Innovative Fourier-based Wave-Front Sensors for High Contrast Imaging : from Laboratory to On-Sky Experimentation

Name of the laboratory: The PhD will be shared between 3 institutes: LAM (Marseille – France), ONERA (Paris-France) and INAF (Arcetri, Florence- Italy). **This PhD is funded.**

Thesis advisor & co-advisors:
ONERA – Thierry Fusco (Thierry.fusco@onera.fr)
LAM-Marseille – Benoit Neichel (Benoit.neichel@lam.fr)
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Presentation of the project

Europe is currently preparing the largest telescope of the world: the ELT [European Extremely Large Telescope (https://www.eso.org/public/france/videos/elttrailer/). Planned by the end of 2025, this huge telescope of 39 m diameter will allow answering fundamental questions of contemporary astrophysics by imaging exoplanets or studying large scales of the universe. However, images of astrophysical objects done by ground based telescopes suffer from the distortion caused by the atmospheric turbulence which reduces the capacity of instruments to distinguish objects too close to each other. Adaptive Optics [AO] is a technique which allows restoring this loss of angular resolution by correcting the effects of atmospheric turbulence. In operation, on several astronomical observatories for almost 25 years, This technology is based on a deformable mirror which corrects in real time the incoming wave front by using information coming from a sensor which measures the turbulent phase called «Wave Front Sensor » [WFS]. WFS is the heart of any AO system. Ultimately it drives the final performance of the AO and thus of the associated astrophysical instrumentation.

For direct imaging of exoplanet applications, the state of the art AO instruments – SPHERE@ESO (https://www.onera.fr/fr/actualites/loptique-adaptative-de-lonera-au-coeur-de-la-chasse-aux-exoplanetes and GPI@GEMINI – are both using classical Shack-Hartman WFS [SHWFS]. Those instruments have been designed for an extreme Wave-Front control, hence a very high sub-aperture density. They typically provide 40x40 phase measurement points across the 8meter telescope pupil. It has been shown that one of the main performance limitations of these instruments comes from the fast atmospheric residuals, which are not properly compensated by the AO correction. Figure1 illustrates this case on real SPHERE data: when the atmospheric conditions are evolving faster than the AO correction rate, significant residuals from uncorrected star light pollute the images in the region where exoplanets could be discovered. The exoplanet detectability is reduced by factors 2 to 10. To tackle this issue, the AO corrections must be applied at a faster rate, typically 2 to 3 times faster than the 1 kHz which is the current standard for both SPHERE and GPI. Using the same SHWFS, this would mean dramatically reducing the limiting magnitude, and hence the number of suitable targets. This also means having access to a noiseless detector running at > 3kHz, which may be at the limit of what current technologies can do, but out of the scope of future ELT requirements. Indeed, scaling a SPHERE-like instrument for the ELT would require more than 200x200 phase measurement points across the pupil, and the need for noiseless, large format (>1 million pixels) detectors. Hence **Exoplanet detectability will be improved (x10) with faster (x2-3), more sensitive (1-2mag) and optimized Wave-Front Sensors.**

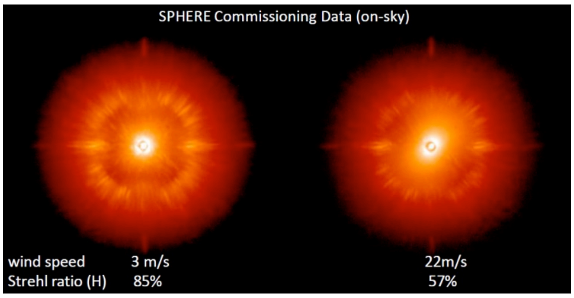

Figure1 ; Impact of wind speed on SPHERE data. Temporal error is the main limitation for the system. Faster and more sensitive WFS are required to improve the performance

