4.4 SPEED

A. Context and state of the art

Current state-of-the-art and prospects of exoplanets observations

As Co-investigators (Co-Is) of the recently commissioned ESO/SPHERE instrument at the VLT, members of the *Institute Convergence* are actively involved in R&D activities for preparing efficient high-contrast imaging instruments for exoplanet detection and characterization envisioned for the forthcoming generation of ground-based observatories (the extremely large telescopes, ELTs).

High-contrast imaging of exoplanet provides an ideal window to characterize planets and their host system though spectro-photometry of planetary atmospheres, or planet-disk interactions for instance. Though searching for exoplanets with direct imaging is one of the major scientific drivers for both space and ground-based programs, it suffers from technological challenges as the contrast issue demands exquisite image quality and stability. Direct imaging of extra-solar planetary systems constitutes a multiple layer of challenges, and practical hurdles are numerous: e.g., small angular separation between planets and stars, high contrast ratio between a planet and its host star.

While the second generation of dedicated high-contrast instruments on 8-m class telescopes (e.g., SPHERE, GPI, SCExAO, Project 1640) are greatly expanding the sample of directly imaged planets, exploring the planetary parameter space to hitherto-unseen regions ideally down to Terrestrial planets imposes a major technological breakthrough for the forthcoming decades. The technological gap barring the way towards this appealing science must be tackled now in preparation for future programs (>2030).

Given the current state-of-the-art and prospects of exoplanet observations from space (KEPLER, GAIA, JWST) and the ground (e.g., SPHERE, GPI), a high contrast imager for an ELT will mainly focus on the characterization of exoplanets from Jupiter down to Earth masses in the solar neighborhood, and the detection and characterization of very young giant planets. In this context, nearby M-dwarfs are more and more on the focus of ongoing and planned surveys. The high density of M-dwarfs in the solar neighborhood makes them good candidates for searches for young planets, ensuring a favorable contrast, though they show some unfavorable properties (intrinsically faint especially at optical wavelength, rapid rotation and strong magnetic activity, etc.)

In this context, members of *Institute Convergence* were involved in the E-ELT exoplanet imaging camera EPICS (Kasper et al., 2010) phase *A* conceptual study (as Co-Is) that highlighted the complexity of the error budget affecting the propagation of light in such a new class of instrument. As a result various technological limitations were identify to be addressed through numerous development programs (e.g., high-order deformable mirrors, real-time systems, wavefront sensors, etc.). Notwithstanding these obstacles that some of which will probably require technological breakthroughs to surmount, additional concerns affecting the exoplanet search problem require that brand new challenges intrinsically inherent from this new class of telescopes (ELTs) must be tackled in the meantime (Fresnel effects, complexity of the telescope pupil, etc.).

The next generation of ground-based observatories…

After completion, the E-ELT (the European 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 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. 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. This requires significantly improving high-contrast capabilities at close angular separations with respect to the state of the art of 8-m class telescopes. The increase of the primary mirror diameter is indeed a common need for both space and ground-based observations, and segmented telescopes offer a practical path towards dramatically enlarging telescope diameter. 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.

…and practical hurdles

This unavoidable need for spatial resolution and photon sensitivity leads to telescopes that by design are less and less optimal for the exoplanet search problem (e.g., ELTs, JWST, HDST). 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 (due to the limited number of spare segments and short lifetime of the segments coating), 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 addition, one must consider that ELTs will start resolving 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 (coronagraphic leakage is proportional to the square of stellar radii).

It is also uncertain whether the high-precision phasing requirements deemed appropriate for a high-contrast instrument can be achieved, and instrument level solutions must be seriously considered.

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.

On top of that, 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. 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 specialized 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.

The SPEED project

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 mid-2013 to study solutions for optimizing high-contrast imaging with unfriendly telescope apertures.

SPEED — the Segmented Pupil Experiment for Exoplanet Detection — in development at the Lagrange Laboratory by members of *Institute Convergence*, aims at preparing strategies and technologies for high-contrast instrumentation with segmented telescopes. This instrumental platform offers an ideal environment in which to make progress in the domain of ELTs or space-based mission 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 (exoplanets around M-stars is the main science driver of the project).

