Tip-Tilt-Focus Estimation at PAA for GEO Feeder uplinks aided by Laser Guide Star

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*: PhD funded by ONERA/CNES

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Introduction

Context: High data rate optical ground to GEO links impacted by anisoplanatism

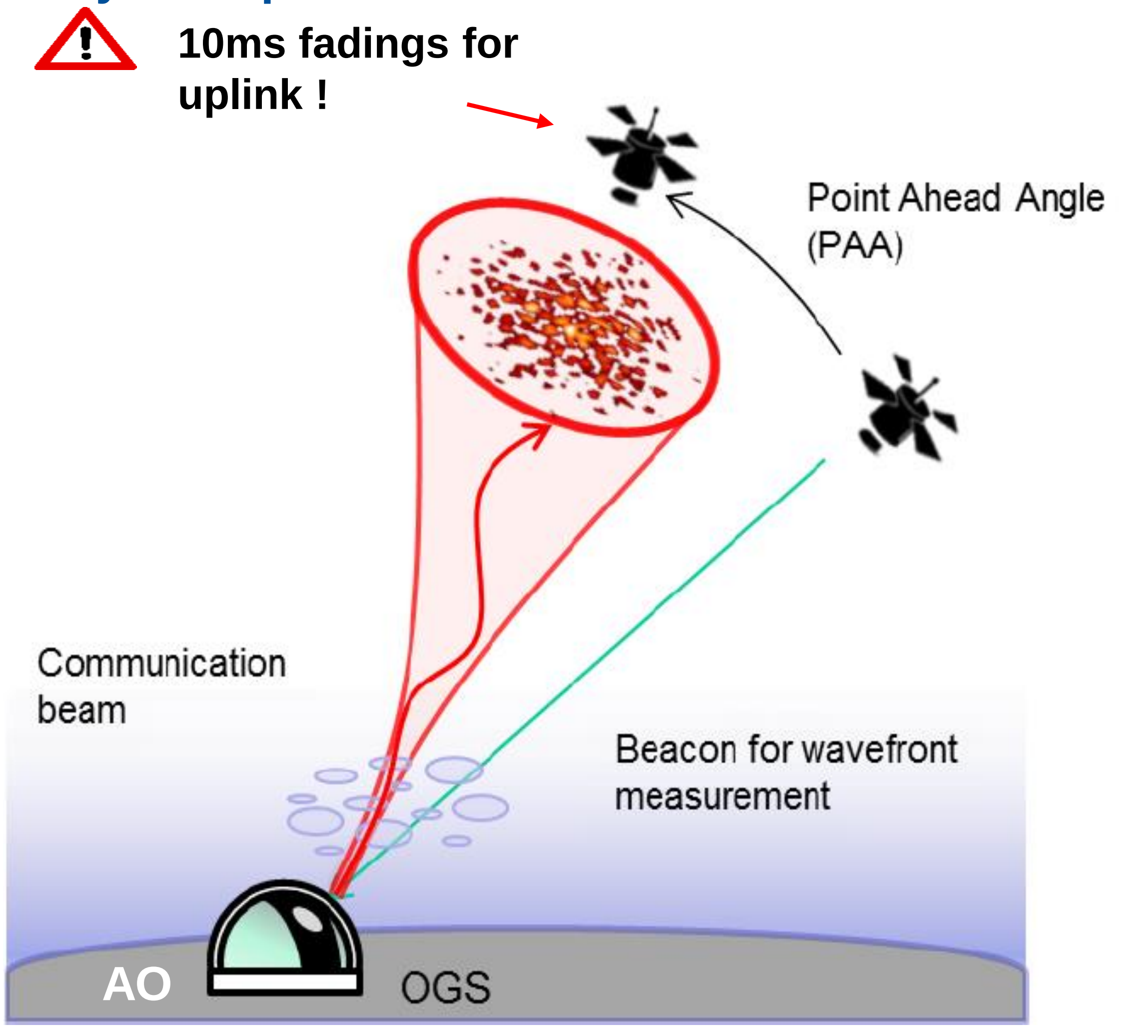
Main issue: atmospheric turbulence

Random fluctuation of coupling efficiency.

Solution: Adaptive Optics (AO)

Uplink correction: not optimal

Because of link geometry: Point ahead angle (PAA).



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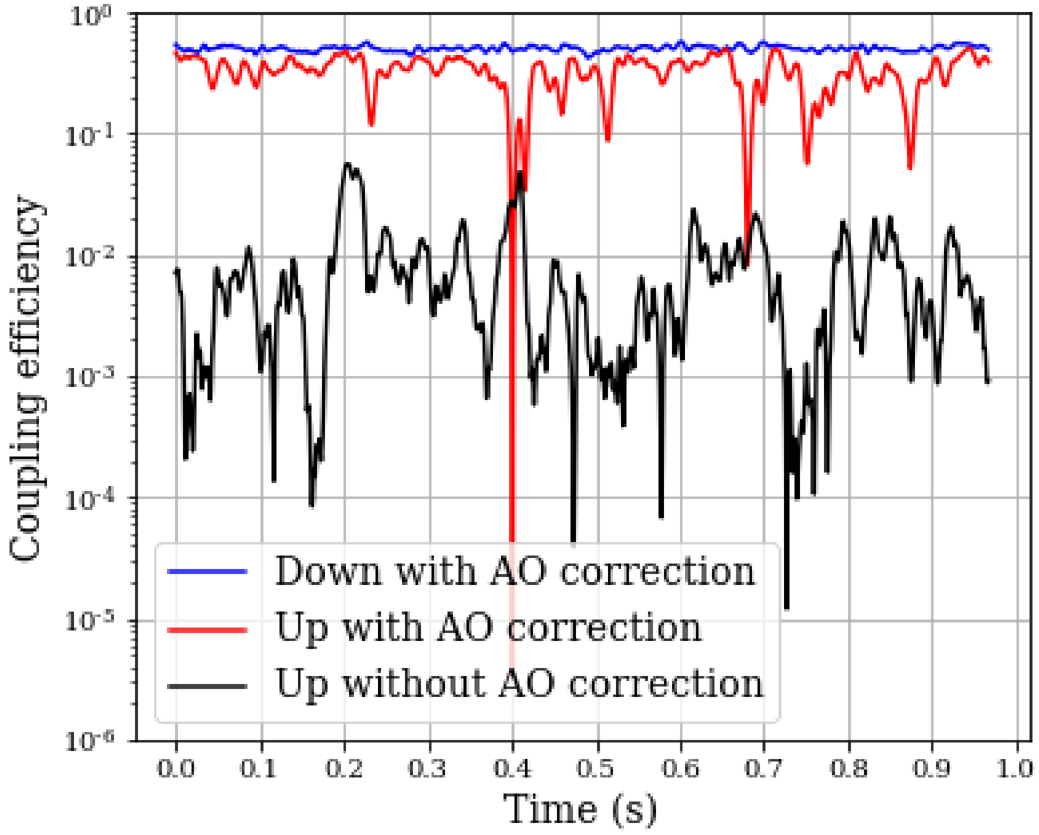

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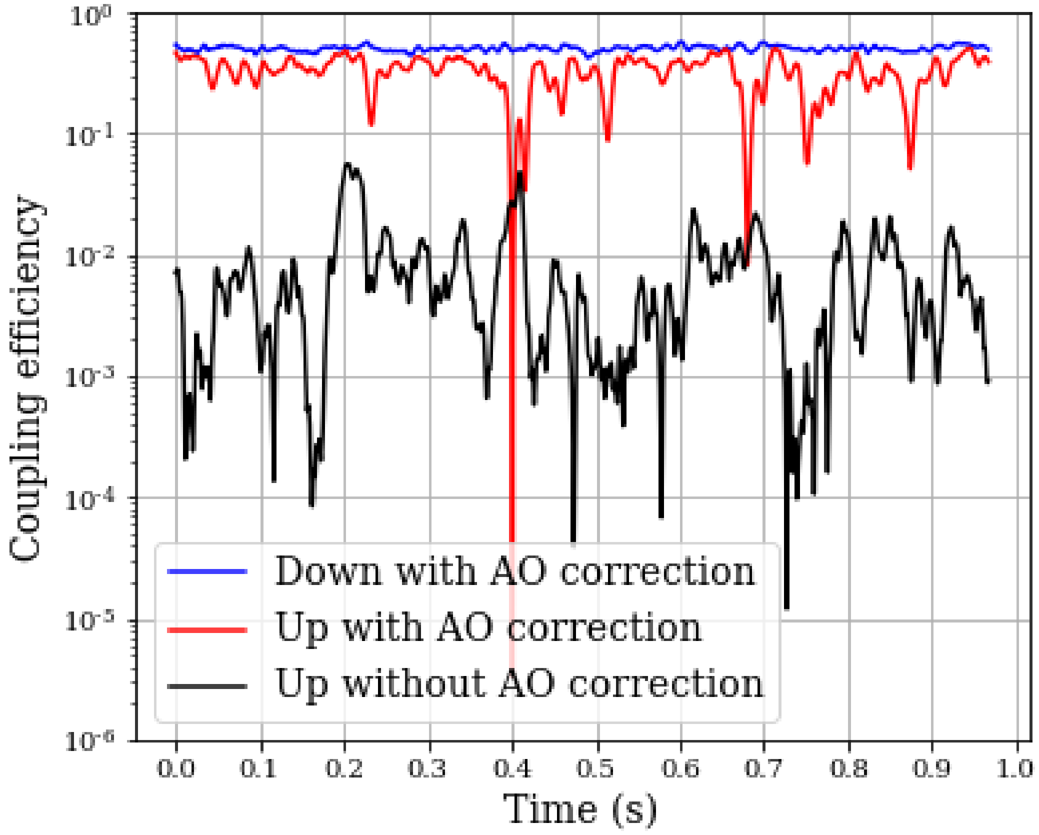

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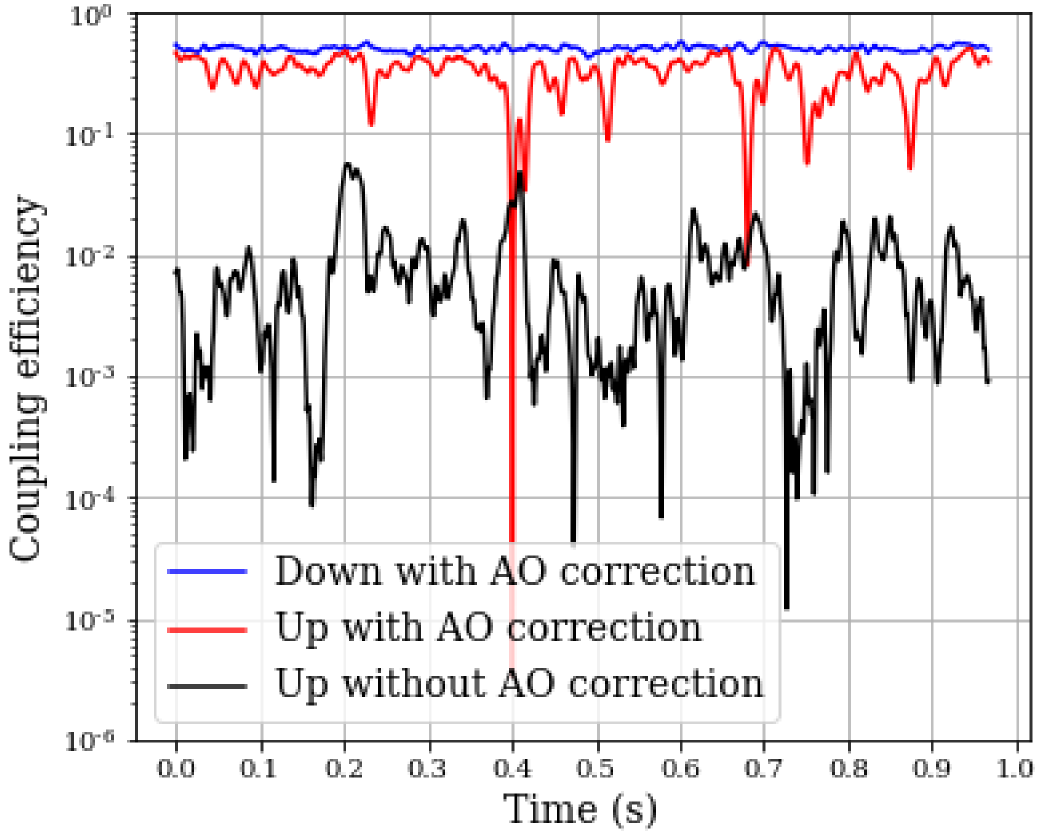

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How to improve information signal reliability over this fading channel ?