Optimizing a wave-front sensor means maximizing the Signal to Noise Ratio of each phase measurements, that is nothing but (1) Finding the most efficient transformation procedure of phase into photons, (2) Minimizing the number of useful pixels on which the signal is coded; (3) Developing new signal processing approaches to deal with the various noises inherent to photon detection: photons, detector read-out, background. In that context several innovative sensors have been proposed in the past decades to overcome the historical SHWFS. The most impressive example is certainly the introduction of the Pyramid WFS, proposed by **INAF** in 1996, which provides AO-corrected images with an astonishing quality at the Large Binocular Telescope. Very recently, **LAM** and **ONERA** have propose an unified and rigorous analytical description of a new particular class of WFS which includes the Pyramid WFS: the Fourier Filtered WFS [FF-WFS] (see https://anr-wolf.com/index.php/wolf-the-project/). It has allowed to identify the three clear stages (beam shaping, spatial Fourier filtering, pupil plane detection and its associated signal processing) required for an efficient wave front measurement and how each stage impacts the WFS performance.

The goal of this thesis is to put together the unique expertise of **INAF, ONERA and LAM** in order to push further the concept of FF-WFS for high-contrast imaging and extrasolar planet detections both on Very and Extremely Large Telescopes. In particular, reaching the ultimate AO performance will imply to be able to deal with new problematics related to the new generation of extremely large segmented telescopes. Two case will be addressed:

1) the Large Binocular Telescope (LBT http://www.lbto.org/) case with its two 8m telescopes co-phased to synthetize a 24m telescope pupil in one direction. This telescope is already in operation and thanks to the INAF contribution to the thesis we will have a direct access to the telescope and its current instrumentations with possibility to propose upgrades and on sky tests of new concepts
2) the European Extremely Large Telescope (ELT) with highly segmented pupil (789 segments of 1.4m) and its future (horizon 2030) Planet Finder Instrument (PCS).

In both case one of the main challenge will be to develop and optimize a dedicated WFS that will be able measure both the turbulence itself and the telescope residual defects (co-phasing residue, spider induced turbulence and differential piston effects) at nanometric level. To do so, the PhD work will be divided in three main tasks.

First, the candidate will take benefit of this major breakthrough in the WFS approach and the design-oriented tools that have been developed at LAM and ONERA to propose a WFS that could answer to problematics of LBT and ELT next generation of planet finder instrumentation. Combining this tool with end-to-end simulation, he/she will (i) perform a comprehensive analysis of FFWFS ultimate performance in a segmented telescope environment and (ii) develop robust sensors allowing to deal with various exogenous conditions inherent to their use in operational conditions within complex environments (pupil fragmentation due to spiders, residual co-phasing errors, etc).

Second, using the LOOPS bench (see https://anr-wolf.com/index.php/wolf-the-project/ressources-2/ressources/) already available at LAM, an experimental validation of the WFS concept within an AO loop environment in a representative context of the two considered telescopes (reproduction of the two LBT pupils or the ELT segmented pupil) will be conducted. This essential step will allow us to define the calibration and observation procedures that will be required for an operational demonstration on the telescope.

Finally, some very preliminary on-sky tests could be foreseen using state-of-the-art AO instrumentation accessible for INAF, ONERA and LAM teams at Observatoire de Haute Provence, William Herschell Telescope (Canary Islands) and Large Binocular Telescope (Tucson Arizona)

PhD setting

The PhD candidate will spend most of his time at LAM (Laboratoire d'Astrophysique de Marseille), with frequent travels to INAF Arcetri and the LBT (Mont Wilson).

Funding

Funding is provided by ANR-WOLF (https://anr-wolf.com/) and INAF.

Application

Applicants should email (single pdf file)

- a curriculum vitae and a list of publications;
- a one-page motivation letter;
- the contact details of up to three reference persons (no need for the reference letters at this stage)
- a short research statement describing past achievements and future projects

to Benoit Neichel (Benoit.neichel@lam.fr) and Thierry Fusco (Thierry.fusco@onera.fr). Also, please arrange for letters of reference (pdf) to be e-mailed to the project leaders and indicate the contact details of up to 3 reference persons. Deadline is the 1st March 2019. Past this date, applications will be considered depending on availability until filled. The UP and its partners are actively committed to equal opportunity in employment.

