Analytical vs. end-to-end numerical modeling of adaptive optics systems: comparison between the PAOLA code and the Software Package CAOS

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Abstract

We compare in this poster the analytical approach together with the so-called end-to-end approach in the framework of astronomical adaptive optics (AO) modeling. The two tools used for this purpose are well-known and already widely used within the astronomical AO community. PAOLA (Performance of Adaptive Optics for Large (or Little) Apertures), as presented by Jolissaint, L., 2010, J. Opt. Soc. Am. A 27, 2055 on the one hand, and the Software Package CAOS (see Carlibel, M. et al 2005, Mon. Not. R. Astron. Soc. 356, 1263) on the other hand. This is indeed done in order to inter-validate the two codes, but also in order to search for trade-offs, or let’s say, optimal compromises, permitting then to face either exploratory researches or large instrumental project performance evaluations while combining as far as possible effectiveness and certainty. As preliminaries to the full comparison, we first test the fundamental fitting error and anisoplanatic error (equivalent to our test of the servo-lag error), and find a very satisfactory agreement. We then make a first attempt of full comparison by simulating within both models a complete 8m-class telescope AO system, varying the photon noise contributing to the whole wavefront sensing (WFS) noise.

Preliminaries: Fitting Error

Within the CAOS-based model the residual waveform is here simply the difference between the incoming turbulent atmosphere waveform and its projection onto a deformable mirror (DM) influence function (IF) basis. A statistically-averaged point-spread function (PSF) is then deduced by running a large number of independent realizations of the turbulent atmosphere. Instead, the PAOLA models considers the Kolmogorov phase space power spectrum (PSD), set to zero inside the AO-corrected spatial frequency domain / f < 1/2 [px/rgb] here for computing the fitting error (FE) structure function, from which the AO optical transfer function (OTF) is deduced, and so on up to the overall PSF. The turbulent atmosphere considered in both models is characterized by f_k=14 cm/m, and L_θ=25 m, with 1000 independent 128 x 128 phase screens (with the addition of sub-harmonics) within the CAOS-based simulation. The DM pitches considered within the PAOLA model (0.5 m, 1.8 m, and 2 m) correspond to sets of, respectively, 289, 81, 25, and again 25 IF within the PAOLA model. This approach has its limits: (1) because the CAOS-based simulation assumes here a perfect WFS, aberrations above the AO cutoff frequency can be somewhat affected by the DM correction, while in a real system these high-order frequencies remain as they are; (2) PAOLA assumes a perfect DM, totally correcting any phase within the AO cutoff frequency, which would need the IF to be sinc-like (the Fourier transform of a sinc being a delta function), but of course IF are not sinc functions. These effects are clearly visible in the FE PSF shown below (left CAOS and right PAOLA) 2D representations and first plot from the left). The CAOS PSD has features above the cutoff frequency, and shows a smooth transition to zero. Reversely, the PAOLA PSD shows a perfect Kolmogorov PSD above the cutoff frequency, and a perfect one-to-zero transition. Due to the structural relationship between the PSD and the PSF, these differences show up in the PSF (see second plot), but the overall Strehl (see last plot) is not really affected.

In order to make the PAOLA model closer to the CAOS result, we would need to implement into PAOLA a DM spatial transfer function model, a particularly interesting feature when the structure of the PSF within the cutoff frequency domain needs to be precisely known, as for instance when studying the performance of extreme AO with a possible coronagraph. Moreover, and in order to reproduce exactly the low-high spatial frequency transition, we would also need to better sample the structure (see Carbillet, M. et al 2005, Mon. Not. R. Astron. Soc. 356, 1263) on the other hand. This is indeed done in order to inter-validate the two codes, but also in order to search for trade-offs, or let’s say, optimal compromises, permitting then to face either exploratory researches or large instrumental project performance evaluations while combining as far as possible effectiveness and certainty. As preliminaries to the full comparison, we first test the fundamental fitting error and anisoplanatic error (equivalent to our test of the servo-lag error), and find a very satisfactory agreement. We then make a first attempt of full comparison by simulating within both models a complete 8m-class telescope AO system, varying the photon noise contributing to the whole wavefront sensing (WFS) noise.

Preliminaries: Anisoplanatic Error/Servo-lag Error

The second most frequent source of AO error is angular anisoplanatism and servo-lag error. These two errors are somewhat correlated: a lateral shift of the turbulent layers during one loop period (responsible for the servo-lag error) is equivalent to an angular shift of the wavefronts during the same loop period (responsible for the anisoplanatic error). The PSF (right 2D representation and top row from the left) shows the PSD. The fact that the CAOS-based simulation assumes here a perfect WFS, aberrations above the AO cutoff frequency can be somewhat affected by the DM correction, while in a real system these high-order frequencies remain as they are; (2) PAOLA assumes a perfect DM, totally correcting any phase within the AO cutoff frequency, which would need the IF to be sinc-like (the Fourier transform of a sinc being a delta function), but of course IF are not sinc functions. These effects are clearly visible in the FE PSF shown below (left CAOS and right PAOLA) 2D representations and first plot from the left). The CAOS PSD has features above the cutoff frequency, and shows a smooth transition to zero. Reversely, the PAOLA PSD shows a perfect Kolmogorov PSD above the cutoff frequency, and a perfect one-to-zero transition. Due to the structural relationship between the PSD and the PSF, these differences show up in the PSF (see second plot), but the overall Strehl (see last plot) is not really affected.

(Final Attempt Of) Full Error Comparison, Featuring Wavefront Sensor Photon Noise

We are here exploring the real expected overlap between PAOLA and CAOS, each source of error being included (but angular anisoplanatic here). The PSF (right 2D representation and top row from the left) shows the PSF from the bottom right to the left; m_θ = 14, 15, 16, and 18, and the predicted Strehl. Other relevant AO system parameters adopted are: wind velocities=8 m/s, 16 m/s, and 20 m/s, which are included as close-loop... The fact that the CAOS-based PSD does not drop as deep as the theoretical PSD is probably a sign of a lack of numerical convergence (1000 independent realizations only). The second plot shows the PSF profiles while the last plot shows the off-axis decrease of the Strehl. In all cases, the CAOS model and the PAOLA model agree.

These results are to be considered as they are: very preliminary. But several comments can already be expressed: (1) the impact of the waffe mode (the dots at the corners of the AO corrected domain) is missing in the PAOLA code, each source of error being included (but angular anisoplanatic here). The PSF (right 2D representation and top row from the left) shows the PSF from the bottom right to the left; m_θ = 14, 15, 16, and 18, and the predicted Strehl. Other relevant AO system parameters adopted are: wind velocities=8 m/s, 16 m/s, and 20 m/s, which are included as close-loop... The fact that the CAOS-based PSD does not drop as deep as the theoretical PSD is probably a sign of a lack of numerical convergence (1000 independent realizations only). The second plot shows the PSF profiles while the last plot shows the off-axis decrease of the Strehl. In all cases, the CAOS model and the PAOLA model agree.

Let us finally note that a by-product of this work is also the Software Package PAOLAC, an embedding of PAOLA within the CAOS problem-solving environment, which is being adapted to the last features of PAOLA (including close-loop)... CAOS problem-solving environment: http://fizeau.unice.fr/caos | PAOLA code: laurent.jolissaint@aquilaoptics.com | Any question: marcel.carlibel@unice.fr or laurent.jolissaint@aquilaoptics.com