

Optimisation Optique et Numérique d'un Lien Sol-Satellite Haut Débit

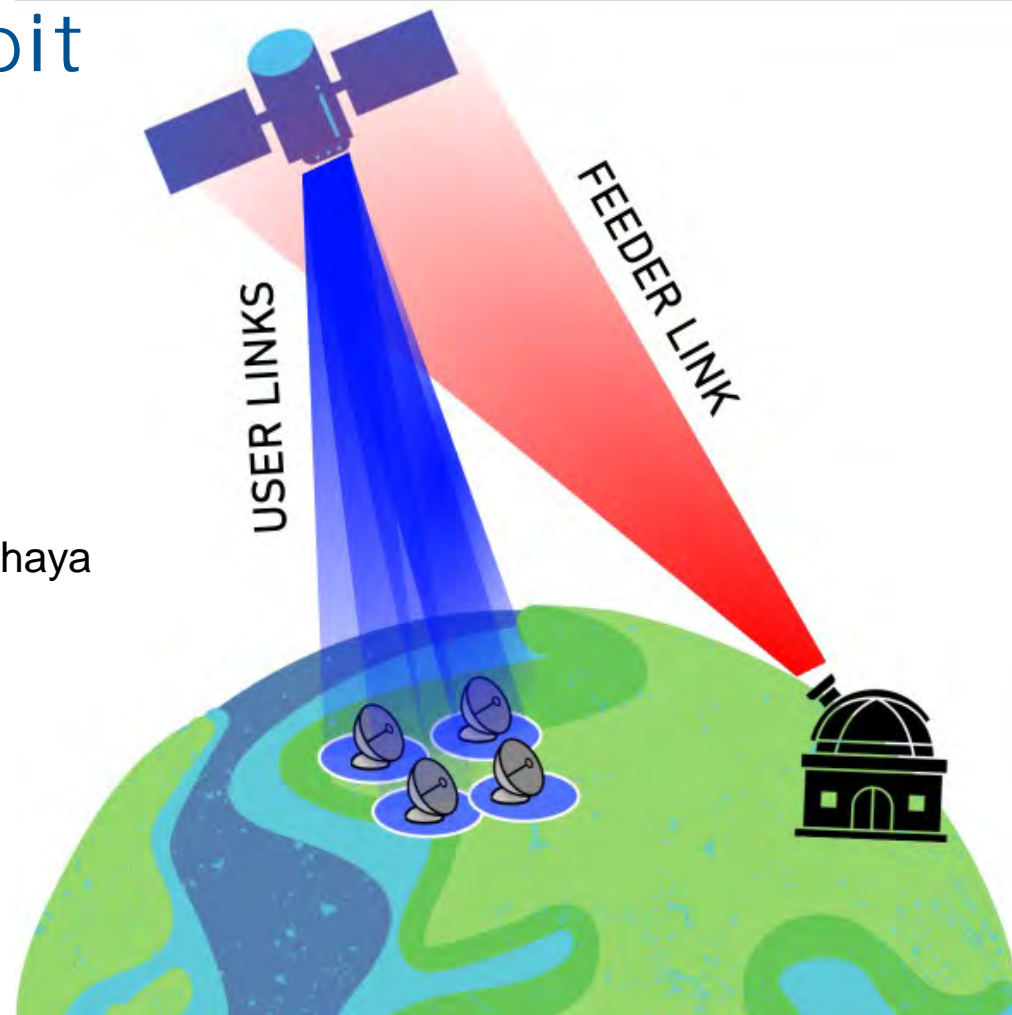
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Financeurs: CNES / ONERA



Contexte: communications spatiales

Objectif:

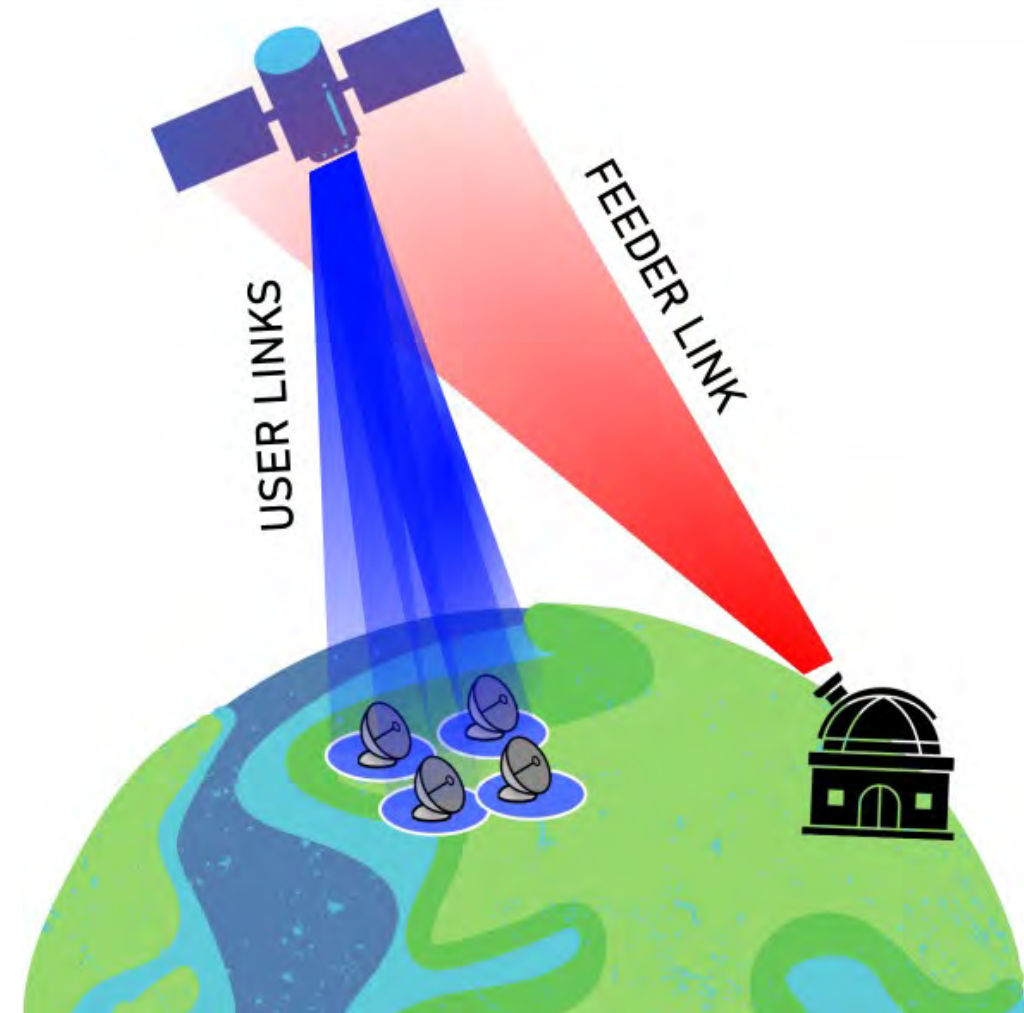
Etendre la couverture internet globale en complétant le réseaux fibré terrestre.

Pour atteindre de hauts débits:

→ Optique:

- Grande bande passante = hauts débits

Contrainte: → Turbulence atmosphérique



Problématique générale: la turbulence atmosphérique

Problématique:

Onde optique perturbée en phase et en amplitude durant la propagation à travers l'atmosphère:

→ Fluctuation du signal reçu à bord du satellite.

Or: transmission d'information

→ Repose sur changements d'états de l'onde E-M
(Ex: Lumière, pas de lumière).

Donc: Perte d'information.



0 1 0 1 0 1

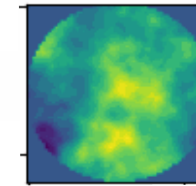
CANAL



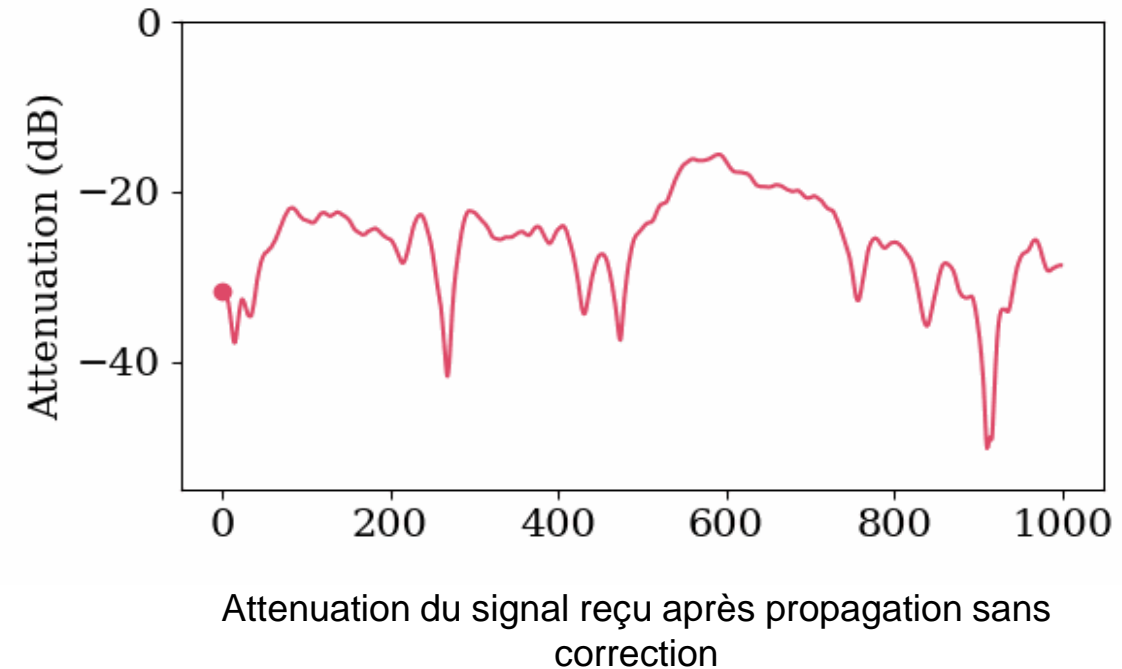
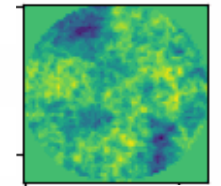
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PHASE



