Exploitation of the ultimate spatial and spectral resolution of the ELT by coupling PSF prediction and 3D deconvolution: Application to Solar System objects observations

Name of the laboratory: Laboratoire d'Astrophysique de Marseille / ONERA

Thesis advisor: Thierry Fusco, Olivier Mousis
Email and address: Thierry.fusco@onera.fr ; Olivier.mousis@lam.fr
Tel: 06 62 48 48 36
Co-advisor: Benoit Neichel, Olivier Groussin

Context: Europe has just started the construction of the biggest optical ground-based telescope: the European Extremely Large Telescope (ELT). With a diameter of 39m, this giant will probe the Universe with an unprecedented sensitivity and spatial resolution. Starting operations in 2024, it will implement several instruments, over which is HARMONI - the ELT Integral Field Spectrograph (IFS). HARMONI will cover the visible and near-infrared part of the spectrum, providing the ELT's core spectroscopic capability. It will exploit the E-ELT's scientific niche in its early years, starting at first light. To get the full sensitivity and spatial resolution gain, HARMONI will work at diffraction limited scales. This will be possible thanks to Adaptive Optics (AO) which compensates the quickly varying aberrations induced by the earth's atmosphere and restore the ultimate spatial resolution of the ELT. Our team (LAM/ONERA) is in charge of designing and developing the AO module of HARMONI.

HARMONI is a workhorse instrument, and it will tackle a large range of science cases, from solar system objects, exoplanets, resolved stellar populations in nearby galaxy or detailed study of high-redshift galaxies. Over the different science cases covered by HARMONI, the LAM's astronomers are leading the scientific preparation for the detailed study of solar system planets and their satellites.

AO is particularly suited to studying the origin and evolution of small bodies (asteroids, comets, trans-Neptunian objects), giant planets and their satellites. With an unprecedented spatial resolution from the Earth, one can expect breakthrough in understanding their physical properties and chemical composition. In particular, AO is crucial to resolve small bodies binary systems (e.g. binary asteroids), to study surface geological and compositional heterogeneities of giant planet satellites (e.g. Io's volcanoes) and largest small bodies (e.g. Ceres), and to conduct exosphere and atmosphere studies through the entire solar system (e.g. Europa, Jupiter, Pluto…). In order to get the highest angular resolution when dealing with these extended object, deconvolution of the data by the instrumental response becomes critical. The aim is to enhance low contrast features in the data, in effect by removing the characteristic broad AO Point Spread Function (PSF) halo that dilutes them.

When dealing with deconvolution, a proper knowledge of the PSF becomes extremely important for accurately extract the astrophysical signal. Unfortunately, the fields of view of IFS instruments, and HARMONI in particular, are too small (or the PSF is so field dependent) that they often do not contain any undisturbed PSF calibrator. In order to proceed, it thus becomes necessary to estimate the PSF from auxiliary data. One approach could be to derive the PSF using analytical models which are fed with some basic parameters (turbulence profile, AO system parameters, guide star parameters) and heuristically tuning it to the actual system PSF. A more complete, but challenging approach, is to actually reconstruct the PSF over the field based on the AO loop parameters.

The goal of this PhD project is to propose PSF estimation algorithms, coupled with 3D deconvolution techniques, for AO-assisted IFS observations of solar system targets.

The PhD work will start with actual observations of Neptune obtained with MUSE and its newly commissioned Laser Tomography AO mode (so-called MUSE NFM). The spatial resolution obtained in those images is a low as 50 mas (corresponding to a spatial scale of approximately 1000 km at Neptune), with a spectral resolution of about 3000. These images, acquired during the commissioning, represents the best data ever obtained from ground-based telescope. The PhD student will carry the data reduction and analysis and compare those data cubes with previous observations to highlight the temporal development of discrete clouds. This data set will be completed with further observations in order to probe both short and long time scale for clouds evolution.

Beyond those scientific results, this data set will serve as a testbed for 3D deconvolution methods, and in particular, the impact of different PSF models on the extracted spectra will be studied. This work will highlight the potential gain provided by deconvolution, and the sensitivity of the process to PSF calibration issues. PSF estimation will be done based on recent work developed by our team where we show that analytical PSF profiles parameters can be linked to system and environment parameter such as the turbulence strength or its outer scale. Based on a large data set of more than 130 observations obtained with MUSE, we demonstrate than an accuracy of 10% can be achieved on the PSF parameter estimation assuming a knowledge of the basic atmospheric parameters with the same accuracy (Fusco et al. in prep). The student will also benefit from 3D deconvolution tools developed at ONERA (e.g. MISTRAL), that will need to be adapted for the solar system science cases.

Based on the experience gained with those observational data, the student will then develop a simulation model for HARMONI. This simulation will include a fine representation of the instrument response, as well as the AO PSF. The student will develop adequate 3D-deconvolution analysis tools, and prepare for the scientific exploitation HARMONI.

The student will be at the heart of an international team involving astronomers, data specialists and AO experts. All the support in terms of tools, data and expertise is available.

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ADS link:

Thierry Fusco: https://goo.gl/15Y79V
Olivier Mousis : https://goo.gl/N3LKUC