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Analysis of AO modeling for pseudo-synthetic interaction matrix at the LBT

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ABSTRACT

The performance of an Adaptive Optics (AO) System relies on the accuracy of its Interaction Matrix which defines the opto-geometrical link between the Deformable Mirror (DM) and the Wave Front Sensor (WFS). Any mis-registrations (relative shifts, rotation, magnification or higher order pupil distortion) will strongly impact the performance, especially for high orders AO systems. Adaptive Telescopes provide a constraining environment for the AO calibration with large number of actuators DM, located inside the telescope with often no access to a calibration source and with a high accuracy required. The future Extremely Large Telescope (ELT) will take these constraints to another level with a longer calibration time required, no artificial calibration source and most of all, frequent updates of the calibration during the operation. To overcome these constraints, new calibration strategies have to be developed either doing it on-sky or working with synthetic models. The most promising approach seems to be the Pseudo-Synthetic Calibration. The principle is to generate the Interaction Matrix of the system in simulator, injecting the correct model alignment parameters identified from on-sky Measurements. It is currently the baseline for the Adaptive Optics Facility (AOF) at the Very Large Telescope (VLT) working with a Shack-Hartmann WFS but it remains to be investigated in the case of the Pyramid WFS.

Keywords: Adaptive Optics, Calibration, Interaction Matrix, Pseudo-Synthetic Interaction Matrix, ELT, Pyramid WFS, Mis-Registrations

1. INTRODUCTION

The good behavior of any AO system relies on the quality of its calibration. Defining accurately the link between each actuator of the DM and the corresponding WFS subapertures is indeed necessary to produce the surface that corresponds to the optical aberrations measured by the WFS. This information is stocked in the Interaction Matrix of the system which concatenates the WFS signals corresponding to a set of calibration patterns, chosen to span the entire space of the DM. The calibration is however only valid at the time of the measurement and if the system registration evolves during the operation, the system performance will be impacted. Updating the calibration becomes then necessary.

The particular design of the adaptive telescopes provides a constraining environment for the AO calibration: The DM has usually a large number of actuators to provide a high order AO correction to the instruments and is located inside the telescope, far away from the WFS and often with no access to a calibration source. These two features establish two major constraints as it can take a long time to calibrate the system, taking in consideration that the ASM/WFS registration may evolve faster in time than for a post-focal AO system and requiring thus regular updates of the corresponding calibration. In the case of a high order AO system, the sensitivity to such mis-registrations becomes critical and a high accuracy calibration is necessary.

The future Extremely Large Telescope (ELT) will push these constraints to another level with a larger number

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of actuator (4356) and a larger distance between WFS and DM. Updating the calibration regularly during the operation will then be required as the size and weight of the telescope will create larger mechanical constraints and thus lead to misalignments of diverse optical systems, resulting in mis-registrations between the DM and the WFS.
To overcome these constraints, new strategies have been investigated, by speeding up the measurement[1,2] or changing the way to estimate the interaction matrix, working on synthetic models[3] or measuring it on-sky.[4,5]

The on-sky approach consists in measuring experimentally the interaction matrix, finding a way to get rid of the turbulence effects. This approach ensures to have a direct calibration of the system registration at the time of the measurement but can become demanding in terms of telescope time for large number of actuators systems and is thus not suited for regular updates. The sensitivity to the seeing conditions is still to be investigated, especially for a Pyramid WFS, and if such a calibration is done during the operations, the impact on science has to be quantified. The two main on-sky strategies consists in using a fast push-pull measurement to freeze the turbulence or to multiplex signals on the DM and retrieve their signature in the WFS space using a demodulation process.[6]

The synthetic approach consists in reproducing the behavior of the AO systems in simulator to generate synthetically the interaction matrix of the system, injecting mis-registrations parameters to replicate the registration of the real system. That way, a fast update of the calibration becomes easy and fast to achieve. It relies only on a good estimation of the mis-registrations parameters. Therefore, the community has been converging toward this pseudo-synthetic approach that takes advantage of both strategies: The calibration data are generated from a simulator to provide fast updates and the model mis-registrations parameters measured using on-sky data/measurements. The principle of the pseudo synthetic approach is summarized in Figure 1

