PROPOSITION DE SUJET DE THESE

Title: A new WFS concept for Extreme AO systems dedicated to direct extrasolar planet imaging on VLT and ELT. From theory to on-sky validation

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(à rappeler dans toute correspondance)

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Keywords :

Astronomical Telescope, Adaptive optics, Fourier Filtered Wavefront Sensor, Super-Resolution, on-Sky Validation, extrasolar Planet

Profile et compétences recherchées :

Engineering school of Optics, Master in Astronomy, Optics, Physics

Présentation du projet doctoral, contexte et objectif :

Context :
Adaptive optics [AO] equips the majority of optical instruments for astronomical observation from the ground. The technological and industrial maturity of the main components of AO systems and the progress made in the understanding of the calibration and operation processes have resulted in instruments of unequalled performance and reliability on most telescopes of the 8/10m diameter class.
Nevertheless, the increase in the size of telescopes (with the forthcoming advent of the Extremely Large Telescope[1] [ELT] combined with the ever-increasing demand for ultimate performance in terms of correction of disturbances (whether generated by atmospheric turbulence or by the telescope itself), efficiency and operational robustness, constantly renews the scientific and technical challenges associated with AO. **This calls for innovative upstream research, in particular in the field of wavefront analysis and control.**

One of the most exciting promises of this new generation telescope is probably the detection of rocky exoplanets around sun-like stars.
Figure 1 shows a the first ever image of a multi-planet system around a Sun-like star located about 300 light-years away and known as TYC 8998-760-1. This amazing picture has been taken in 2020 by the SPHERE instrument[2,3] installed on the 8-m diameter Very Large Telescope [VLT] in Chile with its extreme AO (SAXO) developed by ONERA[4]. Although still limited to gas giants because of the "small" diameter of current existing telescopes, the next generation of 39-m ELT equipped with exquisite AO systems will allow for the discovery, the direct imaging and the spectral characterization of planets down to Earth-like masses. Detecting presence of water, or even complex molecules in an exoplanet would revolutionize our view of the Universe and offer strong evidence for life on other planets. Imaging exoplanets with an ELT is however extremely challenging, and technological breakthroughs are still required. Stars are typically billions of times brighter than the exoplanet we are trying to image and any uncorrected starlight completely swamps the signal coming from the planet. One of the key milestones toward imaging exoplanets is to significantly improve the AO performance. For exoplanet imaging it translates to "extreme" adaptive optics for extreme wavefront control, combining high actuator count deformable mirrors, fast real-time control algorithms, and the use of **very high resolution, extremely sensitive and accurate (nanometric precision) Wave-Front Sensors [WFS]**. Exoplanet detectability could be improved (x10) with faster (x2-3), more sensitive (1-2mag) and specifically optimized (against noise and aliasing) Wave-Front Sensors.

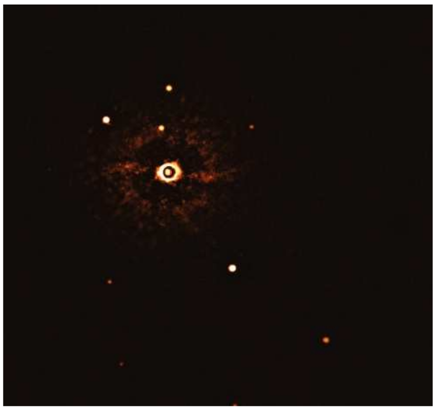

Figure 1 First ever image of a multi-planet system around a Sun-like star

The very goal of the thesis is to pave the way toward the development the optimisation and the operational exploitation of such devices

Objectives:
Among the recent innovations in WaveFront Sensing for AO, the Fourier Filtering Wave-Front Sensors (FFWFS) are of particular interest[5]. Indeed, they can potentially offer the highest sensitivity while being simple to implement. Nevertheless, to achieve the ultimate performance of such sensors (in terms of spatial resolution, sensitivity and accuracy), FFWFS must operate in their peak performance regime (no modulation) and be coupled with Super-Resolution processes recently proposed in the WFS field[6,7]. This will allow access a wider range of spatial frequencies and thus significantly increase the WFS spatial resolution.
If the theoretical performance of these sensors is now well established[8,9], there are still very few operational systems integrating FFWFS and none of them is reaching their full potential. **There is thus a strong need in terms of development, lab tests and on sky validation of non-modulated super-resolved FFWFS**. This will allow bettering understanding of its performance and limitations in complex and representative environments and preparing the 3rd generation of instrumentation on the VLT (2025-2030) and the 2nd generation on ELT (2030-2040).

