PROPOSITION DE SUJET DE THESE

Intitulé : Mitigating and harnessing scintillation for the second generation of Adaptive Optics systems dedicated to laser links from LEO satellite to the ground

Référence : **PHY-DOTA-2026-23**
(à rappeler dans toute correspondance)

Début de la thèse : Octobre 2026 à Janvier 2027 selon le type de financement	**Date limite de candidature :** 01/06/2026

Mots clés :

Optique adaptative, turbulence atmosphérique, scintillation, télécommunications sol-satellite.
Adaptive optics, atmospheric turbulence, scintillation, ground-sat optical communications.

Profil et compétences recherchées :

Ecole d'ingénieur ou master 2 avec spécialisation en optique et/ou contrôle-commande

Sujet :

Présentation du projet doctoral, contexte et objectif :

Context :

In the face of ever-growing data volumes and transmission rates in telecommunications, coupled with the proliferation of satellite constellations, the electromagnetic environment is becoming increasingly saturated (frequency allocation issues) and contested (interference, eavesdropping). Against this backdrop, the need for high-bandwidth, secure, and robust communication solutions has become vital across both civilian and military sectors. Free-space optical communications are emerging as a key solution for deploying intrinsically discreet, ultra-high-speed, and interference-resistant satellite networks or point-to-point links.

However, free-space optical links are prone to atmospheric channel induced impairments, in particular because of turbulence. To maintain signal quality, Adaptive Optics (AO) is a key technology, already proven in astronomy, where ONERA boasts leading expertise [1]. For communication applications, notably, ONERA is developing experimental means both in laboratory settings (PICOLO bench [2]) and on-sky (FEELINGS ground station, see Figure 1, which achieved a world-first in first-generation AO [3]), as well as numerical models. These tools enable the study real-time compensation of atmospheric turbulence under conditions representative of satellite links.

Figure 1 : ONERA's Optical Ground Station, FEELINGS (© M. Cherfi).

This thesis topic deals with the more specific context of downlink communications between satellites in Low Earth Orbit (LEO) and the ground. This type of link is particularly demanding: the satellite transits quickly, spends most of its orbit at low elevation, and the strong turbulence on the line of sight generates significant perturbations to the optical beam, both in phase (wavefront distortion) and amplitude (scintillation). These effects substantially complicate the operation of Adaptive Optics. However, this thesis targets the more challeging configuration of LEO feeder links, where a bidirectional link between the ground and the LEO satellite is considered.

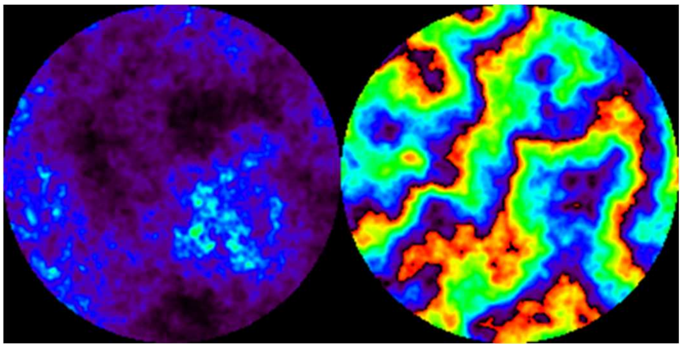

Figure 2 : Strong perturbations in the optical ground station pupil (amplitude on the left, phase on the right).

Doctoral Project: Accounting for Scintillation in Second-Generation Adaptive Optics for LEO-Ground Telecommunications

The impact of scintillation on Adaptive Optics (AO) performance is particularly significant in laser communications through turbulent atmosphere. In state-of-the-art first-generation AO systems, scintillation is considered a disturbance affecting wavefront analysis, reconstruction, and control, resulting in substantial losses in telecom link efficiency: increased complexity of the telecom layer, reduced data rates, and heightened latency.

However, scintillation also provides valuable information on the tomographic distribution of turbulence along the line of sight. If harnessed, this information could significantly enhance the quality of the optical carrier. The central scientific challenge of this thesis can thus be summed up as: “using scintillation without being impaired by it”.

Previous work at ONERA (theses by Pablo Roblès [4], Perrine Lognoné [5], Timothée Vène [6], and Kyliann Robert [7]) has established the concept of second-generation AO for optical telecommunications: scintillation-robust Shack-Hartmann based wave front sensing, predictive phase control based on Linear Quadratic Gaussian approach to reduce temporal error, and point-ahead angle (PAA) precompensation to anticipate satellite trajectory. Nonetheless, these efforts are preliminary: currently, these approaches are either at the proof-of-concept stage or partially validated in laboratory settings without considering real-time impact of scintillation on the AO system. Moreover, they have never been tested on-sky.

