# PROPOSITION DE SUJET DE THESE

## Intitulé : Artificial Intelligence for Adaptive Optics (AI4AO): From theory to practice

Référence **PHY-DOTA-2025-09**
*(à rappeler dans toute correspondance)*

| **Début de la thèse :** 10/2025 | **Date limite de candidature :** 06/2025 |
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**Mots clés :**

Astronomical Telescope, SSA, Adaptive optics, wavefront sensing, control, Machine Learning

**Profil et compétences recherchées :**

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

**Présentation du projet doctoral, contexte et objectif :**

**Scientific context:**
ONERA's Optics Department (DOTA) and the Marseille Astrophysics Laboratory (LAM) are actively involved in the development of cutting-edge instrumentation for high angular resolution observations from the ground. In particular, our group is working on the preparation and validation of the next generation of Adaptive Optics (AO) concepts. The aim of AO is to correct the detrimental effects of the atmosphere on observations, and obtain very high quality (diffraction limited) images.

In the field of astronomy, AO-assisted observations have been at the heart of major discoveries such as the detailed study of the massive black hole at the centre of our galaxy, the first images and spectra of extra-solar planets, detailed images of asteroids or the precise morphology and dynamics of very distant galaxies. AO has transformed astronomy by offering unrivalled image quality, and it is now unthinkable to design a large optical telescope without this technology. As a result, the next generation of "Extremely Large Telescopes" (40m-class diameter) due to start operation by 2030 will all be equipped with OA, and the LAM and ONERA teams are working together on these developments.

Beyond its importance for astronomy, AO has direct applications in fields such as medical imaging, optical metrology, high-speed optical telecommunications and defence. Among others AO is crucial for Space Situational Awareness (SSA) by enabling high-resolution imaging of low-orbit satellites and space debris management. To this end, ONERA is currently developing the PROVIDENCE project, a 2.5-meter robotic telescope located at the Observatoire de Haute Provence. As a major project for ONERA, this telescope will both serve as a platform for producing operational data exploitable by the various communities (defence, astronomy, industry) and for testing on sky new concepts and components for AO and very high-performance imaging.

The aim of the PhD project is to explore the use of innovative Artificial Intelligence (AI) and Machine Learning (ML) methods in particular, with a view to: (1) improving the performance of future AO systems; (2) proposing systems that are self-adapting and therefore robust to environmental variations; (3) potentially exploring hardware simplifications thanks to the increased intelligence associated with detection.
This very upstream action will find applications for giant ground-based telescopes (ELT),telescopes dedicated to space observation (PROVIDENCE) and ground to space optical telecommunications (FEELINGS & PROVIDENCE).

**Description of the work:**
Adaptive optics (AO) is a real-time (kilo-hertz), multi-modal (typically from a few hundred to a few thousand spatial modes) process for measuring/correcting optical aberrations generated by atmospheric turbulence. This process is usually managed by a closed-loop control process, based on 3 key elements:
1) a Wave-Front Sensor (WFS) that measures the incoming disturbance, or its residual uncorrected at the previous iteration if the system is operated in a closed-loop scheme. The signal output by this component is usually noisy and suffers from non-linearity,

2) a corrector (often a deformable mirror) that corrects for the reconstructed wavefront obtained from the WFS measurement process. This corrector is also imperfect, with complex temporal dynamics, coupling between correction modes and a non-linear response.
3) a controller, whose purpose is to convert measurements into commands to the mirror and perform the appropriate temporal filtering. This controller is generally based on linear "Matrix-Vector Multiplication" (MVM) models.

Recently, the use of Artificial Intelligence to assist with tasks related to Adaptive Optics has become more widespread. As a result, our research group has begun to explore a number of activities, including
(1) The use of neural networks to overcome the non-linearities of wavefront sensors (see, for example, Weinberger et al. (2024)).
(2) The use of Reinforcement Learning to predict atmospheric turbulence and anticipate (on a scale of a few ms) the correction to be applied to catch up with fast turbulence (see for example Dray et al, Camelo et al. (2023)).
(3) The use of Gaussian processes to assess and predict the performance of optical links (see Klotz et al 2023).
(4) The use of neural networks for data analysis and image interpretation (see, for example, Kuznetsov et al.(2024)).

