

Simplified model(s) of the GRAVITY+ adaptive optics system(s) for performance prediction

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Abstract

In the context of the GRAVITY+ upgrade, the adaptive optics (AO) systems of the GRAVITY interferometer are undergoing a major lifting. The current CILAS deformable mirrors (DM, 90 actuators) will be replaced by ALPAO kilo-DMs (43x43, 1432 actuators). On top of the already existing 9x9 Shack-Hartmann wavefront sensors (SH-WFS) for infrared (IR) natural guide star (NGS), new 40x40 SH-WFSs for visible (VIS) NGS will be deployed. Lasers will also be installed on the four units of the Very Large Telescope to provide a laser guide star (LGS) option with 30x30 SH-WFSs and with the choice to either use the 9x9 IR-WFSs or 2x2 VIS-WFSs for low order sensing.

To prepare the instrument commissioning and help the observers to plan their observations, a tool is needed to predict the GPAO performances in terms of Strehl ratio. We developed models based on a Maréchal approximation. Waiting for commissioning data, our model was validated using the TIPTOP toolbox. In this work, we present our models of the NGS modes of GPAO and their calibration with TIPTOP.

GRAVITY+ Adaptive Optics

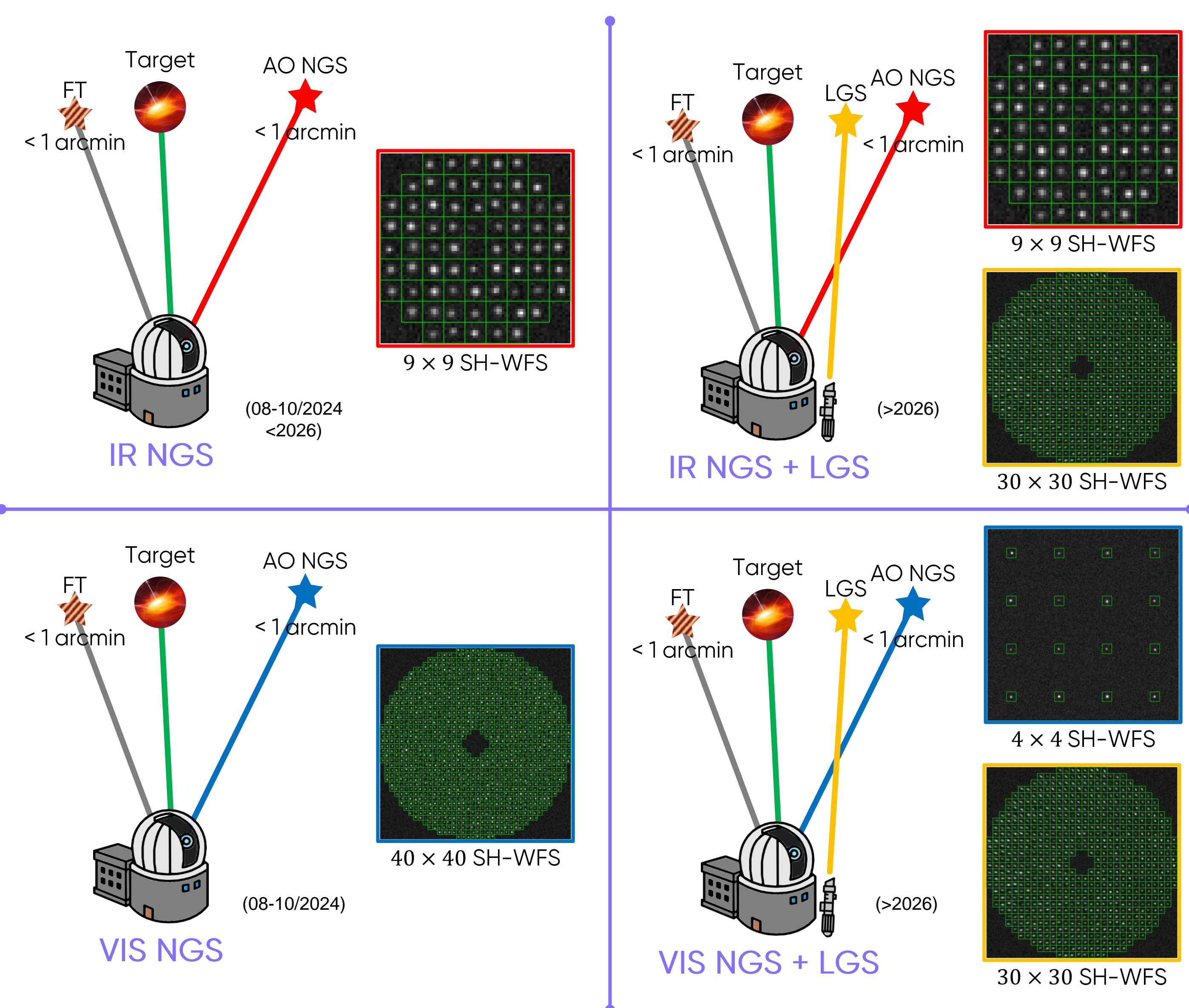


The GRAVITY+ AO system, this is for each unit of the Very Large Telescope Interferometer (VLT):

- A 43 x 43 ALPAO DM with 1453 active actuators,
- Four different AO configurations,
- Four different Shack-Hartmann wavefront sensors (SH-WFS) for low order (LO) and high order (HO) sensing.

SH-WFS size	9 x 9 / LO	4 x 4 / LO	40 x 40 / HO	30 x 30 / HO
