

Comparison between simulations and lab results on the ASSIST test-bench

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ABSTRACT

We present the latest comparison results between laboratory tests carried out on the ASSIST test bench and Octopus end-to-end simulations. We simulated, as closely to the lab conditions as possible, the different AOF modes (Maintenance and commissioning mode (SCAO), GRAAL (GLAO in the near IR), Galacsi Wide Field mode (GLAO in the visible) and Galacsi narrow field mode (LTAO in the visible)). We then compared the simulation results to the ones obtained on the lab bench. Several aspects were investigated, like number of corrected modes, turbulence wind speeds, LGS photon flux etc. The agreement between simulations and lab is remarkably good for all investigated parameters, giving great confidence in both simulation tool and performance of the AO system in the lab.

Keywords: Adaptive Optics, simulations, wavefront sensing, tomography

1. INTRODUCTION

ASSIST [1] is a test-bench that has been installed in the lab at ESO Garching to test the AOF Adaptive Optics Facility systems (see Kolb et al [2] and Oberti et al. [3], for more on system tests with ASSIST and AOF). The ASSIST test system is comprised of the Deformable Secondary Mirror (DSM) adaptive secondary (1170 actuators), some large optics to simulate the VLT, repositionable LGS and NGS sources, three rotating phase screens conjugated to different heights to represent atmospheric layers of turbulence and visible and infrared imaging detectors to evaluate the AO corrected image quality.

All the simulations presented here are done using the ESO end-to-end Octopus simulation tool [4]. Octopus is a full numerical AO model, with the following adaptations to the AOF systems and ASSIST:

- A diffractive Shack-Hartmann wavefront sensor model. We used exactly the same sensor geometry and parameters (pixel sizes and number, quantum efficiency, additional EMCCD noise,..) as used in the lab tests.
- A model of the DSM, which uses with the true actuator geometry and FEA measured influence functions. We used a temporal delay of a total of 3 frames (at a 1kHz sampling frequency) instead of the more conventional 2 frames, to take into account (very roughly) the rise time of ~ 0.7 ms of the DSM. The DSM is conjugated to an altitude of 89m below the primary mirror of the VLT, which was taken into account in the simulations.
- A matrix-vector multiply MAP reconstructor, generated with exactly the same algorithms as the ones used in the real time computer of the AOF. The algorithms implemented in the Real Time Computer of the AOF were actually tested for correctness in the Octopus simulation tool.
- An atmospheric model with the same turbulence characteristics as on the bench (Cn2 profile, outer scale profile and wind speeds for the layers).

As can be seen, care was taken to model the AOF systems as closely as possible, in order to make sure that the performance simulated would be as close as possible to the lab results.

In the following, we will describe a small part of the simulations performed to validate the AO systems performance that was carried out in the lab. These tests were aimed at validating the system performance. However, they also demonstrate the accuracy of the simulation tool, since a good agreement between simulation and lab proves that the simulation represents the system, and also that the system behaves as expected.

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2. ASSIST SPECIFIC EFFECTS

The lab environment does not fully represent the conditions that the system will encounter at the telescope. Some differences arise from the way the ASSIST bench is constructed. Therefore, some test bench specific particulars have to be added to the simulation, to accurately represent the performance observed in the lab.

ASSIST Mirrors AM1 and AM2 have significant wavefront residuals due to their polishing, that will not be present at the VLT. These errors are included in the simulation. Note that the ASSIST optical design is double pass, so the errors are multiplied by two. For simplicity, we did not conjugate the aberrations to their respective heights, we assumed they were in the pupil. We will see that this assumption doesn't limit the accuracy of the simulation.

This is an example of how the simulation has to be tailored to a lab experiment and cannot be used in exactly the same way as for the VLT system simulations. The residual wavefront error (in closed loop, after sensing on the 40x40 SH and correction with the 1170 actuator deformable secondary mirror (DSM)) was found to be 74nm rms. This is a significant contribution to the image quality.

