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

A. Montmerle-Bonnefois[1], C. Petit[1], C.B. Lim[1], J.-F. Sauvage[1], S. Meimon[1], P. Perrault[1], F. Mendez[1], B. Fleury[1], J. Montri[1], J.-M. Conan[1], V. Michau[1], N. Védrenne[1], Z. Sodnik[2], C. Voland[2]

[1] ONERA, [2] ESA

- aurelie.bonnefois@onera.fr

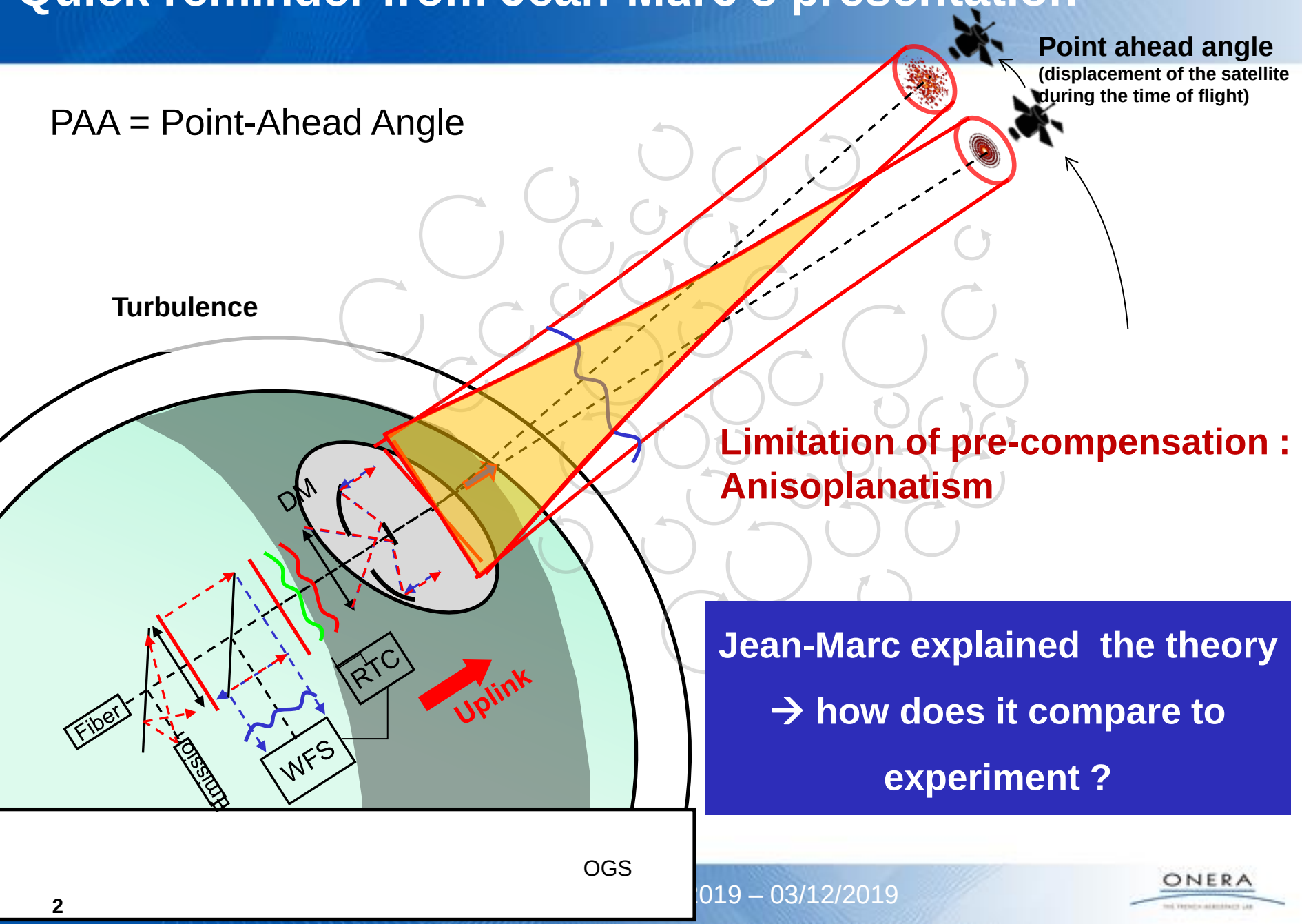
ONERA
THE FRENCH AEROSPACE LAB

esa
European Space Agency

retour sur innovation

Quick reminder from Jean-Marc's presentation

PAA = Point-Ahead Angle



Limitation of pre-compensation : Anisoplanatism

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

Goals of the FEEDELIO experiment

→ FEEDELIO experiment
(FEEDEr LInk with adaptive Optics)

European Space Agency

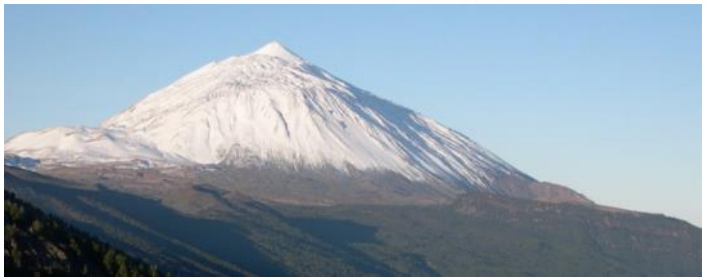
- To provide a convincing experimental demonstration showing the potential of AO for GEO-Feeder Links.
- To evaluate also its limitations, especially regarding angular decorrelation, through experimental demonstration + comparison to performance derived from in-house existing models.
- To get experimental 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.

