FEEDELIO : feasibility demonstration and performance assessment of AO precompensation for GEO FEEDER links

Final Presentation

09/12/21

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Outline

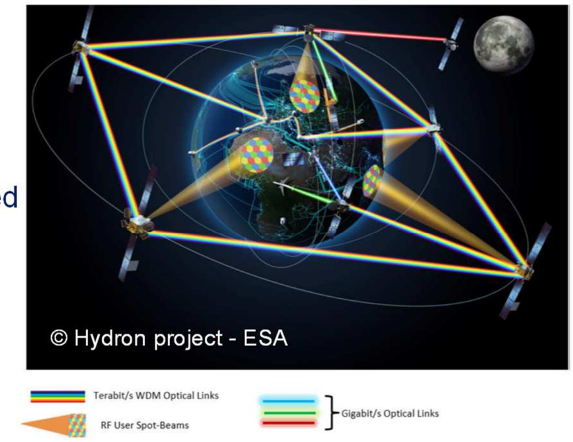
- A (very) brief FEEDER link budget analysis
- Challenges of the feasibility assessment
- The FEEDELIO experiment :
  - Setup,
  - Installation and functional tests
  - Results
- Lessons learned for a GEO feeder link
- Perspectives and follow up activities

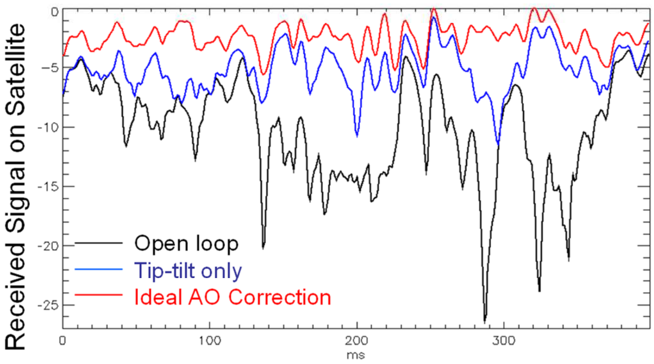
GEO-FEEDER links and channel impairments

A backbone for the very future of globalized internet: no frequency allocation, directivity hence intrinsically secured very high data rate (WDM), up to Tbps

One key challenge : crossing the atmosphere

- Clouds = > site diversity
- Atmospheric turbulence ?



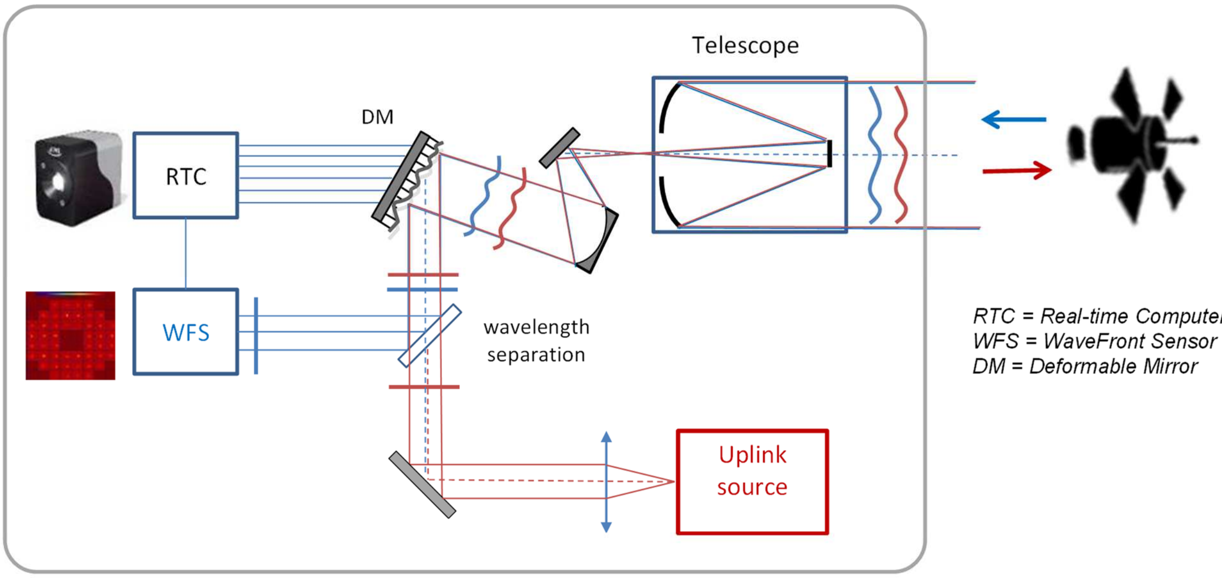


Uplink End2end simulation, D = 20 cm, w_0 = 10 cm, HV profile, θ_0= 10 µrad , r_0 = 3 cm (@550 nm zenith, 7 cm @ 1.5 µm), Bufton wind profile, 5 m/s ground level, 25 m/s for high altitude layer

AO pre-compensation might be the game-changer (if feasible)

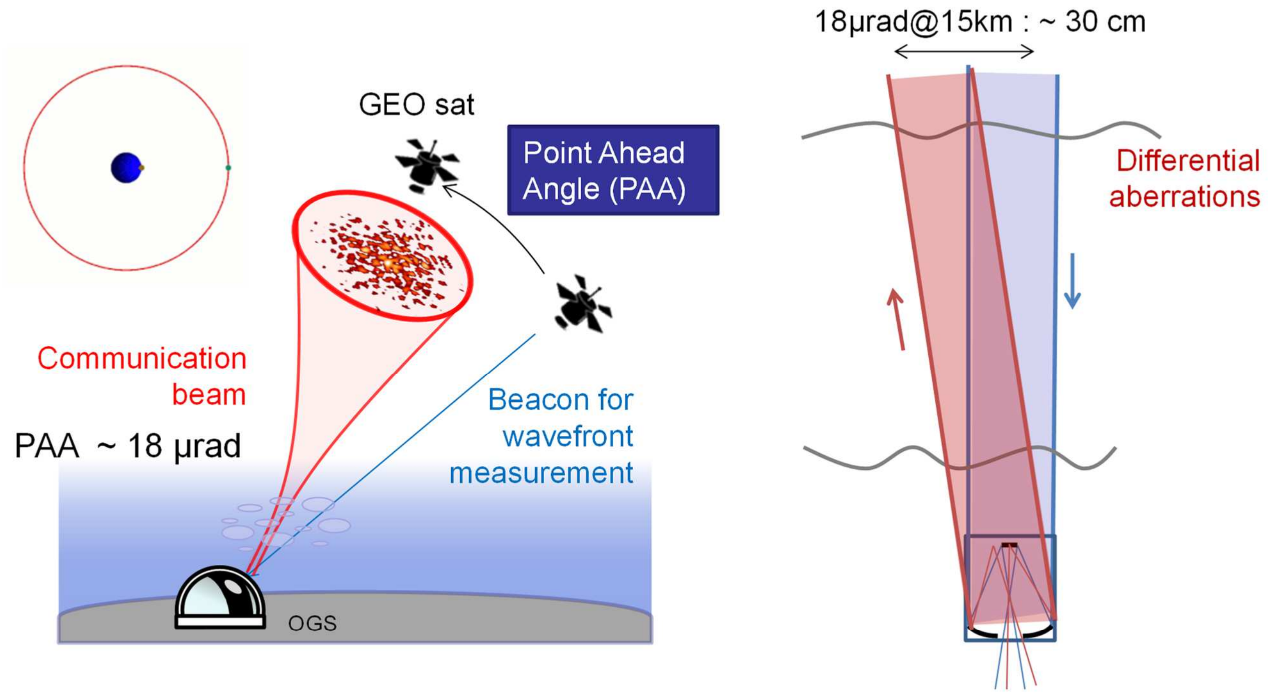
- however average losses and residual fluctuations shall be properly assessed