In this context, LAM and ONERA have jointly developed a unique AO-facility in Europe combining laboratory (LOOPS[10]) and on-sky (Papyrus[11]) benches to test new ideas and new components developed for the next generation of AO systems. The LOOP bench has been used intensively in the LAM premises for more than 5 years now and has demonstrated its ability to trigger and support the development of brand new concepts. In addition to LOOPS, the Papyrus bench has just been released after two and a half years of design, integration and testing. It has seen is first astronomical photons at Observatoire de Haute Provence [OHP] in June 2022 (see PAPYRUS Press Release). Figure 2 shows the very first results obtained with PAPYRUS: the comparison of a seeing limited and AO corrected observation of a double star (HR6212)

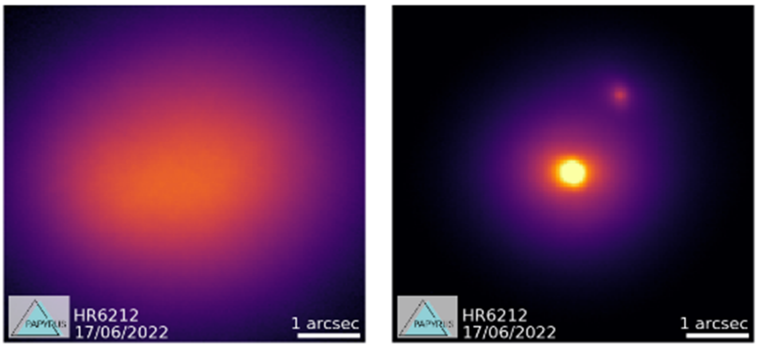

Figure 2 Double Star HR6212, observed the 17th of June 2022 at l'OHP, without (left) and with (right) AO correction using the PAPYRUS bench. Image in the visible at 635 nm.

PAPYRUS is now in the final phase of validation and characterization in its reference configuration (modulated Pyramid FFWFS associated with a conventional wave-front reconstructor). It will be ready, from early 2023, to host new hardware and software components to further increase its performance and its operability.

In that context, the thesis objectives are fourfold :
1) Proposing (from the earliest concept to the final realization) of a non-modulated super-resolved FFWFS to be integrated and tested on the PAPYRUS bench. An intermediate step using the LOOP bench for laboratory tests (with fully mastered experimental conditions) could be considered. The activities will include some theoretical developments, the full simulation of the WFS included in the AO loop (using LAM-ONERA in-house end-to-end simulation tools developed for both VLT and ELT projects), the optical design of specific aspects of the WFS (in particular the interfaces with the PAPYRUS bench) and the development of specific signal processing aspect to reconstructs the measured wave-front from the FFWFS raw signal.
2) Optimizing the calibration and on-line optimization for a robust and yet efficient WFS on sky operation
3) On-sky comparison of the new optimized FFWFS and the reference Papyrus configuration (classical modulated Pyramid) and demonstration of the expected gain in performance and robustness
4) Early proposition (and simulation) of a ELT version of the WFS (in the frame of the Planetary Camera and Spectrograph [PCS] preliminary studies)

The student will build on the developments already carried out by the LAM-ONERA team in the context of SPHERE-SAXO[2,4] development for the VLT and the dimensioning phases of the ELT projects (in particular the HARMONI[12] instrument and its AO suite (see https://www.lam.fr/projets-plateformes/projets-sol-et-spatiaux/article/e-elt-harmoni). Both of them have allowed a fine description and a complete understanding of the problem of extreme AO correction for extrasolar planet direct imaging. Improving the solutions already proposed for the VLT and ELT instruments, or proposing alternative concepts, will be of importance for all future astronomical instruments. The student will have access to all the means of the CELTIC center (joint laboratory LAM/ONERA for Adaptive Optics) and of the ANR WOLF (https://anr-wolf.com/) with in particular the laboratory bench LOOPS and the PAPYRUS AO system installed on the 1.52m telescope of the OHP.

The proposed developments will naturally be used for the High Contrast mode of the HARMONI project[13] but can be extended to the future Planet Finder system AO that will see the light of day in the next two decades (SPHERE+, and RISTRETTO projects on the VLT, ANDES and PCS on the ELT to quote only the principal ones).

It is also important to note that this development will be extremely important for the development of the new generation of Space Situational Awareness [SSA] system for identification and the follow up of Low Earth Orbit [LEO] Satellite or for the study of the close vicinity of Geostationary [GEO] Satellites (detection of small "spy" satellite or thread). Such applications will require accurate, very fast (few thousand of Hz) and very sensitive (low flux regime) wave-front sensors. The un-modulated Super-Resolved pyramid is one promising solution for being integrated in the future ONERA SSA observatory.

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