SH-WFS type	IR NGS	VIS NGS	VIS NGS	LO/HO NGS
Pixels/box	8	12	6	8
Pixel scale	0.51"	0.21"	0.42"	0.8"
Sensor	SAPHIRA	OCAM2	OCAM2	OCAM2

FT: Fringe tracker NGS: Natural Guide Star LGS: Laser Guide Star IR: InfraRed VIS: Visible



Méarachal Approximation (NGS)

$$\rho_{\text{Strehl}} = e^{-\sigma_{\text{tot}}^2} \leftrightarrow \sigma_{\text{tot}}^2 = \underbrace{\sigma_{\text{geom}}^2}_{\sigma_{\text{fitting}}^2 + \sigma_{\text{aliasing}}^2} + \underbrace{\sigma_{\text{lag}}^2}_{\sigma_{\text{noise}}^2} + \underbrace{\sigma_{\text{ph}}^2}_{\sigma_{\text{ph}}^2} + \underbrace{\sigma_{\text{ron}}^2}_{\sigma_{\text{ron}}^2} + \underbrace{\sigma_{\text{iso}}^2}_{\sigma_{\text{iso}}^2}$$

Geometry $\rightarrow \sigma_{\text{geom}}^2 = \alpha_{\text{geom}} \left(\frac{d_{\text{actu}}}{\chi^{-3/5} r_{\text{sci}}} \right)^{5/3}$
 Servo-lag $\rightarrow \sigma_{\text{lag}}^2 = \alpha_{\text{lag}} \left(\frac{v_0}{\chi^{-3/5} r_{\text{sci}} f} \right)^{\beta_{\text{lag}}}$
 Isoplanetism $\rightarrow \sigma_{\text{iso}}^2 = \alpha_{\text{iso}} \left(\frac{\theta_{\text{sci}} \lambda_{\text{ngs}} \chi h_0}{\chi^{-3/5} r_{\text{sci}}} \right)^{\beta_{\text{iso}}}$
 Photon $\rightarrow \sigma_{\text{ph}}^2 = \alpha_{\text{ph}} \left(\frac{\lambda_{\text{ngs}}}{\lambda_{\text{sci}}} \right)^2 \frac{g}{2-g} 2 \cdot N_{\text{ph,ngs}} 1 / N_{\text{ph,ngs}}^2$
 Readout $\rightarrow \sigma_{\text{ron}}^2 = \alpha_{\text{ron}} p_{\text{pix}}^2 N_{\text{pix}}^4 \sigma_{\text{pix}}^2 \frac{g}{2-g} 1 / N_{\text{ph,ngs}}^2$

* $\beta \neq 5/3$ (external scale of the turbulence)