→ Improve the coupled flux statistics by optimizing the pre-compensation phase

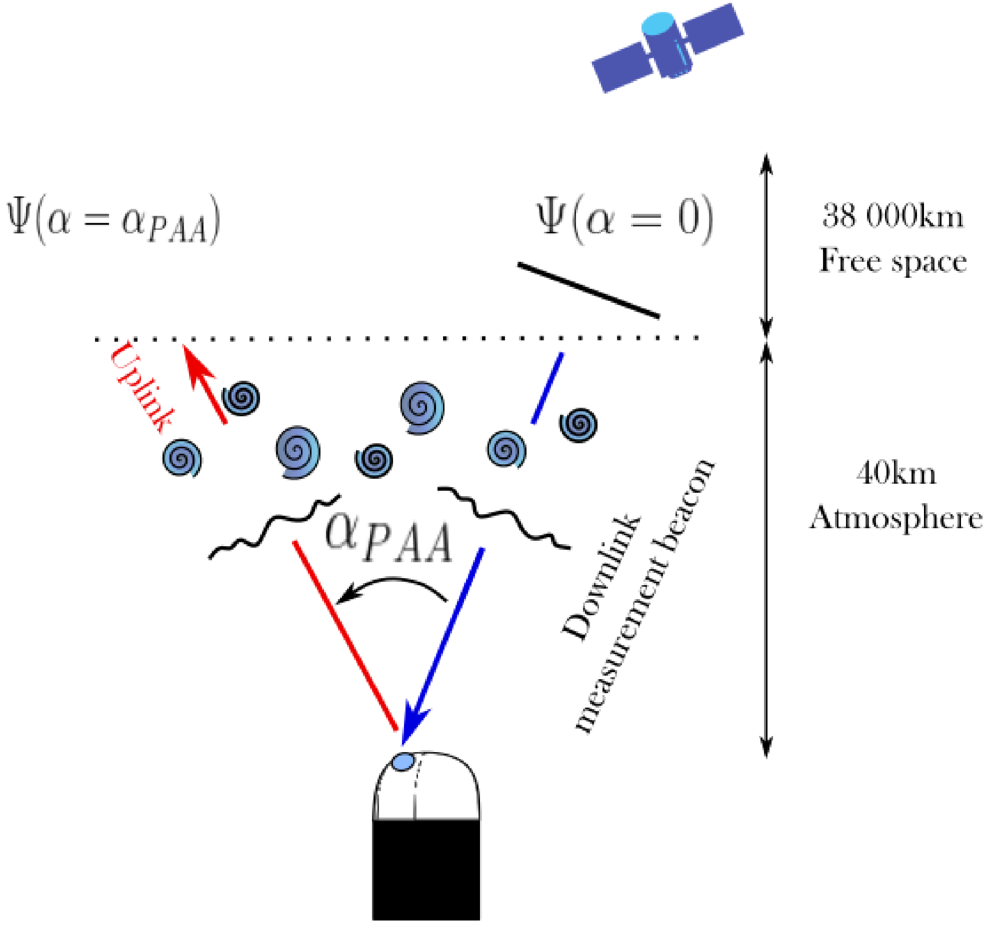
State of the art

How to optimize the pre-compensation phase at PAA ?

Technique 1: Classical pre-compensation [Tyson-1996]

Shared phase correction with the downlink

→ Full anisoplanatism



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Provides Φ measurements at PAA
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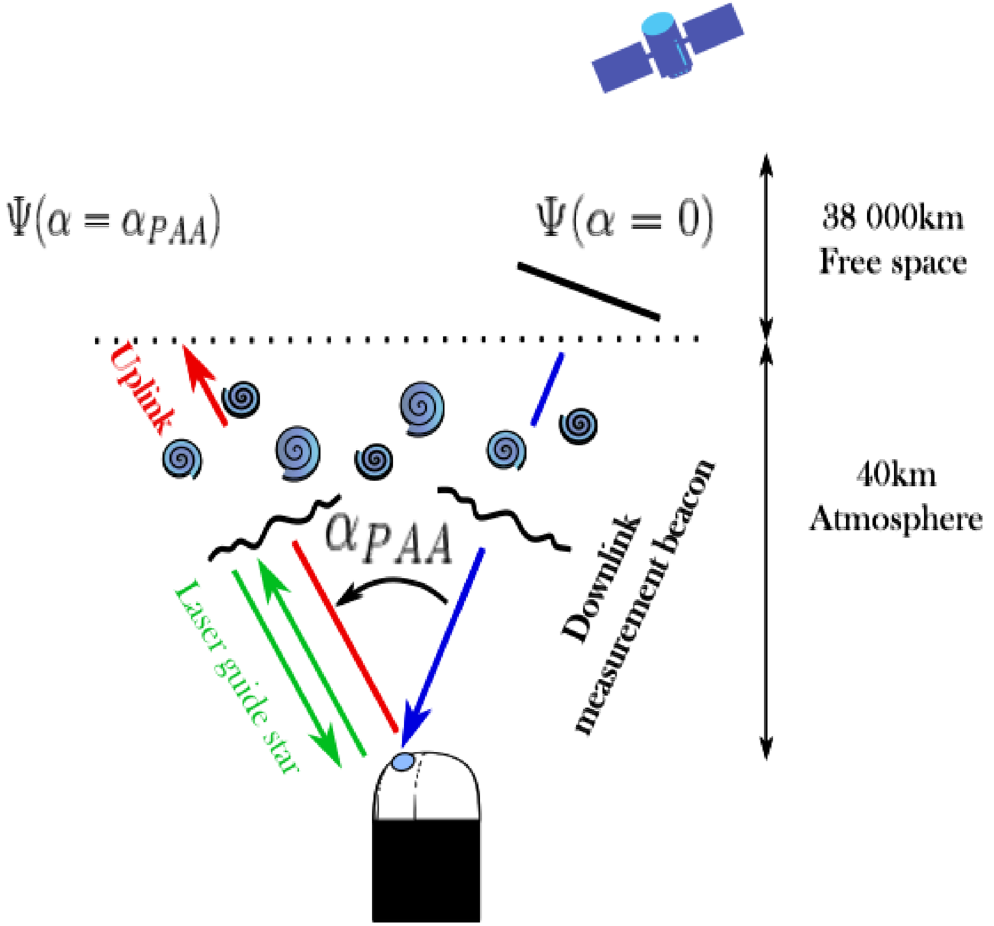

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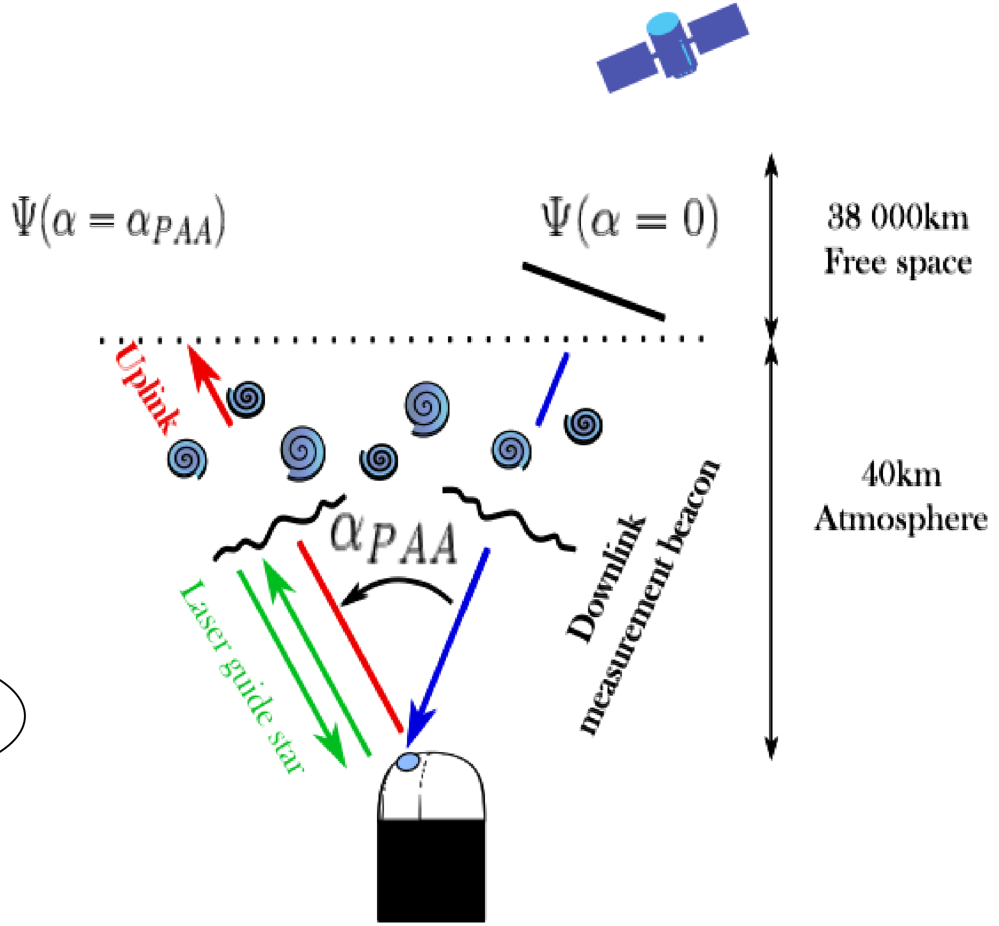
Technique 3: Phase estimation at PAA **[Lognoné-2023]**
Based on on-axis Φ and χ measurements

« MMSE »



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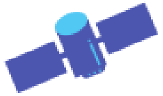

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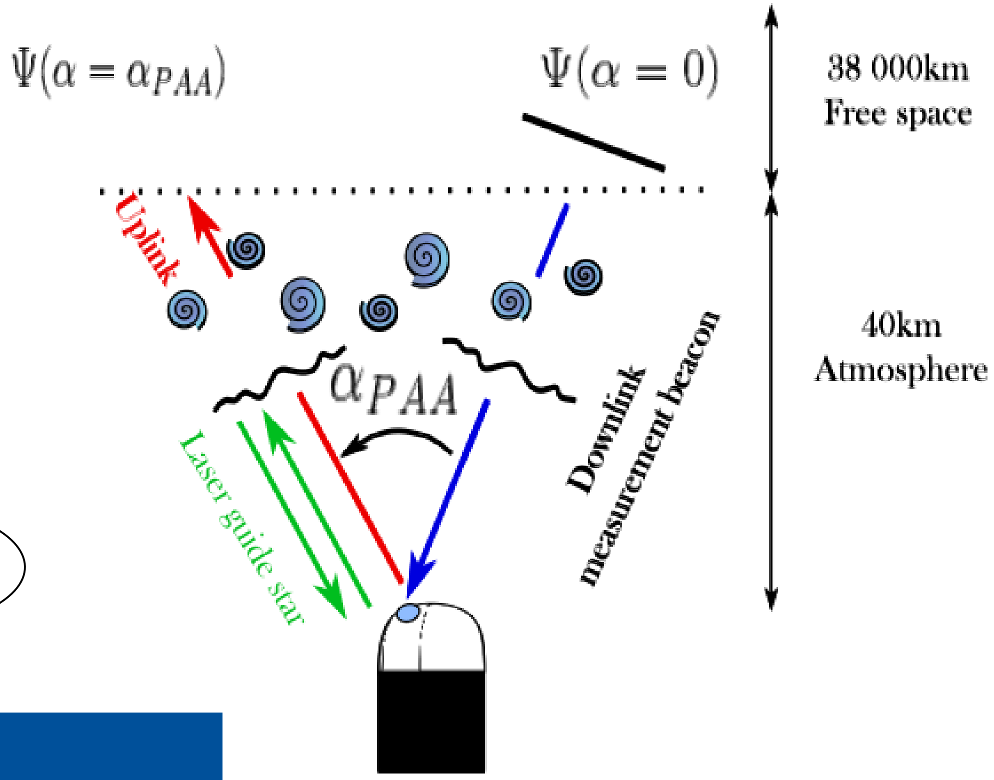
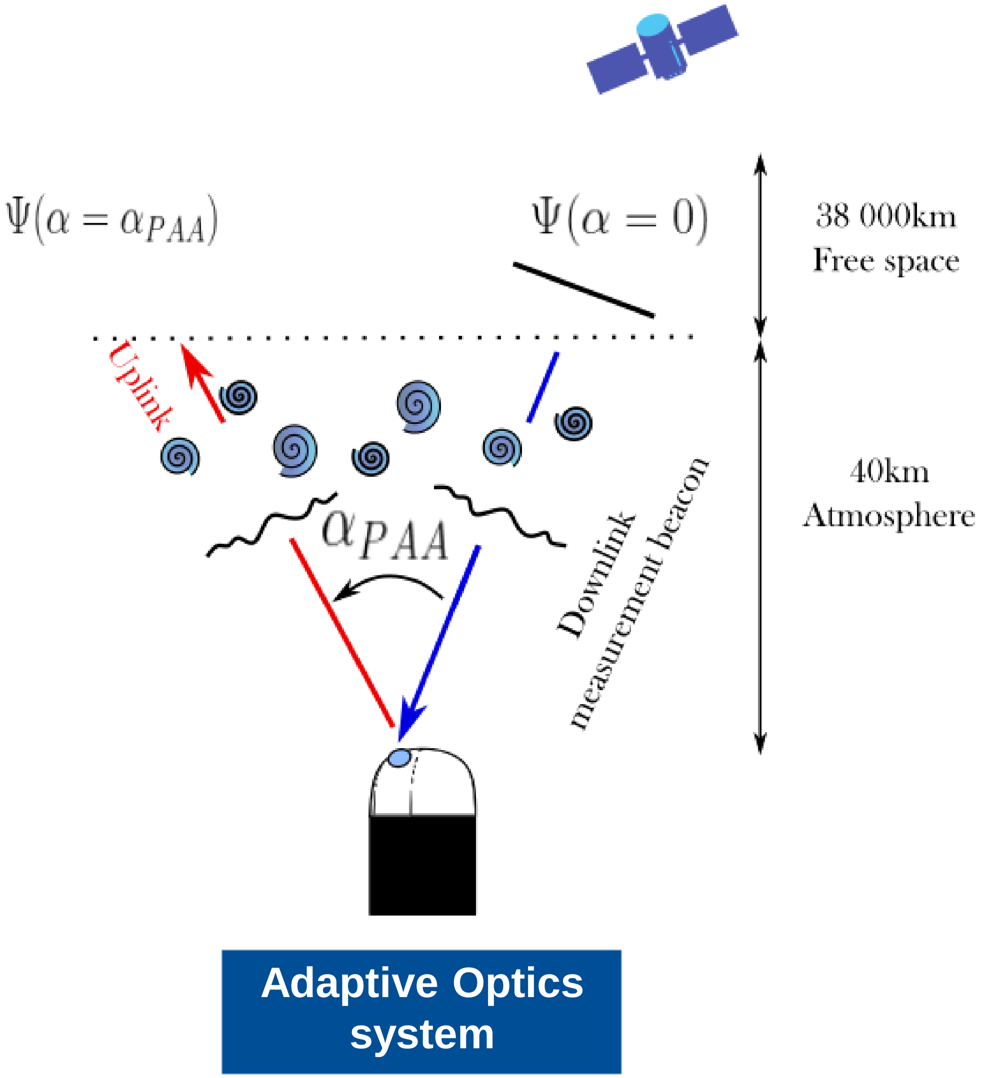