This doctoral project thus proposes to take several steps further than these seminal works:

- Develop and test in laboratory and on-sky predictive reconstruction and control methods, dedicated to LEO downlink, which are not only robust to scintillation but also benefits from it: it consists in investigating how Linear Quadratic Gaussian control approach can handle scintillation, in other words absence or very noisy measurements, to ensure robust correction downlink
- Evaluate, in combination with the control law analysis, the best configuration of the Shack-Hartmann sensor to reduce the impact of scintillation. Here, a global approach shall be considered to define the best combination between wavefront sensing strategy and control solution to minimize the impact of scintillation on phase predictive correction.
- Determine necessary parameters related to the turbulence profile along the line of sight for predictive control laws using telemetry data collected by AO. The potential contribution of Artificial Intelligence (convolutional neural networks) will be particularly examined for this purpose.
- Extension of the previous results to investigate the potential gain of point-ahead angle precompensation at the PAA in LEO feeder links.

The student shall address these points targeting on sky validation with the FEELINGS ground station.

Thesis Milestones:

The ultimate objective is to test on-sky the second generation of Adaptive Optics (AO) on-sky using the FEELINGS ground station for LEO-Ground links.

To achieve this, the PhD student will follow several key steps:

- Experimental Data Exploitation: utilize experimental data from the FEELINGS ground station to refine the reference scenarios used as representative contextual data into modeling.
- Algorithmic Development: work on a numerical twin of the FEELINGS ground station (developed in parallel within another framework) to design, test, and integrate: Control laws incorporating scintillation effects, calibration procedures, and identification methods.
- Real-Time Implementation and Optimization: optimize and test the new concepts on the PICOLO-LISA bench, validating their performance in fully controlled conditions.

- On-Sky Testing with FEELINGS, ONERA's Ground Station.

Thesis Outcome:

Upon completion, the ambition is to have a robust Adaptive Optics solution, experimentally validated, capable of significantly enhancing the quality and reliability of ground-to-satellite optical communications.

Additional Notes:

Collaboration with other projects or teams might be necessary for accessing satellite payloads or utilizing parallel developments (e.g., the numerical twin of the FEELINGS station).

The thesis will involve a mix of theoretical work, simulation, experimental setup operation, and data analysis.

The outcome is expected to contribute not only to the specific application of LEO-Ground optical communications but also to broader advancements in Adaptive Optics and predictive control methodologies in a wider context.

Environment and Collaborations:

The doctoral student will be integrated into an experienced team at ONERA, working in tandem with a doctoral student (in the early stages of their thesis) and a postdoctoral researcher specialized in Adaptive Optics applied to Optical Telecommunications (TBC). They will have access to top-tier experimental facilities, notably the PICOLO-LISA bench for laboratory development and validation; and the FEELINGS ground station for on-sky experimentation.

The thesis will also benefit from a rich project environment to come in the team, allowing for high probability of access to GEO (Geostationary Earth Orbit) and LEO (Low Earth Orbit) satellite payloads via the FEELINGS ground station during the thesis, as well as real-time computing resources compatible with the on-sky implementation of LQG (Linear Quadratic Gaussian) and AI-based control laws envisioned in the thesis.

Academic collaborations are also planned with the University of Durham (United Kingdom) and the Laboratoire d'Astrophysique de Marseille, enabling the expansion of scientific exchanges on Adaptive Optics and Optical Communications.

Références :

[1] Première mondiale : l'ONERA établit une liaison optique laser pré-compensée par optique adaptative à plus de 38 000 km https://onera.fr/sites/default/files/communiques/pdf/2024-07/CP-ONERA-20240711-FEELINGS.pdf

[2] Robles, P., "Emulating and characterizing strong turbulence conditions for space-to-ground optical links: the PICOLO bench", Journal of Astronomical Telescopes, Instruments, and Systems, vol. 9, Art. no. 049002, 2023. doi:10.1117/1.JATIS.9.4.049002.

[3] Prix Nobel de physique 2020 : contribution ONERA soulignée par la Ministre des Armées : https://www.onera.fr/fr/actualites/prix-nobel-de-physique-2020-contribution-onera-soulignee-par-la-ministre-des-armees.

[4] Pablo Robles, « Predictive adaptive optics for satellite tracking applications », thèse de doctorat (2023).

[5] Perrine Lognoné, « Optimisation des liens télécom sol-GEO haut débit à l'aide de stratégies optiques et numériques », thèse de doctorat (2023).

[6] Timothée Vène, « Analysis and mitigation of the scintillation effects on a LEO-to-ground optical link corrected by adaptive optics in strong perturbation regime », these de doctorat (soutenance prevue en novembre 2025)

[7] Kyliann Robert, « Adaptive Optics with predictive control for space to ground optical communications : towards on-sky validation with FEELINGS », thèse en cours (soutenance prévu en 2027).

Collaborations envisagées : Durham university, Laboratoire d'astrophysique de Marseille

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