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SPEED — Get Ready for the (PCS) Rush Hour

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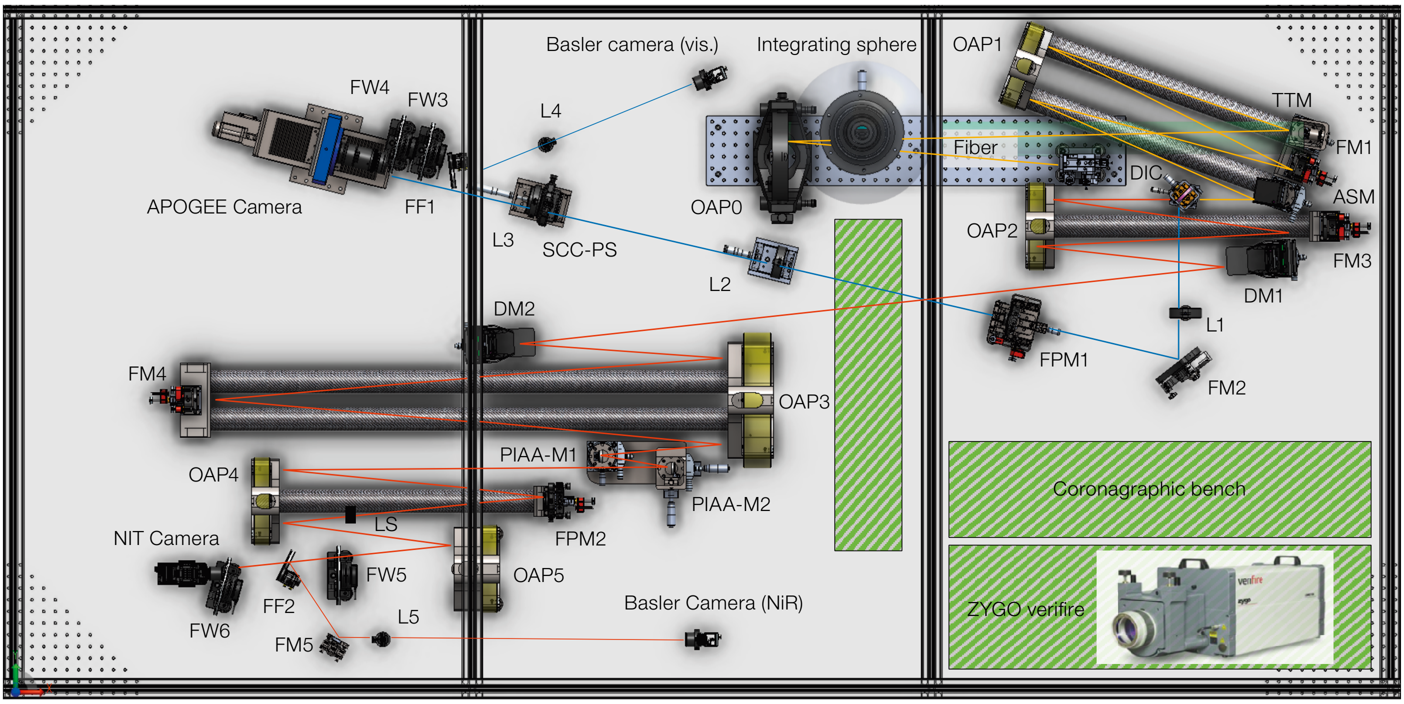
The Segmented Pupil Experiment for Exoplanet Detection (SPEED) optical test bed is now ready for operation. SPEED is dedicated to high-contrast imaging at short angular separations with segmented telescopes. Its optical design allows a wide range of applications and the immediate goal is to demonstrate a high-contrast dark hole close to the stellar vicinity. This will be achieved by a combination of optimal wavefront shaping architecture, small inner working angle coronagraphy, and efficient complex field sensor for fine cophasing and dark hole generation.