We propose:
To combine 2 and 3 to estimate the uplink tip tilt and focus at PAA by incorporating high order LGS measurements in the phase estimation.

System model

System:

→ Reciprocal approach to compute the phase error and the reciprocal coupled flux



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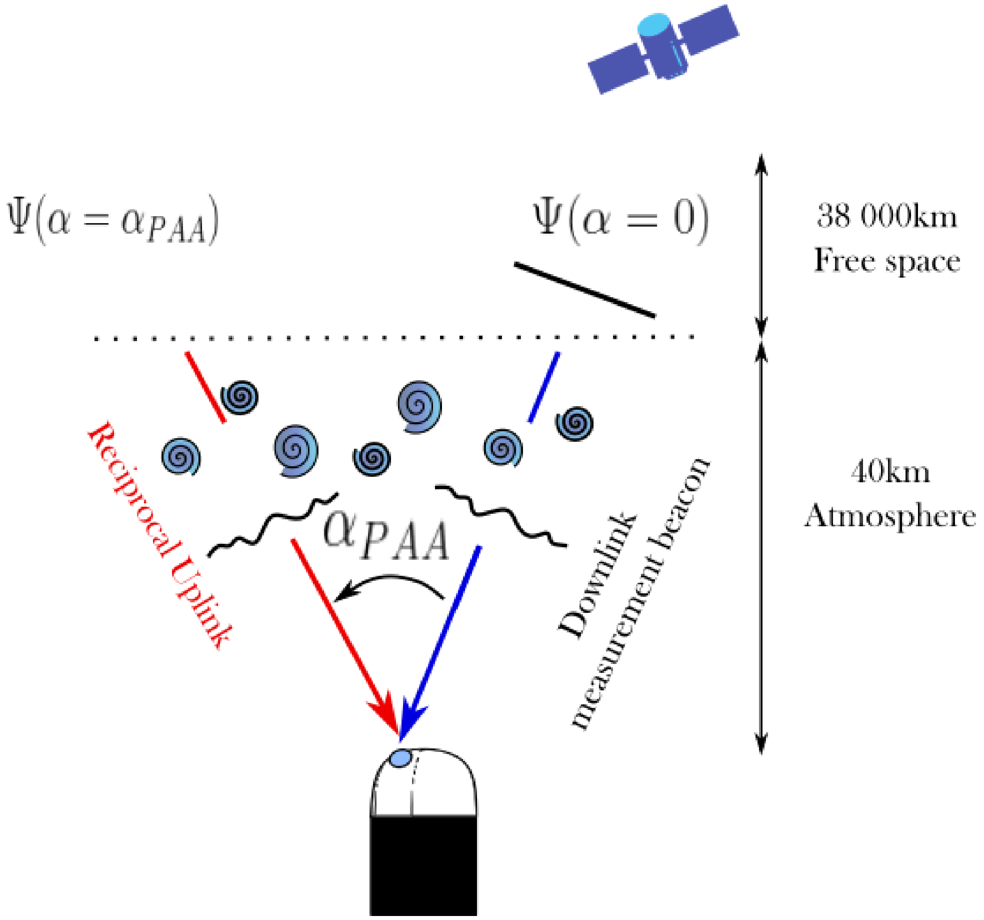

Adaptive Optics system

System model

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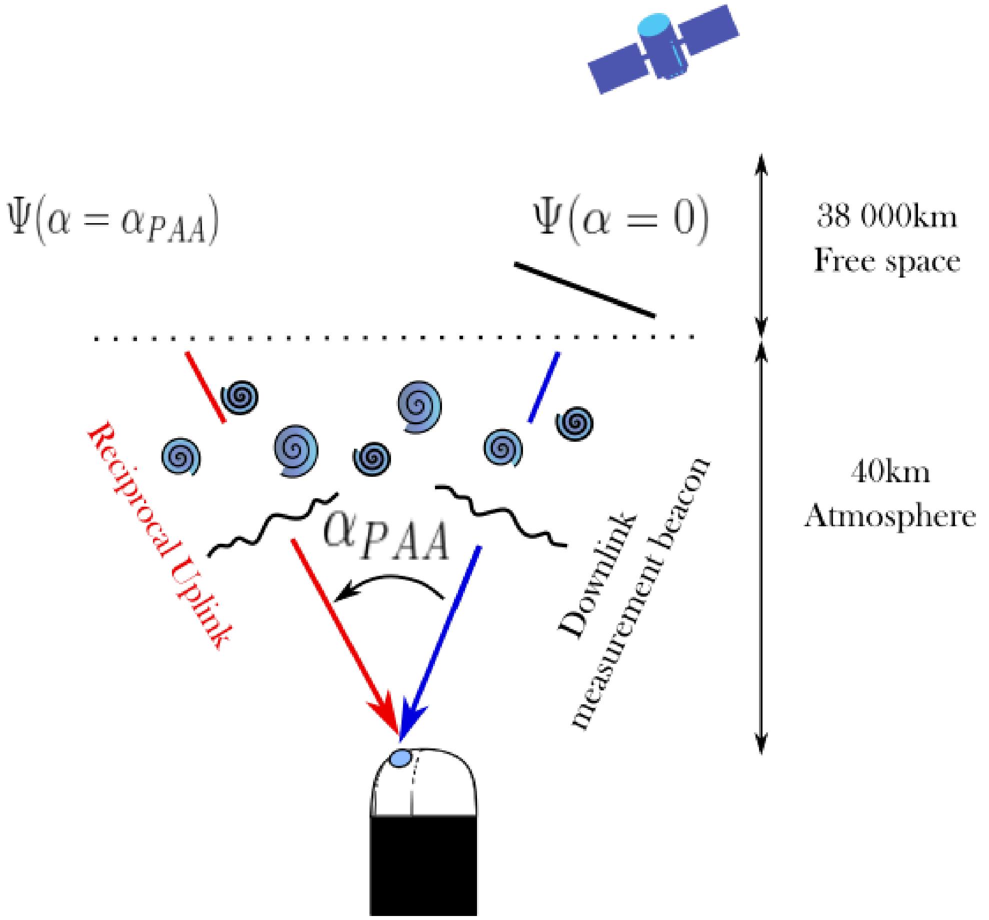
Phase analysis:

→ Zernike Modal formalism:

$\Phi = (a_2, \ldots, a_N)$ and $\chi = (b_1, \ldots, b_N)$



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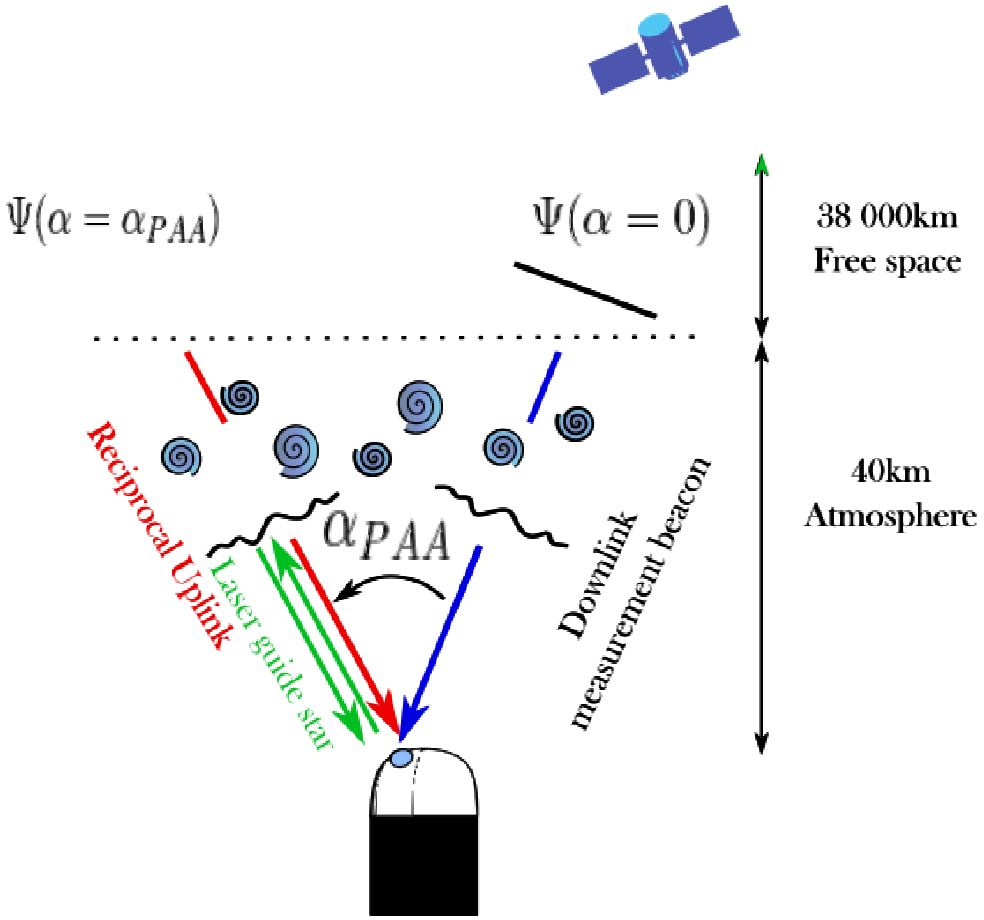
LGS system assumptions:

- Punctual monostatic LGS
  - ➢ Perfect high order measurements



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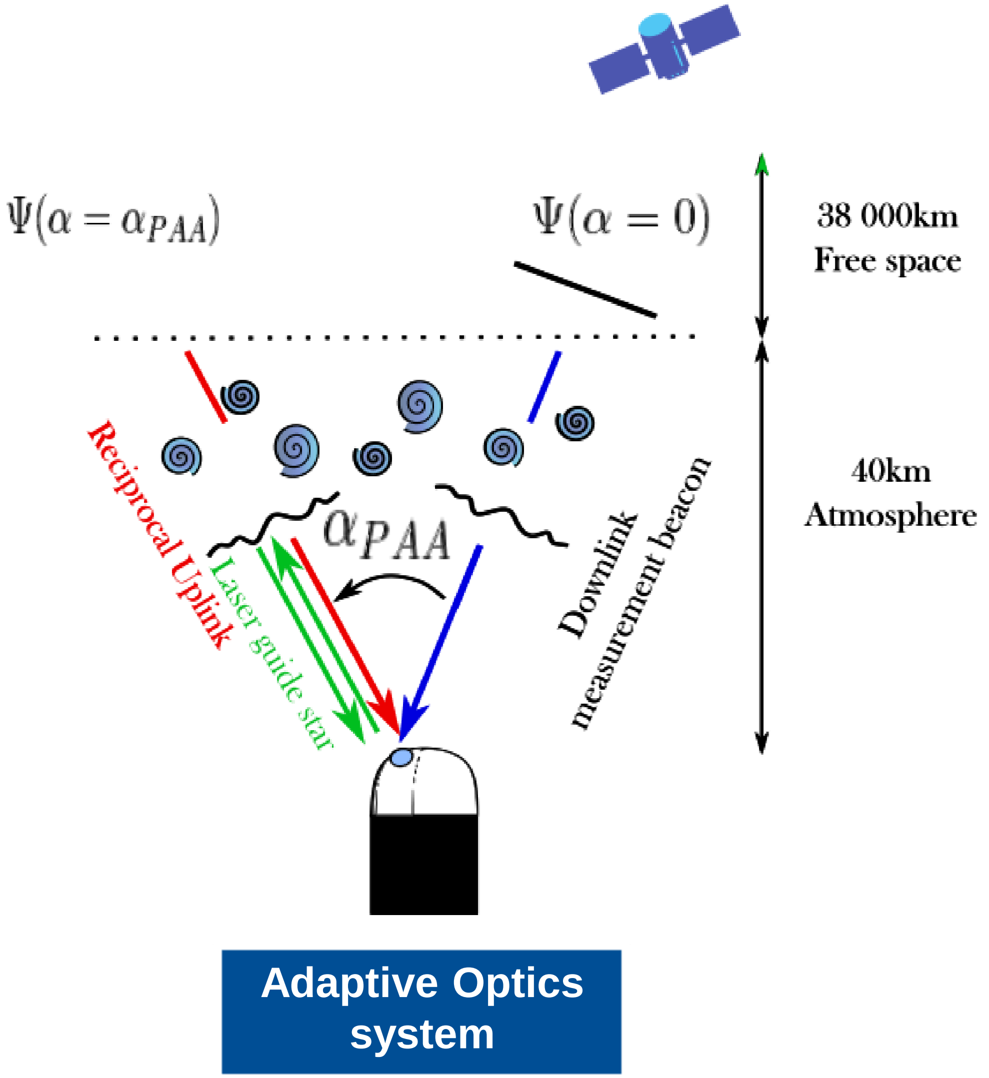
Adaptive optics assumptions:

Error budget : Anisoplanatism and fitting



Benchmark

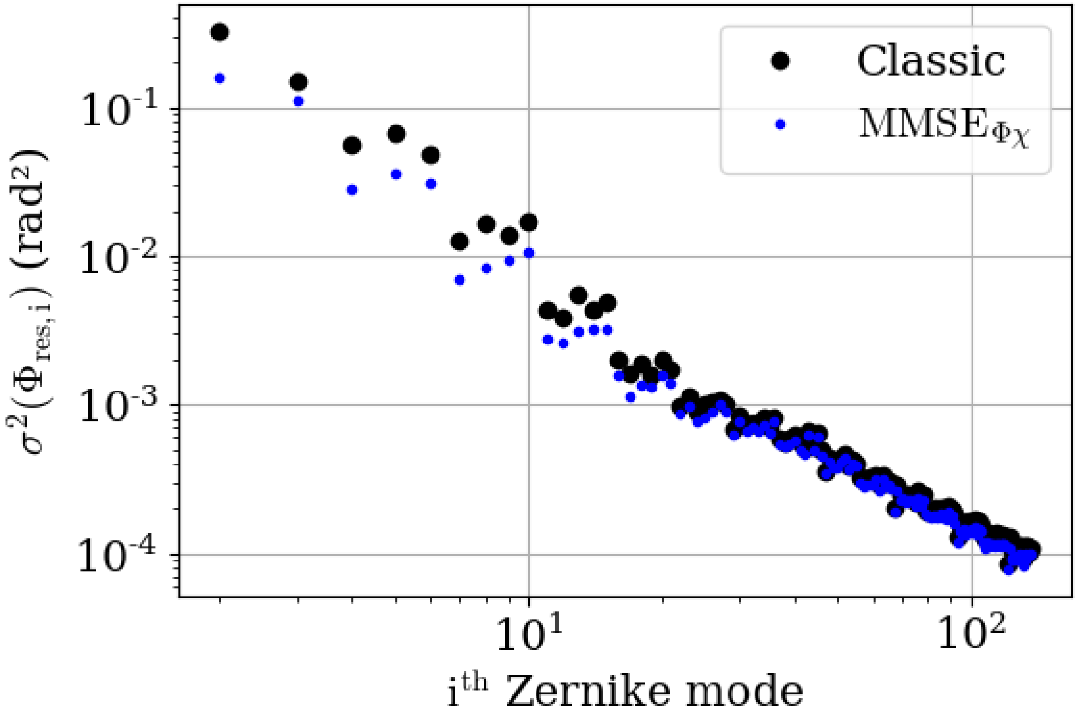
Systems without LGS:

- Classical case, full anisoplanatism:

$$\mathbf{\Phi}_{\text{res,classic}} = \mathbf{\Phi}_{\text{PAA}} - \mathbf{\Phi}_0$$

- MMSE:

$$\mathbf{\Phi}_{\text{res,MMSE}} = \mathbf{\Phi}_{\text{PAA}} - \mathbf{\Phi}_{\text{MMSE}}$$



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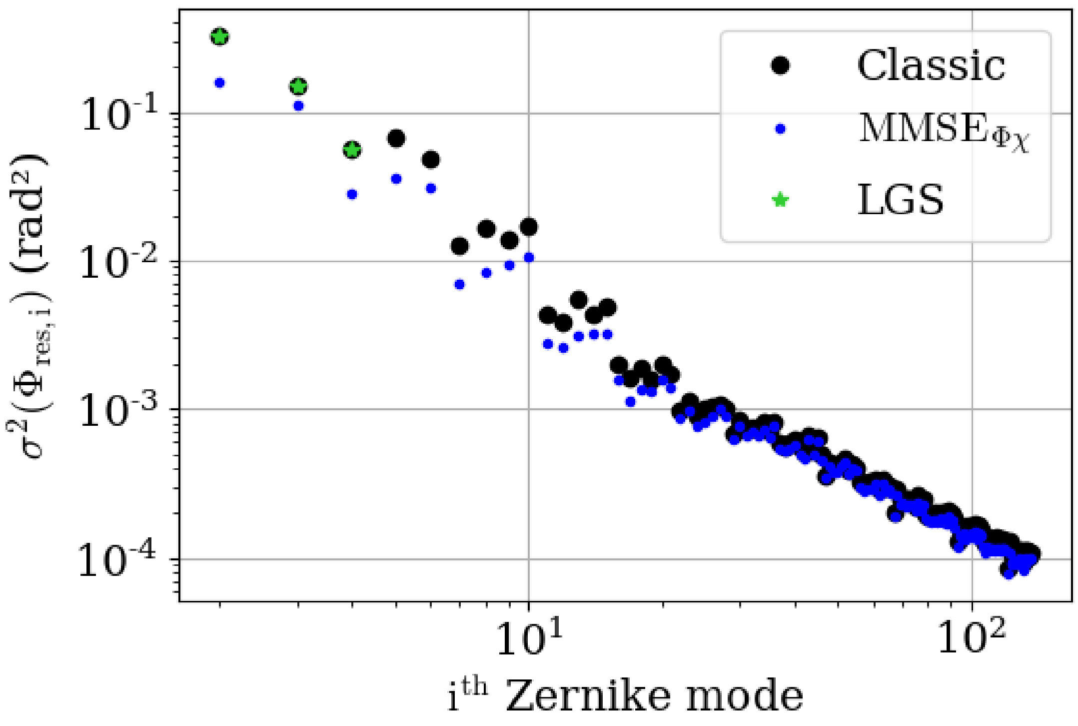
Systems with LGS:

We suppose perfect measurements on high order modes:

$$\mathbf{\Phi}_{\text{res,LGS}} = \begin{pmatrix} \mathbf{\Phi}_{\text{PAA,TTF}} \\ \mathbf{\Phi}_{\text{PAA}} \end{pmatrix} - \begin{pmatrix} \mathbf{\Phi}_{\text{corr,TTF}} \\ \mathbf{\Phi}_{\text{PAA}} \end{pmatrix}$$



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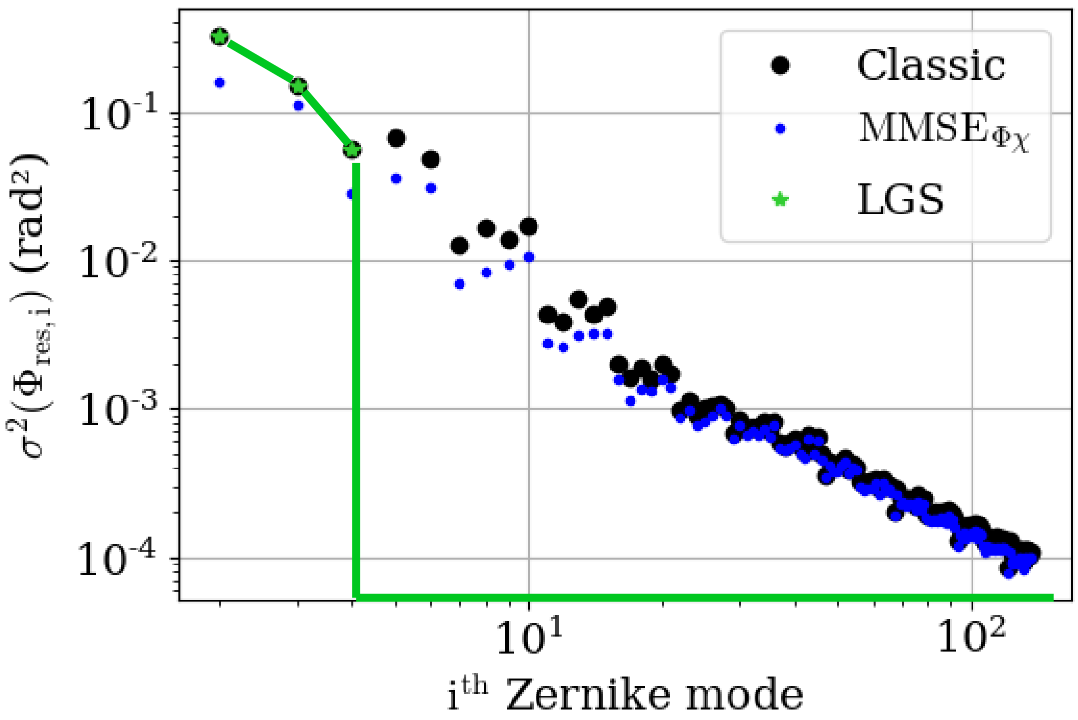

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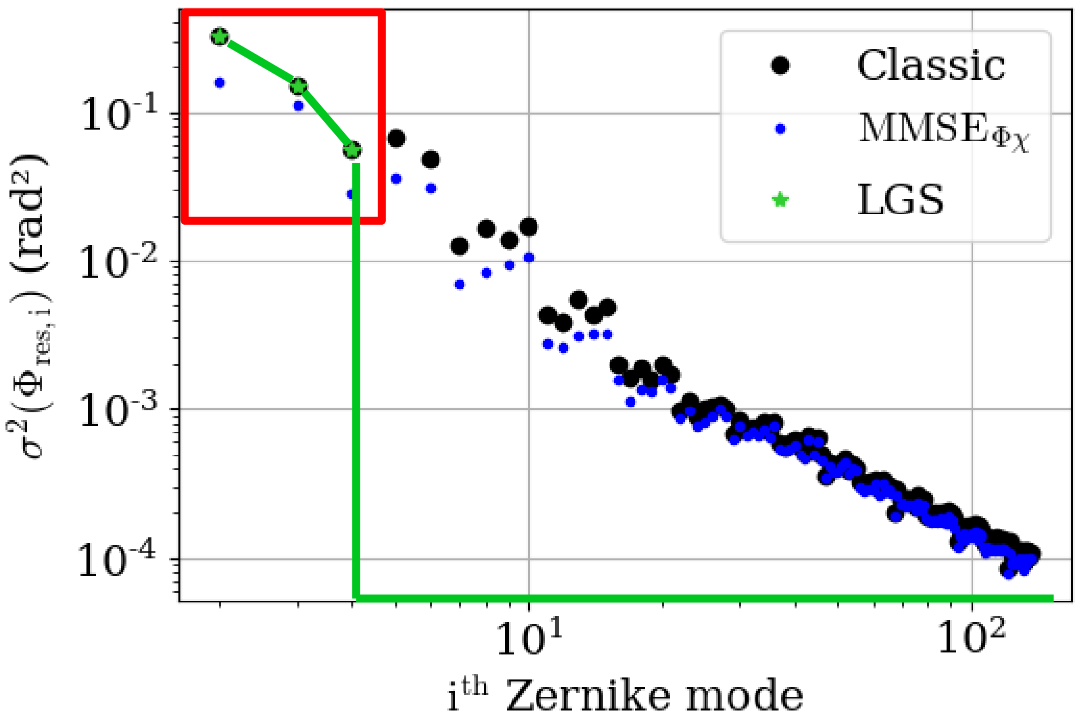