The SPEED project and thus our team is involved in efforts in science-grounded instrument conception and contrast design especially considering Fresnel/Talbot effect. The relationship between scientific requirements (performance requirements) and instrumental requirements is not trivial and generally quite complicated. Current exoplanet imager systems are rarely limited by residual atmospheric speckle noise, but rather by quasi-static speckles, evolving on larger timescales and taking origin from internal aberrations sources. Contrast is usually determined by various factors including cross talk effects. In this context, an additional and specific care must be considered regarding Fresnel and Talbot effects, which are fundamentally uncorrectable when the optical design

is frozen. Fresnel propagation terms and Talbot effect are important class of perturbation: a pure phase aberration on an optical surface mixes between phase and amplitude aberrations as light propagates. In a collimated beam, this oscillation effect occurs over a distance called the Talbot distance that is proportional to the square of the aberration spatial period and inversely proportional to the wavelength of light (hence the Talbot distance is chromatic). This effect is particularly important as phase aberrations if correctly sensed can be corrected with a single deformable mirror, but amplitude aberrations cannot. Optical phase and amplitude errors can be corrected using two-sequential DM architecture assuming well mastering of these effects. The optimization of such an optical architecture regarding to Fresnel/Talbot effects and the instrument contrast design is one of the key aspect we are tackling in the SPEED project. While these effects were barely considered on 8-m class telescopes, they will be preponderant for ELTs (contrast requirements are much more demanding, and beam compression is cruder).
The overall objective of the SPEED project is to advocate R&D for the future generation of high-contrast imaging instruments. In particular, SPEED aims at increasing the technological readiness level of several subsystems to a satisfactory status for a 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. The technological requirements are ambitious and considered to be not yet ready for key components and subsystems. The primary objective of the SPEED project is therefore to provide a strong contribution to these efforts.

B. Current activity

The SPEED testbed is under development at the Nice University (Lagrange laboratory) in an ISO7 classroom. The finalization of the SPEED optical design is nearly completed after extensive numerical simulation efforts. An end-to-end simulator code for adequately specifying the key parameters related to the Fresnel/ Talbot effects has been extensively developed and used in 2015/ 2016 in the context of a PhD work. Integration is starting this year. In the mean time, a novel focal plane co-phasing sensor has been proposed and studied by means of numerical simulations and will be developed and tested in the laboratory in 2016 (in the context of another PhD). Most of the critical hardware is already in-house (segmented deformable mirror, continuous face-sheet deformable mirrors, imaging cameras (optical and near-infrared), tip/ tilt, electronics, light sources, etc.) and under extensive test and characterization. The SPEED bench is mainly made of reflective optics with excellent optical quality. The first parabola has been delivered in March 2016 and exhibits ~1 nm rms over the beam diameter surface.

C. Future steps

Short and middle term developments
We plan to start the integration of the SPEED bench in fall 2016. Alignment, integration and tests (AITs) will last at least for two years to successively integrate all the components, while in parallel (starting mid-2016) short-term and single task separated testbeds will be developed to independently contribute to confirm/further analyze various research aspects: novel co-phasing sensors, Fresnel properties, very small IWA coronagraph, stability, etc.

Long-term outcome
Together with its initial ambition, the SPEED project has been conceived as an initiator for a real instrument, either dedicated to the VLT (or similar class of telescopes), or to an incentive demonstrator/precursor instrument for the E-ELT-PCS. For instance, 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.

For this, we intend to take advantage of a large number of new ideas and know-how that will be inherited from the SPEED experiment to build a simplified, single science-oriented 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) that our team intends to promote after completion of the SPEED research objectives. Such an instrument could be seen as both a complementary program for SPHERE (M-stars are not covered by the SPHERE science cases) and an exploratory program for exoplanet direct imaging with the E-ELT-PCS, tackling an important science objective. Such a project 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.

References:

[1] Kasper et al., EPICS: direct imaging of exoplanets with the E-ELT. Proceeding of the SPIE 2010

[2] Martinez et al., The Segmented Pupil Experiment for Exoplanet Detection: SPEEDing up R&D towards high-contrast Imaging instruments for the E-ELT, The Messenger 2015 n° 159

[3] Kasper et al., Roadmap for PCS, the Planetary Camera and Spectrograph for the E-ELT. Proceeding of AO4ELT 3rd Edition, 2013.