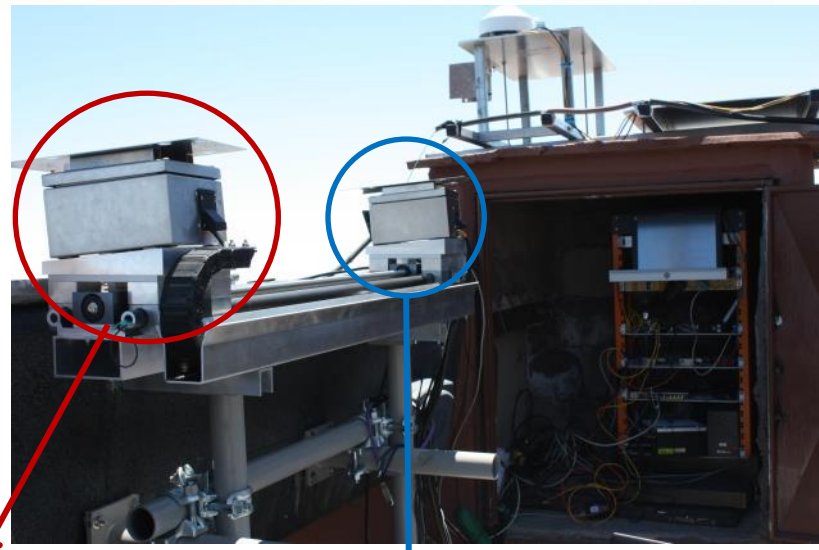
→ **Slant path experiment in Tenerife**

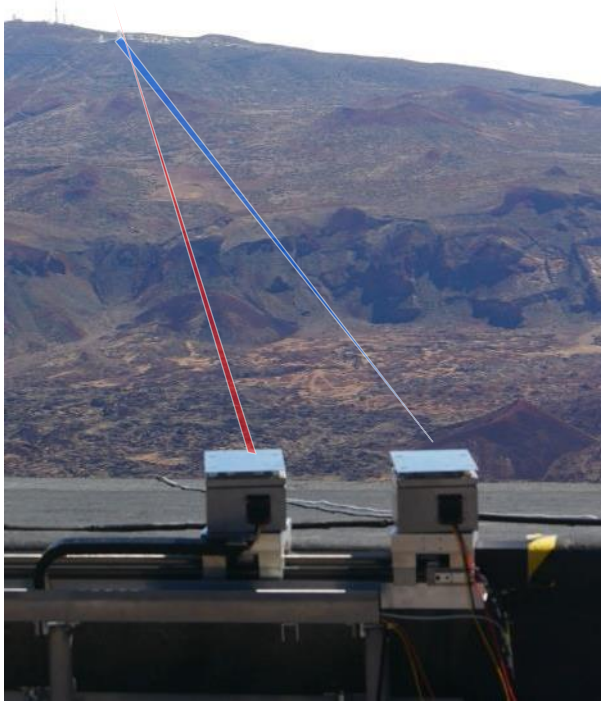
FEEDELIO slant path demonstration of a GEO Feeder Link

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

Satellite Terminal Breadboard (STB)







Rx

Ex

Off-axis module: **Receiver** emulator

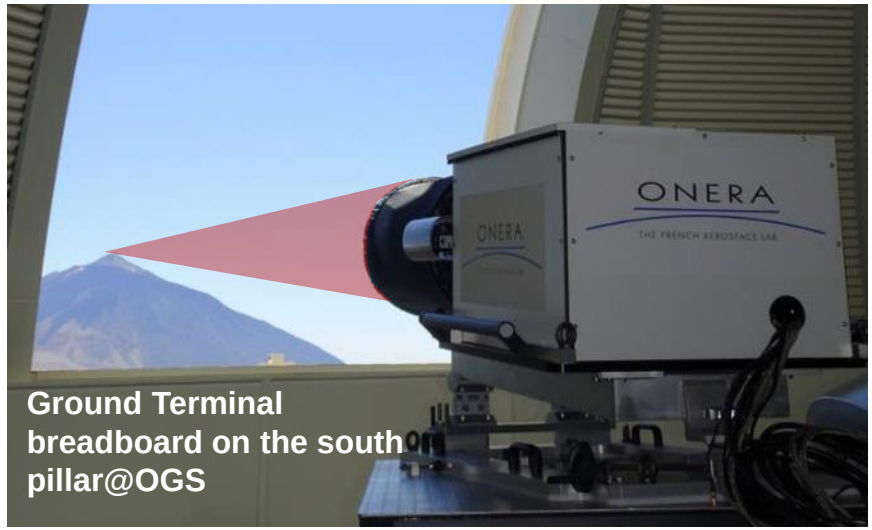
- Receives uplink AO-corrected beam
- Adjustable angular distance: up to 100 µrad
- Beam focused on target, Beam diameter ≈ 5cm, DRx = 1.7 mm → « like a GEO-FL »

On-axis module:

- = GEO Satellite **Emitter** emulator
- Emits downlink ref beam for AO

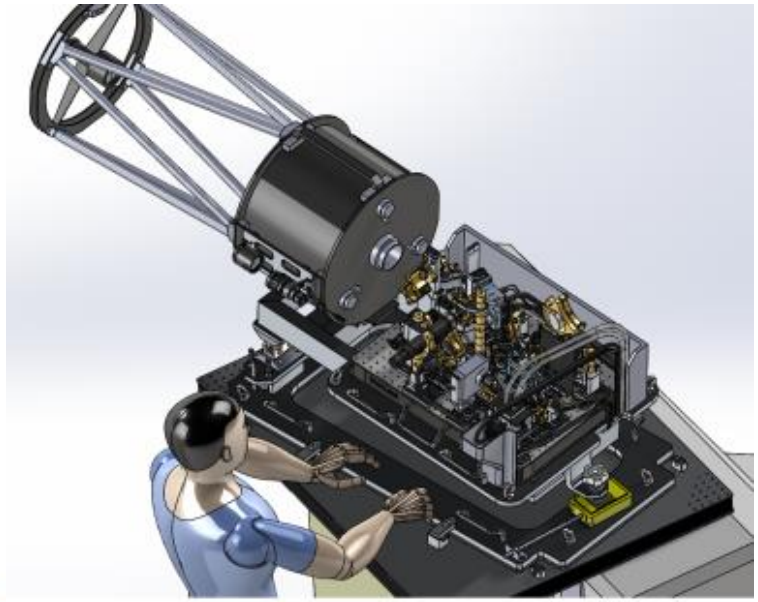
+ Reference for uplink signal statistics (PAA = 0)

Ground Terminal Breadboard (GTB)