LOG-AMPLITUDE



Solution: Optique adaptative

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→ Correction en temps réel de la phase

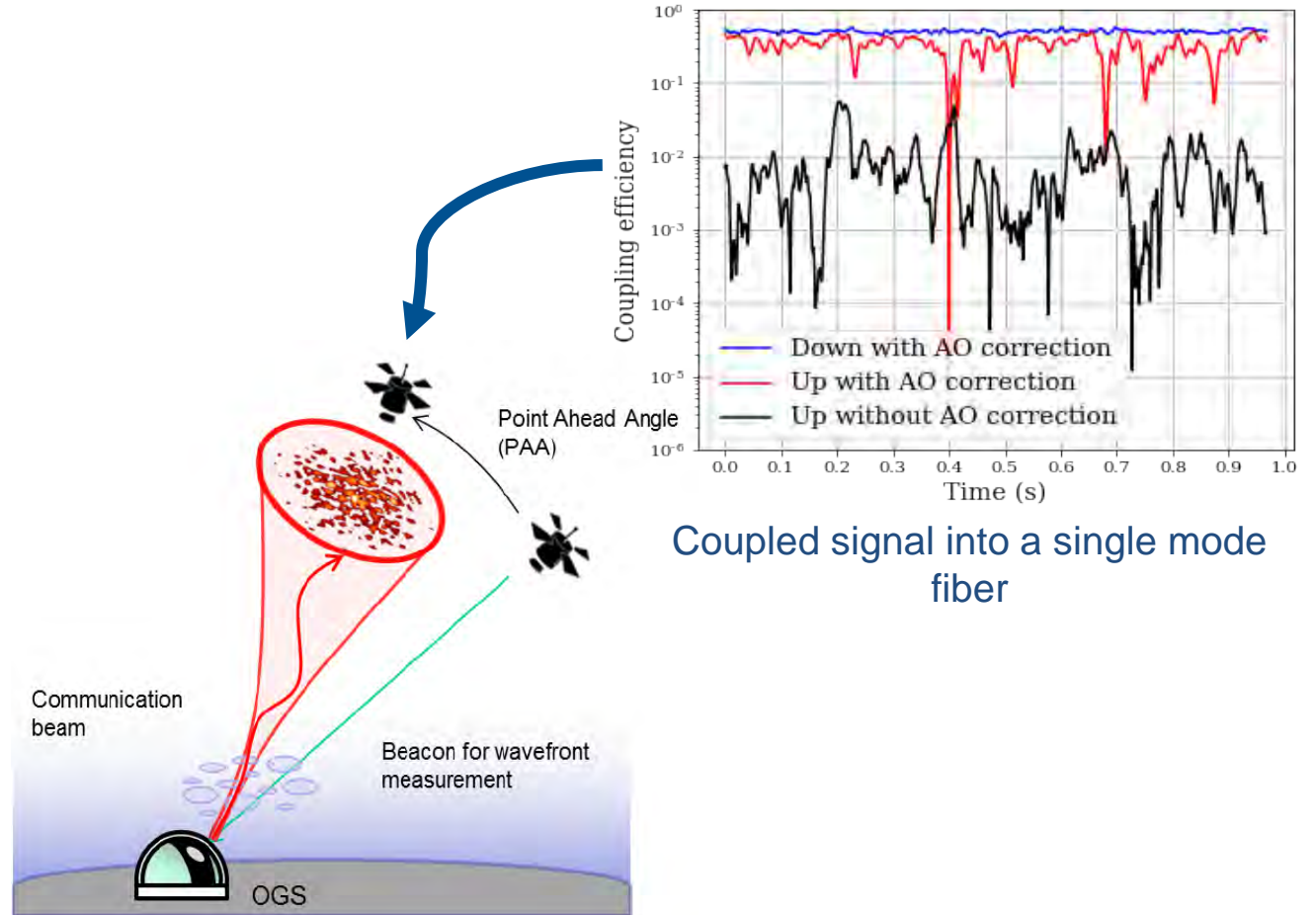
Cas du lien montant:

Pointage en avant du fait des vitesses relatives du satellite et de la terre

→ Correction basée sur la mesure du lien descendant pas optimale.

Conséquence:

Toujours de longues et profondes atténuations du signal qui vont dégrader le lien de télécommunication.



Coupled signal into a single mode fiber

Comment communiquer de manière fiable et à hauts débits du sol vers un satellite ?

Méthode: stratégies optiques et numériques

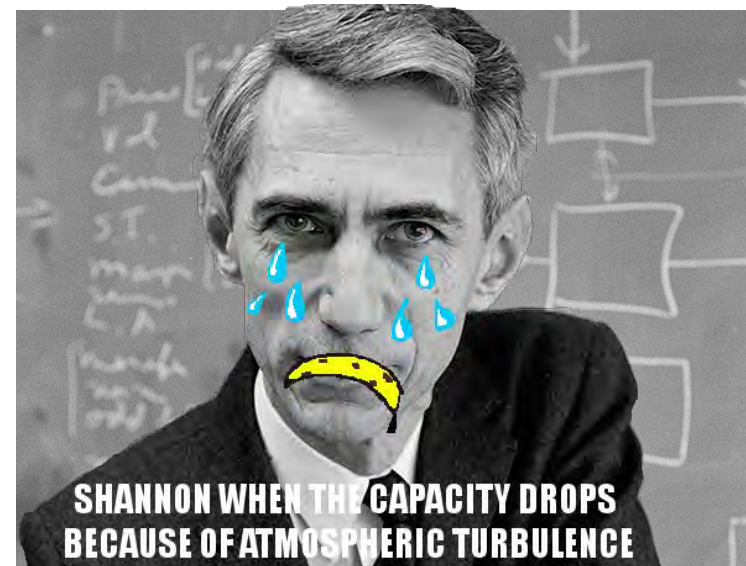
Débit maximal théorique: la capacité

→ Soit débit R supérieur à la capacité C = erreurs

→ Soit débit R inférieur à la capacité C = pas de haut débit

Canal atmosphérique:

→ Débit maximal théorique fortement dégradé



OPTIQUE

Objectif:

Repousser la limite fondamentale en agissant sur le canal physique.

NUMERIQUE

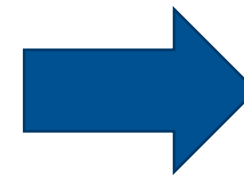
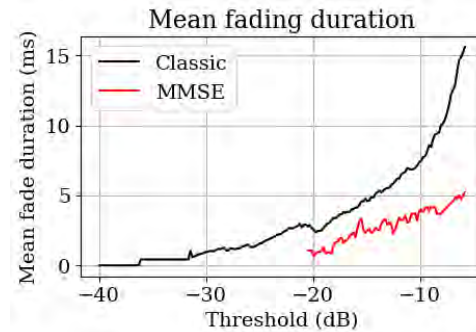
Objectif:

Atteindre la limite fondamentale grâce à des traitements numériques et un codage approprié.

Résultats

Optimisation de la correction d'optique adaptative :
 → Estimation de phase au pointage en avant

[4] Submitted, P. Lognone, et al (2022).



Optical and digital communication strategies for the optimization of high capacity ground-GEO telecoms
 Perrine Lognone, PhD student 3rd year, ONERA/CNES/Telecom Paris
 Supervisors: Jean-Marc Conan (ONERA), Sheng Xueyi (Telecom Paris) - CNES Advisors: Boucraa Benhammer, Hugo Meric

Context : Optical Feeder Links
 Role: Relay nodes in future networks between users and core network, very expensive line.
 → Bi-directional optical links.
 Targeted data rate: 10 Gbps by wavelength.
 Issue: Signal distortion due to atmospheric turbulence.
 → Adaptive optics.