Science case and challenges

Direct observation of exoplanets is challenging but essential to the study and understanding of the properties of exoplanets' atmospheres, for which few data are available. The majority of exoplanets so far known were discovered by indirect methods and, despite the progress with the second generation of high-contrast imaging (HCI) instrumentation, direct imaging detections remain marginal (~ 1%). Directly imaging and characterising a fairly large number of exoplanets requires an optimal combination of telescope and instrument to provide extremely high contrast, very good sensitivity, and exquisite image quality and stability. Among the target stars, low-mass M-stars are particularly attractive because of the considerable number they represent within 20 light-years of the Sun, and because they are arguably the most common environment with the potential to harbour life. Observing habitable planets around nearby M-stars is of the greatest scientific importance but represents an extreme instrumental challenge. The Planetary Camera and Spectrograph (PCS; Kasper et al., 2021) for ESO's Extremely Large Telescope (ELT) must provide an imaging contrast of 10^{-8} at 15 milliarcseconds angular separation from the star (1.5 to 2 λ/D in the near-infrared) and 10^{-9} at 100 milliarcseconds and beyond. A promising path to reach these capabilities is a combination of extreme adaptive optics (XAO) supported by a second-stage AO to reduce the temporal delay, an HCI system, and high-dispersion spectroscopy (HDS). Various activities are under way in the community on these topics, for example SPHERE+ (Boccaletti et al., 2020), HiRISE (Vigan et al., 2018), RISTRETTO (Blind et al., 2022), KPIC (Mawet et al., 2018), MagAO-X (Males et al., 2018), SCExAO (Lozi et al., 2018) as well as many laboratory-based developments[1].

In this context, the Segmented Pupil Experiment for Exoplanet Detection (SPEED)[2] facility offers an ad hoc environment to improve HCI considering the ELT pupil fragmentation and to assess the impact on control and control stability of quasi-static speckles. SPEED is positioned within a three-body problem:

Figure 1. 3D CAO view of the SPEED test-bed. Colour code: telescope simulator and common path (yellow), visible path (blue) and near-infrared path (red). Abbreviations: TTM — tip/tilt mirror, OAP — off-axis parabola, ASM — active segmented mirror, DM — deformable mirror, FM — flat mirror, DIC — dichroic, L — lens, SCC-PS — self-coherent camera-phasing sensor, FPM — focal plane mask, PIAA-M1 & PIAA-M2 — phase induced amplitude apodisation mirror 1 & 2, LS — Lyot stop, APOGEE — visible camera, NIT — near-infrared camera, Basler — pupil camera (visible and NiR), FF — flip-flop mirror, FW — filter wheel.



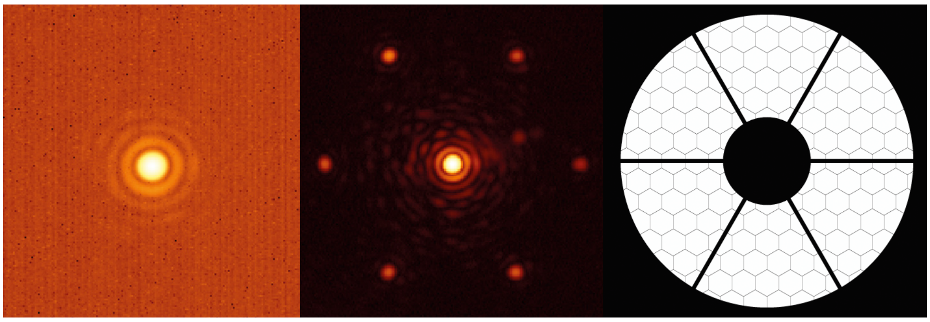


Figure 2. From left to right: near-infrared arm (*H* band, 1.65 μm, Strehl ratio = 98%) point spread function image; visible arm (650 nm, Strehl ratio = 93%) point spread function; and an image illustrating the telescope pupil.

improving, at the HCI system level, the contrast (deeper), and the angular separation (closer), to access new scientific targets (fainter). Integrated into an ISO7 clean room at the Lagrange Laboratory of Côte d'Azur University, SPEED will be an optimal cocoon for studying coronagraphy, control and shaping of the wavefront, and fine correction of cophasing error by considering the effects, disturbances, and instabilities generated by pupil fragmentation. Active control and temporal stability of residual wavefront errors is one pillar to consider for improving detection yields and getting access to object classes with masses ideally down to exo-Earths. The bench is now completed and is entering a period of intense exploitation before being made available to the community.