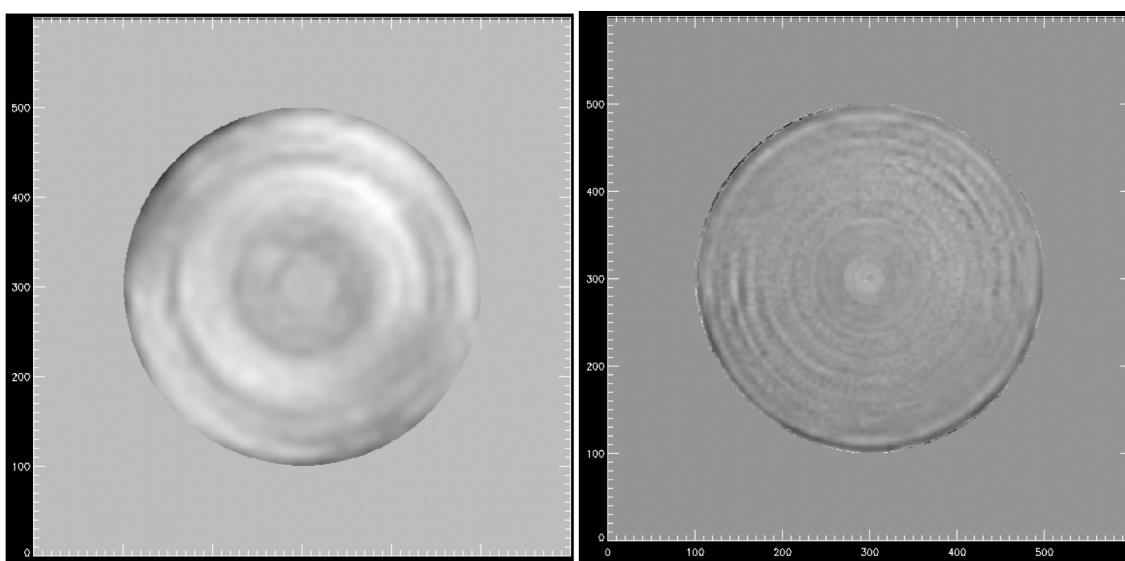


Figure 1: On the left, shape of the DSM after a SCAO loop is closed. On the right, the residual (DM shape – (AM1+AM2)). No turbulence, ASSIST AM1 & AM2 mirrors only.

In all the following simulations of this paper, these two phase screens are included. In the next section, we tackle the first AO system, the Maintenance and Commissioning Mode.

3. MCM - SCAO

The Maintenance and Commissioning Mode (MCM) is a SCAO system, using a single 40x40 Shack-Hartmann wavefront sensor to control the DSM adaptive mirror, using a natural guide star (at infinity) as a reference source. Its purpose is mainly to test that the DSM works as specified. We compared the Strehl ratio on the ASSIST bench to the simulated one, as a function of the flux on the WFS. In addition, we analytically modeled the contributions to read-out-noise and photon noise, and used them to superimpose to the simulation results. Considering there is a significant uncertainty on the evaluation of the experimental Strehls (static aberrations, limited sampling,...), we can see in the plot, that all methods (lab, numerical simulation, analytical formula) agree quite well.

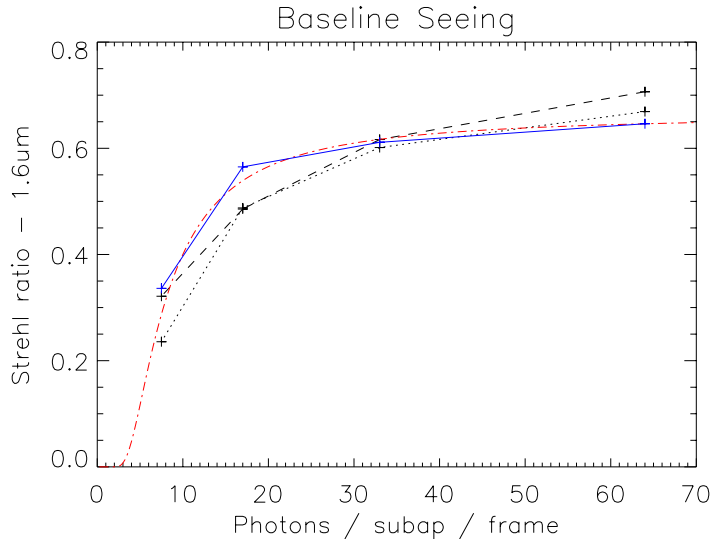


Figure 2: For the MCM SCAO system, Strehl (1.6um) as a function of photons detected by the WFS. Blue: Assist Strehl from slopes, red: analytic formula, black dash: simulated Strehl from slopes, black dots: simulated Strehl from PSF. Here, the results are for a nominal seeing.