Issue : Point-Ahead Anisoplanatism
 PAAL issue: To mitigate atmospheric turbulence: Adaptive optics (AO).
 AO pre-compensation based on diversity.
 BUT: Point-Ahead angle → AO pre-compensation sub-optimal.
 Consequences on Telecom signal: 10ms nodes at 100Gbps = 10¹¹ bits/sect.

System and Channel Modeling
 Bidirectional reciprocal System: $\Psi(r, t) = A_{in} e^{i\Phi(r,t)} + A_{out} e^{i\Phi(r,t)}$
 W/ the phase: $\Phi_{PAAL} = \Phi_{PAAL} - \Phi_{PAAL}$
 • The log-amplitude fluctuations: γ
 • Key metrics:
 To evaluate the quality of AO correction: $\langle \Phi_{PAAL} \rangle$
 To evaluate the Telecom signal quality: $\langle \Phi_{PAAL} \rangle$
 • Coupled flux: $\langle \Phi_{PAAL} \rangle$
 where M_{ij} is a Gaussian mode.

Channel modeling
 SISO model: $Y = X \cdot H$
 Reciprocal End-To-End
 Pseudo-Analytical [1,2]
 Coupled flux

Telecom performance metrics
 Channel Capacity: $C = \max_{(X,Y)} \log_2(1 + \text{SNR}(X,Y))$
 Outage Probability: $P_{outage} = P(\text{SNR}(X,Y) \leq \text{Rate})$
 Conclusions:
 1) Need of physical modeling to evaluate the Telecom performance.
 → Refined pseudo-analytical model.
 2) Channel characterization with Telecom metrics accurate for fading channels.
 → Outage probability.

Physical Reliability Mechanisms
 Problem statement: How to make the link reliable at the physical layer?
 State of the Art Methods:
 1. Slave satellite
 2. Classical (Astro) [4]
 3. Laser Guide Star [5]
 4. MMSE Whiteley (Astro) [5]
 New method to estimate the phase at PAAL (8):
 • Criteria to minimize:
 $\Phi = \Phi_{PAAL} - \Phi_{PAAL}$
 • Linear criteria:
 $\Phi_{lin} = \Phi_{PAAL} - B \gamma_{lin}$
 • MMSE linear estimation:
 $R_{MMSE} = \arg \min_{\Phi} E[\Phi_{lin}^2]$
 • Theoretical error:
 $\sigma_{\Phi_{lin}} = E[\Phi_{lin}^2]$
 • Method novelty:
 $\gamma_{lin} = \begin{pmatrix} \Phi \\ X_0 \end{pmatrix}$

Results
 Bit/bit phase variance @ $\gamma_{lin} < \gamma_{classical}$
 10k Coupled Flux Time-Series
 Conclusion:
 → +2.5dB gain
 → Mean fading duration = by 3 with respect to the classical method

Conclusions and Perspectives
 Conclusions:
 • Model:
 • Refinement of E2E functional tools
 • Refinement of pseudo-analytical model
 • Physical reliability mechanisms:
 • Development of new software tools for pre-compensating the PAAL and reducing the fading duration.
 • Telecom reliability mechanisms:
 • Exploration of the diversity to characterize the Telecom link.
 Perspectives:
 • Model:
 • Analytical development, Temporal characterization
 • End-to-end evaluation of the Telecom performance.
 • Physical reliability mechanisms:
 • Refinement of the model.
 • Telecom reliability mechanisms:
 • Physical diversity...

Bibliography
 [1] Lognone, P., Conan, J.-M., Meric, H., & Xueyi, S. (2021). Adaptive optics for high data rate satellite-to-ground links. In *Optical Fiber Communication and Photonics for Space Communications* (2021) pp. 1-12. IEEE.
 [2] Lognone, P., Conan, J.-M., Meric, H., & Xueyi, S. (2021). Adaptive optics for high data rate satellite-to-ground links. In *Advanced Photonics Congress* (2021) pp. 1-12. SPIE.
 [3] Lognone, P., Conan, J.-M., Meric, H., & Xueyi, S. (2021). Adaptive optics for high data rate satellite-to-ground links. In *Advanced Photonics Congress* (2021) pp. 1-12. SPIE.
 [4] Whiteley, M. A., & White, R. M. (1988). Optimal linear minimum variance pre-compensation for atmospheric turbulence. *OSA*, 6(12), 2189-2196.
 [5] Lognone, P., Conan, J.-M., Meric, H., & Xueyi, S. (2021). Phase Estimation at Point-Ahead angle for AO Pre-Compensation Ground-to-GEO Satellite Downlinks. Submitted to Optics Express.

Merci pour votre attention !