Ground Terminal breadboard on the south pillar@OGS

- Telescope diameter: D = 35 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)



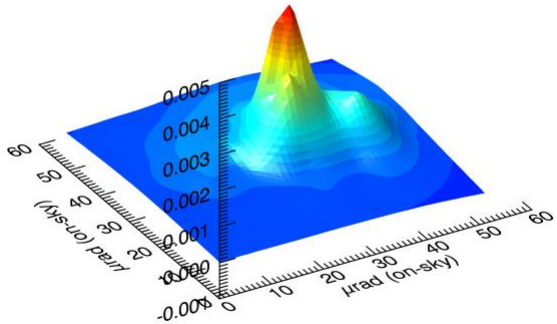
Védrenne et. al., Proc. of IEEE ICSOS (2017),
Montmerle Bonnefois et Al., Proc of ICSO (2018)

Experimental feedback

FSM = Fine Steering Mirror
NCPA = Non Common-Path Aberrations

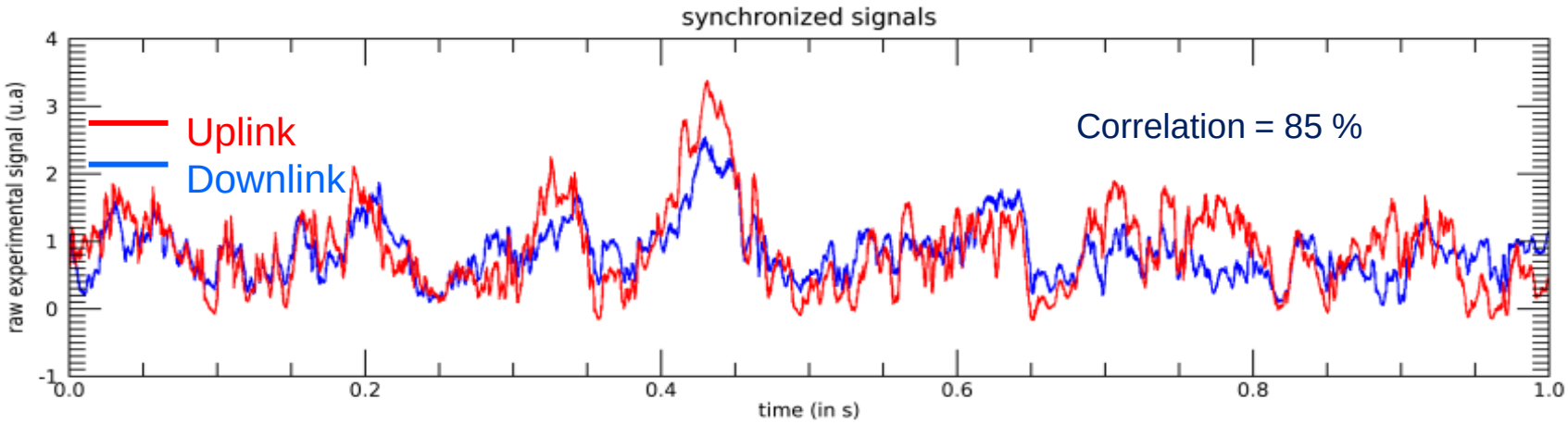
AO-precompensated feeder links = traditional AO + :

- 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

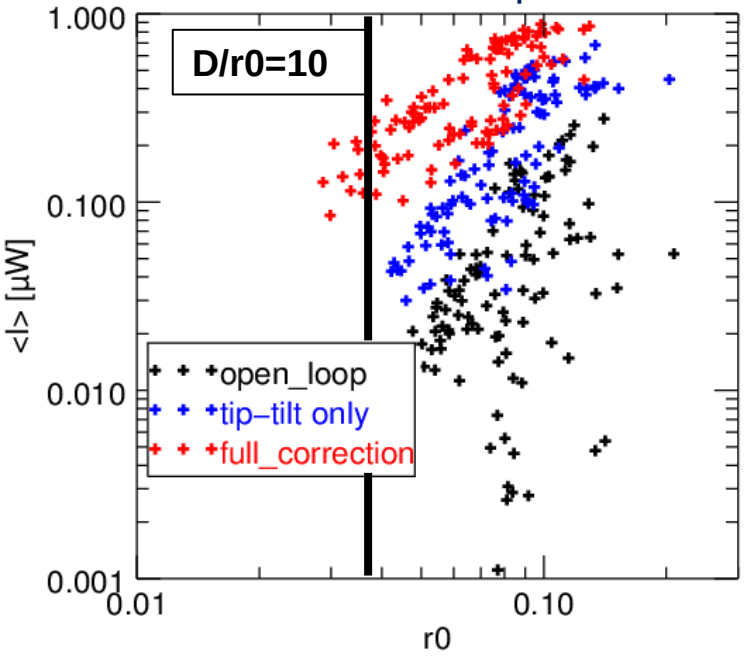


Time [s]