This result allows us to have confidence in the basic “bricks” of the AO simulation tool: measurement noise modeling and propagation in closed loop, temporal behavior of the AO loop running at 1kHz (providing the decay as a function of number of detected photons), and fitting and aliasing errors and turbulence modeling (peak performance of the AO system). It also demonstrates that the AO system is performing as specified.

The next system that will be analyzed is the GRAAL Ground Layer mode.

4. GRAAL - GLAO

The GRAAL Ground Layer AO system corrects a very wide 8’ field of view for science observations in the near infrared. For this, it uses 4 sodium laser guide stars in a square pattern on the sky, located outside the science field of view and a visible light tip-tilt sensor. It uses an averaging algorithm on the 4 LGS wavefront sensors to only correct the turbulence near the ground.

In these simulations, we use a nominal flux for the LGSs, which doesn’t limit the system performance (high flux regime), and the LGS spot elongation simulated by the bench is the shortest one.

The LGSs being so far apart from each other, the thickness of the turbulence slab corrected by the AO system is quite thin. This is demonstrated by the curve below (Figure 3), where the lowest turbulence layer’s altitude was changed on the bench (and the simulation) to study the sensitivity to GL altitude. We can see that a movement of the lowest turbulent layer (containing ~63% % of the total turbulence) significantly changes the system performance. This shows that the system is very sensitive to the actual structure of the ground layer. The agreement is remarkably good between simulation and lab results. This shows that the simulation tools accurately represents the influence of an atmospheric model distributed in height. The beam propagation of the LGS light in the atmosphere is therefore correctly simulated.

We have used here not the usual metric of Strehl ratio, but rather the gain in the box containing 50% of the energy of the PSF, at 1.6um. This allows to more accurately describe the performance, which is more a seeing enhancer than a conventional AO system delivering the diffraction limit of the telescope.

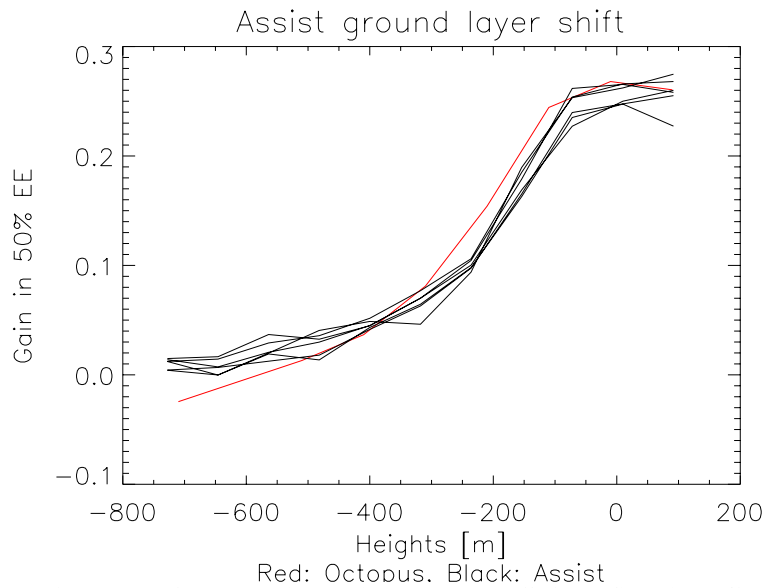


Figure 3: The performance is dominated by the Cn2 profile, since GRAAL can only correct the first few hundred meters of turbulence. We compared the performance of GRAAL using the 3 phase screens of ASSIST, moving the lowest layer in height. In red, Octopus simulations (on-axis only), in black the lab (several positions in the field).

The next steps were to investigate other aspects in this GLAO system, like the impact of number of corrected modes on the DSM and the wind speed of the atmospheric turbulence screens.

