FEEDELIO: demonstrating the feasibility of adaptive optics compensated GEO feeder links

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Quick reminder from Jean-Marc’s presentation

PAA = Point-Ahead Angle

Point ahead angle (displacement of the satellite during the time of flight)

Turbulence

Limitation of pre-compensation: Anisoplanatism

Jean-Marc explained the theory → how does it compare to experiment?
Goals of the FEEDELIO experiment

- To provide a convincing experimental demonstration showing the potential of AO for GEO-Feeder Links.
- To evaluate also its limitations, especially regarding angular decorrelation, through experimental demonstration + comparison to performance derived from in-house existing models.
- To get experimental feedback on AO precompensation without payload nor link budget constraints, before aiming at a real GEO satellite with ONERA ground station in the coming years.

→ Slant path experiment in Tenerife
FEEDELIO slant path demonstration of a GEO Feeder Link

STB : Satellite Terminal Breadboard
GTB : Ground Station Terminal Breadboard
Commissioning : April 2019 (aka the Evil April)
Satellite Terminal Breadboard (STB)

On-axis module: **GEO Satellite Emitter** emulator
- Emits downlink ref beam for AO
- Reference for uplink signal statistics (PAA = 0)

Off-axis module: **Receiver** emulator
- Receives uplink AO-corrected beam
- Adjustable angular distance: up to 100 µrad
- Beam focused on target, Beam diameter ≈ 5cm, DRx = 1.7 mm → « like a GEO-FL »
Ground Terminal Breadboard (GTB)

- Telescope diameter: $D = 35\, \text{cm}$
- South pillar of OGS
- AO system* (45 cm x 60 cm x 30 cm):
  - DM 11x11 actuators (Alpao 97-15 fast upgrade)
  - 1.5 kHz sampling freq.
- 8 x 8 subapertures Shack-Hartmann with COTS Raptor Owl HS sensor
- ONERA’s design RTC (Shakti provider)
- Fast Steering Mirror for fast switching between on-axis and PAA directions
- single mode fiber coupling (downlink)

Experimental feedback

AO-precompensated feeder links = traditional AO +:

- Open-loop optimization of the coupling between FSM and STB:
  - Semi-automatic maximization of the coupled flux on the off-axis module
  - Estimated precision = 0.5 µrad (beam div = 4 µrad)

- Optimization of a bidirectional link: minimization of the downlink/uplink NCPA
  → On-axis reciprocity of the link: first proof (to our knowledge) of reciprocity on an AO compensated link

![Graph showing synchronized signals with Correlation = 85%]

FSM = Fine Steering Mirror
NCPA = Non Common-Path Aberrations
AO performance – on-axis

STB signal statistics as a function of turbulence strength

Amelioration of signal statistics in all conditions → AO works!
Is it as good as theory says?
AO performance – on-axis – comparison to theory

APPROACH: Signal statistics on Shack-Hartmann
→ Estimation of turbulence and wind profile (ONERA model)
→ Estimation of theoretical AO performance
→ Estimation of signal statistics (ONERA model)

Open-loop value ≠ theo value
→ static tip-tilt adjusted « by hand »
→ Variations with refraction, thermomechanical effects
→ tip-tilt compensation = mandatory
AO performance – on-axis – comparison to theory

APPROSSH : Signal statistics on Shack-Hartmann
→ Estimation of turbulence and wind profile (ONERA model)
→ Estimation of theoretical AO performance
→ Estimation of signal statistics (ONERA model)

Low scintillation: AO perf ≈ theo value
## From downlink correction... to uplink pre-compensation

### ON axis short term irradiance distribution

\( r_0 = 10 \text{ cm, } \sigma_i^2 = 0.06 \)

### Focal plane @ GTB

<table>
<thead>
<tr>
<th></th>
<th>Open loop</th>
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<tbody>
<tr>
<td>Medium turbulence 14/04, 9h40</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
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<tr>
<td>Same sequence, Long exposure (10 s)</td>
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<td><img src="image5.png" alt="Image" /></td>
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AO performance – on-axis – comparison to theory

APPROACH: Signal statistics on Shack-Hartmann
→ Estimation of turbulence and wind profile (ONERA model)
→ Estimation of theoretical AO performance
→ Estimation of signal statistics (ONERA model)

Low scintillation: AO perf = theo value
Strong scintillation: AO perf ≠ theo value
→ Poor performance of WFS (by design, could be better), but still - loop closed and stable
→ GEO Feeder: limited scintillation, typ. close to Rytov regime
→ not representative of a GEO-feeder link
From downlink correction... to uplink pre-compensation

![Mountain Image](image)

**ON axis short term irradiance distribution**

\[ r_0 = 10 \text{ cm}, \sigma_i^2 = 0.06 \]

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AO performance – off-axis – comparison to theory

**APPROACH**: Signal statistics on Shack-Hartmann

- Estimation of turbulence and wind profile (ONERA model)
- Estimation of theoretical AO performance
- Estimation of signal statistics (ONERA model)

In this example, turbulence conditions during sequence acquisition ≈ (quite) stationary

- Variations of mean ROP with PAA = anisoplanatism
- Relevant set of data
AO performance – off-axis – comparison to theory

APPROACH: Signal statistics on Shack-Hartmann
→ Estimation of turbulence and wind profile (ONERA model)
→ Estimation of theoretical AO performance
→ Estimation of signal statistics (ONERA model)

Open loop: theory ≠ model because of static tip-tilt
With AO: theory ≈ model
→ Good understanding of AO error budget
AO performance – off-axis – comparison to theory

APPROACH: Signal statistics on Shack-Hartmann
→ Estimation of turbulence and wind profile (ONERA model)
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QUESTION: relevancy of an « equivalent GEO-FL PAA » with slant path turb profiles?
→ Experiment = order of magnitude
→ Precise value = modelization
Conclusions and Perspectives

- **AO precompensation works**! FEEDELIO confirms AO feasibility for pre-compensation in a relevant environment: non stationary turbulence with potentially strong turbulence conditions variations, significant and quantified anisoplanatism.

- **Critical step for the validation of AO correction for GEO-FL**:
  - Experimental feedback + good understanding of AO error budget
  - Inputs for optimization of ONERA ground station: FEELINGS

To be coming soon:

- Analysis of **power fluctuations data**
- Additional data acquisition planned for a richer statistics wrt turbulence conditions
Some references:

The FEEDELIO team

THANK YOU FOR YOUR ATTENTION!