Principle of Adaptive Optics Pre-compensation



RTC = Real-time Computer
WFS = WaveFront Sensor
DM = Deformable Mirror

Limit to AO performance : the angular decorrelation



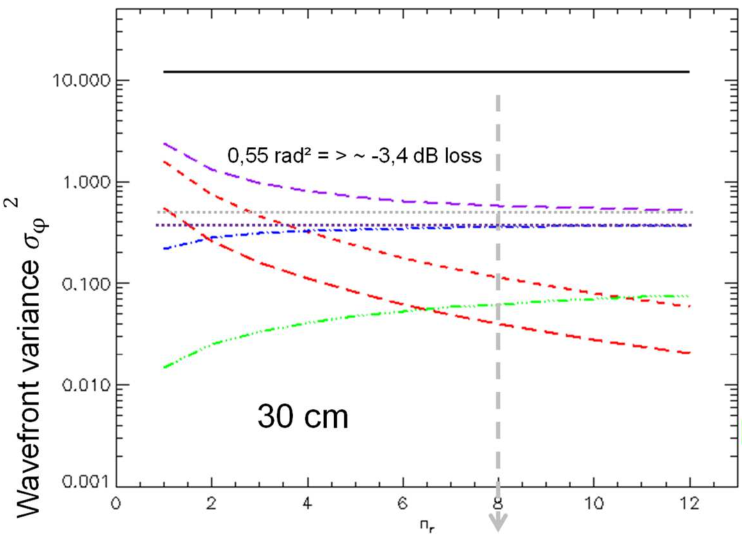
Isoplanatic angle θ_0 (10 µrad typ.): $\theta / < (\varphi(x,\theta) - \varphi(x,0))^2 > = 1\ rad^2$

Requires C_n^2 profile knowledge

AO error budget

Average power loss $\propto \rho_0 \, e^{-\sigma_\varphi^2}$

Anisoplanatism



Turbulence

Total

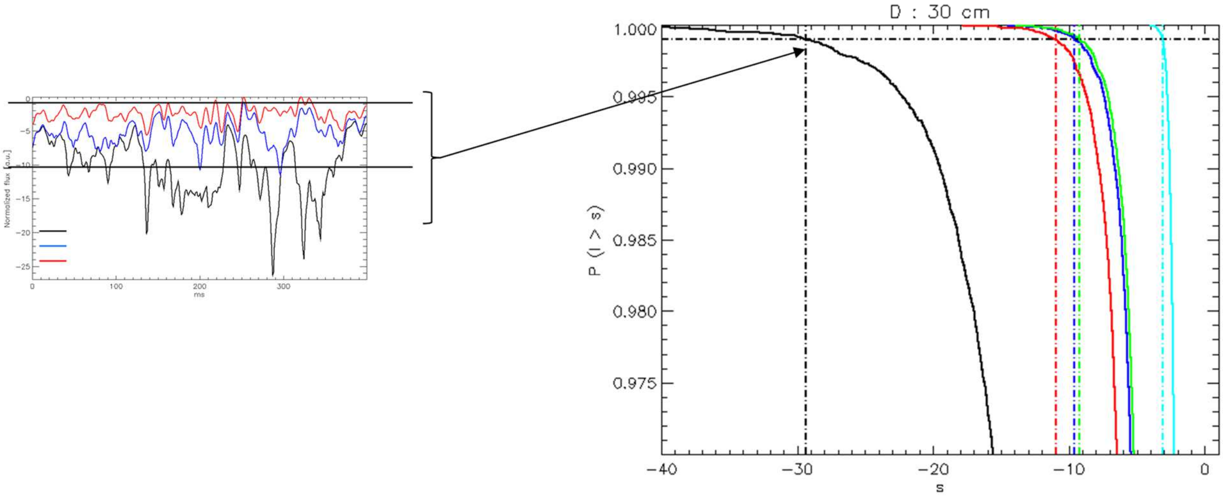
Limited number of actuators

Limited sampling freq (~1500 Hz)

PAA limits the gain brought by AO
AO design must be adapted (to avoid overspecification)
Saturation at 7 radial orders

AO power penalty : availability threshold @ 99.9%

Cumulated probability density function (CDF) for D = 30
AO correction :
nr = 1 (TT) ; 4 ; 8 ; 12 & perfect correction



99.9% threshold : average losses and fluctuations, no obscuration

$S_{99.9\%}$ in dB :
D = 30cm : -29.3 (- 6.8) ; -11.0 (- 3.4) ; - 9.6 (- 2.7) ; - 9.2 (-2.6) ; - 3.1 (-0.9)

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*: J.-M. Conan, N. Védrenne, A. Montmerle-Bonnefois, C. Petit, M.-T. Velluet, C. Robert, C. B. Lim, V. Michau, G. Artaud & B. Benammar, "Adaptive optics for ground – GEO-satellites optical links: from system design to experimental demonstration," Proc. of COAT Conference, 2019

Link budget relevance ?

	Value
Link parameters	
Wavelength (µm)	1,6
Vertical attenuation : absorption & scattering (dB)	-0,5
Vertical attenuation : clouds (dB)	-2,2
Elevation angle (deg)	30,0
Satellite distance (km)	38263,0
Rx telescope diameter (cm)	0,3
Transmitter	
Emitted power per lambda (dBm)	47,0
Optical transmission (dB)	-3,6
Tx diameter	0,3
Static wavefront error - HF uncorrected by DM - (dB)	-0,3
Reciprocity error losses (dB)	0,0
Tx gain (dB)	115,7
Transmitter emitter power (dBm)	158,8
Propagation	
Attenuation absorption & scattering (dB)	-0,9
Attenuation clouds (dB)	-4,4
Free Space Propagation (dB)	-289,8
Modulation (duty cycle 1/2) (dB)	-3,0
Receiver	
Rx gain (dB)	115,7
Optical transmission (dB)	-2,0
Coupling losses	-1,0
Pointing error losses (dB)	-3,0
Without turb (dBm)	-29,7
Turbulence + AO Turbulence + AO (r_0= 7 cm, D =30 cm , **D/r_0 = 4,3; n_r = 8**)	
Precompensation average power losses	-2,7
Link margin for a 99.9% proba. of uninterrupted link	-6,9
with turbulence and pre-compensation	-39,3
Goal (dBm) NRZ-OOK - 10 Gbps, 10-6 BER	-42,3

Feasibility confirmation in a « relevant » environment ? (variable turbulence conditions)

Reliability of the anisoplanatism induced power penalty ?

FEEDEr Link adaptive Optics (FEEDELIO) experiment*

European Space Agency

*: contract N° 4000120300/17/NL/PS

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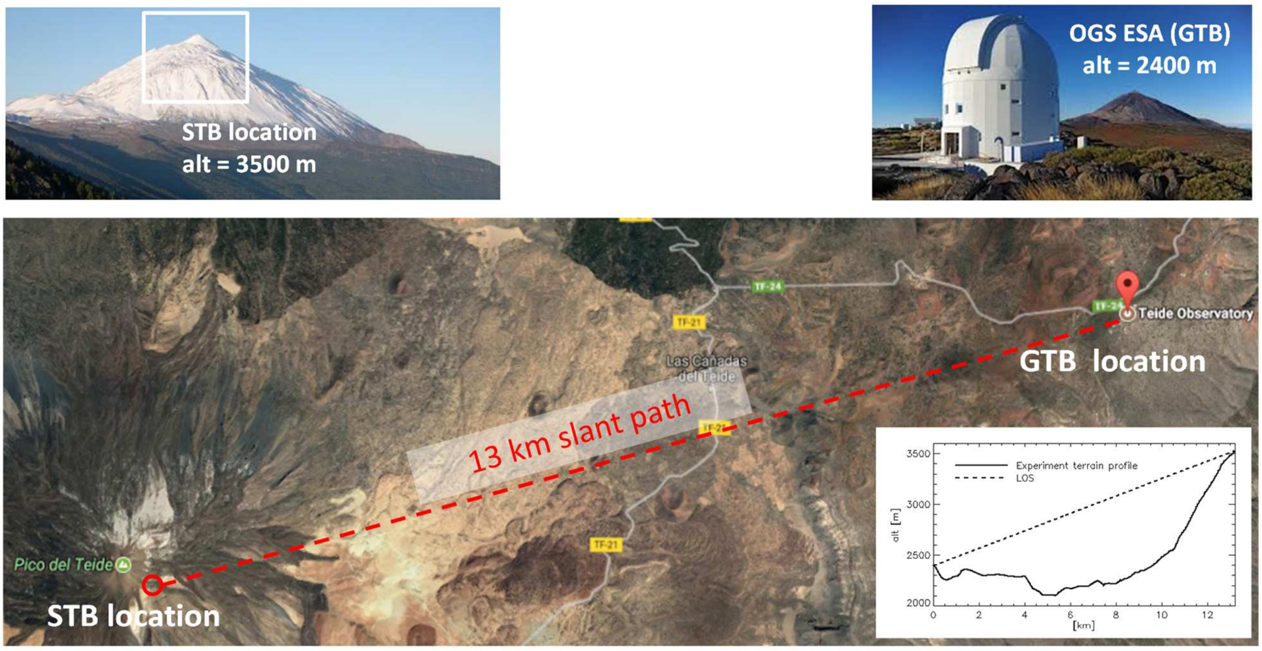
FEEDELIO: slant path demonstration of a GEO Feeder Link



