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PROPOSITION DE SUJET DE THESE

Intitulé : Strategies for adaptive optics precompensation of optical telecommunication ground-to-satellite uplinks: application to GEO and LEO feeder links

Référence : **PHY-DOTA-2022-16**
(à rappeler dans toute correspondance)

Début de la thèse : Octobre 2022	**Date limite de candidature :** Mai 2022

Mots clés : Optique adaptative, Télécommunications optiques, turbulence, contrôle-commande

Profil et compétences recherchées :

profil ingénieur, écoles généralistes, ou master, compétences automatique, optique, traitement du signal

Présentation du projet doctoral, contexte et objectif :

Context:

The exponential growth of the needs in data transfer drives an increasing interest for high capacity optical links between the ground and telecommunication satellites, either in Low Earth Orbit (LEO) or Geostationnary Earth Orbit (GEO). Currently the most appealing configuration relies on bidirectional ground / satellite optical links, or feeder links. Links with GEO satellite, so-called GEO-Feeder links, aiming at about one Terabit/s, are currently under development, while feasibility of LEO feeder links is still under investigation. The strong requirements in performance of such systems imply innovative developments on all the segments of the chain: high power sources, modulation/demodulation format and handling of the propagation channel. The latter segment concerns mainly the management of atmospheric turbulence effects that induce not only a mean loss on the optical signal but also deep fadings (>15 dB) with long durations (few milliseconds) compared to the symbol time. The mitigation of these effects is therefore essential to reach the required data rates.

In GEO as well in LEO case, Adaptive Optics (AO) is used on the ground side to sense and correct for atmospheric turbulence effects on the downlink beam, before injection in a single mode fiber. The reciprocity principle [Shapiro-2012] allows showing that this correction is also relevant to pre-compensate the uplink beam. However this principle is partly valid due to the point-ahead angle, this angle between down and uplink beams is imposed by the differential dynamics between the ground station and the satellite on its orbit. This point-ahead angle limits the efficiency of the uplink pre-compensation (anisoplanatism effect) and therefore the uplink performance [Conan-2019]. GEO and LEO uplinks differ, due to the amount of point ahead angle (some 3 times bigger in LEO), turbulence level (evolving along time and possibly significantly higher in the LEO case). In that respect, the LEO case can be seen as a worst case. Still, due to satellite scrolling, channel characteristics may be more predictive in this latter case.

ONERA is currently defining and integrating an optical ground station, FEELINGS, including a telescope and an optical set-up embedding adaptive optics to demonstrate and investigate GEO-feeder links with AO pre-compensated uplink beam. This station is also equipped for LEO links. One of the key scientific issue is thus the compensation of the anisoplanatism effect induced by the point-ahead angle and the optimization of the uplink performance.

Research project:

The PhD work is in line with these developments and aims at developing innovative strategies to circumvent anisoplanatism and increase the performance of optical uplinks, through adaptive optics precompensation, in the GEO and LEO cases. This objective relies on the following research topics:

- Development of astute control strategies so as to reduce point-ahead anisoplanatism.
- Development of identification methods required for the control optimisation.
- Evaluation of channel statistics and link performance.

First, ONERA is currently investigating means to mitigate anisoplanatism effects through AO precompensation in the context of GEO feeder links. Second, predictive AO control solution has been developed for LEO-to-ground optical telecommunication downlinks, to reduce temporal error, providing an initial framework that could be extended to GEO links.

Building on these prior works, the PhD student will propose innovative control solutions to reduce anisoplanatism on the GEO feeder uplink. Extension of the results to the LEO feeder case shall also be investigated.

To evaluate the gain brought by the previous approaches, the student will consider telecommunication channel characteristics and performance (coupling, fading statistics). Operational implementation shall be considered with the goal of on sky demonstration. In that prospect, identification of the turbulence conditions and relationship with control strategies shall be evaluated, in particular in terms of performance robustness.

To address these issues the PhD work will rely on analytical and numerical analysis but will also particularly focus on the experimental implementation and characterization of the proposed solution, benefitting from in lab resources and the development of the FEELINGS ground station. For that, the student shall:

- Develop the above mentioned innovative control solutions handling anisoplanatism and temporal aspects.
- Implement and validate these concepts on the ONERA GEO feeder link AO plateform. In lab tests shall be carried out by use of the PICOLO laboratory turbulence simulator [Velluet-2020]. Adaptation of the PICOLO bench to address GEO feeder link shall be part of the work.
- Compare results to numerical simulations and evaluate the performance and limitations of the proposed concepts. Impact on the telecommunication channel shall be investigated.
- Prepare on sky tests and demonstrations, in particular focusing on the identification algorithms that shall have been designed to adjust the control law to channel characteristics. These on-sky tests can make use of the FEELINGS ground station demonstration.
- Robustness issue shall be considered for an operational solution. The student shall investigate the impact of error model and strategies to mitigate them.

In summary, the PhD work will provide innovative concepts for the compensation and reduction of turbulence effects on ground-GEO optical links, essential element for the development of future GEO-Feeder systems, and prepare LEO feeder links. These concepts shall be validated in the lab and eventually during on sky tests.

Environment:

The student will have access to ONERA simulation tools (semi-analytical models and end-to-end code TURANDOT-AOST) [Canuet-2018, Camboulives-2018]. He/she will also benefit from various experimental results of ONERA : First European demonstration of LEO downlink AO correction and injection [Petit-2016], first experimental demonstration of uplink pre-compensation on a slant line of sight relevant of the ground-GEO scenario: the FEEDELIO project [Védrenne-2019] that led to successful on-site tests in 2019 and 2021 in Tenerife (Canary Islands, Spain). He/she will access to the FEELINGS AO system and the PICOLO turbulence lab simulator. The student will also benefit from the outcomes of the EU funded project VERTIGO aiming at an outdoor experimental demonstration of a high data rate link in 2022 with the AO system of FEELINGS.

J. H. Shapiro & A. L. Puryear, “Reciprocity-enhanced optical communication through atmospheric turbulence. Part I: Reciprocity proofs and far-field power transfer optimization,” Opt. Commun. Netw. 4, 947 (2012).

J.-M. Conan, A. Montmerle-Bonnefois, N. Védrenne, C. B. Lim, C. Petit, V. Michau, M.-T. Velluet, J.-F. Sauvage, S. Meimon, C. Robert, J. Montri, F. Mendez, P. Perrault, G. Artaud & B. Benammar, “Adaptive Optics for GEO-Feeder Links: from performance analysis via reciprocity based models to experimental demonstration,” COAT-2019 (2019).

M.-T. Velluet, C. Petit, C., L. Le Leuch, A. Bonnefois, J.-M. Conan, F. Cassaing & N. Védrenne, “PICOLO: turbulence simulator for adaptive optics systems assessment in the context of ground-satellite optical links”, Proc. SPIE Vol. 11532, p. 1153207, (2020).

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Collaborations envisagées : CNES	
Laboratoire d'accueil à l'ONERA Département : : Optique et Techniques Associées Lieu (centre ONERA) : Châtillon **Contact** : C. Petit Tél. : 0146734754 Email : cyril.petit@onera.fr	**Directeur de thèse** Nom : J.-M. Conan Laboratoire : Onera Tél. : 0146734748 Email : jean-marc.conan@onera.fr

Pour plus d'informations : https://www.onera.fr/rejoindre-onera/la-formation-par-la-recherche