Concept and design choices

SPEED, as depicted in Figure 1, combines a light source module, a telescope simulator (orange line), and a dichroic reflecting in the visible light to cophasing optics (blue line) and transmitting the near-infrared light (red line) towards wavefront shaping, coronagraphy, and the science camera. The common path includes all the optics needed to feed the beam to the cophasing and science paths. The telescope simulator consists of the combination of an active segmented mirror (ASM) with 163 segments controlled in piston and tip-tilt, and a physical mask magnetically fixed on the structure of the tip-tilt mirror (TTM; for beam stability control) to simulate the presence of a large central obscuration and secondary support structures mimicking the ELT pupil (see Figure 2, right panel). The cophasing unit (blue line) is based on image-plane analysis using the Self-Coherent Camera Phasing Sensor (SCC-PS; Janin-Potiron et al., 2016) and Fast-Modulated Self-Coherent Camera (FM-SCC; Martinez, 2019). The near-infrared path (*H* band, red line) includes a wavefront control and shaping module made of two Kilo-C deformable mirrors (DM) of 952 actuators (DM1 and DM2) separated by free-space propagation. Both DMs are out-of-pupil planes, enabling efficient correction of phase and amplitude errors (Beaulieu et al., 2017). The coronagraph, a Phase Induced Amplitude Apodisation Complex Mask Coronagraph (Guyon et al., 2014), or an Apodised Pupil Complex Mask Coronagraph (APCMC), offers high throughput and close to ~ λ/D inner working angle (IWA). A FM-SCC is being integrated into the near-infrared arm of the bench at the Lyot Stop (LS) plane. The bench rests on a 1.5 × 2.4 metre table with active vibration isolation supports. The area where the table is installed is isolated from building vibrations.

SPEED incorporates a lot of devices: four detectors, two webcams, three lamps, ~ 25 motorised functions, five sensors, 12 piezo actuators, two shutters, three DMs, one TTM, amongst others. We select reflective optics for the whole design, except for the phasing unit arm. Super-polished off-axis parabolas (OAP) are employed to minimise optical aberrations down to 3 nm RMS over a 10-mm beam diameter surface with power spectral density (PSD) following a f^{-3} power law. We operate the bench completely covered with protection panels forming a nearly closed box to minimise internal turbulence and optimise stability. The instrument boasts five observing modes: three engineering modes enabling pupil control and monitoring in the near and visible arms, a science observing mode for monitoring and correcting in close loop the alignment of the telescope primary mirror segments (fine cophasing optics), and a science observation mode for real-time coronagraphic and dark hole observations. The bench also accommodates on its table a separated coronagraphic test bed (Figure 1, hatched area) for controlling the performance of the coronagraph focal plane masks before inserting them into the SPEED optical path. In addition, we use a ZYGO interferometer for metrological and alignment purposes.

Along with the evolution of the architectural design, a simulation model tool through an end-to-end simulator (e2e) was developed for specifications, performance control, evaluation, and analysis (Beaulieu et al., 2017, 2020). The SPEED e2e is a high-fidelity performance, design analysis and verification tool that incorporates Fresnel diffraction propagation using PROPER (Krist et al., 2007) combined with a realistic system model, and up-to-date optical bench design. It considers simulated wavefront sensing and control, including as-built optics with measured wavefront errors, and guarantees that the simulator is in step with the SPEED bench optical contrast design. A by-product of the SPEED e2e is to simulate and test hardware parts or pieces of algorithms that the bench itself does not yet support.

Our wavefront-shaping architecture for high-contrast imaging at short separations consists of a pair of out-of-pupil DMs separated by 1.7 m (DM1 is at 0.2 m and DM2 is at 1.5 m from the pupil). It was determined based on significant efforts in complex modelling by considering the intrinsic properties of the optics setup, including polishing frequency distribution, relative beam size, the distance between optics, DM optical location (in a collimated beam — out-of-pupil plane or in a pupil plane — versus converging beam) and separation, DM properties (actuator number, etc.). High-contrast imaging at short separations with multi-DM architecture requires large DM separations, and exhibits a significant performance dependence on the DM location, on the amount of aberrations and the power spectral density (PSD) power law and on the dark hole size. It is not impacted by highly aberrated optics as long as they are located in a collimated beam (cophasing errors, deformable mirrors windows, dichroic), but it is affected by finite DM stroke, adjacent non-functional actuators, phase errors on the coronagraph or near the focal plane, and optics aberrations downstream of the coronagraph.