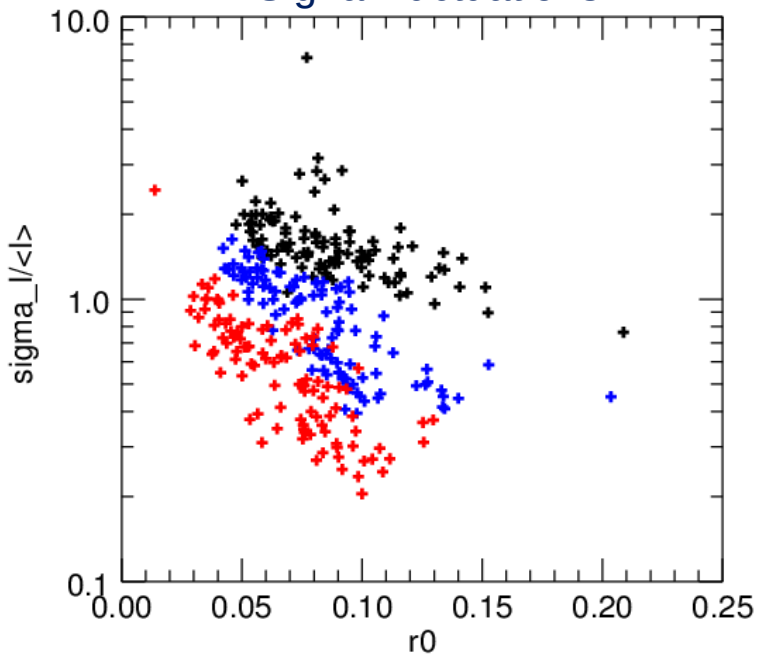
AO performance – on-axis

STB signal statistics as a function of turbulence strength

Mean received power



Signal fluctuations

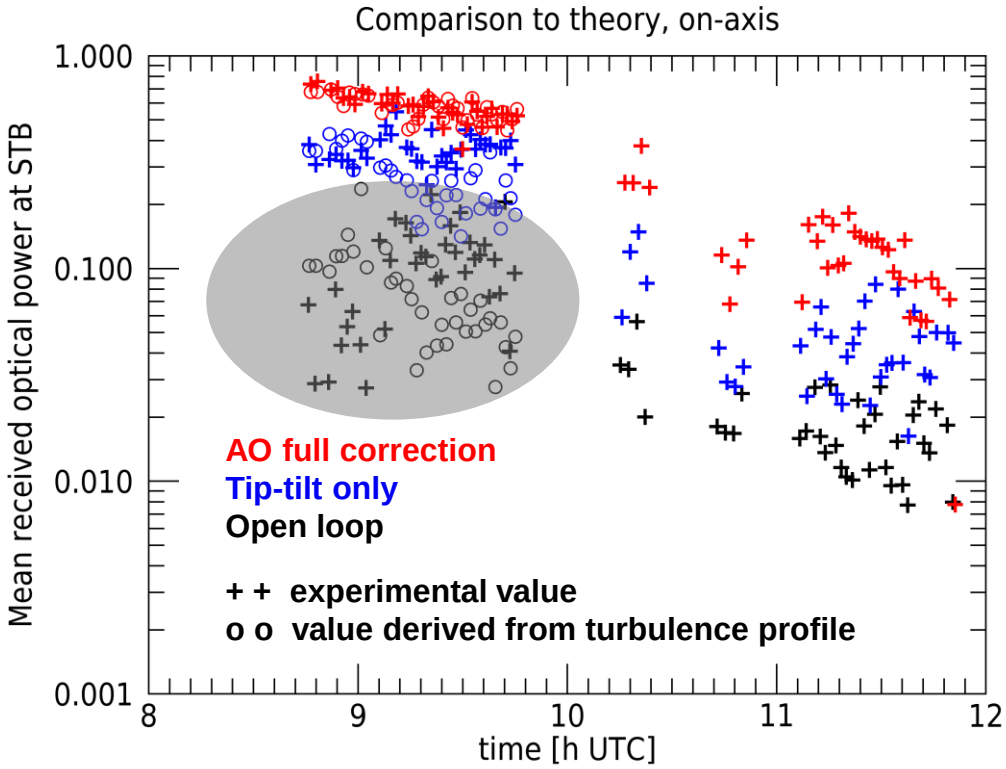


Amelioration of signal statistics in all conditions → AO works !
Is it as good as theory says ?

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

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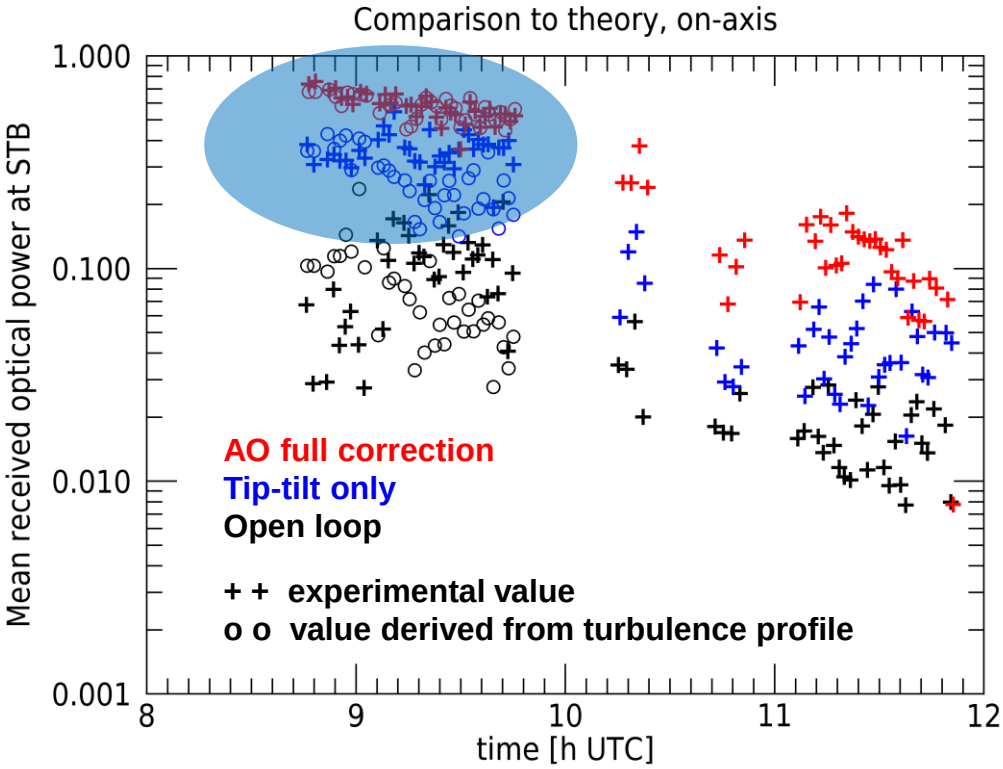
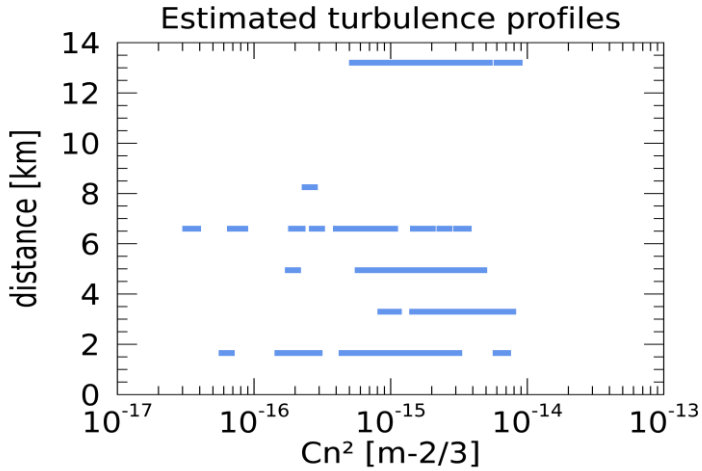