D. International collaborations

We collaborate with:

- O. Guyon, Associate professor, Department of Astronomy and Steward Observatory University of Arizona (USA), Project investigator (P.I) of the Subaru SCExAO instrument.

- M. Kasper, Astronomer, ESO European Southern Observatory (Germany), Project investigator of the ELT-PCS instrument.

E. List of people involved in the project

Permanent researchers:

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Students & PhDs:
- Janin-Potiron P., PhD
- Beaulieu M., PhD
- IUT trainee

F. Most significant publications of the team

Janin-Potiron, P., Martinez, P., Baudoz, P. & Carbillet, M. **Self-coherent camera as a focal plane phasing sensor, A&A (2016) submitted.**

Martinez, P., Preis, O., Gouvret, C., Dejongue, J., Daban, J-B., Spang, A., Martinache, F., Beaulieu, M., Janin-Potiron, P., Abe, L., Fantei-Caujolle, Y., Mattei, D. Ottogali, S. & Carbillet, M. **The Segmented Pupil Experiment for Exoplanet Detection : SPEEDing up R&D towards high-contrast Imaging instruments for the E-ELT, The ESO Messenger n° 159 (2015).**

Janin-Potiron, P., Martinez, P., Baudoz, P. & Carbillet, M. **The self-coherent camera phasing sensor : a new tool for co-phasing segments for ELTs, Proceeding of AO4ELT 4th Edition (2015).**

Beaulieu, M., Abe, L., Marinez, P., Gouvret, C., Martinache, F., Preis, O., Dejongue, Janin-Potiron, P. & J., Vakili, F. **A Fresnel propagation analysis for SPEED, Proceeding of AO4ELT 4th Edition (2015).**

Preis, O., Martinez, P., Gouvret, C., Dejongue, J., Daban, J-B., Spang, A., Martinache, F., Beaulieu, M., Janin-Potiron, P., Abe, L., Fantei-Caujolle, Y., Mattei, D. Ottogali, S. & Carbillet, M. **System analysis of the Segmented Pupil Experiment for Exoplanet Detection - SPEED - in view of the ELTs. Proceeding of the AO4ELT 4th Edition (2015).**

Martinez, P., Preis, O., Gouvret, C., Dejongue, J., Daban, J-B., Spang, A., Martinache, F., Beaulieu, M., Janin-Potiron, P., Abe, L., Fantei-Caujolle, Y., Mattei, D. & Ottogali, S. **SPEED the Segmented Pupil Experiment for Exoplanet Detection, Proceeding of the SPIE (2014).**

Short CV of participants

P. Martinez, UNS Associate professor. Expert in high-contrast imaging instrumentation. Project investigator of SPEED. Involved in the ESO/SPHERE instrument, and the ELT/PCS (formerly EPICS) phase A conceptual study. 22 referred publications, 74 references.

L. Abe, Associate astronomer, Expert in exo-planet detection and characterization instrumentation and transiting planets observations from Antarctica. Involved in the Subaru/HiCIAO and ESO/SPHERE instruments. 87 refereed publications.

M. Carbillet, UNS Associate professor w/ HDR. Expert in astronomical high-angular resolution (numerical modeling, adaptive optics, coronagraphy, imaging). Involved in the ESO/SPHERE instrument. 33 refereed publications, ~100 conference publications.

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O. Preis, CNRS, Instrumentation and system engineer. Project manager of SPEED and JOVIAL (Jupiter Oscillation through Velocity Image at severAl Longitudes) projects.

C. Gouvret, CNRS, Optical instrumentation engineer (optical design and simulation, integration).

J. Dejonghe, UNS, design engineer in instrumentation, opto-mechanics studies.

A. Spang, CNRS, Optical instrumentation engineer. Coauthor of 50 referred publications.

Y. Fantei-Caujolle, CNRS, Computing/software engineer. Involved in the ESO/MATISSE instrument.