical remapping without losing photons), a complex focal plane mask, and a PIAA^{-1} module (called PIAA inverse, to recover the translational invariance of the point spread function lost with the PIAA module). As the PIAACMC development will require intensive efforts in the manufacturing and testing process, a step 0 coronagraph based on conventional pupil apodisation will be considered in the early stage of the experiment.

Coronagraphic wavefront sensor

A low-order wavefront sensor is critical to ensure that starlight remains centred at the coronagraphic plane. Since the PIAACMC is part of a family of coronagraphs that is optimised for the detection of companions at very low angular separations, it is highly sensitive to low-order aberrations, especially tip-tilt errors (pointing errors). The SPEED bench therefore includes a robust and efficient wavefront sensor to measure tip-tilt as well as defocus, namely the coronagraphic low-order wavefront sensor (CLOWFS; Vogt et al., 2011). Since the PIAACMC is a phase-mask-based coronagraph, the light used for the analysis is taken at the Lyot-stop plane, i.e., reflected towards an optical element that refocuses the light onto the LOWFS camera. A dedicated tip-tilt mirror upstream in the optical path will be used to correct for the tip-tilt estimation from the CLOWFS. As the PIAACMC has to cope with stellar angular size up to 0.5 mas, residual jitter (tip-tilt) must be no larger than the stellar angular size in the error budget, hence

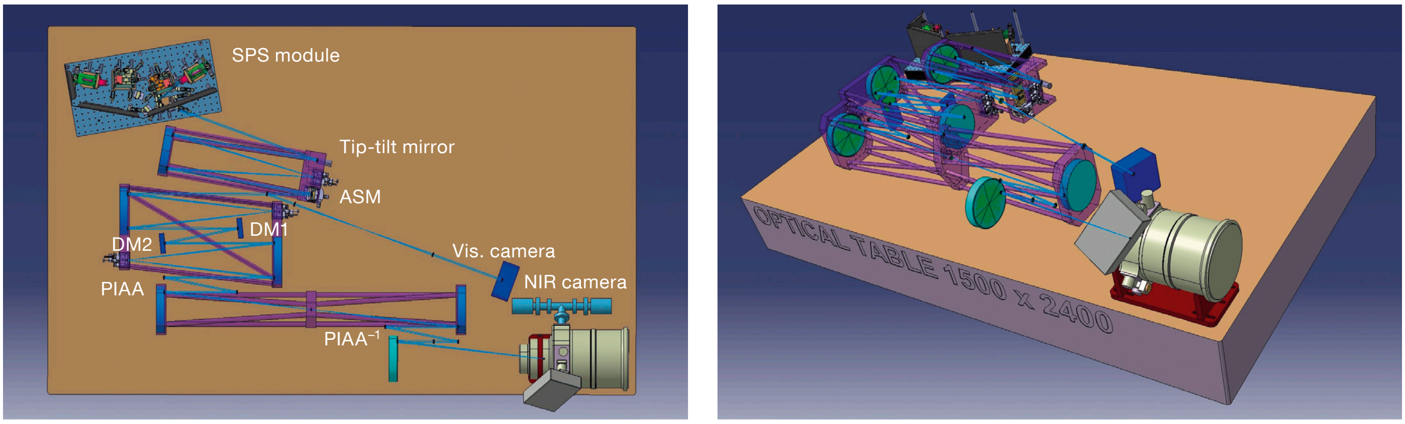

Figure 2. 3D optical/mechanical views of the SPEED bench are shown: from above (left) and inclined (right).

no larger than few 10^{-2} λ/D at 1.6 µm. On top of that, in order to achieve point spread function raw contrast of 10^{-7} at such small IWA with the PIAACMC, quasi-static pointing should likely be accurate to about 10^{-3} λ/D at 1.6 µm. Such tiny levels have already been demonstrated at the 10^{-2} level at the Paris Observatory (Mas et al., 2012) and at the 10^{-3} level at the Subaru Telescope (Vogt et al., 2011).