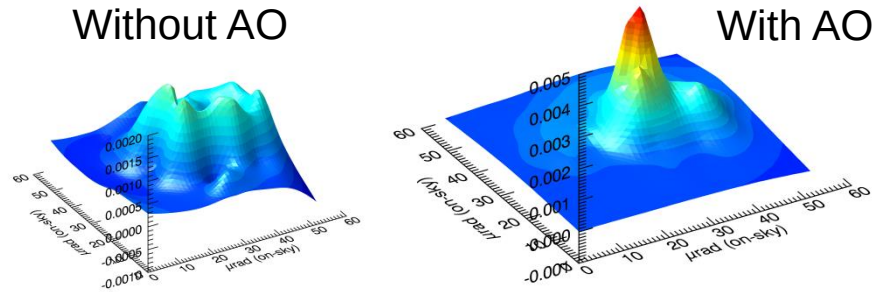


Low scintillation: AO perf ≈ theo value

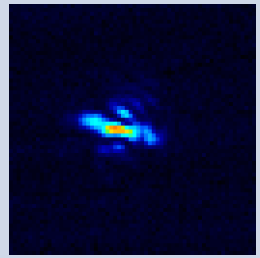
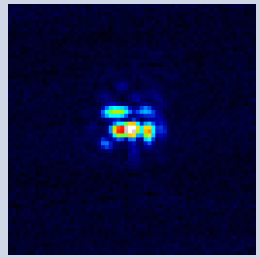
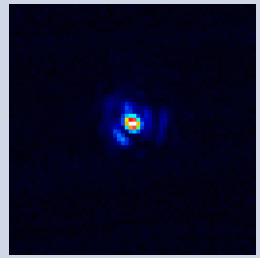
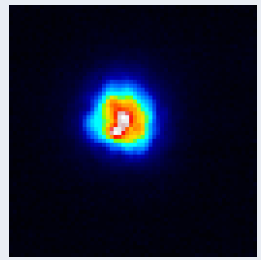
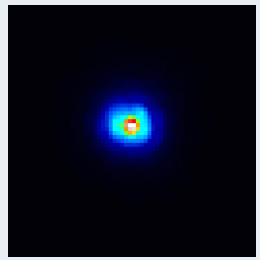
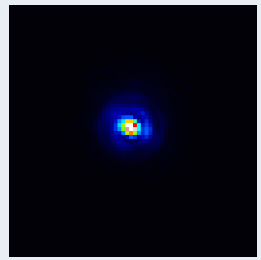
From downlink correction… to uplink pre-compensation

Without AO

With AO



ON axis short term irradiance distribution (r_0 = 10 cm, σ_i^2 = 0,06)

Focal plane @ GTB	Open loop	Tip-tilt only	Full correction
Medium turbulence 14/04, 9h40			
Same sequence, Long exposure (10 s)			

AO performance – on-axis – comparison to theory

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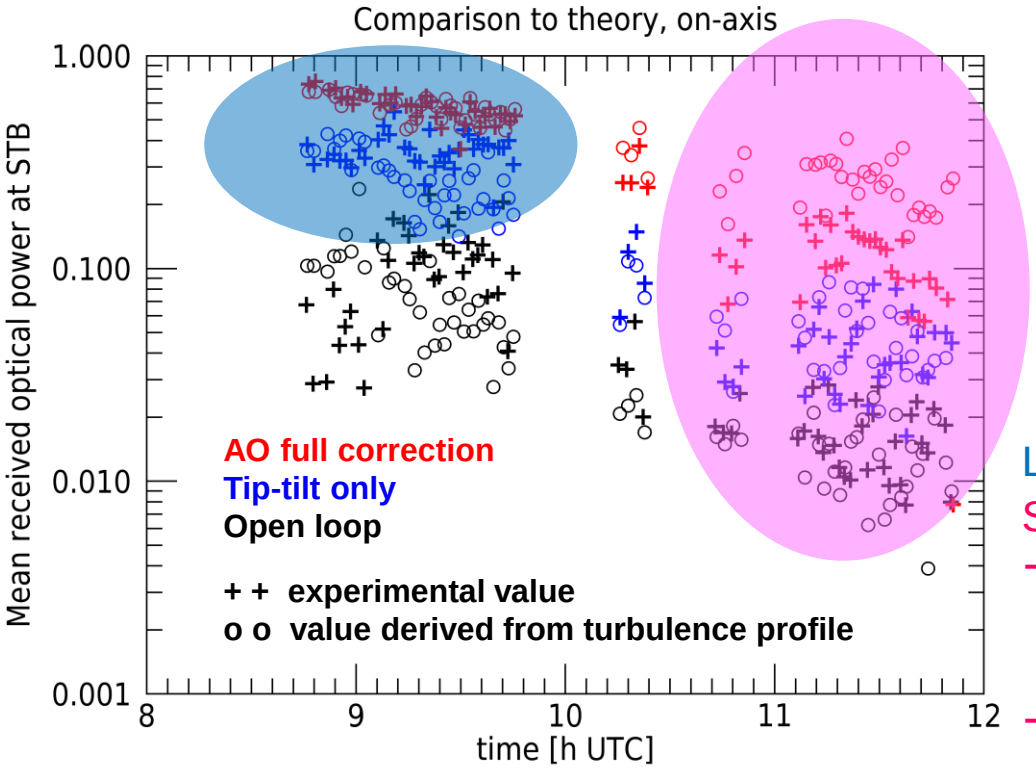
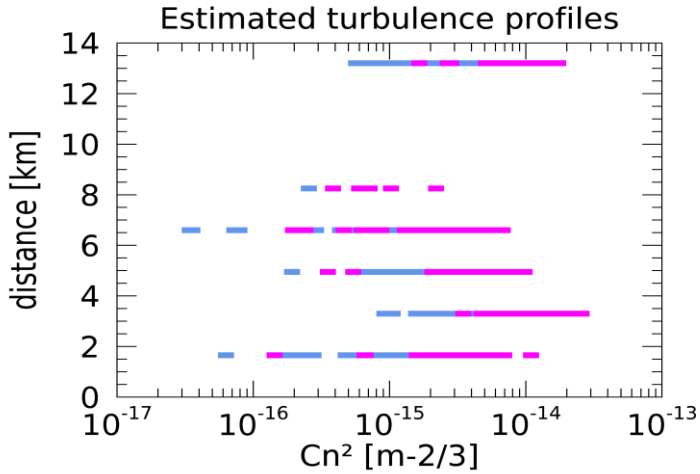