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As we study LGS systems:
→ Focus on Tip Tilt and Focus analysis

Tip tilt and focus estimation

Theoretical phase estimator

Phase error:

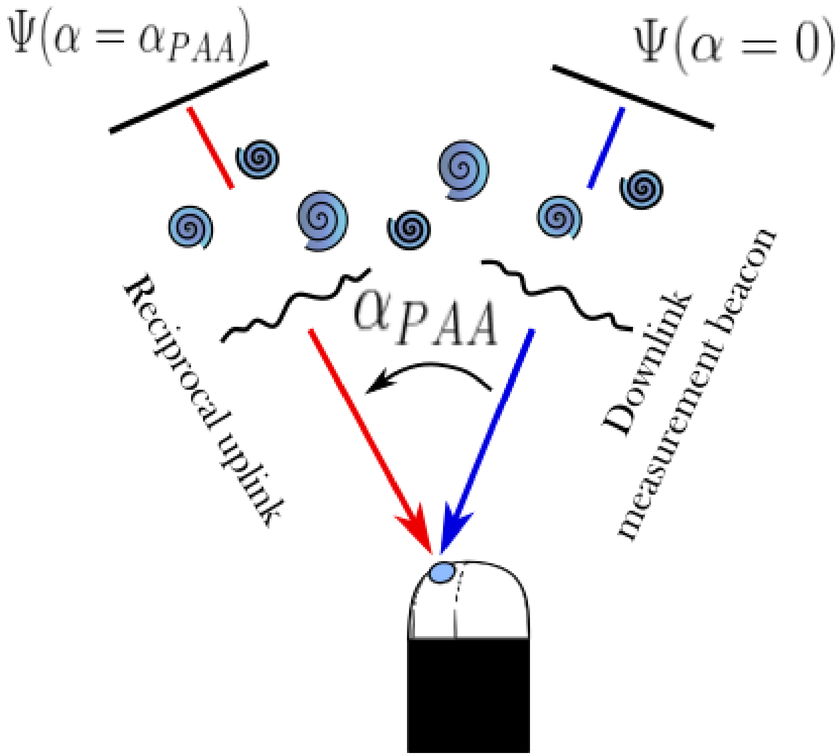
$$\mathbf{e} = \mathbf{\Phi}_{\mathrm{res}} = \mathbf{\Phi}_{\mathrm{PAA}} - \widehat{\mathbf{\Phi}}_{\mathrm{PAA}}$$

Linear estimator:

$$\widehat{\mathbf{\Phi}}_{\mathrm{PAA}} = \mathbf{R}\mathbf{y}_{\mathrm{m}}$$

MMSE estimation:

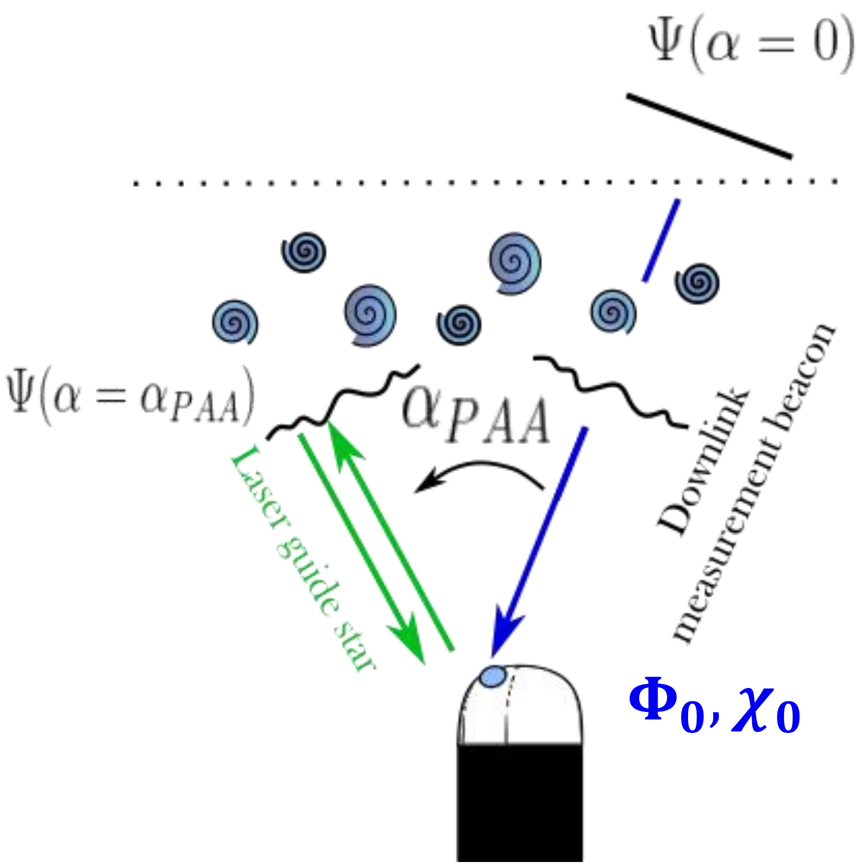
$$\begin{aligned}\mathbf{R}_{\mathrm{MMSE}} &= \min_{\mathrm{R}} \mathbb{E}[(\mathbf{\Phi}_{\mathrm{PAA}} - \mathbf{R}\mathbf{y}_{\mathrm{m}})^{\mathrm{T}}(\mathbf{\Phi}_{\mathrm{PAA}} - \mathbf{R}\mathbf{y}_{\mathrm{m}})] \\ &= \mathbf{\Gamma}_{\mathbf{\Phi}\mathbf{y}_{\mathrm{m}}}(\alpha)\mathbf{\Gamma}_{\mathbf{y}_{\mathrm{m}}\mathbf{y}_{\mathrm{m}}}(0)^{-1}\end{aligned}$$



Tip tilt and focus estimation

Specification of the measurement vector

Reminder: $\boldsymbol{R}_{MMSE} = \boldsymbol{\Gamma}_{\Phi y_m}(\alpha)\boldsymbol{\Gamma}_{y_m y_m}(0)^{-1}$



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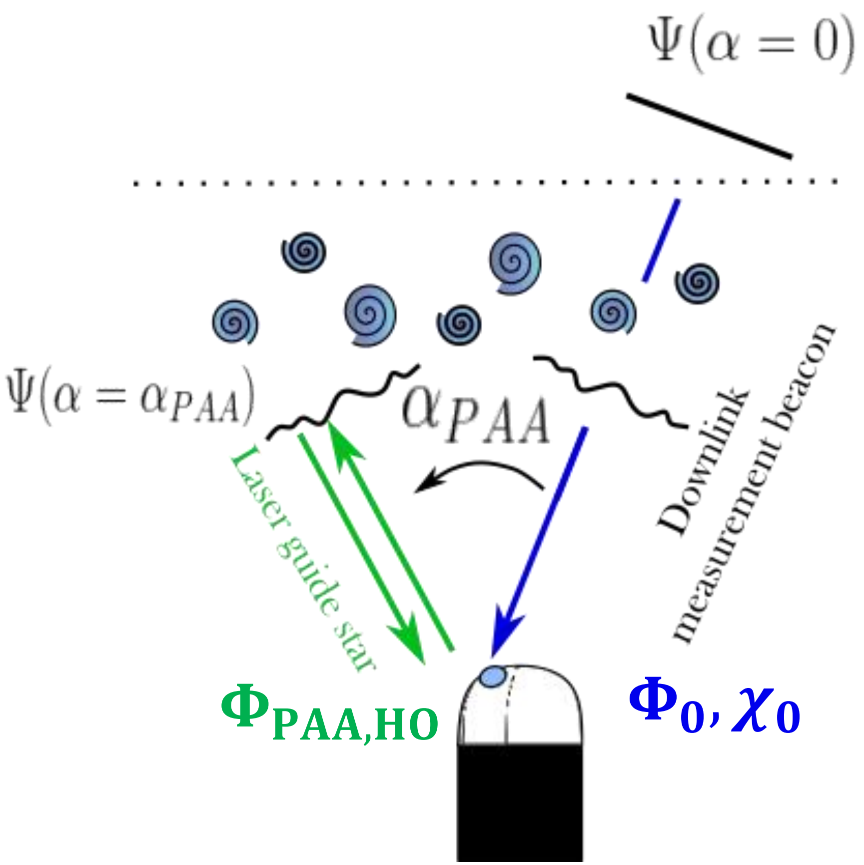
New method

→ Estimate of $\Phi_{\mathrm{PAA,TTF}}$

$$\mathbf{y}_{\mathbf{m,LGS}} = \begin{pmatrix} \boldsymbol{\Phi}_0 \\ \boldsymbol{\chi}_0 \\ \boldsymbol{\Phi}_{\mathbf{PAA,HO}} \end{pmatrix}$$



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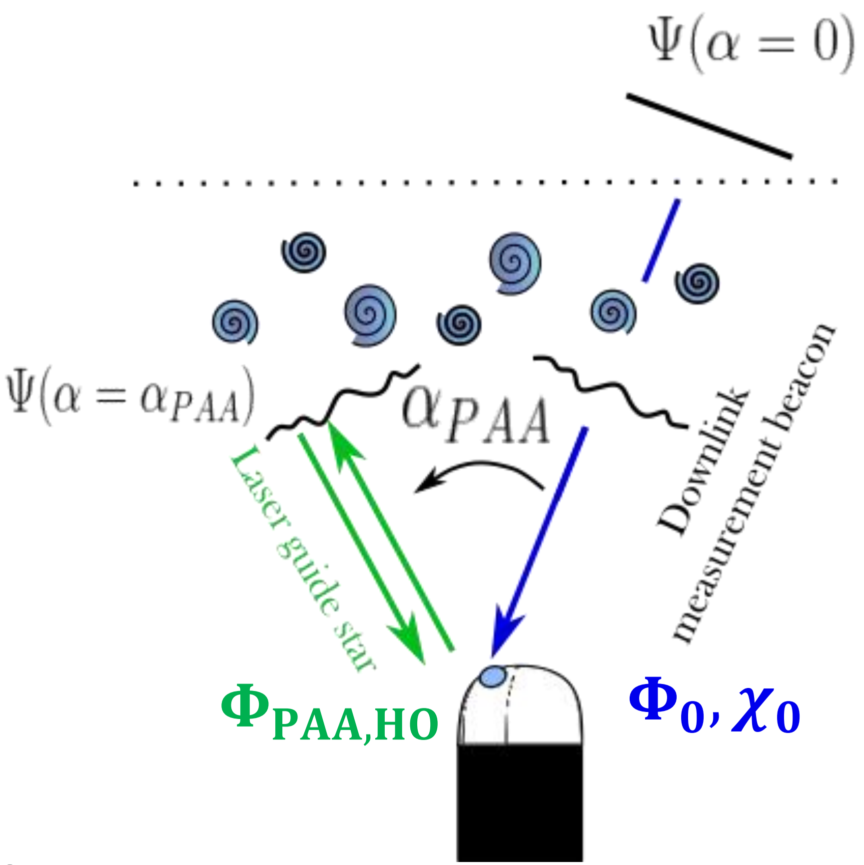