Imaging cameras

The infrared camera works at 1.65 µm with an internal *H*-band filter. Its read-out noise is 12 e- rms/pixel and quantum efficiency > 60%. It is a 1k by 1k Hawaii array (engineering grade) from which we select only a quadrant of 512 pixels (enough considering the field of view of 64 λ/D); it is read in double-correlated sampling mode. The optical camera for the phasing unit is an Apogee camera with 1024 × 1024 pixels with 2.2 e- rms/pixel read-out noise, and 92% quantum efficiency.

Current status

The SPEED testbed is temporarily installed at the Côte d'Azur Observatory and will be relocated to Nice University in early 2016 (in an ISO7 class room). It is placed on an optical table with air suspension, and reflective optics has been adopted for the whole design, except for the phasing unit arm. The testbed is located in a cleanroom in a nearly closed box to minimise internal turbulence and optimise stability. The bench environment is being intensively characterised. The stability of the whole system is one of the major concerns and will be characterised, monitored, pre-compensated by design as far as possible, and efforts will focus on developing actively controlled solutions to ensure the required level of stability for reaching the objectives of the project.

The finalisation of the SPEED optical design is underway pending extensive numerical simulation efforts. An end-to-end simulator code is nearly complete for adequately specifying the remaining parameters related to the Fresnel/Talbot effect. Mastering of these effects is mandatory for instrumental and contrast design. Integration is planned to start in mid-2015. Most of the critical hardware is already in-house and under extensive test and characterisation.

The SPEED project: A step towards the ELT-PCS and a path toward PRIS^{2}M

The overall objective of the SPEED project is to advocate R&D for the future generation of high-contrast imaging instruments. Devising a practical solution for broadband high-contrast capabilities operated at very small angular separation on unfriendly/complex apertures is an outstanding problem in high-contrast instrumentation. In particular, SPEED aims at increasing the technological readiness level of several subsystems to a satisfactory status for any high-contrast instrument for the E-ELT, especially for the E-ELT Planetary Camera and Spectrograph (PCS) instrument (Kasper et al., 2013). Although selected for construction, the ELT-PCS is subject to technical readiness, whereas it is considered mandatory for the E-ELT to achieve its primary science case (imaging and characterisation of exoplanets ideally down to Earth-like planets in the habitable zone). The technological requirements are ambitious and considered to be not yet ready for key components and subsystems, but with a clear R&D roadmap (Kasper et al., 2013) it should be possible to avoid any major showstopper. The primary objective of the SPEED project is therefore to provide a strong contribution to these efforts.

Together with this initial ambition, the SPEED project has been conceived as an initiator for a real instrument, likely in visitor mode, either dedicated to the VLT (or similar class of telescopes), or to an incentive demonstrator/precursor instrument for the E-ELT-PCS (assuming the presence of a visitor port with access to a single conjugated adaptive optics [SCAO] system). The recent two-phase approach to the E-ELT construction could foresee an early on-sky demonstration of PCS technologies on a 8-metre telescope as the optimal approach. Using an 8-metre telescope as test bed for E-ELT high-contrast imaging instrumentation could indeed be a major asset and could leverage significant scientific gain over the SPHERE instrument.

A large number of new ideas and know-how could be inherited from the SPEED experiment to build a simplified, single purpose, and thus efficient, instrument. For instance, a small IWA observing instrument to search areas very close to M-dwarfs could straightforwardly emerge from the SPEED project. This is the ambition behind the PRIS^{2}M project (Planet Research Instrument at Small Separations from M-dwarfs) under exploration at the Lagrange Laboratory. Such an instrument could be seen as both a complementary programme for SPHERE (M-stars are not covered by the SPHERE science cases) and an exploratory programme for exoplanet direct imaging with the E-ELT-PCS, tackling an important science objective. It could bridge the gap between current exoplanet imaging instrumentation and the E-ELT-PCS slot, or alternatively anticipate by ten years the operation of a high-contrast imaging instrument at the E-ELT. The high density of M-dwarfs in the Solar Neighbourhood makes them good candidates for searches for young planets, ensuring a favourable contrast. M-dwarfs are important for understanding the mechanisms of planet formation and are currently the focus of several ongoing survey programmes.

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