Calibration and instrument control

Non-common-path aberrations (NCPA) are present to some extent in all high-contrast imaging data, and contribute additional speckle noise which is strongest at small angular separations and thus detrimental to coronagraphic performance. For SPEED, these aberrations are typically estimated to contribute an average wavefront error of approximately 40 nm RMS. An offline differential optical transfer function (Codona et al., 2013) compensation procedure has been operated to further reduce these NCPAs to 28 nm RMS using the ASM for the correction. This is an impressive result, considering that the ASM is segmented and that the main contributor to the wavefront error budget is the ASM itself with 30 nm RMS wavefront error (mostly dominated by segment focus and astigmatism errors that the ASM cannot correct for). The optical quality of the SPEED test bed near-infrared arm is, without correction of the NCPA, of the order of ~ 96 % Strehl ratio at 1650 nm. Correcting for NCPA improved the Strehl ratio to a very high ~ 98 %, i.e., $\lambda/40$ RMS at 1650 nm (Figure 2, left panel). The final near-infrared point spread function image demonstrates exquisite image quality. The optical quality of the SPEED test bed visible arm is, without correction of NCPA, of the order of ~ 86 % a Strehl ratio at 650 nm and drops to ~ 93 % with NCPA correction (Figure 2, middle panel).

The SPEED test bed, being more complex than a simple laboratory test bench but less demanding than an on-sky instrument at a telescope, requires a specific and adapted system and software control development that enable the bench to operate efficiently and safely (Martinez et al., 2022a). The bench is controlled through a dedicated control network that interconnects three workstations and uses the instrument software (SPEED control software, SCS) that enables control of all the sub-systems consistently and reliably. The SCS is in charge of controlling all the bench functions, coordinating the execution of actions, implementing all observation, calibration, and safety procedures, and providing a quick look for monitoring the status of ongoing observations and conditions. Interactions with external parties such as the building centralised technical management, internal and external network, as well as a backup system, are also incorporated. We enforce a great deal of error checking at compile-time and at run-time through a crash log diary and command feedback window (CFW) and CFW log file so that there are various recordings of what has happened. We pay close attention to implementing any non-trivial functionality in such a way that it can be tested without the need to start the entire software or a substantial part of it that belongs to hardware and in particular sensitive hardware. For that reason, the SCS includes an emulator mode that allows diagnostic or implementation and testing, connecting only emulated hardware if needed. The safety of hardware is a priority and consists in protecting every piece of hardware from damage using a series of safeguards within the code. We implement an additional layer of security on top of the security sometimes offered by hardware controllers. Operational conditions, such as environmental conditions, are of concern because they may prohibit the use of specific hardware. They are therefore constantly tracked and verified. We also avoid conflict of use and manage error codes or status codes to track anomalies and leave the hardware in a safe state.

Roadmap for the next years

The SPEED test bed is aligned, completed, and ready for exploitation. It saw first light in the visible in 2020 and the near-infrared in summer 2022 (Martinez et al., 2022b). In the coming years we plan to (1) support and validate the high-level primary objectives defined in our top-level requirements, (2) initiate an upgrade programme of the bench towards a more representative environment of the ELT, including for instance an XAO residual turbulence generator using phase screens or a spatial light modulator, (3) make the bench available to the community as a representative environment with unique capabilities for testing hardware and algorithms given the PCS instrument. Ultimately, this laboratory experience will help refine computational models, leading to performance and tolerance predictions for future instrument architectures.

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Links

[1] Website of the community of adaptive optics and high-contrast test-beds: https://sites.google.com/view/highcontrastlabs/home?authuser=0
[2] SPEED project website: https://lagrange.oca.eu/en/lag-speed-home