# Optimisation of data-reduction from Adaptive-Optics assisted Astronomical Observations

**Name of the laboratory**: The PhD will be shared between 2 institutes: CENTRA in Porto (Portugal) and LAM (Marseille – France). The work will be developed in collaboration with ONERA and ESO Garching. **This PhD is funded.**

**Thesis advisor & co-advisors:**
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CENTRA in association with LAM invites applications for a PhD student position. Candidates will develop innovative research into **data-analysis algorithms aimed to extract the most precise measurements of photometric brightness, astrometric position, and morphology for planets, stars, and galaxies** from **adaptive-optics assisted observations on current and future ground-based telescopes.**
The successful candidate will work at both ends of this collaboration with data from W.M. Keck and VLT-MUSE.

## Context: high-resolution & precision astronomy

High-resolution images from large ground-based telescopes have revolutionized visible and near-infrared astronomy over a wide range of astrophysical fields, including finding and characterizing exoplanets, black holes, brown dwarfs, and the earliest galaxies in the Universe. These discoveries relied on adaptive optics (AO) systems, which compensate in real-time for the blurring effects of the Earth's turbulent atmosphere (called "seeing"). AO systems give superior spatial resolution over space-based alternatives at a fraction of the cost and have been deployed on nearly all of the world's largest telescopes, as the European Very Large Telescope (VLT) and its 10m-class telescopes counterparts. The power of AO is now widely recognized and it will be built into the 1st-light instruments of ALL the next-generation giant telescopes -- the European ELT, the Giant Magellan Telescope and the Thirty Meter Telescope (Ramsay+ 2014, Matt+ 2006, Sanders+ 2014) with diameters up to 40m.

### PSF knowledge is key

Yet, any observation is inevitably seen after a convolution with a point spread function (PSF) i.e. the image of an unresolved object such as a star. In other words, even for a perfect optical system, an image of a point-like source will instead appear as a blob of light whose width is given by $\lambda/D$, where D is the diameter of the telescope and $\lambda$ is the wavelength of light. When imaging through Earth's atmosphere without AO, the seeing-limited image resolution is more than 100 times worse than a perfect telescope would deliver. Imaging with AO produces a PSF that is much closer to perfect. Despite its effectiveness, AO suffers from several limitations which led to more complex tomographic systems with multiple laser sources to observe potentially anywhere in the sky. These are now proven concepts to provide a first stage of pre-facto compensation.
Still, residual AO correction errors produce PSF changes that vary with time and space which are difficult to model (Veran+, 1997, Gilles+, 2012).

The improvement of data-reduction post-facto relies on knowledge of the AO-delivered PSF. PSF knowledge is crucial for either the study of crowded regions and of objects with highly contrasted fine structures such as galaxies, jets/outflows and compact clusters.
A PSF could be acquired just before and/or just after the science observation but this is usually insufficient since PSF acquisition and observations would not be simultaneous with unacceptable additional telescope overhead.
Instead, it could be estimated from the observations directly. However, in many science cases, estimating the PSF from the science images alone proves difficult due to crowding and background noise, which limit one's ability to isolate an empirical PSF.
Although the basic structure of the AO-corrected PSF is known with a (usually) diffraction core superimposed on an extended halo, the relative contributions are hard to estimate because of changing conditions and system performance. This is so in classical natural guide-star systems, let alone laser-based systems and multi-wavefront-sensor systems as those under design for the European ELT.
The alternative is to estimate the PSF using external information such as AO system telemetry (Gilles+ 2012, Martin+ 2016, Ascenso+ 2015) and measurements of the vertical distribution of turbulence in the Earth's atmosphere (Britton+ 2006, Beltramo-Martin+ 2018). This is a complex problem as the optical system must be calibrated to unprecedented levels of accuracy (Ragland+ 2016).
We therefore reach a point where breakthrough science with AO-assisted observations on current and future ground-based telescope requires new paradigms in data-analysis algorithms in order to extract the most precise measurements of photometric brightness, astrometric position, and morphology for planets, stars, and galaxies.

## Data-driven approaches

We are particularly keen on using Deep Neural Networks for Inverse Problems in Imaging, opening up the realm of data-driven, model-independent approaches where we move from a knowledge domain (regularization/smoothing of the inverse problem) to the heuristic domain where large datasets are used in the learning and correct tuning of the networks.
We will foster access to and dissemination of the most representative observatories' data in particular VLT's imagers and IFU's – for instance the European Southern Observatory's integral field spectrograph MUSE. The latter will operate in ground-layer mode (allowing AO correction in a large 1 arcminute field-of-view – PSFR for this case has been covered under OPTICON-FP7) and later on in Narrow Field Mode providing laser-tomography correction across 7.5 arcseconds field of view.