STB : Satellite Terminal Breadboard
GTB : Ground Station Terminal Breadboard

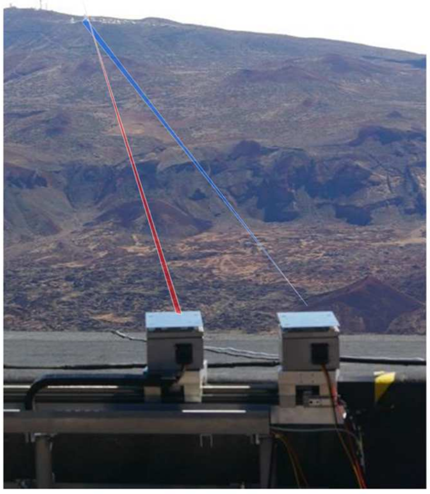
The line of sight and general considerations

Idealous weather
Distant volcanic eruption (hopefully)
Variable atmospheric transmission conditions

Commissioning :
April 2019 (aka the *Evil* April)
20 days of experiment, 3 days of exploitable data

Commissioning :
October 2021
15 days of experiment, 5 days of exploitable data
(Wi-Fi instability correlated to dusty atmosphere)

Satellite Terminal Breadboard (STB)



Rx

Off-axis module:
- = GEO Satellite **Receiver** emulator
- Receives uplink AO-corrected beam
- Φ = 1.7 mm
- Adjustable angular distance: up to 100 µrad

Ex

On-axis module:
- = GEO Satellite **Emitter** emulator
- Emits downlink ref beam for AO

\+ Reference for uplink signal statistics (PAA = 0)

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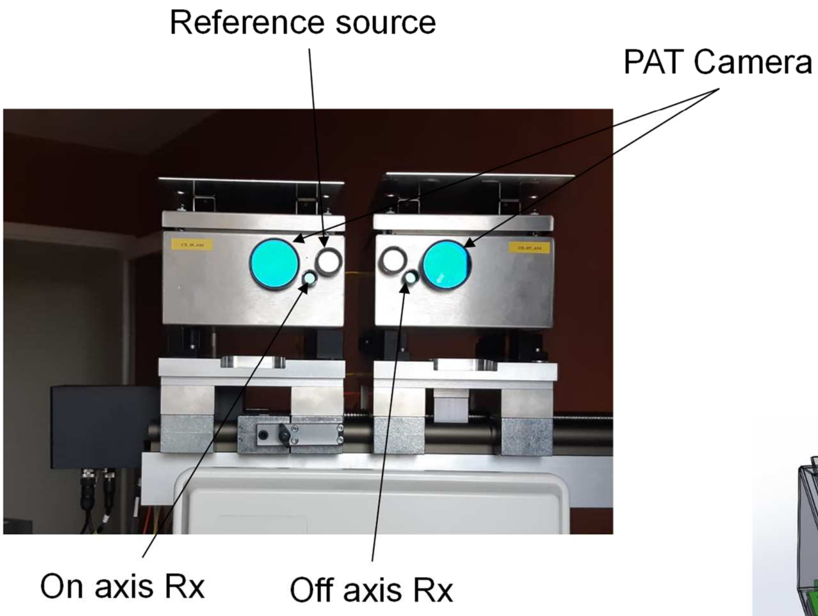
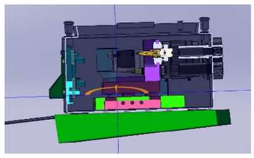
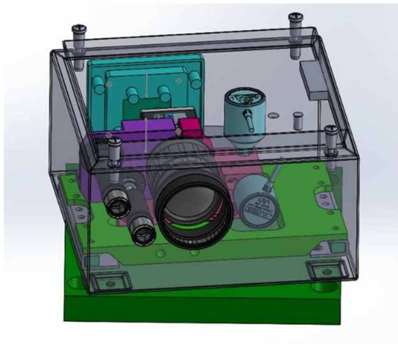
STB module



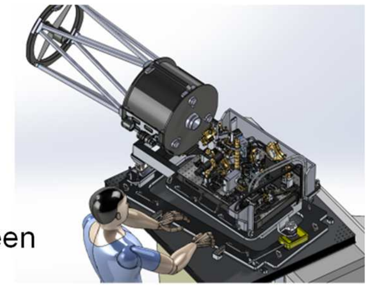




Ground Terminal Breadboard (GTB)

- 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)

Ground Terminal breadboard on the south pillar@OGS



Zoran « Crane master » Sodnik

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

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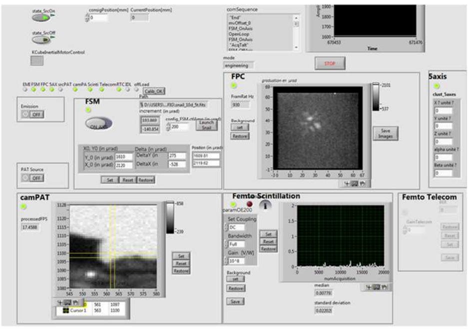
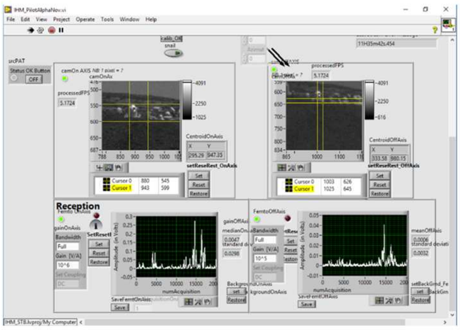
Man machine interface and acquisition process





- Lab view GUI
- **Basic operations sequencing :
  - Ref source on axis on
  - Close loop
    - Load a control matrix (ex : no correction)
    - Target the on-axis module
    - * Acquire received power on-axis
    - Acquire received power off-axis
  - Load another matrix (ex : tip/tilt only)
  - Return to * up to having investigated the scope of desired corrected modes
  - Then move the off-axis module and get back to **

For a range of position from 0 to 60 µrad typ.) (video)

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Acquired data overview (2019)

In red : in-depth analyzed data

date	heure UTC	sequence names	Status femto on-axis data UP	Status femto off-axis data	Status femto on-axis data DOWN
10-avr	11h16 11h22	onax_ofax_01 onax_ofax_02	non traitées	non traitées	
	14h35	fullseq01	NOK	NOK	NOK
11-avr	00h20 07h50 08h06	fullseq02 fullseq03 fullseq04	OK -sauf données TT car mauvaises tensions d'offset	NOK	NOK
	08h38	fullseq05	OK	NOK	NOK
	12h45 12h47	onax_ofax_03 onax_ofax_04	non traitées	non traitées	
	13h58	fullseq06	OK	OK	NOK
acquisition nouvelle matrice d'acquisition					
		fullseq07	erreur, à jeter		
	19h43	fullseq08	?	?	
	22h01 22h42	fullseq10 fullseq11	OK	OK	NOK
	23h14 23h36	fullseq12 fullseq13	NOK	NOK	NOK
12-avr	00h07	fullseq14	OK	OK	NOK
	00h32 01h43	fullseq15 fullseq16 fullseq17 fullseq18 fullseq19	NOK	NOK	NOK
	08h30	fullseq20	OK	OK	OK
	10h21	**fullseq21**	OK	OK	OK
		fullseq22	erreur, à jeter		
	22h25	fullseq23 fullseq24 fullseq25	NOK	NOK	OK
13-avr	00h21	fullseq26 fullseq27 fullseq28	NOK	NOK	OK
	09h13 11h25	fullseq29 fullseq30 fullseq31 fullseq32	NOK	NOK	OK
acquisition nouvelle matrice d'acquisition					
		Seqonaxisz01 seqonaxisz02 seqonaxisz03	pb de paramétrages de gains, à jeter		
		fullseq33	gain femto trop faible, à jeter		
	23h03	**fullseq34**	OK mais mauvaises tensions d'offset	OK	NOK