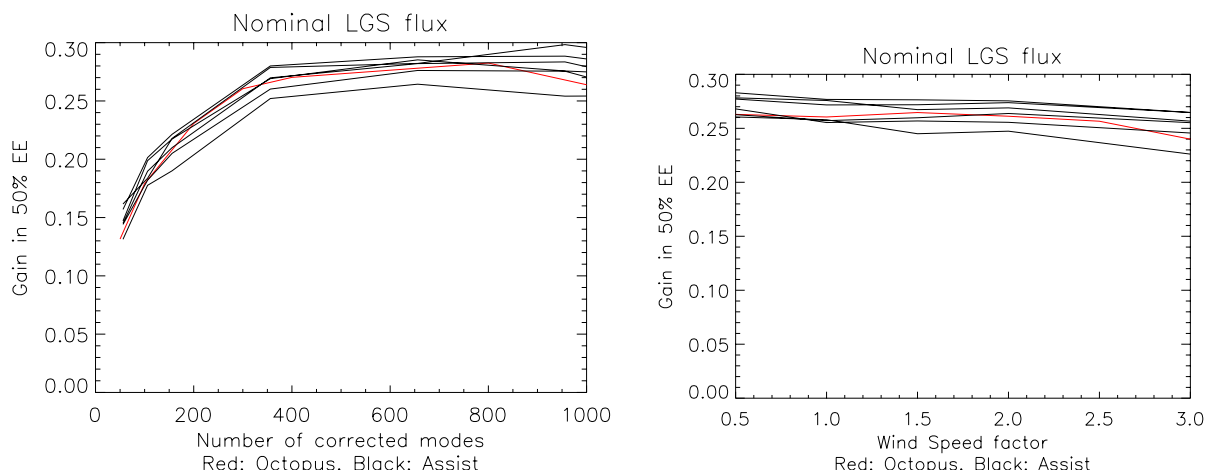


Figure 4: Performance as a function of number of corrected modes (on the left) and wind speed increase wrt nominal (right) for the GRAAL GLAO system. In black, the lab results (several places in the corrected FOV) and the simulations (in red, on-axis only).

The curve (Figure 4, left) shows how the performance of the GLAO system changes with the number of corrected modes. The agreement is very good between simulation and test bench. Correcting ~ 400 modes is enough to obtain optimal performance. Note that the different black curves show different positions in the science field of view (in simulation, we only show the central point, to not overload the curve). This demonstrates that the control matrix modal filtering is simulated properly, and that the properties of the GLAO control algorithm are in perfect agreement between simulation and lab. The next test (Figure 4, right) uses the standard 3 layers of turbulence, but their rotation speeds were accelerated by a uniform factor compared to their baseline speeds. This tests the dependency of the performance to the atmospheric coherence time. We can see that here again, the performance is very well predicted by the simulation

tool, which confirms that the temporal evolution of the phase screens (and the AO's control system in GLAO mode) works fully as expected.

We now move to the next AO system, another GLAO system, GALACSI.

5. GALACSI – WFM – GLAO

The GRAAL GLAO system in the Wide Field Mode (WFM) corrects a 1' science field of view in the visible to feed the MUSE spectrograph. Lasers are repositioned into a more compact configuration compared to the GRAAL case, and the performance is evaluated in the visible (0.625 μm), in terms of Ensquared Energy gain (compared to seeing) in a 0.2'' pixel.

In the first plot (Figure 5), we again change the conjugation height of the first turbulence layer, and plot the performance as a function of the content of turbulence in the first 200m. We can see an excellent agreement between simulation and lab, confirming that the sensitivity of the visible light GLAO system is as simulated. The second plot (Figure 5), shows that the impact of the AO loop gain is also very well modeled, which demonstrates that the errors like temporal delay and integrator control law behavior are modeled properly.

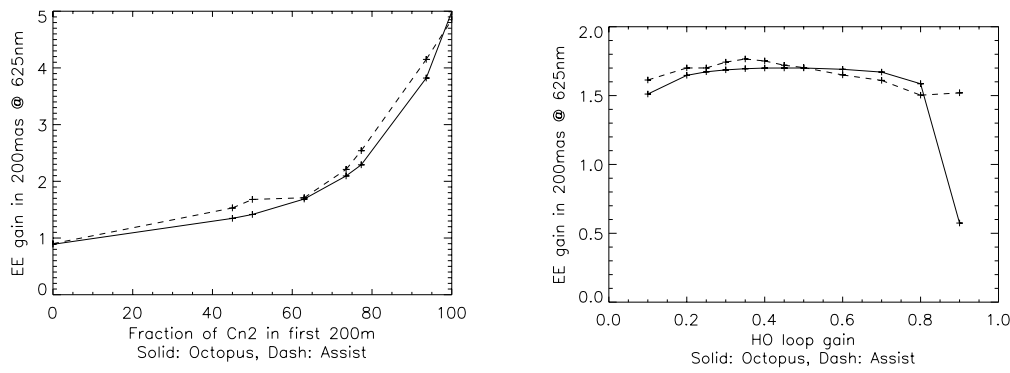


Figure 5: Performance for the GALACSI WFM, as a function of fraction of turbulence in the first 200m (left) and high order loop gain (right). Solid line is the Octopus simulation, dash is the lab results, both cases are on-axis.

