Optical and digital communication strategies for the optimization of high capacity ground-GEO telecoms

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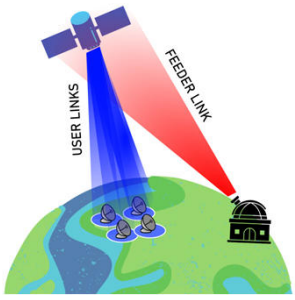
Context : Optical Feeder Links

Role: Relay node in future networks between users and core network, very capacitive link.
→ Bidirectional optical link.

Targeted data rate: 10 Gbps by wavelength.

Issue: Signal distortion due to atmospheric turbulence.

→ Adaptive optics



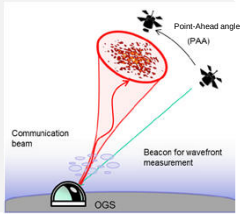
Issue : Point-Ahead Anisoplanatism

PAA issue

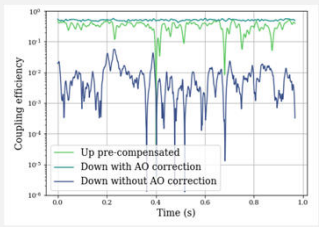
To **mitigate** atmospheric turbulence:
- Adaptive optics (AO).

Uplink scenario:
- AO pre-compensation based on downlink.

BUT: Point-Ahead angle
→ AO pre-compensation sub-optimal.



Consequences on Telecom signal



Coupled signal into a single mode fiber

→ 10ms fades at 10Gbps = 10^8 bits lost

System and Channel Modeling

Bidirectional reciprocal System

- **Physical quantities:**

Reciprocal residual field:

$$\Psi(\mathbf{r},t) = \mathbf{A_0} e^{\chi(\mathbf{r},t)+i\Phi_{res}(\mathbf{r},t)}$$

With:
- The phase: $\Phi_{res} = \Phi_{PAA} - \Phi_{OA}$,
- The log-amplitude fluctuations: χ

- **Key metrics:**

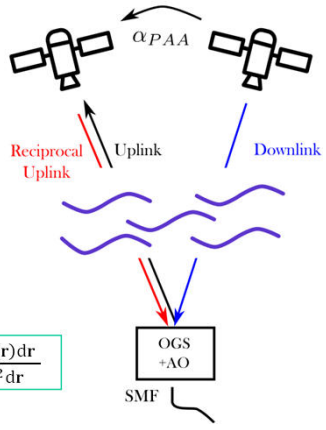
To evaluate the quality of AO correction:

$$< \Phi_{res}^2 >$$

To evaluate the Telecom signal quality:

- Coupled flux: $f_c(t) = \frac{\iint \Psi(\mathbf{r},t) M_0(\mathbf{r}) d\mathbf{r}}{\iint |M_0(\mathbf{r})|^2 d\mathbf{r}}$

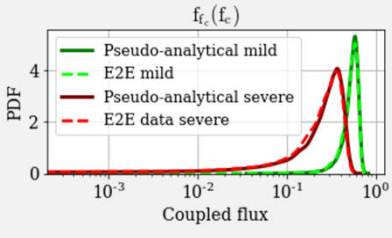
where M_0 is a Gaussian mode.



Channel modeling

SISO model: **Y = fX+N**

Reciprocal End-To-End
↓
Pseudo-Analytical [1,2]



↓
Full Analytical

Telecom performance metrics

- **Channel Capacity:**

→ What is the max bit-rate achievable to have an error free channel ? [3]

$$C = \max_{p_X(X)} I(X;Y) = \log_2(1 + SNR(f_c))$$

- **Outage Probability:**

$$P_{outage} = P(C(SNR(f_c)) \leq Rate)$$

Conclusions

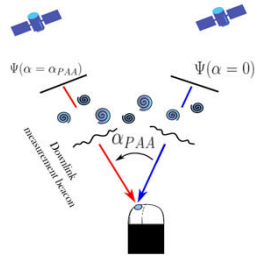
1) Need of physical modeling to evaluate the telecom performances:
→ Refined pseudo-analytical model.
2) Channel characterization with Telecom metrics accurate for fading channels:
→ Outage probability

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 (Aniso) [4]
3. Laser Guide Star [4]
4. MMSE Whiteley (Astro) [5]



Slave satellite illustration (1).

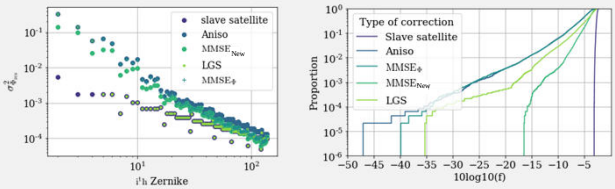
New method to estimate the phase at PAA [6]:

- Criteria to minimize:
$$e = \Phi_{PAA} - \hat{\Phi}_{PAA}$$
- Linear criteria:
$$e_{lin} = \Phi_{PAA} - R y_m$$
- MMSE linear estimation:
$$R_{MMSE} = argmin_R \mathbb{E}[e_{lin}^t e_{lin}]$$
- Theoretical error:
$$\Gamma_{\Phi_{res}} = \mathbb{E}[e_{lin} e_{lin}^t]$$
- Method novelty:

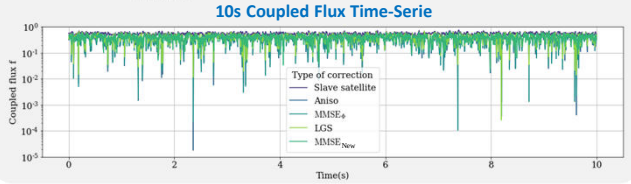
→ Optimisation of y_m.

Results

Residual phase variance & $P(f_c \leq f_{threshold})$



10s Coupled Flux Time-Serie



Conclusion:
→ >15dB gain
→ Mean fading duration ÷ by 3 with respect to the classical method

Conclusions and Perspectives

Conclusions

- **Model:**
  - Reciprocal adaptation of E2E numerical tools
  - Refinement of pseudo-analytical model
- **Physical reliability mechanisms:**
  - Development of a new off-axis phase estimator providing high dB gain and reducing the fading duration.
- **Telecom reliability mechanisms:**
  - Exploration of the metrics to characterize the Telecom link

Perspectives

- **Model:**
  - Analytical development, Temporal characterization
- **End-to-End evaluation of the Telecom performances**
- **Physical reliability mechanisms:**
  - Estimator extension
- **Telecom reliability mechanisms:**
  - Pre-coding, Temporal diversity…

Bibliography

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[3] Shannon, C. E. (1949). Communication in the presence of noise. *Proceedings of the IRE*, *37*(1), 10-21.

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