Acquisition parametrization issues

date	heure UTC	sequence names	Status femto on-axis data UP	Status femto off-axis data	Status femto on-axis data DOWN
14-avr		Seqonaxisz04 --> Seqonaxisz11	OK mais mauvaises tensions d'offset		NOK
	00h16	fullseq35 fullseq36	OK mais mauvaises tensions d'offset	OK	NOK
	06h47	fullseq37	doute		
	07h09	fullseq38	doute		
		seqonaxisz12	plantage RTC + fond changeant		
reboot RTC					
		seqonaxis13 --> seqonaxisz14	pb gain		
	08h52 09h44	**seqonaxis15** **--> seqonaxisz48**	OK		NOK
	10h12	fullseq39	OK	OK	NOK
	10h41	fullseq40	OK	OK	NOK
	11h07 11h50	**seqonaxisz49** **--> seqonaxisz75**	OK		NOK
	21h00 21h54	seqonaxisz76 --> seqonaxisz94	OK		OK
	22h08	fullseq41	OK	OK	OK, mais flux faible
		fullseq42	avortée		
	22h36 23h31	fullseq43 fullseq44 fullseq45 **fullseq46**	OK	OK	OK

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Acquired data overview (2021)

date	heure UTC	sequence names	Status femto on-	Status femto off-	Status femto on-axis data		Reciprocity	Status RTC data	Turbulence	Comment
13-oct		newfullseq01								test sequence - imperfect calibration
		newfullseq02								motor out of service
14-oct	9h40	newfullseq03							très faible	Zéro turbulence. Doutes étalonnage FSM. Données TTonly uplink bizarres. Couplage downlink
	9h56	newfullseq04							très faible	Zéro turbulence. Données TT only bizarres. Plutôt
15-oct	7h42	newfullseq05							moyenne - joli anisoplanétisme	Première séquence après une nuit : fibre de source uplink mal connectée (-> flux faible), FSM_out connecté seulement en cours de séquence
	9h21	newfullseq06							forte	Flux toujours trop faible, mais sinon série plutôt
	9h40	newfullseq07							très forte	Flux toujours trop faible, mais sinon série plutôt
	10h08	newfullseq08								Wi-Fi problem - no STB data
	11h32	newfullseq09								wrong FSM calibration
16-oct		newfullseq10								motor out of service
	7h37	newfullseq11							assez forte. Pas mal d'aniso	
	7h43	newfullseq12							modérée	super clean
	8h16	newfullseq13							modérée	super clean
	8h34	newfullseq14							similaire à la précé	super clean
	8h54	newfullseq15								Wi-Fi problem - no STB data
	9h27	newfullseq16							lots of scintillation	unstationnary turbulence
	9h48	newfullseq17							extremely strong turbulence	
	22h	newfullseq18								motor out of service
	22h12	newfullseq19								some strange STB off-axis values, but can probably be filtered
		newfullseq20								motor out of service
17-oct	7h07	newfullseq21								motor out of service
	7h12	newfullseq22							low turbulence	clean
	8h06	newfullseq23								HMI crash
	8h09	newfullseq24							medium turbulence	clean, but strange TT values
		newfullseq25								motor out of service
	9h26	newfullseq26							medium turbulence	clean, but strange TT values
	9h46	newfullseq27							medium turbulence	clean, but strange TT values
	10h35	newfullseq28								looks like small r0 but small anisoplanatism ?
	11h10	newfullseq29								looks like small r0 but small anisoplanatism ?
	12h01	newfullseq30							lots of scintillation	unstationnary turbulence
18-oct	6h40	newfullseq31								motor out of service
	7h50	newfullseq32							very low turbulence	clean, but strange TT values
		newfullseq33								motor out of service
	8h39	newfullseq34								Wi-Fi problem - no STB data - motor unstable
	10h48	newfullseq35							stong turbulence	clean, but strange TT values
	12h52	newfullseq36							very strong turbule	clean, but strange TT values

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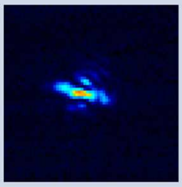
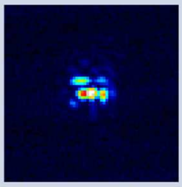
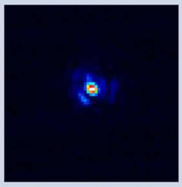
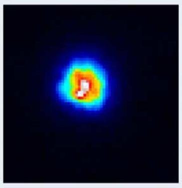
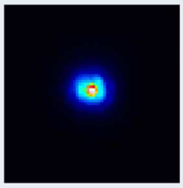
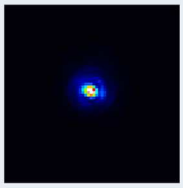
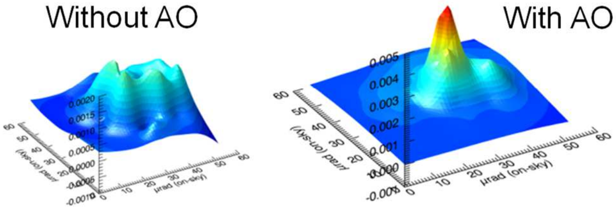
From downlink correction… to uplink pre-compensation

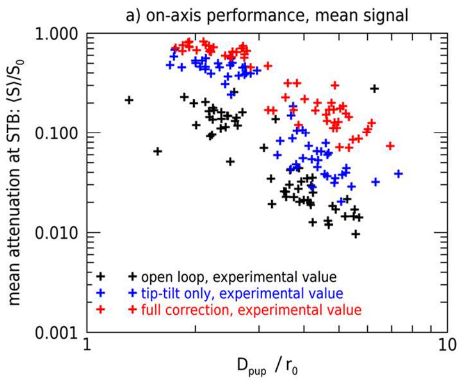
AO is feasible (and provides significant increase of on-axis perf. ☺

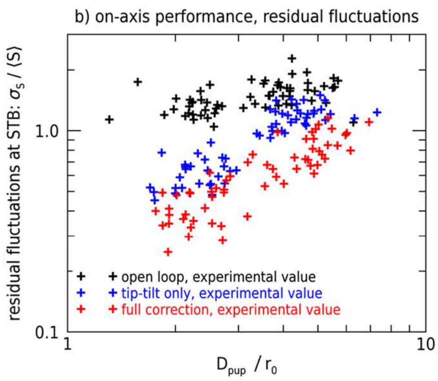
Focal plane @ GTB	Open loop	Tip-tilt only	Full correction
Medium turbulence 14/04, 9h40			
Same sequence, Long exposure (10 s)			