Figure 6 shows a final plot for this system, where we compare the impact of the DM's registration compared to the SH wavefront sensor. For small displacements, the agreement is good, but for larger displacements, the lab system seems to be less sensitive than simulated. We are still investigating the reasons for this behavior.

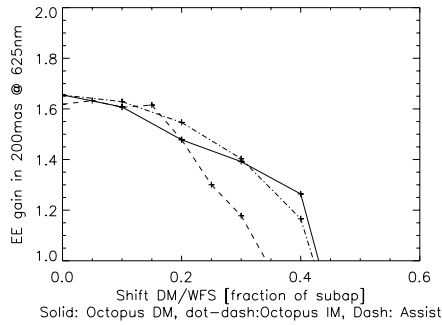


Figure 6: Performance for the GALACSI WFM, as a function of fraction shift of the WFS compared to the DSM. Solid line and dot-dash are the Octopus simulation (different versions of the control matrix), dash is the lab results, both cases are on-axis.

All in all, we can say that the simulation represent very well the system's performance also in this mode of the AOF. Finally, the next AO systems represents another AO more, Laser Tomography AO, LTAO.

6. GALACSI – NFM - LTAO

The most demanding AO system here, in terms of performance, is the Laser Tomography (LTAO) system, called GALACSI Narrow Field Mode (NFM).

This system uses an infrared low order (2x2) sensor and the 4 LGSs, in a tight configuration (LGSs in $10''$ from the center) to get maximum performance on-axis. The goal of this system is to correct for the cone effect in the visible (625nm), to get diffraction-limited performance, and therefore the metric is Strehl ratio. In order to more accurately measure Strehl (which proved to be challenging to assess precisely enough at short wavelengths, where it is small), we used an infrared camera, which measures the Strehl at 1.6um. The system will work in the visible though.

The following two figures show the relative Strehl ratio (corrected for static aberrations) for different atmospheric conditions and different reconstruction algorithms (LTAO, with two different methods and GLAO). We can see that the performance is well modeled by Octopus. An excellent agreement is observed, demonstrating that tomographic AO performance is correctly simulated.

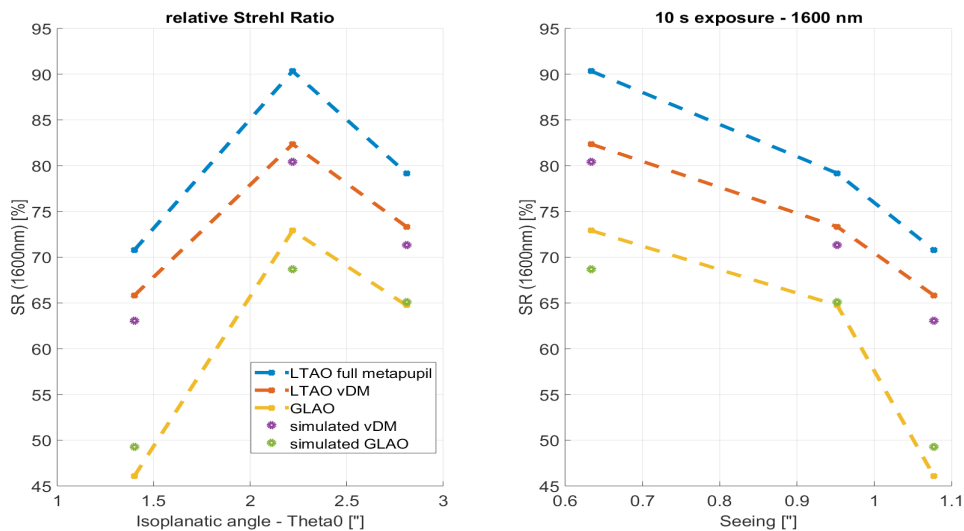


Figure 7: Relative SR versus isoplanatic angle [Left] and seeing [Right] obtained with the best vDM, KL and GLAO reconstructors (optimum tuning of number of corrected modes and MAP reconstructor regularization parameter), compared to results obtained by simulation [dots]

The final plots here show the visible light performance (which are representative of the system's science operating wavelength) for different NGS flux levels, representative of the operational magnitudes for the natural guide star. We can again see excellent agreement.