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where $\boldsymbol{\Phi}_0$, $\boldsymbol{\Phi}_{PAA,HO}$ and $\boldsymbol{\chi}_0$ are vectors of the projections of the physical quantities onto the Zernike polynomial basis, as:

$$\boldsymbol{\Phi}_0 = (a_2^0 \ \ldots a_n^0)^T, \boldsymbol{\Phi}_{PAA,HO} = \left(a_5^{\alpha_{PAA}} \ \ldots a_n^{\alpha_{PAA}}\right)^T,$$

and $\boldsymbol{\chi}_0 = (b_1^0 \ \ldots b_n^0)^T$

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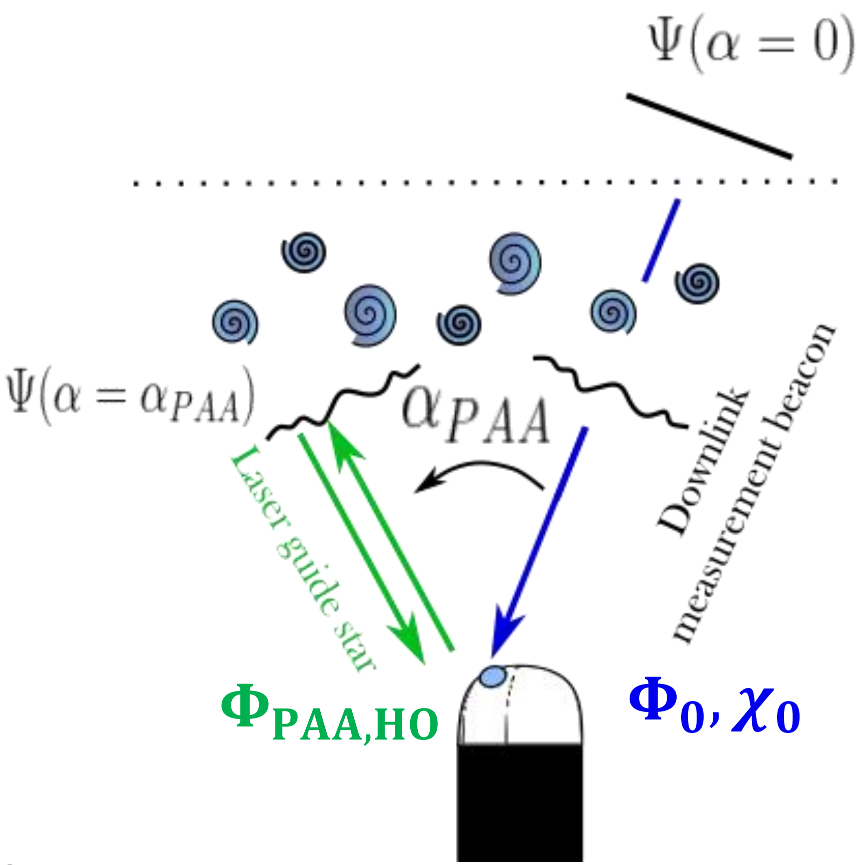

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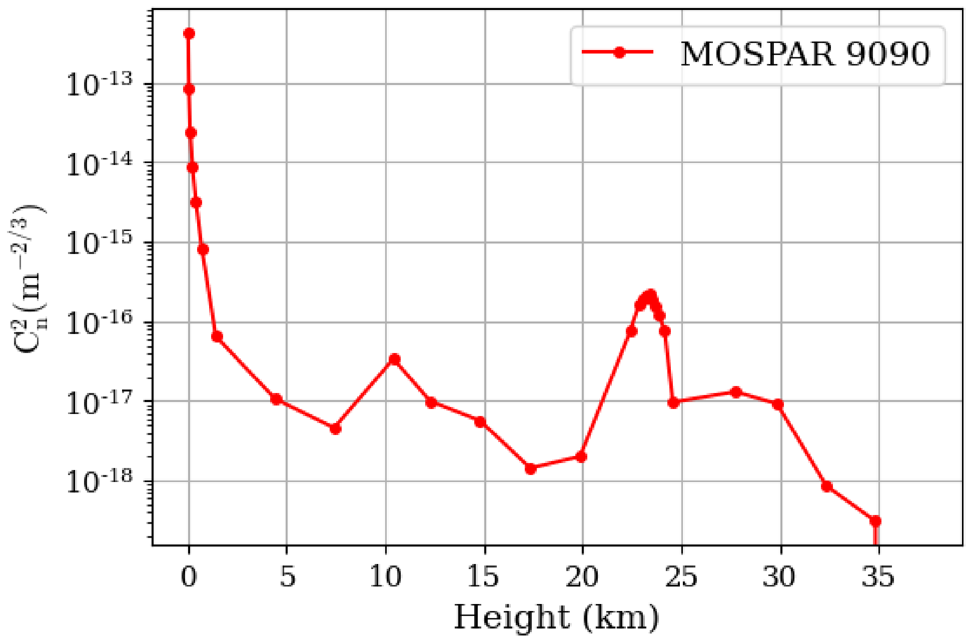
Analytical estimator depends on:
- C_n^2 **profile**
- **OGS parameters: D,** k_0, α_{PAA}

Estimator performances

OGS and atmospheric parameters



OGS parameters	
D	60 cm
$\theta_{elevation}$	30°
θ_{PAA}	18,5 µrad
λ	1550 nm
AO parameters	
N_{AO}	136
f_{samp}	4,7 kHz

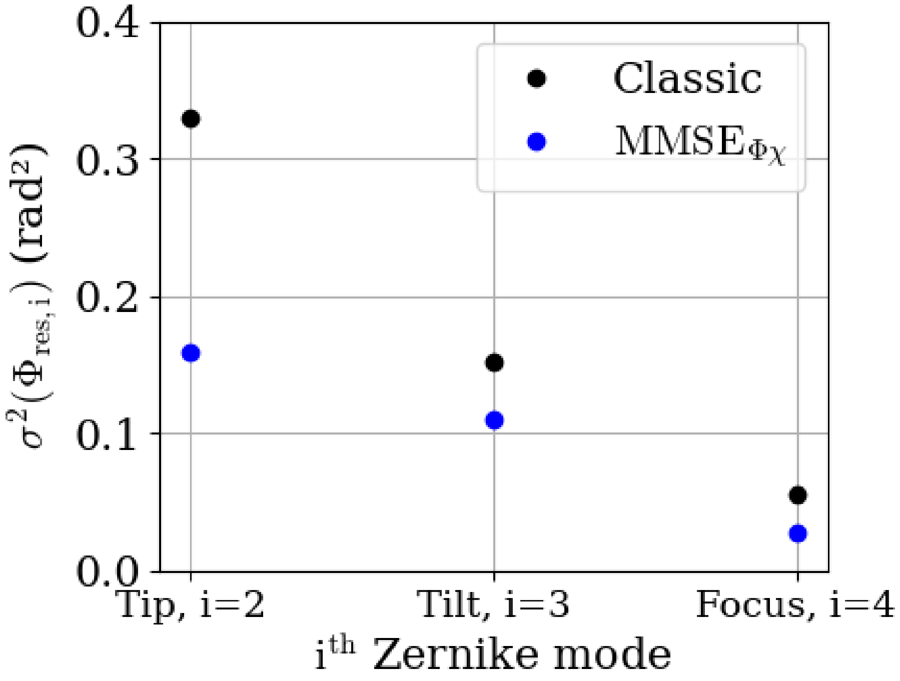
r_0 at 1550 nm	4,0 cm
σ_χ^2	0,08
θ_0	6,8 µrad
(v_g, v_t)	(10, 30) $m.s^{-1}$

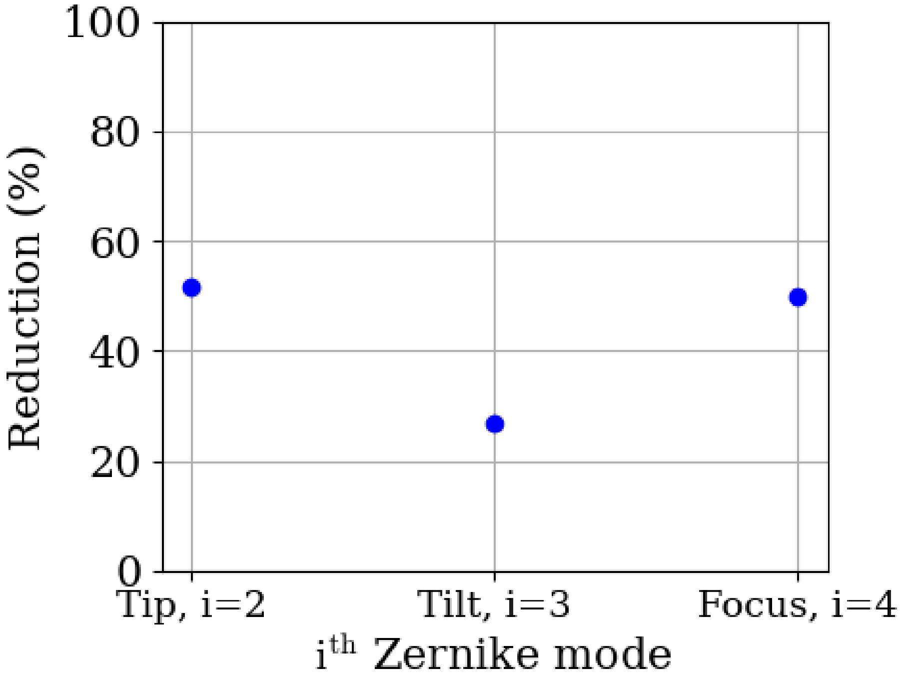
→ **47000 E2E samples generated**

We thank James Osborn (Centre for Advanced Instrumentation, Durham University) for kindly providing the turbulence profile data base described in [Osborn-2018]

Estimator performances

Gain on Tip Tilt and Focus residual phase variance





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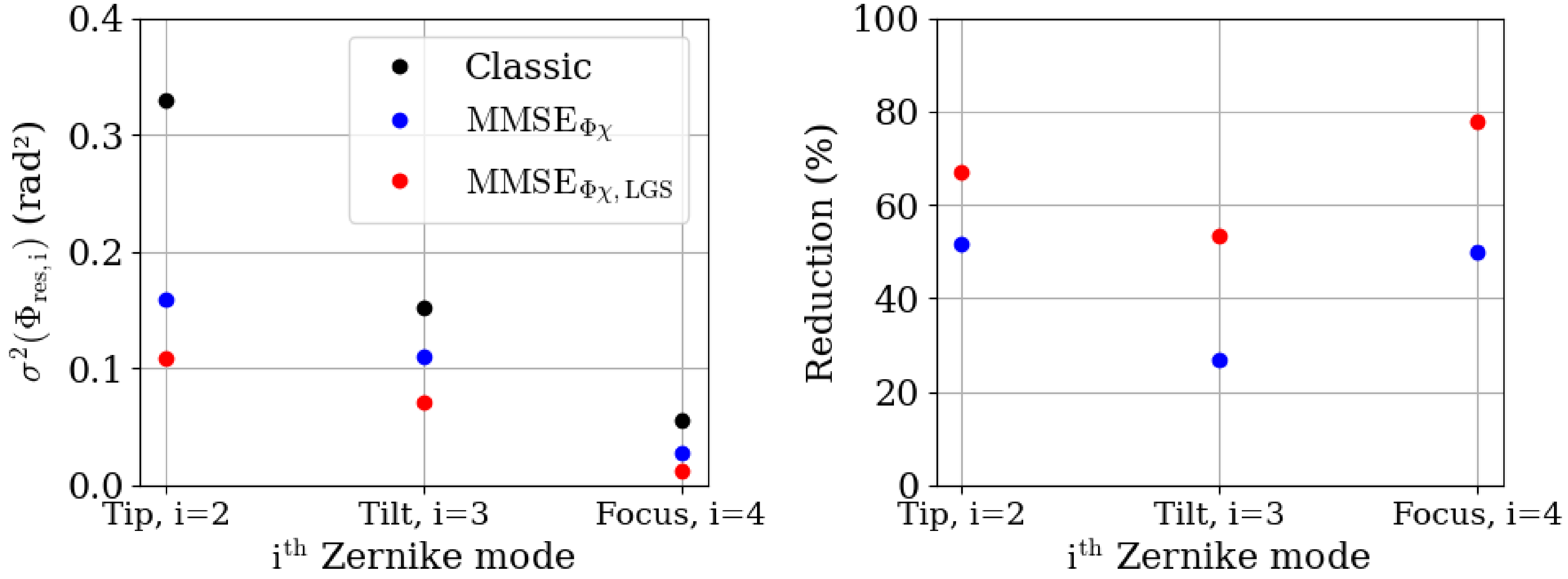
$\sigma^2_{\text{TTF,classic}} = 0{,}53\ \text{rad}^2$

$\sigma^2_{\text{TTF,MMSE}_{\Phi\chi}} = 0{,}29\ \text{rad}^2$

$\sigma^2_{\text{TTF,MMSE}_{\Phi\chi,\text{LGS}}} = 0{,}19\ \text{rad}^2$



We observe:

→ Tip reduced by **70%**, tilt by **50%**, focus by **80%** with respect to the classical case.