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

Example of on-axis results

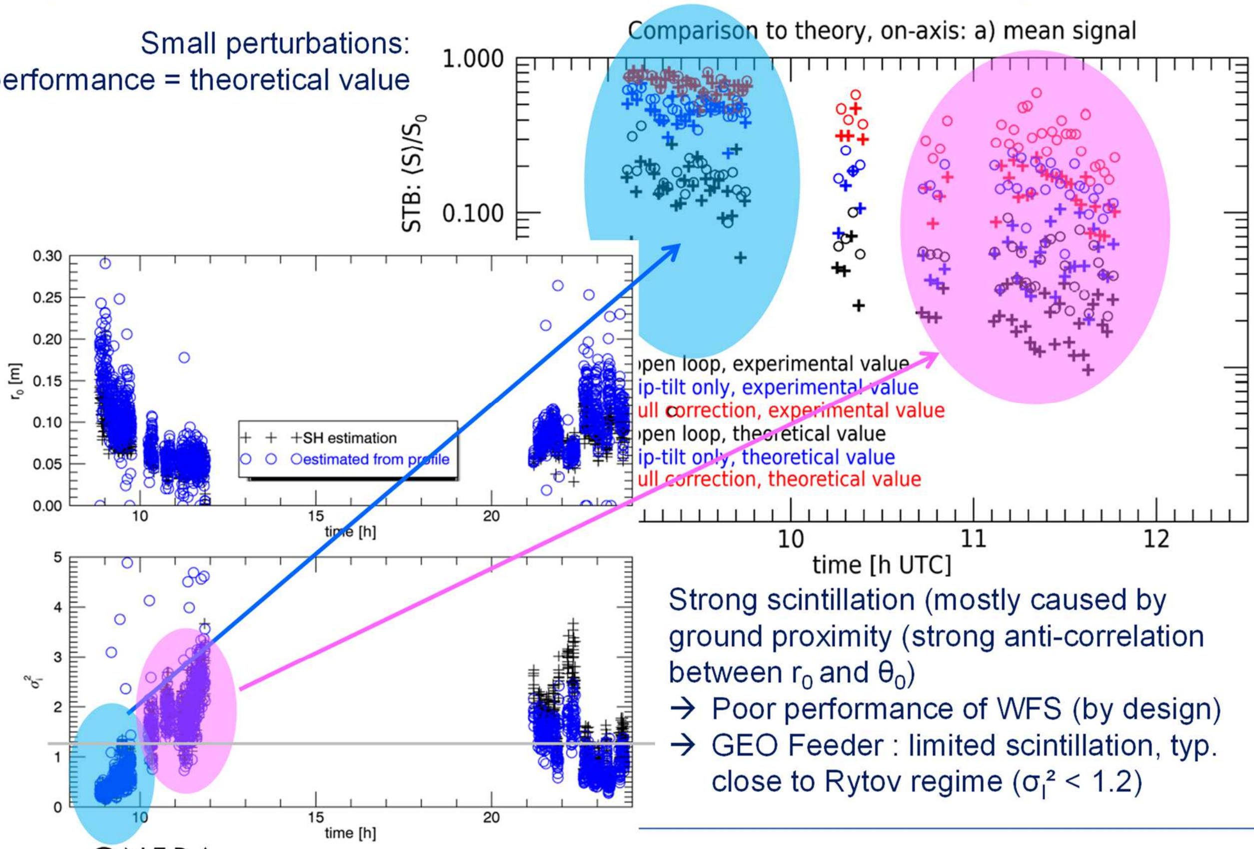




date	heure UTC	sequence names	Status femto on-axis data UP	Status femto off-axis data	Status femto on-axis data DOWN
14-avr		Seqonaxisz04 --> Seqonaxisz11	OK mais mauvaises tensions d'offset		NOK
	00h16	fullseq35 fullseq36	OK mais mauvaises tensions d'offset	OK	NOK
	06h47	fullseq37	doute		
	07h09	fullseq38	doute		
		seqonaxisz12	plantage RTC + fond changeant		
reboot RTC					
		seqonaxis13 --> seqonaxisz14	pb gain		
	08h52 09h44	**seqonaxis15** **--> seqonaxisz48**	OK		NOK
	10h12	fullseq39	OK	OK	NOK
	10h41	fullseq40	OK	OK	NOK
	11h07 11h50	**seqonaxisz49** **--> seqonaxisz75**	OK		NOK
	21h00 21h54	seqonaxisz76 --> seqonaxisz94	OK		OK
	22h08	fullseq41	OK	OK	OK, mais flux faible
		fullseq42	avortée		
	22h36 23h31	fullseq43 fullseq44 fullseq45 **fullseq46**	OK	OK	OK

AO performance – on-axis – comparison to theory

Small perturbations:
AO performance = theoretical value



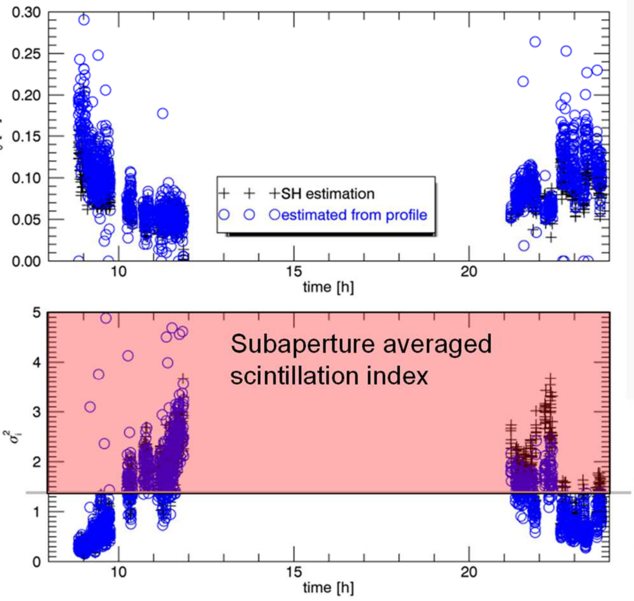
Strong scintillation (mostly caused by ground proximity (strong anti-correlation between r_0 and θ_0)

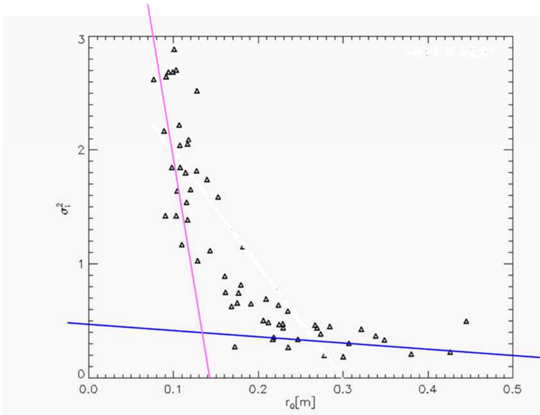
→ Poor performance of WFS (by design)

→ GEO Feeder : limited scintillation, typ. close to Rytov regime ($\sigma_I^2 < 1.2$)

Turbulence conditions and experimental constraints

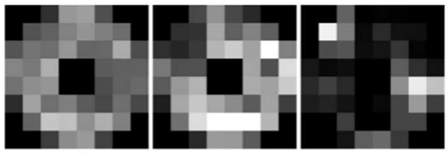
Wide variability of turbulence conditions





Two turbulence regimes :

- Medium to high r_0, small scintillation (small perturbations): nominal operation
- Smaller r_0 with strong correlation with strong scintillation: ground influence



σ_I^2 0.05 0.8 1.04

→ Poor performance of WFS (by design)

→ GEO Feeder :

→ Limited scintillation, typ. close to Rytov regime ($\sigma_I^2 < 1.2$), midday turbulence strenght too strong (not relevant for GEO FEEDER)

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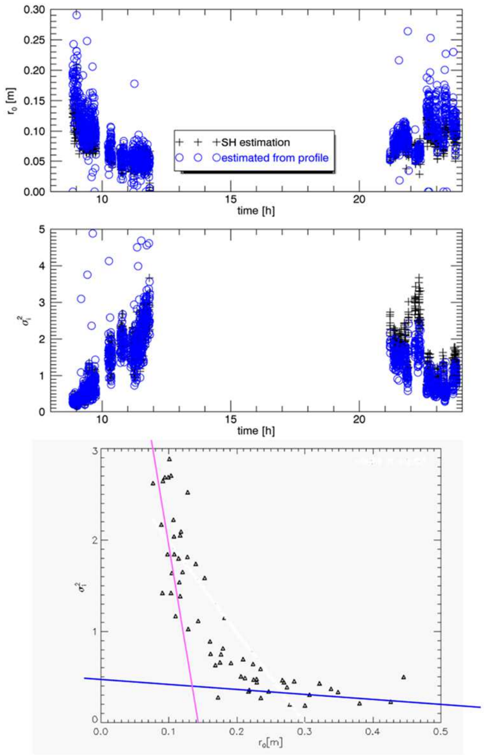
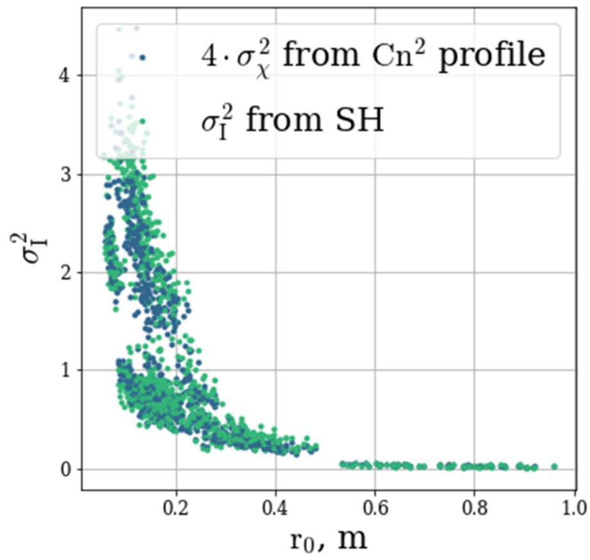
Ground proximity influence

