# Adaptive optics for space-to-ground optical telecommunication links: modeling, optimisation and experiment.

Optics may represent a promising solution to overcome the growing saturation of radio-frequency based satellite to ground telecommunication networks. It indeed allows a significantly higher throughput with reduced power consumption and increased security. The deleterious effects of atmospheric turbulence are however a potential show stopper, as they impair beam propagation and injection of the incoming signal into single mode fibres. Use of existing terrestrial fibre based technologies becomes impossible.

Recently NASA and Onera, in partnership with CNES, have separately demonstrated the correction of atmospheric turbulence effects through adaptive optics, improving optical telecommunication links and single mode fibre injection. For that, AO takes benefit from a small portion of the useful optical signal to measure and correct the turbulence effects. Still, the gain brought by AO significantly reduces at low elevation due to the fast and strong evolution of turbulence conditions as well as the diminution of collected flux. Consequently, telecommunication link quality and duration are strongly reduced. This issue mainly concerns LEO satellite telecommunication, which high scrolling speed leads to short telecommunication duration, but may also concern GEO satellites or airborne terminals communications. A similar issue affects LEO satellites and debris observation from the ground, with AO, for civil or defence applications partaking to the space situational awareness issue.

An operational system shall however be able to work continuously, whatever the turbulence conditions (good at high elevation, poor at low elevation). This implies real-time evaluation and optimal management of the non stationary turbulence and flux conditions inherent in scrolling satellites. These conditions significantly differ from usual astronomical conditions of use of AO.

The objective of this thesis is to push the limits of the current systems and allow their functioning in the various regimes, inherent in satellite-to-ground telecommunication, including transient situations. This shall provide extended link duration. In this prospect, the thesis will focus on the fine understanding and modelling of the impact of scrolling on AO performance, in particular at low elevation. Then original control solutions such as adaptive control will be developed and validated based on the relevant performance criterion. Optimisation of AO with respect to such criterion will inevitably rely on the knowledge of the actual turbulence conditions along the trajectory. Finally, the solutions proposed shall be experimentally validated, benefitting from the various assets available at Onera. Technological breakthrough are expected and may allow an efficient use of space-to-ground optical links.

The thesis shall thus be structured around three axis.

First one concerns the modelling of AO performance along the trajectory in particular considering low elevation scrolling. The goal is to refine the error models of AO focusing on the contributions of scrolling and scintillation. The improvement of pseudo-analytical models shall allow in the end providing a tool for real-time evaluation of AO performance on sky, with respect to the relevant performance criterion. This tool shall help adjusting in real-time the parameters of AO, or the coding and interleaving tools for the telecommunication layer. So as torefine the performance criteria (coupling factor, fading statistics), the student will rely on the results of previous thesis. This modelling shall also provide in the end the necessary tools to ensure multi-parametric design of AO systems with respect to turbulence, targets and operation conditions in a statistical approach.

The second axis concerns the actual optimisation of AO performance based on the previous analysis, through the development of advanced control solutions for AO. The goal is to define strategies to optimize the performance criterion along the trajectory. For instance, the deterministic evolution of some conditions (turbulence strength, flux) along the trajectory may be exploited through predictive control. The proposed solutions shall however adapt to overall conditions and ensure robust performance. Turbulence condition monitoring tools, already developed in the team, may be used in this end. The student may also consider optimising some specific contributors of the global error budget depending on the elevation. In the end,

this work shall help the optimisation and co-design of AO and the upper-layers of coding/interleaving for given populations of satellites.
Finally, though this work will rely on numerical simulation tools partly developed at Onera, the student will aim at validating experimentally the various concepts and solutions on the various assets available at Onera. It first includes an operational AO system dedicated to space-to-ground LEO telecommunication. The student will also benefit from a complete ground-station currently under construction at Onera, dedicated to LEO and GEO satellites communication, that will participate to an operational demonstration. Finally, the student will also benefit from a turbulence lab simulator designed for non stationary, low elevation optical links. These various assets shall allow on sky validation of the concepts.
This work will be carried out in strong synergy with LEO satellites and debris imaging in one hand, and astronomical instrumentation on the other hand, due to tight relations between these subjects. This work will thus benefit from the close collaboration between Onera and LAM, through their integrated team. IT will also benefit from synergies with two other PhDs involving quantum key distribution telecommunication and wavefront sensing in strong conditions.
This PhD work will be carried out within the framework of various CNES and ESA studies, in partnership with notorious industries (Airbus, Thales …) and will benefit from recent on sky experiments. It participates to the telecommunication field of application developed by the team, a major theme considering its very high innovative potential.

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