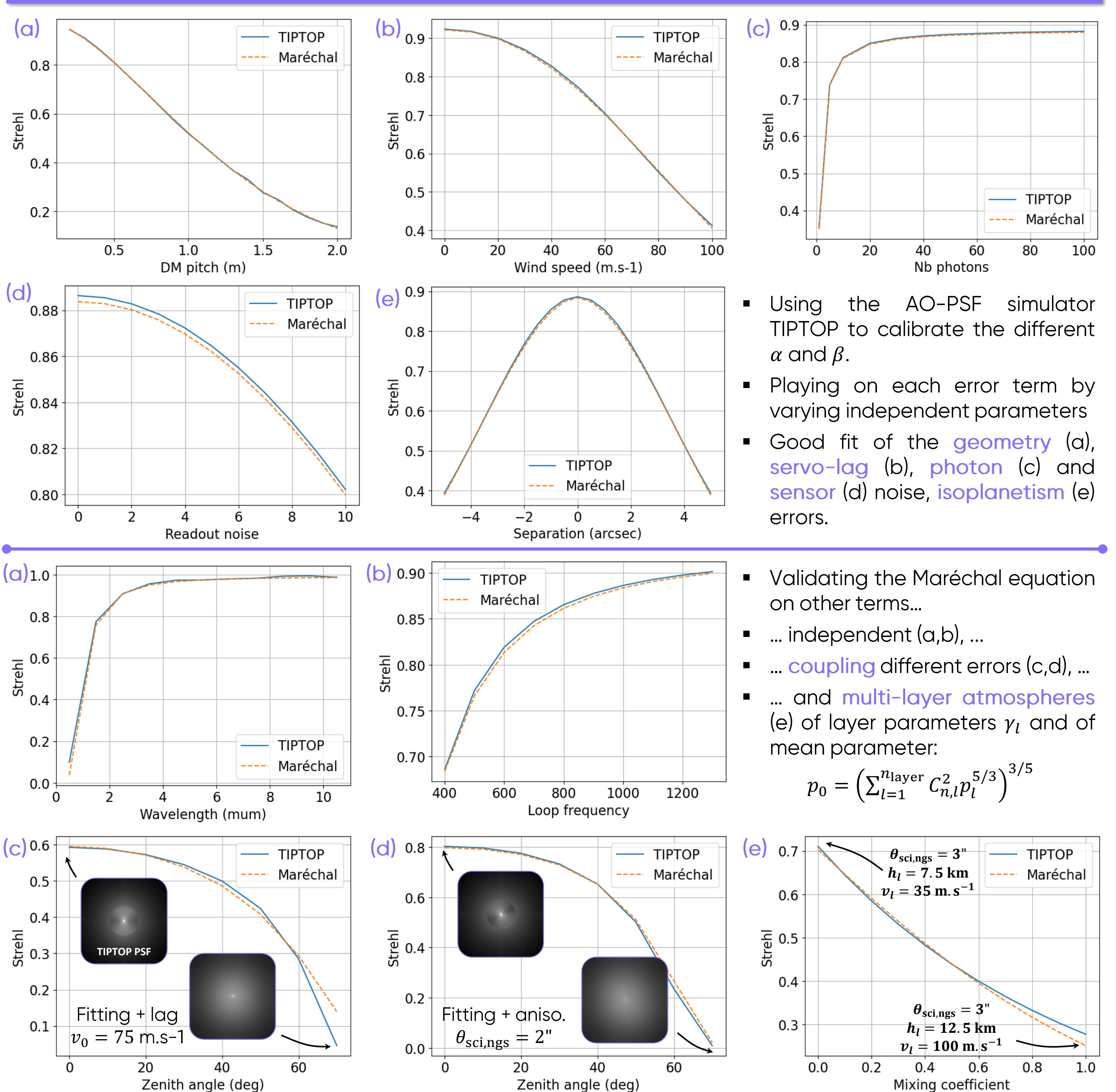
AO system

f , loop frequency / g , loop gain
 $\theta_{l,l'}$, angular distance* between $l \leftrightarrow l'$
 N_{modes} , number of GPAO modes*
 $d_{\text{actu}} = D_{\text{tel}} / (2\sqrt{N_{\text{modes}}/\pi} - 1)$, inter-actuator distance
 N_{pix} , pixel number on a SH-WFS box side
 $N_{\text{ph},l} = \Phi_l \frac{D_{\text{wfs}}^2}{f}$, number of photons in a Sh-WFS box
 σ_{pix} , pixel readout noise / p_{pix} , pixel scale