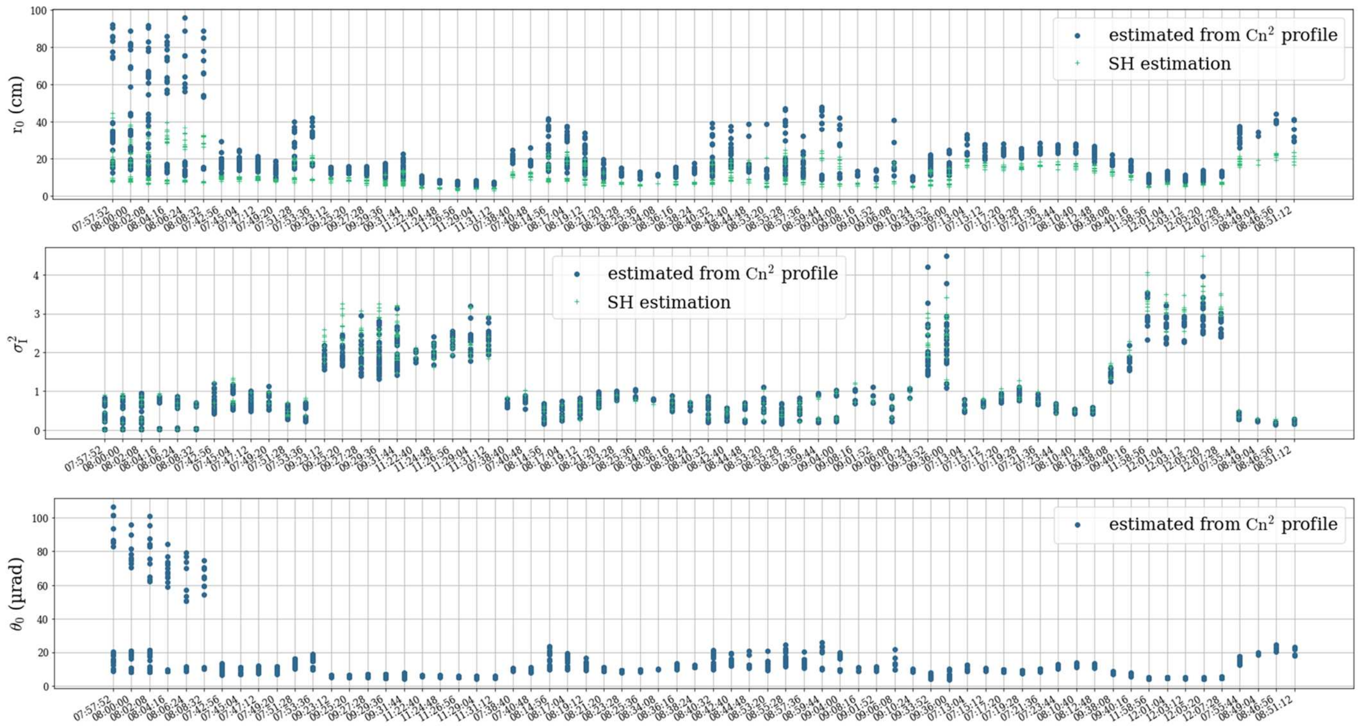


April 2019



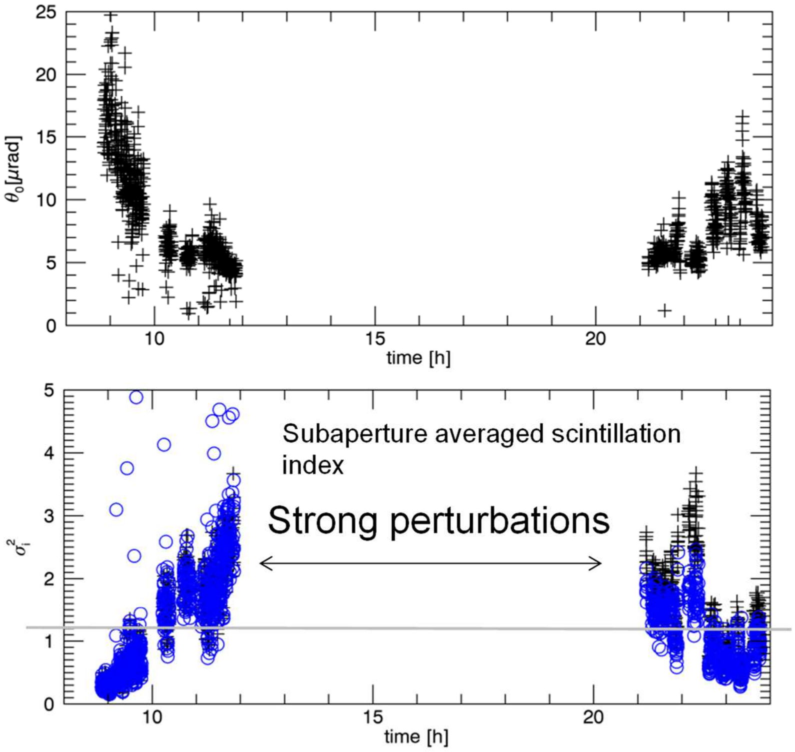
October 2021

Zoom on October 2021 : 1 day of data



➔ Large diversity of turbulence conditions during the october experiment

What about off-axis perf : quantifying anisoplanatism



Shack Hartmann WFS
⇒ slopes and intensities
+
spatial correlation model

⇒ *C_n^2 profile

⇒ Turbulence parameters estimation from SH data

⇒ $\widehat{r}_0$, $\widehat{\sigma}_I$, $\widehat{\theta}_0$

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N. Védrenne, A. B. Montmerle, C. Robert, V. Michau, J. Montri, and B. Fleury, "C_n^2 profile measurement from Shack-Hartmann data: experimental validation and exploitation," in *Optics in Atmospheric Propagation and Adaptive Systems XIII*, 2010, vol. 7828, p. 78280B.

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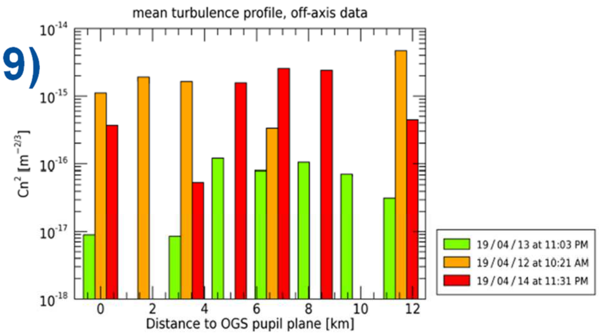
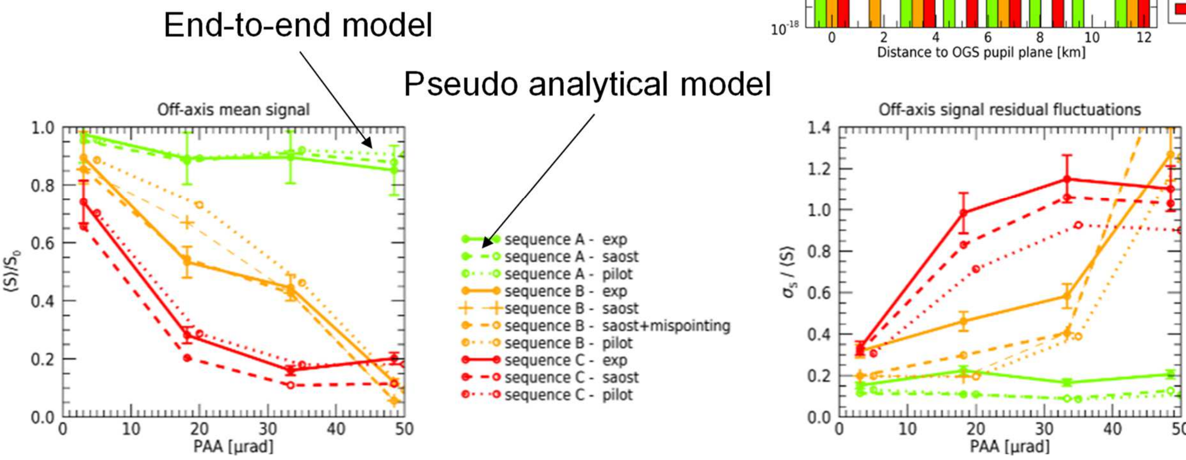
Off-axis main results synthesis (April 2019)