Candidates

Excellent candidates with astronomy, applied physics, mathematics, engineering backgrounds with strong signal processing and programming skills are encouraged to apply.

Short bio of advisors

Thierry Fusco get his PhD in 2001, from Paris University VII. He is an experst in Adaptive Optics, and he has been supervising 16 PhD thesis since 2004. The complete list includes:

- **Romain Fétick** « Optimisation des processus de traitement d'images à haute résolution dans le visible. Application à l'imagerie de satellite et l'observation astronomique », première année
- **Cedric Heritier** « Calibration and optimisation of complex AO system on Extremely Large Telescope», deuxième année
- **Lucie Leboulleux** « Contrôle de front d'onde optimal pour l'imagerie à très haut contraste - Application au cophasage de miroirs segmentés », troisième année
- **Olivier Fauvarque** « Optimisation des analyseurs de front d'onde à filtrage optique de Fourier. », Thèse soutenue en 2017
- **Anaïs Bernard** « Développement de nouveaux outils de traitement et d'analyse pour l'Optique Adaptative Grand Champ », Thèse soutenue en 2017
- **Silver Gousset** « Optimisation d'un système d'Optique Adaptative pour l'observation de l'espace et mise en oeuvre d'un détecteur proche infra-rouge innovant en analyse de front d'onde ». Thèse soutenue en 2015
- **Cedric Plantet** « Etude d'un nouveau concept d'analyse de front d'onde en plan focal appliqué à l'optique adaptative en astronomie ». Thèse soutenue en 2014
- **Remy Villecroze** « Modélisation d'un système d'optique adaptative à grand champ pour la reconstruction de la réponse impulsionnelle multi-spectrale des futurs spectro-imageurs 3D du VLT et de l'ELT ». Soutenue en 2014
- **Manal Chebbo** « Simulation fine d'optique adaptative à très grand champ pour des grands et futurs très grands télescopes ». Thèse soutenue en 2013

- **Marie Ygouf** « Nouvelle méthode de traitement d'images multispectrales fondée sur un modèle d'instrument pour la haut contraste : application à la détection d'exoplanètes ». Thèse soutenue en 2012
- **Amélie Parisot** « Calibrations et stratégies de commandes tomographique pour les optiques adaptatives grand champ : validations expérimentales sur le banc HOMER », Thèse soutenue en 2012
- **Bruno Emica** "Caractérisation fine des mouvements et aberrations occulaires pour l'imagerie rétienne à haute résolution", Thèse soutenue en 2012
- **Sarah Dandy,** "Optique adaptative à grand champ pour l'observation des galaxies lointaines avec les futurs télescopes géants" – abandon en 3ième année
- **Benoît Neichel.** "Optique adaptative à grand champ pour l'observation des galaxies lointaines avec les futurs télescopes géants".Thèse soutenue en décembre 2008
- **Jean-Francois Sauvage**. "Calibrations et méthodes d'inversion en imagerie haute dynamique pour la détection directe d'exoplanètes". Thèse soutenue en décembre 2007.
- **Magalie Nicolle.** "Analyse de front d'onde pour les optiques adaptatives de nouvelle génération : optiques adaptatives à large champ et optique adaptative extrême". Thèse soutenue en décembre 2006.

Benoit Neichel get his PhD in 2008, from Paris University VII. He also is a specialist in Adaptive Optics and data processing. He has been supervising several PhDs, with Anais Bernard, Olivier Fauavrque, Cedric Taissir Heritier, Zibo Ke, Vincent Chambouleyron. More details can be found at: https://www.lam.fr/recherche-14/groupe-r-d-optique-instrumentation/article/l-equipe on the current PhD programs, and https://www.lam.fr/recherche-14/groupe-r-d-optique-instrumentation/article/alumni for the past programs.