**Building on this initial ground-breaking work, the AI4AO thesis aims to take the next step by (1) proposing new measurement and control architectures, and (2) putting them into operation on real systems, in order to improve robustness and the technology readiness level (TRL).**

As far as measurement is concerned, the wavefront control community has always sought the most linear WFS possible, i.e. those with a linear response between the aberrations to be measured and the intensity detected. This constraint stems from the initial desire to be able to simply (and therefore quickly) calculate the wavefront correction required to improve the image for the widest possible range of conditions. By focusing on linearity, processing of the signal delivered by the detector is certainly facilitated as being described by a filtering process, but to the detriment of other important factors, notably sensitivity, dynamic range, variation of intensity (scintillation), complexity and diversity of the scenes observed (e.g. artificial satellites) or sensitivity to measuring non-continuous aberrations (e.g. local phase discontinuities). The use of learning methods makes it possible to break the "linearity-dynamics-sensitivity" triangle that constrains current WFS designs. Furthermore, in the majority of current AO systems, the phase measurement and reconstruction stage is processed independently of the time filtering and real-time control application. **By bringing intelligence as close as possible to the pixel, the first objective of the thesis will be to jointly optimize the phase reconstruction and real-time correction processes.** Ideally, the thesis work will lead to integrated control solutions, from the wavefront sensor pixels directly to the corrector actuators.
The input data required for training will be produced using realistic numerical simulations, and "digital twin" tools available in our teams. The case study will focus primarily on large-amplitude perturbations, in the presence of scintillation, as expected during low-elevation observations required for optical communications. Emphasis will be placed on solutions offering the greatest robustness to perturbation variations, and on autonomous methods. Last but not least, the constraints associated with the practical implementation of algorithms in a real-time environment will have to be taken into account, in preparation for field validations.

The second part of the thesis will then consist in experimentally validating the proposed solutions. The first step will be to explore how simulation-only learning behaves on experimental benches, and to propose domain adaptation methods, which enable networks to be adjusted to take into account conditions different from those used during learning. We will use experimental benches (LOOPS at LAM, PICOLO at ONERA), and access to sky platforms (PAPYRUS at the Haute Provence observatory, FEELINGS at ONERA's Fauga-Mauzac site, FrOGS, a CNES platform on the Calern plateau). Implementation of the algorithms on a real-time computer will be facilitated by the expertise of the Bertin-ALPAO group, with whom we collaborate through a joint LAM-Bertin laboratory. The optimization of algorithms on Bertin-ALPAO's real-time computers will enable them to be deployed and tested under real conditions on several platforms. Finally, analysis of the performance obtained in real-life conditions, and comparison with the performance expected in simulations, will provide unique feedback for the improvement of future systems.

The results of this thesis will be a milestone in the maturing of these innovative methods, and their extrapolation for use in other applications (astronomy, SSA, etc.).

This work will be carried in close collaboration between several groups including: ONERA, LAM, ALPAO-BERTIN, CNES, University of Valparaiso and Durham University. The student will benefit from the tools, expertise and unique access to large ground-based telescopes available through this network. The student

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will also work closely with the Machine Learning / Deep Learning (ML/DL) department of LAM, and the newly created IALab from ONERA. These groups will support the student in the development of optimized networks and machine learning strategies. This collaborative scheme, merging experts in Adaptive Optics and Artificial Intelligence already provided very successful results, and will be strengthen with this new PhD.

Bibliography:


WFS simplification:
https://opg.optica.org/oe/fulltext.cfm?uri=oe-27-1-240&id=403519
https://opg.optica.org/prj/fulltext.cfm?uri=prj-12-2-301&id=546201

Non-linear WFS reconstruction:
Landman et al., https://arxiv.org/pdf/2401.16325
Weinberger et al., https://ui.adsabs.harvard.edu/abs/2024A%26A...687A.202W/abstract

Reinforcement Learning:
Pou et al., https://arxiv.org/pdf/2405.13610
Nousiainen et al., https://arxiv.org/pdf/2401.00242
Camelo et al., https://hal.science/AO4ELT7/hal-04402880
Nousiainen et al., https://www.aanda.org/articles/aa/pdf/2022/08/aa43311-22.pdf


**Collaborations envisagées :**

Laboratoire d'Astrophysique de Marseille, University of Valparaiso, Durham University, INAF-Arcetri, ESO


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