## Parametric modelling

PSF determination takes on many facets, be it outright simulation with analytic or physical-optics Monte Carlo models, extraction and fitting directly from the science images, as a sub-product of deconvolution or constrained minimisation. A parallel approach consists in using the Adaptive Optics telemetry to reconstruct the PSF from control-loop data (Veran+, 1997).
This approach postulates the PSF as a convolution of kernel PSFs each related in a bijective way to either physical parameters or loop telemetry.
Yet, the end user will unlikely use such parametric model and often an analytic function (of linear combination thereof) prove more practical, especially when they are to be manipulated (and eventually further adjusted) by data reduction pipelines. Therefore, a recent proposal to estimate directly the analytic PSF model fit from telemetry was proposed, cutting potentially one step on the way (Fetick+, 2019).
It has been recognised that the Achilles heel is to properly inform either of these parametric models with accurate parameters. Solutions that mix parameter estimation from both AO telemetry and scientific images promise to help in this endeavour (Martin+, 2018), yet the need from PSFs with sufficiently high signal-to-noise ratio and properly sampling hinder their application in a general case scenario, especially for integral field spectroscopy.

## From model-fitting to inverse problem photometry/astrometry

The source and photometry/astrometry extraction is commonly made by first estimating the PSF (one or several) directly from focal plane images generally from a set of parameters together with bases functions to define the PSF and sometimes a residual table. This set of parameters is fitted to the data using a least squares approach to a cost function that consists in a classical likelihood term defined only by the model residuals and the variances of the data. An optimal approach would rather determine the PSF simultaneously with the photometry/astrometry during inversion of the data (e.g. blind deconvolution or myopic deconvolution). To overcome the initial PSF finding algorithm and the degeneracies and instability caused by partial knowledge of the PSF, a hybrid approach would use to its best both the observations and the system telemetry to jointly estimate the PSF, the observation parameters on which it depends and the photometry/astrometry.

# Work to be carried out

**WP1: PSF reconstruction from multi-Wavefront Sensor telemetry**

The PhD candidate will work and deliver on

- Estimating of PSF model parameters from AO telemetry
- Constraining the parameters with help from focal plane data or other ancillary data

The goal is to investigate semi-analytic methods that incorporate high-fidelity simulations and the joint processing of telemetry and focal-plane observations provided by such simulations to aid the full PSF reconstruction process. For these denoising and feature extraction from large swathes of data is expected, be it simulated of on-sky.

The candidate will develop those efficient methods starting from telemetry to provide the reconstructed AO-PSF across the field. The settings envisaged is those of

1. MUSE Narrow-Field Mode where a highly structured AO-corrected PSF is provided.
2. KAPA Keck All Sky Precision Adaptive optics providing laser-tomography
3. Multi-conjugate AO corrected observations with the 3rd generation VLT instrument on the AOF (MAVIS)

**WP2: photometry/astrometry extraction pipeline**

Under this WP the candidate will use an optimal setting using inverse-problem theory to recast and solve for the joint optimisation of PSF/photometry-astrometry in the most straightforward way, starting with the (adjustable) analytic model fit from WP1, with the goal to providing an unsupervised estimation and the SW tools available to the community that implement it (either in stand-alone mode or as an add-on to standard packages with a large set of users).

# PhD setting

The PhD candidate will enrol with a UPorto doctoral school (depending on profile and preferences from Engineering to Physics) and will spend ½ @ Porto and ½ @ LAM (Laboratoire d'Astrophysique de Marseille). The UPorto co-supervisors are C. Correia and Paulo Garcia. LAM co-supervisors are Benoit Neichel and Thierry Fusco. Expertise in Neural Networks and Machine Learning to be provided by Jaime Cardoso from the Visual Computing and Machine Intelligence Group.

Travel to W.M. Keck Observatory in the Island of Hawaii as well as to Garching bei Muechen in Germany (ESO premises) is highly likely for data acquisition and testing.

# Funding

Funding is provided by OPTICON (http://www.astro-opticon.org/) and ANR-APPLY.

## 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 Carlos Correia (carlos.correia@lam.fr), Paulo Garcia (pgarcia@fe.up.pt), 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

Carlos Correia (http://ccorreia.net/) get his PhD in 2010, from Paris University XIII. He is a specialist in Adaptive Optics and data processing. He has been supervising several post-docs: Charlotte Bond, Olivier Beltramo-Martin, Yoshito Ono & Mikhail Konnik. He also supervised two PhD with Kate Jackson and Masen Lamb.

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.