Low scintillation: AO perf = theo value

Strong scintillation : AO perf ≠ theo value

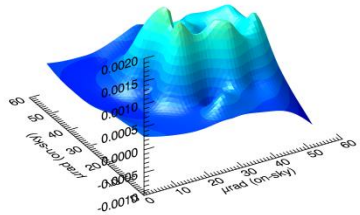
→ Poor performance of WFS (by design, could be better), but still - loop closed and stable

→ GEO Feeder : limited scintillation, typ. close to Rytov regime

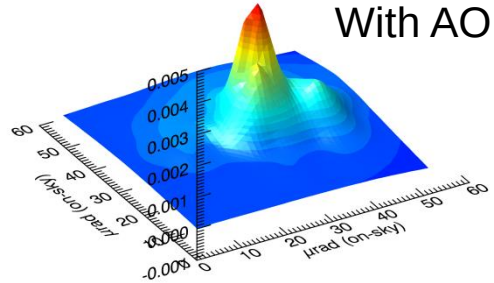
→ not representative of a GEO-feeder link

From downlink correction… to uplink pre-compensation

Without AO



With AO



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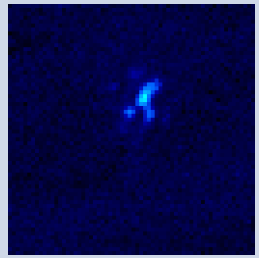
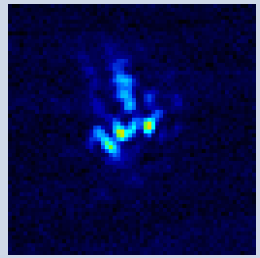
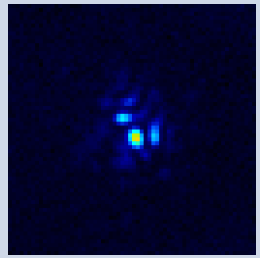
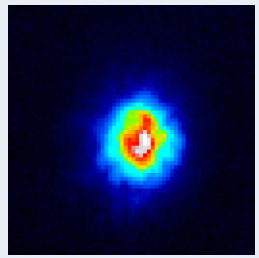
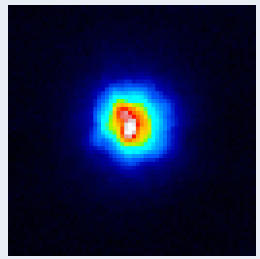
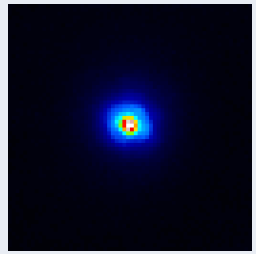
Strong turbulence 14/04, 11h20			
Same sequence, Long exposure (10 s)			

AO performance – off-axis – comparison to theory

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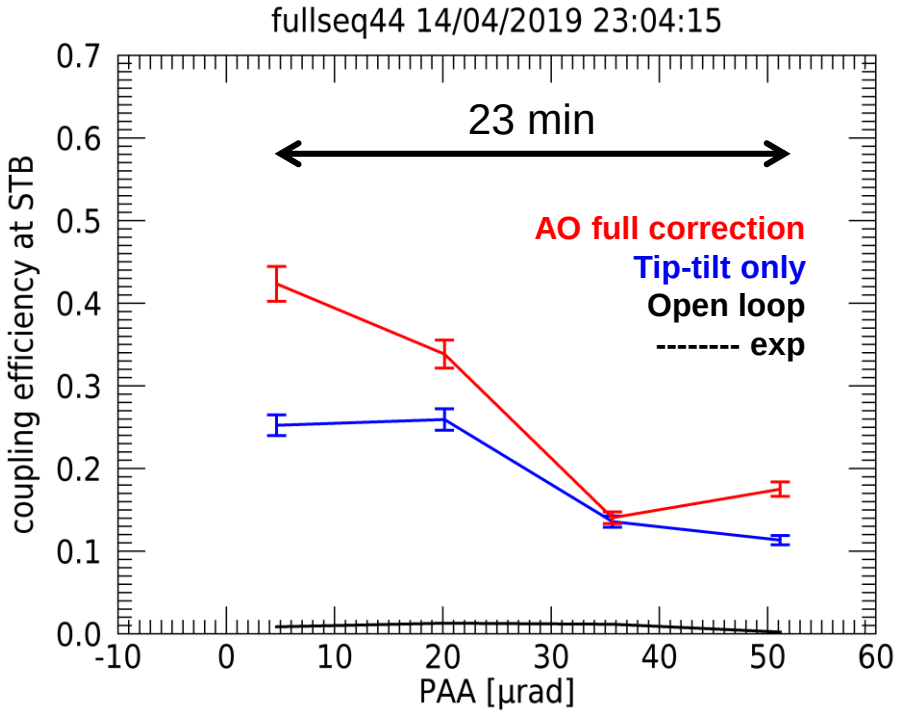