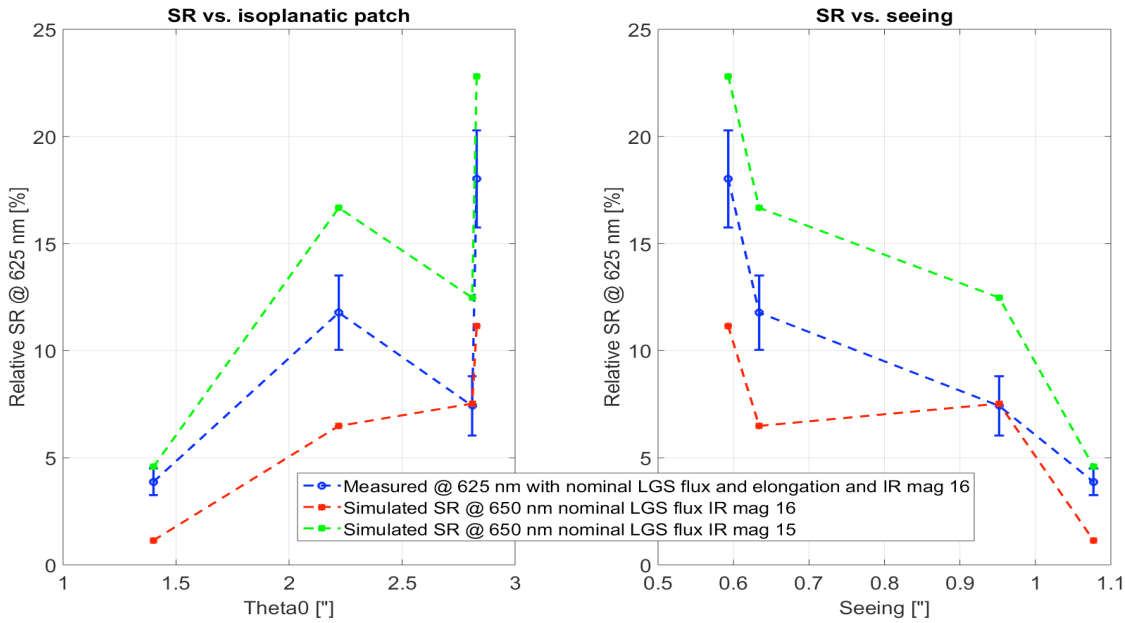


Figure 8: Nominal LGS flux and elongation (short) IR magnitude 16 - SR measured on long exposures @ 625 nm compared to SR simulated @ 650 nm. The error bars stand for +/-1 standard deviation of SR measured on 10 short exposures.

7. CONCLUSIONS

Comparing simulations & real hardware is difficult. Some effects are test-system specific and have to be accounted for, which we did in here by including specific ASSIST effects here. Some parameters (like input Cn2 profile) have to be adjusted to represent the lab system. However, having a perfectly know input in terms of atmospheric turbulence is a must, when one wants to characterize a system accurately.

Our extensive lab tests in a controlled and well-understood environment have demonstrated here that there is an excellent agreement between Octopus AO simulations & our lab experiment using real hardware that is going on the sky. All the tested modes, i.e. SCAO, GLAO and LTAO agree perfectly with simulations. We have here only presented a small subset of the comparisons that have been carried out, but all of them showed a very good agreement. This is a remarkable achievement, considering the amount of tests that were performed, and the wide coverage of parameters that are predicted.

Our tests show that all the AOF systems work as expected AND that our Octopus simulation tool is providing very accurate and realistic results. This gives us great confidence that the systems will reach expected performance on sky.

Our simulation tool is now fully validated, and we can have confidence in the results it provides, for all AO modes, including the most complex tomographic systems. We have demonstrated that we are able to accurately predict the performance of AO systems.

8. REFERENCES

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2. Kolb et al these proceedings 9909-105, 2016
3. Oberti et al., these proceedings 9909-68, 2016
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