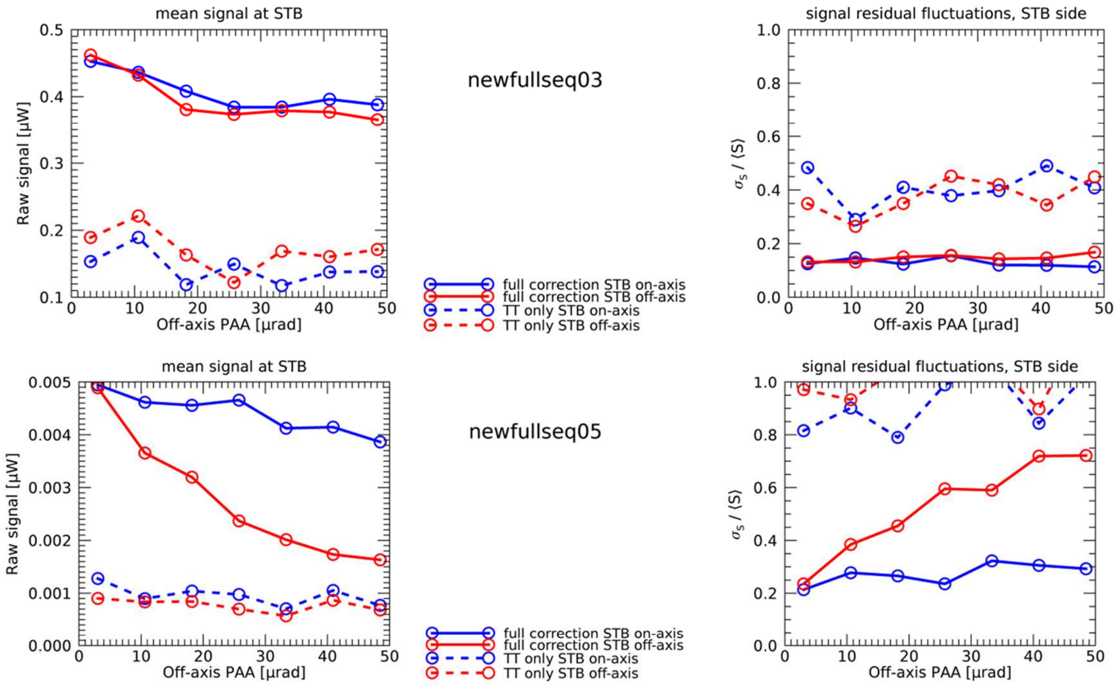
Sequence name	Time and date	r_0	σ_χ^2	θ_0
Sequence A	2019/04/13 at 11:00 PM	89 cm	0.014	46.7 µrad
Sequence B	2019/04/12 at 10:20 AM	12 cm	0.19	18.5 µrad
Sequence C	2019/04/14 at 11:30 PM	15 cm	0.26	7.8 µrad





Cn2 profile assessment => validation of models (both End to end and simplified model)
Illustration of the criticity of Non common path aberrations

Off-axis, example of results for october 2021



→ R&T GOAT with CNES to go further on data analysis

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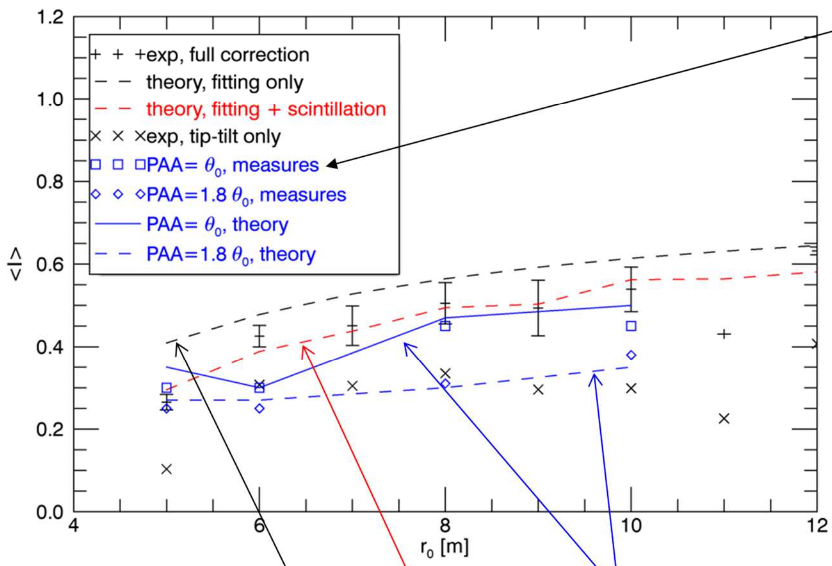
Average experimental power penalty (PP)



Corresponding to identical residual phase variance Modal

$< I > = \rho_0 \exp(- \sigma_{fitting}{}^2 - \sigma_{scintillation}{}^2 - \sigma_{aniso}{}^2(PAA))$

Experimental evaluation consistent with expected term for average
AO with anisoplanatism is always better than tip/tilt (all the more true with power fluctuations)

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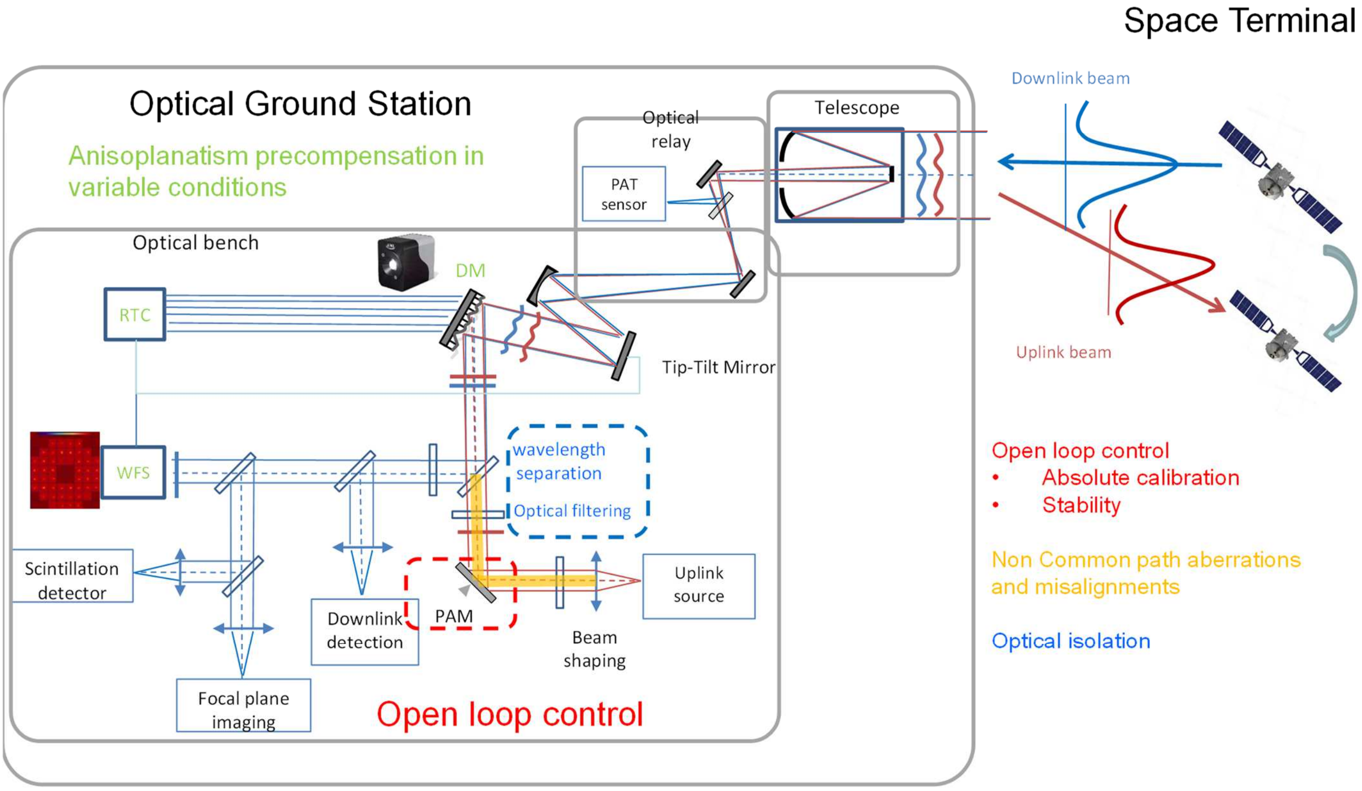
Adaptive Optics for uplink pre-compensation

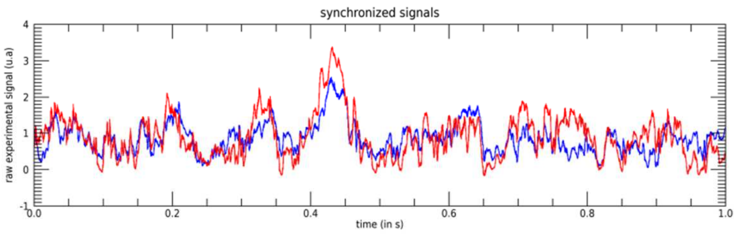


Open loop control
- Absolute calibration
- Stability

Non Common path aberrations and misalignments

Optical isolation

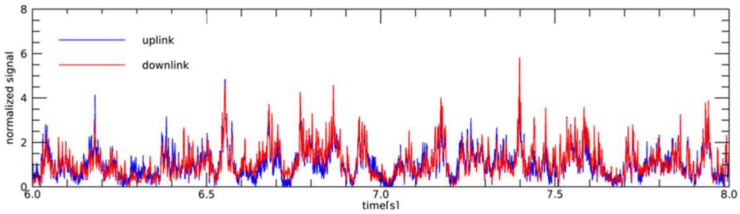
Non common path aberration management and evaluation