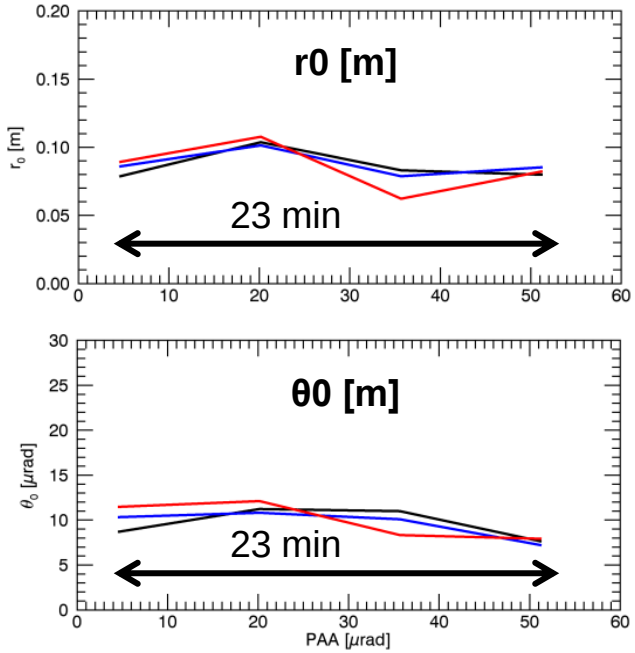

In this example, turbulence conditions during sequence aquisition ≈ (quite) stationary

→ Variations of mean ROP with PAA = anisoplanatism

→ Relevant set of data

AO performance – off-axis – comparison to theory

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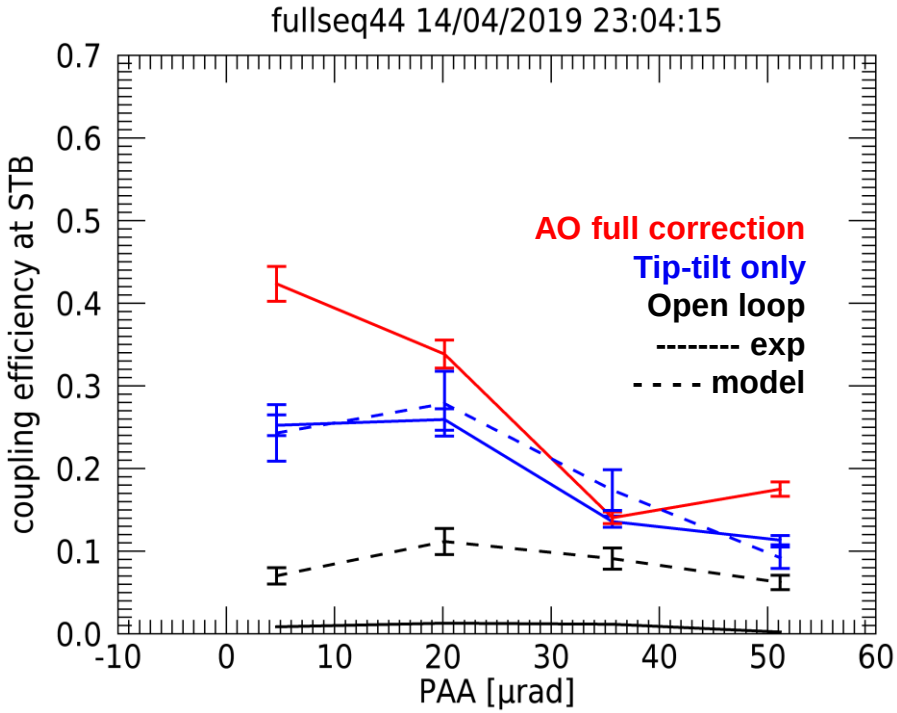