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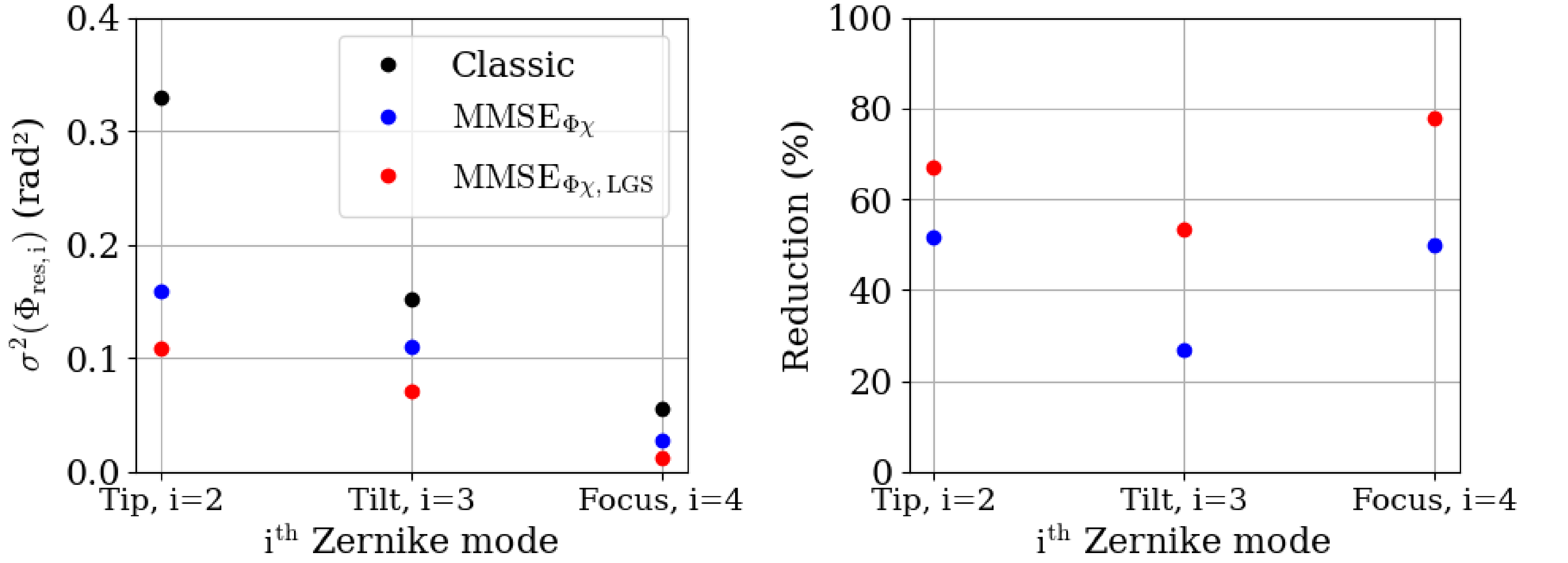

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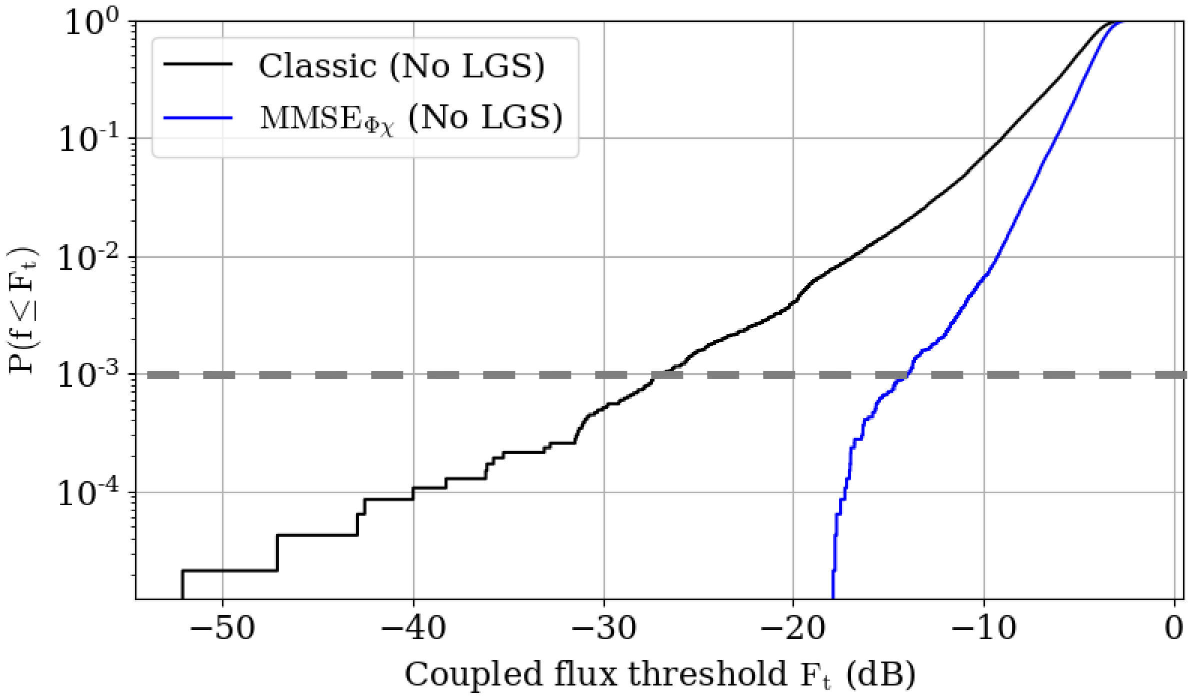
Adding LGS high order measurements brings information and therefore improves the estimation.

Estimator performances
Coupled flux statistics

	Gain with respect to the classical case at $P(f \leq F_t) = 10^{-3}$
$MMSE_{\Phi\chi}$	13 dB
LGS TTF Classic	
LGS TTF $MMSE_{\Phi\chi,LGS}$	



Estimator performances

Coupled flux statistics

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LGS TTF Classic	5 dB
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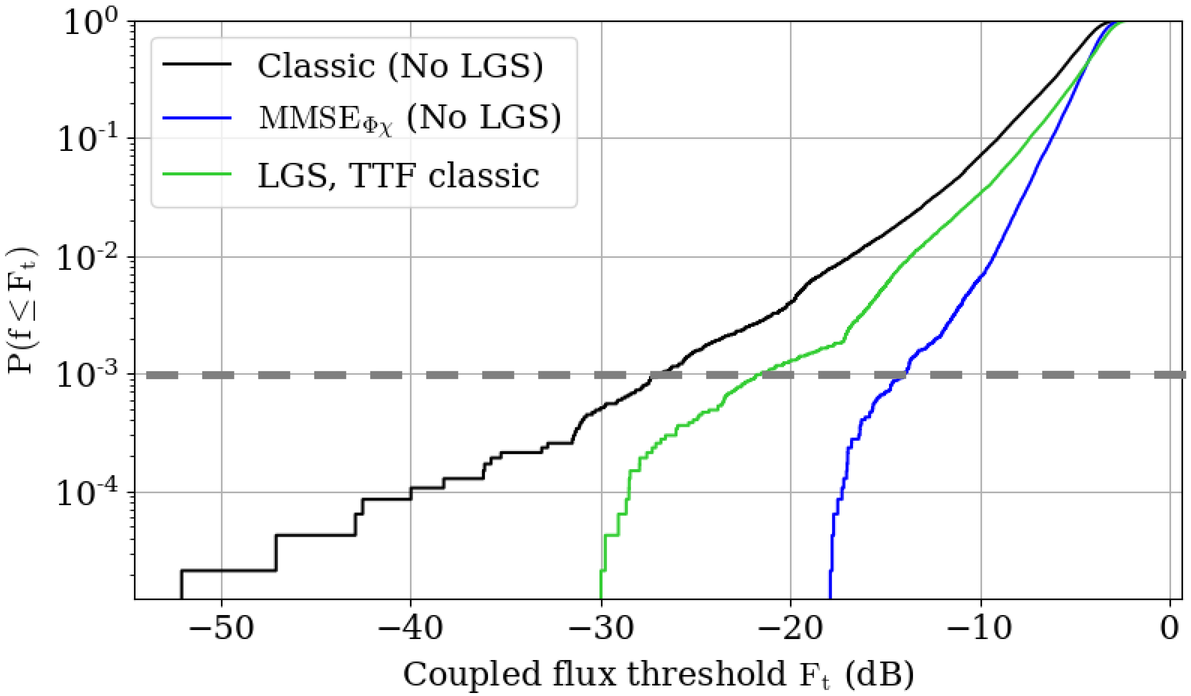

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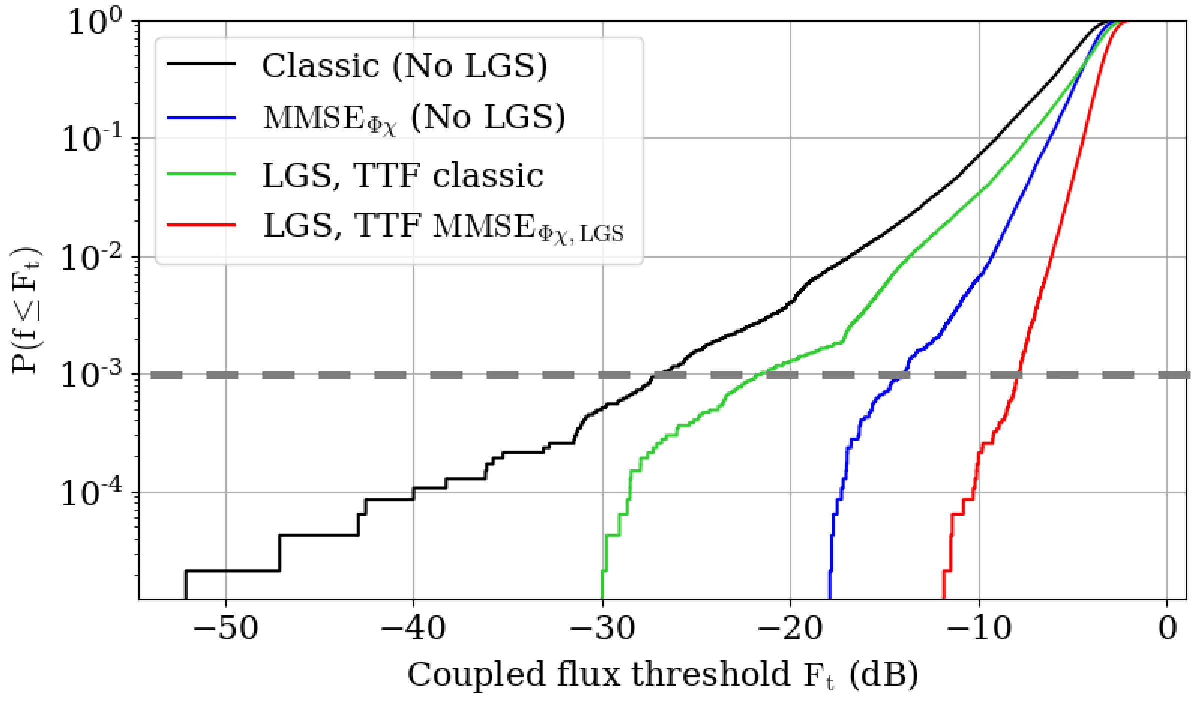

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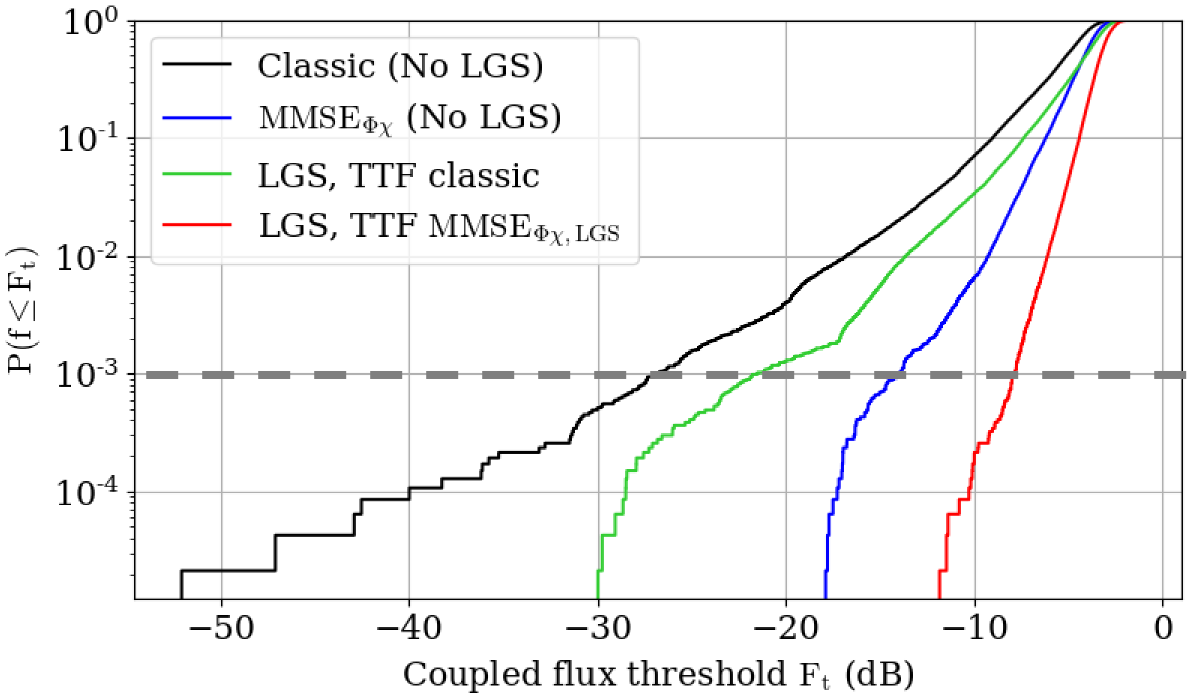