Atmosphere and sources

$l \in \{0, \text{lgs, ngs, sci}\}$, source*
 λ_l , the wavelength* ($l \in \{0, \text{lgs, ngs, sci}\}$)
 $\eta_l = r_0(\lambda_l/\lambda_0)^{6/5}$, the Fried parameter*
 h_0 / h_{lgs} , the altitude* of the turbulence layer / LGS
 v_0 , velocity* of the turbulence layer
 $\chi = 1/\cos \zeta$, the secant of the zenith angle* ζ
 Φ_l , photon flux* of the source l (ph/m²/s)
 Ξ_l , FWHM of the source l
 *ASPRO model parameters

Calibration with TIPTOP



- Using the AO-PSF simulator TIPTOP to calibrate the different α and β .
- Playing on each error term by varying independent parameters
- Good fit of the geometry (a), servo-lag (b), photon (c) and sensor (d) noise, isoplanetism (e) errors.

- Validating the Maréchal equation on other terms...
- ... independent (a,b), ...
- ... coupling different errors (c,d), ...
- ... and multi-layer atmospheres (e) of layer parameters γ_l and of mean parameter:

$$p_0 = \left(\sum_{l=1}^{n_{\text{layer}}} C_{n,l}^2 \rho_l^{5/3} \right)^{3/5}$$

Towards an Update of ASPRO₂

The Astronomical Software to PRepare Observations (ASPRO) is a tool to simulate the performances of a VLT instrument (UV-plane coverage, signal over noise ratio, visibility models, ...) for a given set of configuration, target and turbulence condition.



The tools predicting the Strehl ratios (FT and science) must be updated to accommodate for the new GRAVITY+ configurations and performances. Different questions and needs are at stake.

- Which GRAVITY+ AO mode? \Rightarrow fast tool for mode and stars/objects ranking
- Where to place the LGS? \Rightarrow easy tool for portability, integration and calibration
- Which targets for the NGS and FT? \Rightarrow Predicted SNR?

Perspectives

- NGS model already integrated in the SearchFFT ranking tool (Aspro₂ coming soon...)
- To be used for the commissioning plan of GRAVITY+
- (α, β) parameters to be refined on real data (calibration on the VLT beacons, on-sky, ...)
- Work is on-going to develop and validate a LGS Maréchal approximation

$$\sigma_{\text{tot}}^2 = \sigma_{\text{geom}}^2 + \sigma_{\text{lag,HO}}^2 + \sigma_{\text{lag,LO}}^2 + \sigma_{\text{ph,HO}}^2 (\Xi_{\text{lgs}} \approx 1'') + \sigma_{\text{ph,LO}}^2 (\Xi_{\text{ngs}}) + \sigma_{\text{ron,HO}}^2 + \sigma_{\text{ron,LO}}^2 + \sigma_{\text{iso,HO}}^2 + \sigma_{\text{iso,LO}}^2 + \sigma_{\text{cone,sci}}^2$$

Tradeoff between a seeing and a diffraction limited LO spot

$$\sigma_{\text{cone,sci}}^2 \propto \left(\frac{D_{\text{tel}}}{\chi^{-3/5} r_{\text{sci}}} \frac{h_0}{h_{\text{lgs}}} \right)^{5/3}$$

$$\sigma_{\text{iso,HO/LO}}^2 \propto \left(\frac{\theta_{\text{sci,lgs/sci,ngs}} \chi h_0}{\chi^{-3/5} r_{\text{sci}}} \right)^{5/3}$$

References & Acknowledgments

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 ② TIPTOP: a new tool to efficiently predict your favorite AO PSF, B. Neichel et al., SPIE 2020
 ③ TIPTOP: cone effect for single laser adaptive optics systems, G. Agapito et al., AO4ELT, 2023

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