Thesis subject

Laboratory: ONERA & Laboratoire d'Astrophysique de Marseille

Thesis supervisors: Thierry Fusco (thierry.fusco@onera.fr), Jean-Francois Sauvage (sauvage@onera.fr), Benoit Neichel (benoit.neichel@lam.fr)

Title of the thesis subject: New detection processes applied to adaptive optics

Description of the thesis subject:

Scientific context:

Image acquisition processes are at the heart of scientific activities in high resolution imaging and laser focalisation applied to several domains such as astronomy, space surveillance (SST/SSA), Free-Space Optical telecommunications, etc. These are fields where the only scientifically exploitable information is the electromagnetic wave (light, in the case of the visible and infrared spectral bands) coming from the objects we wish to study or with whom we wish to exchange data at the highest possible rates.

All these applications require adaptive optics to manage external disturbances induced by atmospheric turbulence and the telescope environment itself. In most cases, performance limitations are often linked to the speed of the feedback loop and the intrinsic quality of the data produced by the wave front sensor. The detection stage is therefore a key element of the system. New requirements, particularly in the fields of direct detection and characterization of extrasolar planets, asteroids, low-earth orbit satellites, or free-space telecommunications between ground and space, call for ever faster sensors and measurement processes using wide dynamic ranges. Meeting these needs with conventional technologies requires specific developments that are time-consuming, costly and risky, with limited results.

An alternative is to change the paradigm and consider new detection modes to overcome some of the fundamental limitations of current technologies. In particular, in the near infrared (SWIR for Short Wave InfraRed), new "lin-log" and "even-based" detection modes are beginning to appear. A first prototype SWIR camera integrating these different modes has been developed by LPENS (the Ecole Normale Supérieure Physics Laboratory), based on the SIRIS camera developed jointly by LPENS, and Lytid with a sensor from NIT (New Imaging Technologies). The camera was tested at Pic du Midi on targets with high dynamic like faint inner satellites of giant planets.

SIRIS is a unique camera that combines in the same time during the same exposure true on chip linear and logarithmic responses with the possibility of event based read out mode and/or NDRO (Non Destructive Read Out). In addition, it is a fast, very low noise camera, and from all these features, SIRIS reaches "unlimited' dynamics". See : "SIRIS: a new, fast, high dynamic, and very low noise SWIR camera" (J.Dubouil & al 2024).

The main aim of the thesis is to develop new concepts in wavefront sensors and adaptive optics, based on the specific features of the SIRIS camera. Three innovative read-out modes that address three fundamental limitations of the OA will be studied:

- exploitation of ultra-high dynamics mode to manage observation problems in the presence of strong turbulence (a.k.a scintillation effects) on the wavefront sensor signal. This high-dynamic modes will significantly improve the robustness and the scope of use of AO assisted observation and telecommunication systems.

- exploitation of the "event-based" mode enabling direct measurement of a very high-frequency temporal gradient, minimizing intermediate calculations and providing a direct link between the pixels of the wavefront sensor detector and the deformable mirror actuators. This "RTC-less" mode will significantly increase the bandwidth of current systems, with direct applications in the field of extreme adaptive optics for the detection and characterization of extrasolar planets, SST/SSA and very-high-speed optical telecoms;

- exploitation of the multiple ROI configuration coupled with on-chip computations to perform wide field AO using multi-directional signal coming from the scientific camera itself. This combination of High Dynamics and multi ROI could also be used for coronographic observations of exoplanets when the contrast between the central star et the planet is high

Description of the work:

For the 3 points mentioned above, the research and development strategy will be the same.

The first step will be to get to grips with the camera and characterize its various readout modes, bearing in mind the specific features of adaptive optics. Following this hands-on phase, the innovative readout modes will be integrated into a adaptive optics simulation module, enabling existing concepts to be adapted or new concepts to be studied in order to make the best possible use of the camera's unique features. As a starting point both Shack-Hartman and Pyramid WFS concept will be studied and adapted to account for the “lin-log” and “event-based” modes. As part of a co-design approach, we will be going back and forth between the modification of camera reading modes and optical concepts (for WFS) and control concepts (for the OA loop).

In the second step, once one or two of concepts with the greatest potential (in terms of performance and robustness) will be deeply studied up to an experimental demonstration will be carried out using the various resources (laboratory benches including turbulence simulators : PICOLO at ONERA, LOOPS at LAM) available at our institutes.

Finally, as work progresses and experience is acquired, it will be possible to test a concept on the sky, taking advantage of synergies with existing sky facilities (at the Observatoire de Haute Provence, Pic du Midi or Fauga-Mauzac near Toulouse) to test, under real conditions, some of the specific features proposed in the thesis.

This work will be carried in close collaboration between several groups including: ONERA, LPENS, Observatoire de Paris, LAM and OHP. The student will benefit from the tools, expertise, experimental benches and unique access to large ground-based telescopes available through this network.

References :

G. Gallego *et al*., "Event-Based Vision: A Survey," in *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 44, no. 1, pp. 154-180, 1 Jan. 2022, doi: 10.1109/TPAMI.2020.3008413. keywords:

J. Dubouil, M. Lebreton, F. Colas, D. Darson, "SIRIS: a new, fast, high dynamic, and very low noise SWIR camera," Proc. SPIE 13103, X-Ray, Optical, and Infrared Detectors for Astronomy XI, 1310303 (27 August 2024); https://doi.org/10.1117/12.3018145

Fanpeng Kong, Andrew Lambert, Damien Joubert, and Gregory Cohen, "Shack-Hartmann wavefront sensing using spatial-temporal data from an event-based image sensor," Opt. Express 28, 36159-36175 (2020)

Mitchell Grose, Jason D. Schmidt, and Keigo Hirakawa, "Convolutional neural network for improved event-based Shack-Hartmann wavefront reconstruction," Appl. Opt. 63, E35-E47 (2024)

Monique Cockram, Noelia Martinez Rey, "Characterising an event-based detector for applications to wavefront sensing," Proc. SPIE 13097, Adaptive Optics Systems IX, 130973I (27 August 2024); https://doi.org/10.1117/12.3019185

Daniel Lechner, Andreas Zepp, Marc Eichhorn, and Szymon Gładysz, "Adaptable Shack-Hartmann wavefront sensor with diffractive lenslet arrays to mitigate the effects of scintillation," Opt. Express 28, 36188-36205 (2020)

Clélia Robert, Jean-Marc Conan, Vincent Michau, Thierry Fusco, and Nicolas Vedrenne, "Scintillation and phase anisoplanatism in Shack-Hartmann wavefront sensing," J. Opt. Soc. Am. A 23, 613-624 (2006)

You Zhang, Kaihe Zhang, Bin Lan, Rong Wang, Xueying Li, Tianjun Dai, Chao Liu, "Research on Shack-Hartmann wavefront restoration algorithm under atmospheric scintillation conditions," Proc. SPIE 13231, 4th International Conference on Laser, Optics, and Optoelectronic Technology (LOPET 2024), 132313A (16 August 2024); https://doi.org/10.1117/12.3040111

G. Marchi, C. Scheifling, "Adaptive optics solutions for turbulence mitigation in different scenarios," Proc. SPIE 8161, Atmospheric Optics IV: Turbulence and Propagation, 816104 (6 September 2011); https://doi.org/10.1117/12.892004