1) $MMSE_{\Phi\chi}$ performs better than LGS with Tip tilt focus classic
2) **For LGS systems**: better performance using LGS phase high orders in the estimation

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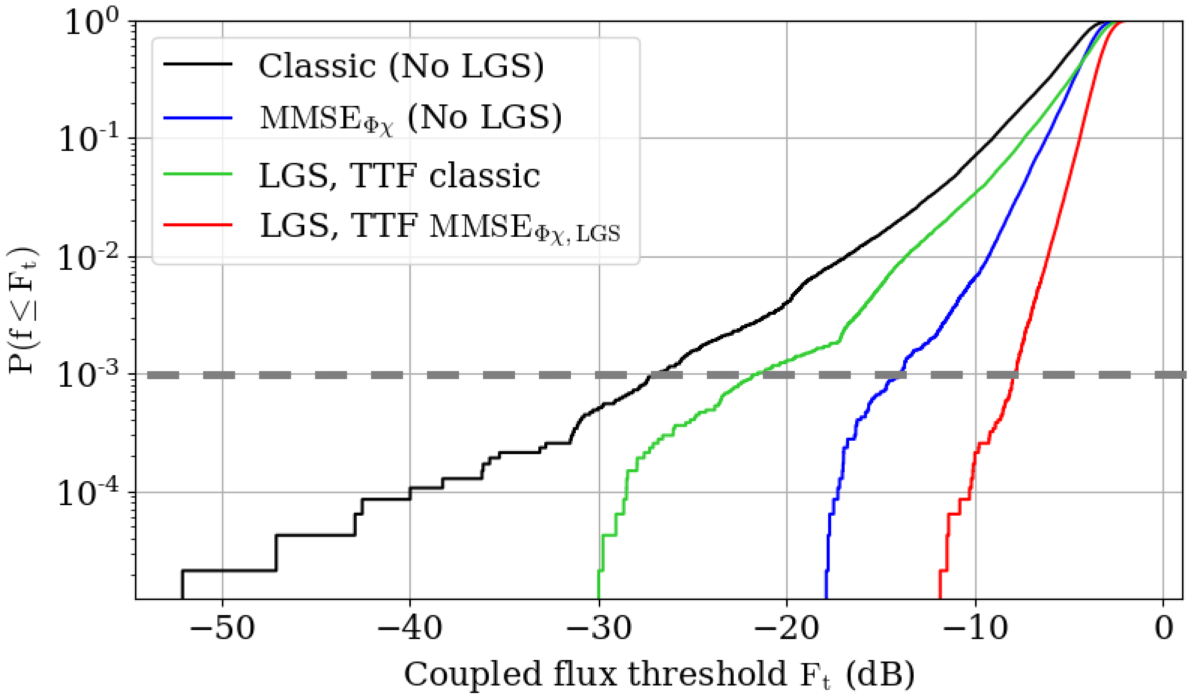
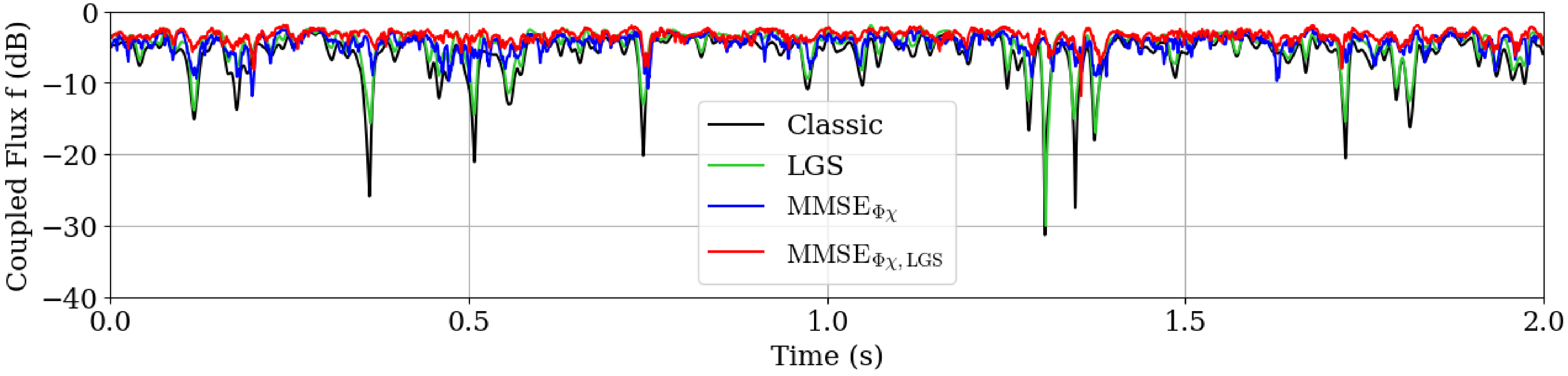


1) $\mathrm{MMSE}_{\Phi\chi}$ performs better than LGS with Tip tilt focus classic
2) **For LGS systems**: better performance using LGS phase high orders in the estimation

This estimation method reduces the occurrence of deep fades:
→ Relax constraints on the link budget.

Estimator performances

Temporal statistics



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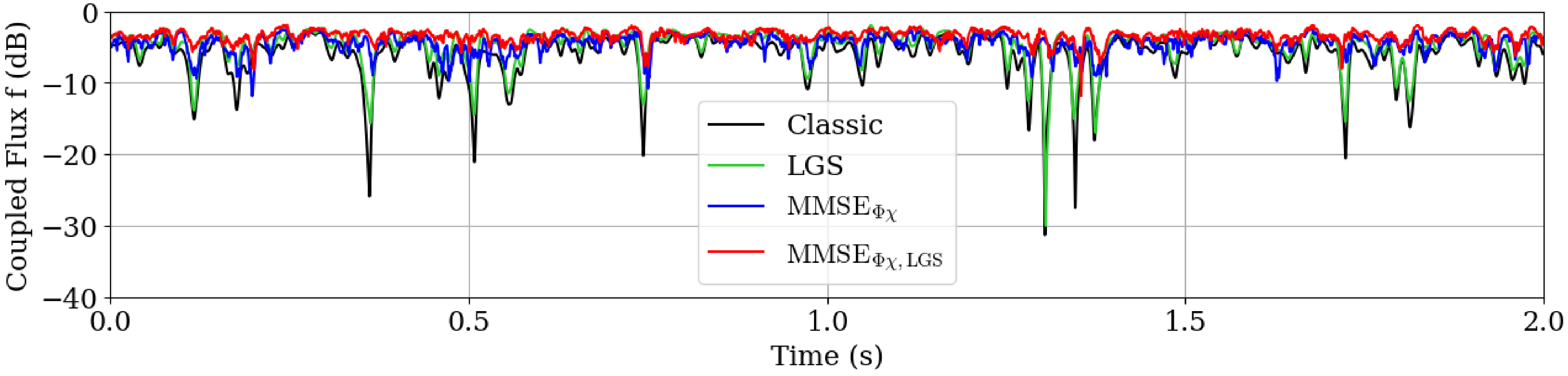

We observe:

- Fading depth and duration reduced with respect to every other methods

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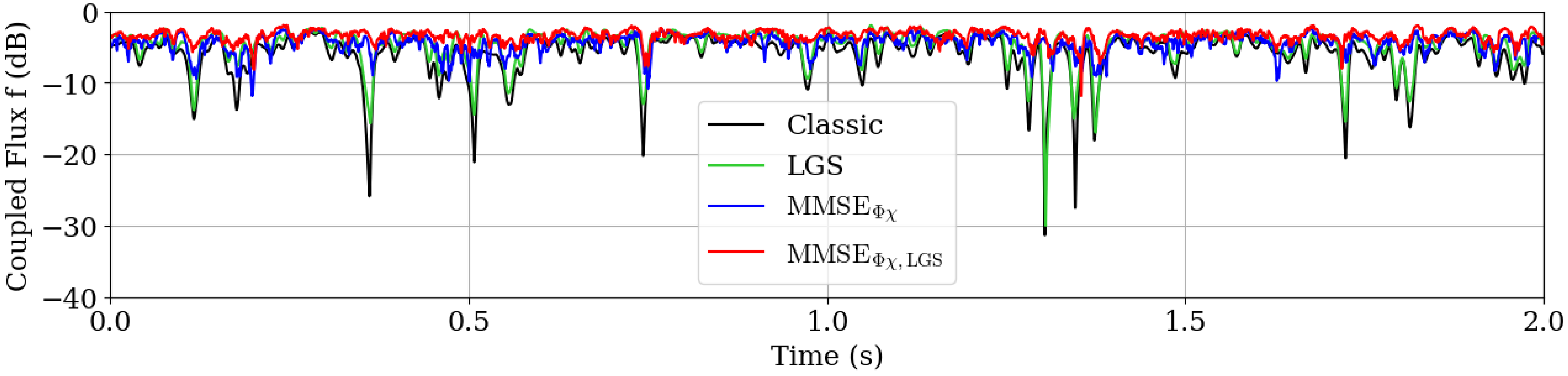

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→ Reduce the link latency and satellite system complexity.

Conclusion and perspectives

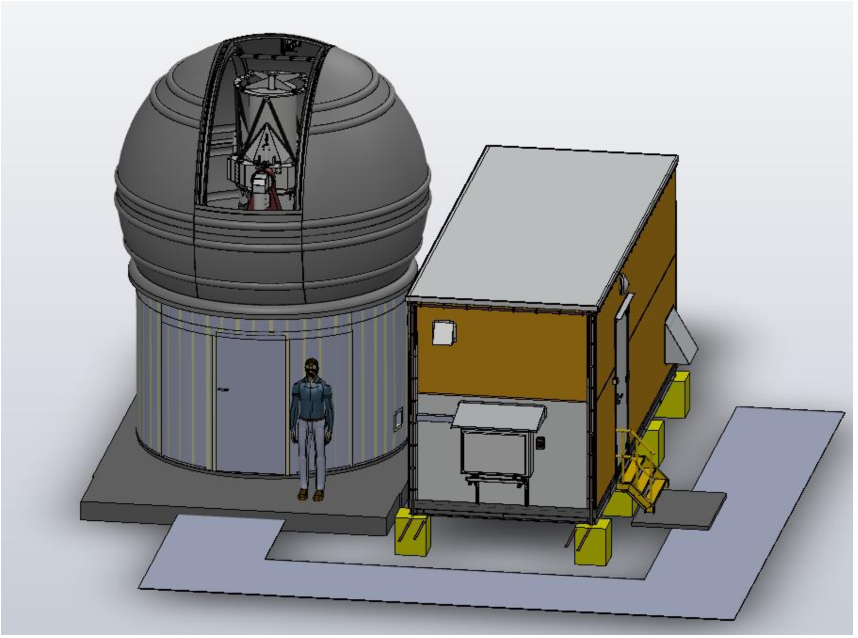
- We derived a new **analytical estimator** relying on **on-axis phase and log-amplitude** and **laser guide star high order measurements**.
- Laser guide star high order measurements bring information to the estimation and therefore further **decrease the tip tilt and focus residual phase variance**.
- This has the consequence to highly improve the statistics and temporal characteristics of the coupled flux aboard the satellite:
  - → Relax **link budget constraints**
  - → Relax constraints on **interleavers duration** : decreased latency and system complexity aboard the satellite.

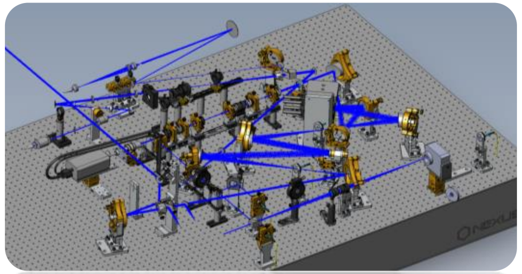
Perspectives

- **Idealized LGS**: this is the upper limit of the performance we can get
  - → Need to study a more realistic LGS system (width of the source, noise, lack of stabilization)
- **Toward implementation**:
  - → Cn2 profile reconstruction to ensure the estimator robustness.

FEELINGS Ground Station

- D = 60 cm robotised telescope (20 cm subaperture option for uplink)
- Compatible with TELEO payload
- GEO and LEO tracking ability
- Compatible with phase and amplitude modulation
- AO (FELIN): 17x17 SH, 4.7kHz, Alpao DM292 + fast TT mirror
- ONERA's RTC (developped by Shakti)
- OS : Laboratory based (LV + IDL), scripts, not automated
- In house high power amplifier
- Weather station, Integral Sky Monitor, Miratlas
- In-house automated post-processing of the experimental data





Thank you for your attention !

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