Adaptive Optics for Kilometer-Scale Free-Space Optical Links in Infrared Interferometry

Scientific Context

Interferometry is one of the most powerful tools in modern astronomy. By combining the light from several telescopes, it creates a "virtual telescope" whose effective size is the separation between them (the baseline). The larger the baseline, the finer the details that can be resolved. With baselines up to 130 m, the Very Large Telescope Interferometer (VLTI) already reveals the motions of stars around the Galactic Center black hole, probes the inner regions of protoplanetary systems, and studies the structure of active galactic nuclei. Extending the baseline to the kilometer scale would unlock an entirely new regime, allowing astronomers to resolve features only a few tens of micro-arcseconds across, including the immediate surroundings of supermassive black holes or atmospheric structures on nearby exoplanets.

Achieving such baselines requires transporting the collected light over 1–2 km while preserving its wavefront quality. This is extremely challenging, since horizontal near-ground propagation is dominated by strong, rapidly varying turbulence. Over these long paths, the beam not only blurs but also scintillates, wanders, and accumulates complex distortions. Interferometry demands wavefront stability at the level of a few tens of nanometers. While AO-assisted Free-Space Optics (FSO) links exist in laser communications, astronomical interferometry imposes far tighter constraints.

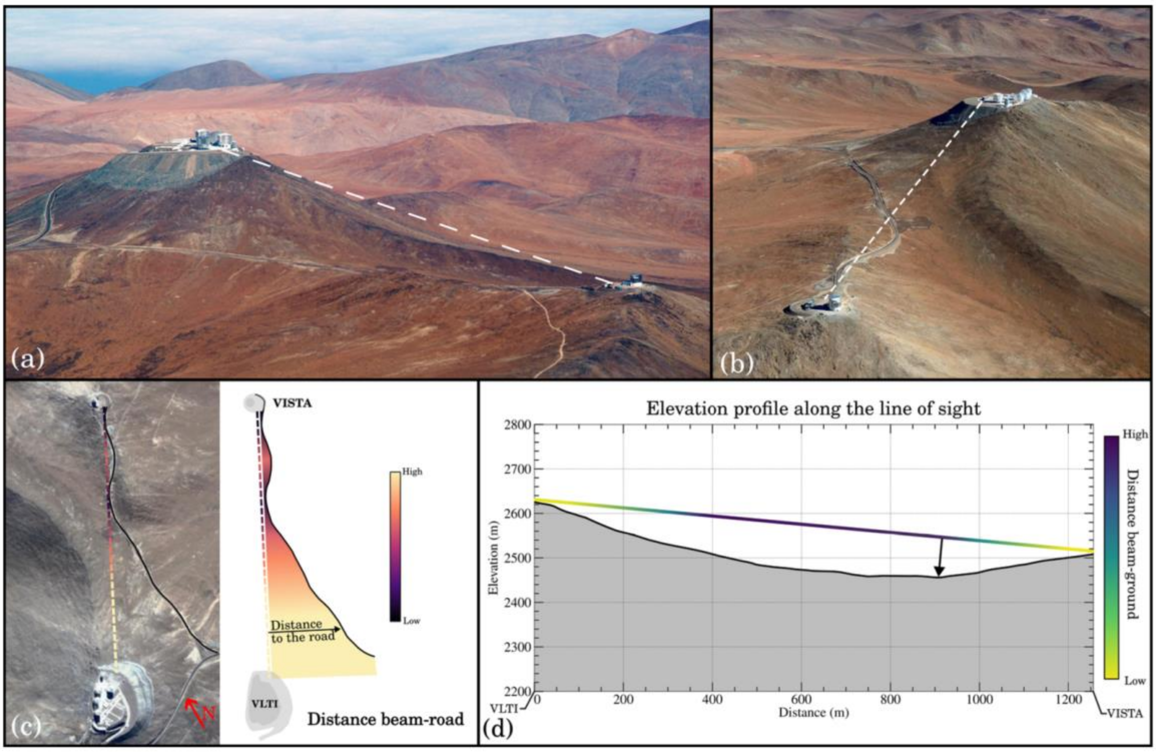

Figure from T. Pichon internship report

Figure 3.1: ***Visualisation of the FSO link***
(a) & (b) : Aerial views | Credit: J.L. Dauvergne & G. Hüdepohl (atacamaphoto.com) / ESO
(c) : Satellite view of the site with qualitative estimation of near-road areas
(d) : Elevation profile along the line of site with qualitative estimation of the distance from the ground

The proposed PhD will develop an AO system capable of stabilizing a near-infrared stellar beam over a kilometer-scale FSO link, paving the way for future ultra-long-baseline interferometric arrays.

Objectives, Methodology, and Expected Outcomes

The goal of the PhD is to design and validate an adaptive optics concept enabling diffraction-limited propagation of near-infrared light over a kilometer-scale horizontal free-space path.

The first step will be to characterize the turbulence along such links. Vertical turbulence above observatories is well known, but near-ground horizontal propagation remains poorly constrained. The student will therefore build realistic models by combining theoretical descriptions, meteorological data, and numerical tools from LAM and ONERA. These models will quantify key effects, scintillation, beam wander, and phase distortions, and define the requirements for wavefront sensing and control.

Building on this foundation, the student will explore wavefront sensing concepts suited to low-flux, compressed pupils. Classical (Shack–Hartmann, pyramid) and more advanced sensors will be assessed in terms of sensitivity, robustness, and ease of implementation. The AO control laws, likely including predictive strategies, will be developed in close collaboration with ONERA, whose expertise in turbulence modeling and real-time control will be central.

A key element of the thesis is the development of an end-to-end simulation platform incorporating Fresnel propagation, multi-layer turbulence, pupil compression, WFS noise, DM models, and closed-loop control. This tool will allow extensive parameter exploration and performance evaluation in terms of Strehl ratio, residual phase, optical path stability, and interferometric coupling.

Beyond simulations, the project includes an essential on-sky component: a pathfinder experiment at the Paranal Observatory using two small (≈30 cm) telescopes placed along a horizontal baseline. This reduced-scale setup will enable direct measurement of horizontal turbulence, test the proposed wavefront sensing and control strategies, and validate the numerical models against real atmospheric conditions. The field campaign will serve as both a feasibility demonstration and a major input to the design of the final AO system.

By the end of the PhD, the student will have produced validated simulation tools, a calibrated turbulence model for horizontal propagation at Paranal, and a consolidated AO architecture suitable for a future kilometer-baseline interferometric link.

Candidate Profile

The ideal candidate has a Master's degree in optics, physics, engineering, or astronomy, with a strong interest in adaptive optics, atmospheric propagation, and scientific instrumentation. Experience in numerical simulation, Fourier optics, or real-time control is helpful, and familiarity with AO benches is an asset but not mandatory. Curiosity, autonomy, and motivation to work at the interface between theory, simulation, and experiment will be essential.

Scientific Environment
The PhD will be conducted within the strong, complementary partnership between LAM and ONERA. At LAM, the student will join a dynamic group working on AO and high-angular-resolution instrumentation for major observatories, with access to advanced AO benches and powerful simulation tools. ONERA will contribute its world-leading expertise in atmospheric turbulence and AO control, supported by unique laboratory facilities for validating wavefront sensing and correction strategies. Regular exchanges between the two institutes will ensure that the research benefits from both theoretical insight and experimental validation, and remains aligned with international developments in the field.

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Contact: Benoit Neichel – benoit.neichel@lam.fr
Thierry Fusco – thierry.fusco@onera.fr