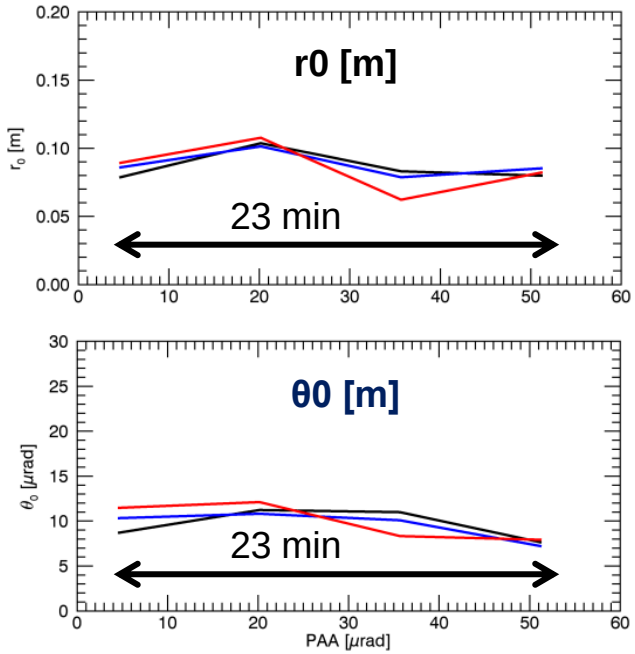

Open loop : theory ≠ model because of static tip-tilt

With AO : theory ≈ model

→ Good understanding of AO error budget

AO performance – off-axis – comparison to theory

APPROACH : Signal statistics on Shack-Hartmann
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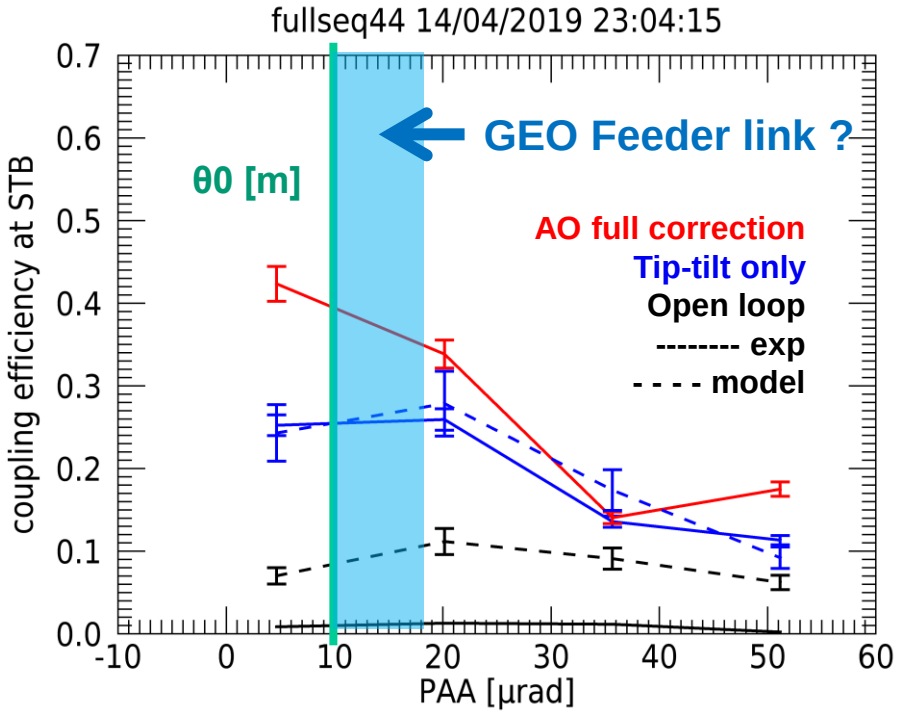
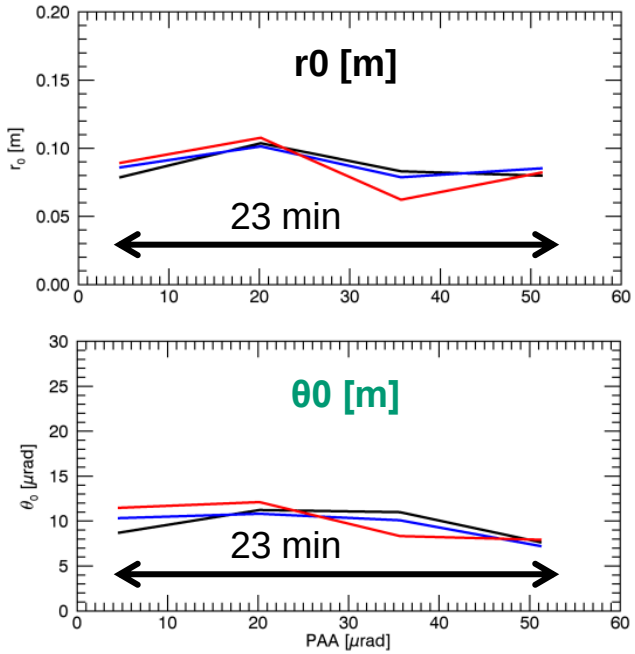




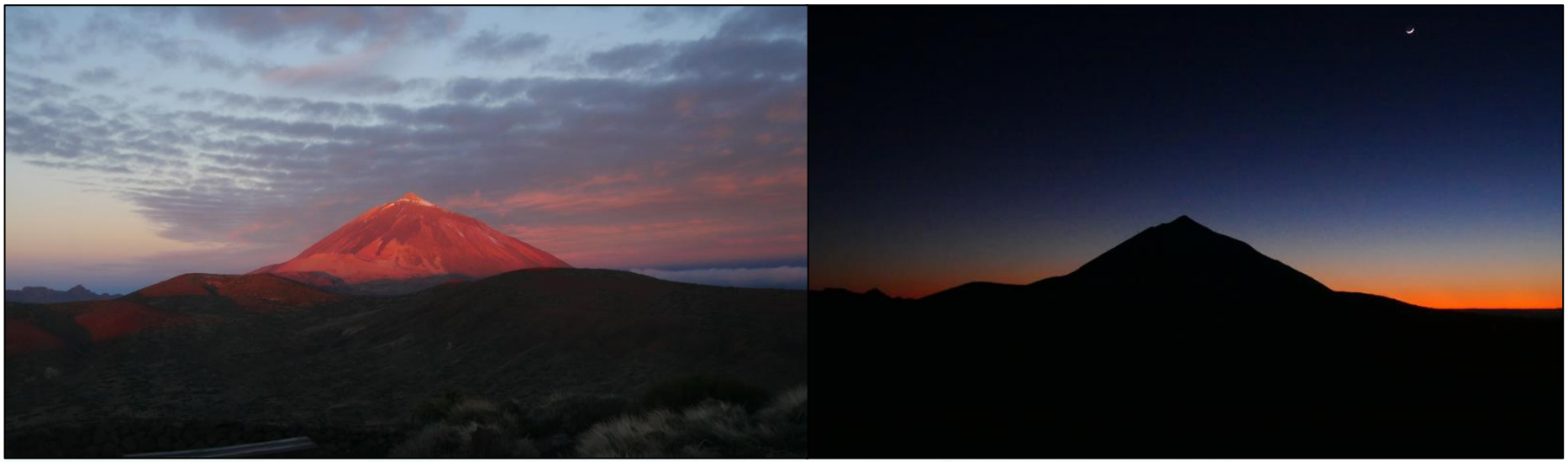
QUESTION : relevancy of an « equivalent GEO-FL PAA » with slant path turb profiles ?
- → Experiment = order of magnitude
- → Precise value = modelization

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 :

- Védrenne, N., et al. "Adaptive optics pre-compensation for GEO feeder links: Towards an experimental demonstration." *2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*. IEEE, 2017.
- Montmerle Bonnefois, A., et al, " Adaptive Optics pre-compensation for GEO feeder links: the FEEDELIO experiment ", Proc of ICSO 2018
- Montmerle-Bonnefois, A., et al. "Adaptive optics precompensation of a GEO feeder link: the FEEDELIO experiment." *Applications of Lasers for Sensing and Free Space Communications*. Optical Society of America, 2019.
- Védrenne, N., et al. " First experimental demonstration of adaptive optics pre-compensation for GEO feeder links in a relevant environment" *2019 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*. IEEE, 2019.
- Lim, C. B., et al. " Single-mode fiber coupling with adaptive optics for free-space optical communication under strong scintillation" *2019 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*. IEEE, 2019.

The FEEDELIO team