Max correlation : 85%

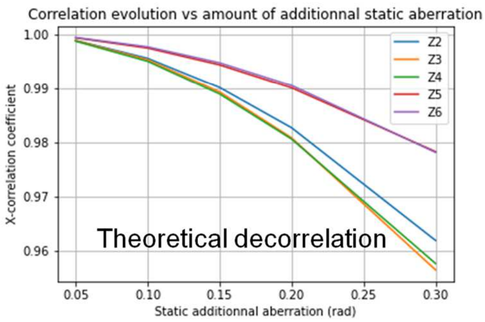
April 2019

Setup adaptation for pure reciprocity experiment (modulo the wavelenght difference)



Max correlation : 95%

October 2021



Possibility to evaluate non common path aberrations from reciprocity evaluation

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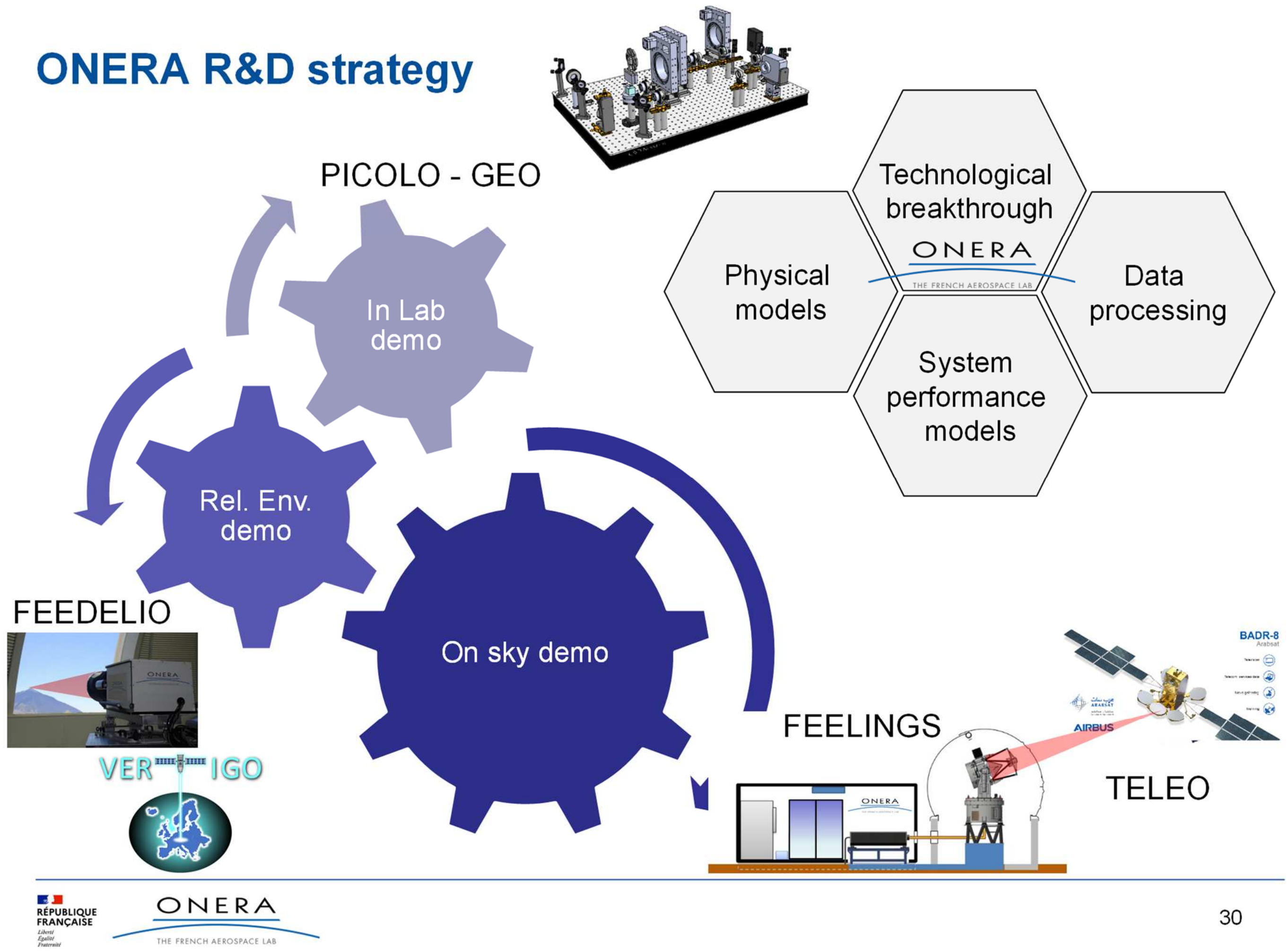
Lessons learned from FEEDELIO wrt to GEO feeder link

- Feasibility of AO precompensation is demonstrated in significantly varying conditions, no showstopper is identified for deploying uplink precompensation with a GEO
- Both End-to-end and simplified performance models are consistent with uplink received power statistics (at least in the Rytov regime)
- Upgrade of the setup between the 2 experiment campaigns enables to demonstrate a 95% correlation on axis
- C_n^2 and wind profile have a strong impact on UL residual signature (to be taken into account in the design of numerically based mitigation techniques)
- Considering the strong impact of the C_n^2 and wind profile on the characteristics of the propagation channel it is highly recommanded to gather profiles statistics to help the definition of the adequate AO system and help the tradeoff
- Paper to be published (submission planned for beginning of 2022)
- Significant amount of data gathered, still remaining to be exploited in depth for October 2021 (CNES activity)


ONERA R&D strategy
PICOLO - GEO
In Lab demo
Rel. Env. demo
On sky demo
FEEDELIO
VERTIGO
FEELINGS
TELEO
BADR-8
AIRBUS
Technological breakthrough
ONERA
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Physical models
Data processing
System performance models
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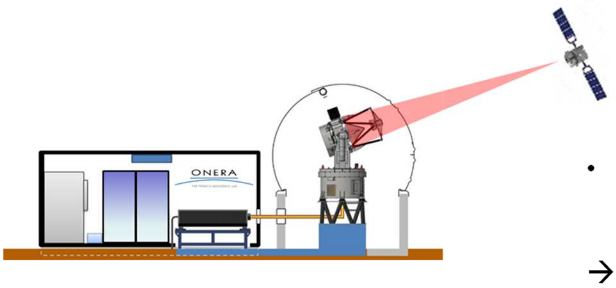
Perspectives : on sky validation with ONERA Ground station FEELINGS

FEEDELIO showed feasability of adaptive optics precompensation

→ Next step : on-sky validation of ONERA's AO bench FELIN



- To **validate** hardware setup (<0,2 µrad point-ahead pointing precision, high power compatibility, uplink/downlink flux ratio, calibration process, etc…)
- To **validate performance models on sky**, including channel characterization (toward numerical twin)
- To **test innovative AO concepts** to mitigate anisoplanatism impact (and scintillation) for very high availability

→ ONERA Ground station : FEELINGS

→ ADS OK to provide TELEO payload access and opened to collaborate with ONERA ex: joint bidding @ESA

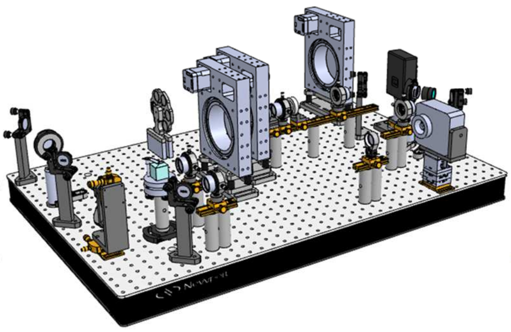
Also : pathfinder = in-lab tests

- ONERA testbed PICOLO
- fully controled environment :

→ toward very high performance / fine optimisation

→ **Innovative concepts tests optimisation** with FELIN and PICO

For now : LEO, downlink → **need for GEO** upgrade



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Perspectives : towards availability assesment of GEO FEEDER links

- ONERA in-house link performance models on a line of sight were validated thanks to FEEDELIO
- Turbulence statistics databases + turbulence profiles models using weather forecast databases are becoming more and more complete and reliable (see: Durham/Osborn database, ONERA MATISSE model)
  - → Possibility to use link performance models on these databases to infer theoretical avaibility of GEO FEEDER links on one given site
  - → Possibility to « map » the earth wrt theoretical site quality (->link availability)
  - → Possibility to compare on-sky turbulence profiles probability / link availability with theoretical models with ONERA OGS FEELINGS