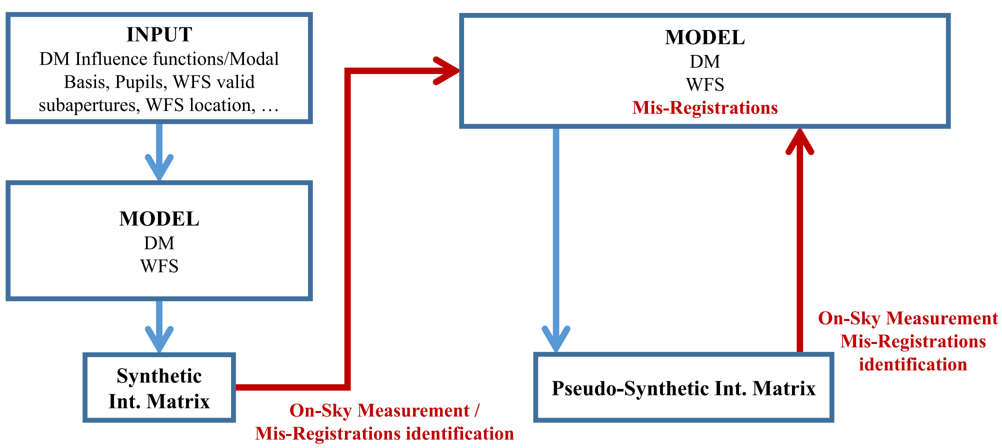

Figure 1: Pseudo-Synthetic Calibration: Experimental data/measurements are required to update a synthetic model and generate a Pseudo-Synthetic Interaction Matrix that is regularly updated using experimental inputs.

In terms of state of the art, modeling efficiently an AO system to generate calibration data for the telescope has been demonstrated on various systems, at the Very Large Telescope[3] or at the Large Binocular Telescope.[4] To track the mis-registrations during the operation, some methods have also been validated using either telemetry data[7] or WFS signals.[8]

Focusing on the calibration of the AOF, the Pseudo Synthetic approach is currently the baseline for all the AO modes, using a Shack Hartmann WFS. In practice, the Interaction Matrix is updated every 5 minutes, using telemetry data to retrieve the mis-registrations parameters.[3]

The purpose of this study is to analyze the feasibility of the pseudo-synthetic approach in the case of a Pyramid WFS, more complex than a SH-WFS with a modal linearity and sensitivity that depends on the seeing conditions. This communication focuses on the development of a model of the LBT-FLAO system[9] described in section 2. Section 3 describes the model alignment procedure. The analysis and validation of the model in simulator is developed in section 4.

2. MODELLING OF THE FLAO SYSTEMS

To provide an efficient synthetic based calibration, two key-elements are necessary: an accurate simulator and the good values for the mis-registrations parameters. In our case, we developed our model in the OOMAO simulator,[10] a full end to end AO simulator. To reproduce accuractly the behavior of FLAO, we focused on the two key-elements of the AO system: the ASM and Pyramid WFS.

The ASM model is composed of 663 actuators (+ 9 broken actuators) disposed in circular concentric rings with a 30 cm radial pitch. We take the influence functions measurements from interferometer as a direct input to take in consideration all the features of the real system. The commands producing the KL modes on the ASM are also used in the simulator to generate the corresponding modes.

The Pyramid WFS is designed to reproduce the geometry of the FLAO WFS, producing pupils of 30 pixels with centers separated of 36 pixels, using a modulation of 3 λ/D and the central wavelength for the wavefront sensing at 750 nm. We impose the valid subapertures map to the model and set its position to maximize the light in the corresponding subapertures. We also normalize the WFS signals to be in line with a double pass measurement using a retro-reflector and adjust the WFS slopes signs to match with the WFS location according to the side of the telescope.

Finally, to retrieve the good registration between ASM and WFS, we used the current interaction matrix used at the telescope as a reference to identify **5 mis-registrations parameters**: shifts α_x and α_y, rotation α_{rot} and magnifications α_{mx} and α_{my}. We define α as the mis-registrations vector :

$$\alpha \triangleq \{\alpha_x, \alpha_y, \alpha_{rot}, \alpha_{mx}, \alpha_{my}\} \tag{1}$$

In practice, we interpolated the ASM influence functions measurements to apply the desired rotation and magnification and we shifted the pyramid pupils to provide a sub-pixel sensitivity.

At the LBT, the baseline for the AO mode is to control 400 KL modes. We reproduced the corresponding calibration procedure to compute the interaction matrix, using a standard SVD to get the command matrix without truncating any mode. The generation of the Interaction Matrix is achieved around the zero-point pf the Pyramid WFS to avoid any non-linear effect. A summary of the model definition, indicating the inputs from the telescope and the outputs of the model is given in Figure 2.

3. ASM/WFS MIS-REGISTRATIONS CALIBRATION

3.1 Model Alignment Procedure

The main challenge of the synthetic calibration is to reproduce the registration between the ASM and Pyramid models to match with the real system. To do so, we extract these parameters from the current interaction matrix used at the telescope. The difficulty here is that these parameters are strongly correlated and we need to define an iterative procedure to get the correct estimation of the parameters.

We define σ_j as the Root Mean Square Error (RMSE) between the synthetic WFS measurement $Y^*(\alpha)$ in the configuration α and the reference WFS measurement Y of the mode j:

$$\sigma_j = RMSE(Y_j, Y_j^*(\alpha)) = \sqrt{\frac{1}{N_S}\sum_{n=1}^{N_S} |Y_j - Y_j^*(\alpha)|^2} \tag{2}$$

where N_S is the number of WFS slopes.

The alignment procedure consisted in minimizing the quadratic norm of $\sigma_N = \{\sigma_i\}_{i=1,2,\dots,N}$ adjusting α and eventually playing on the number of modes N:

$$\chi_N(\alpha) = arg_{min} ||\sigma_N||_2 \tag{3}$$

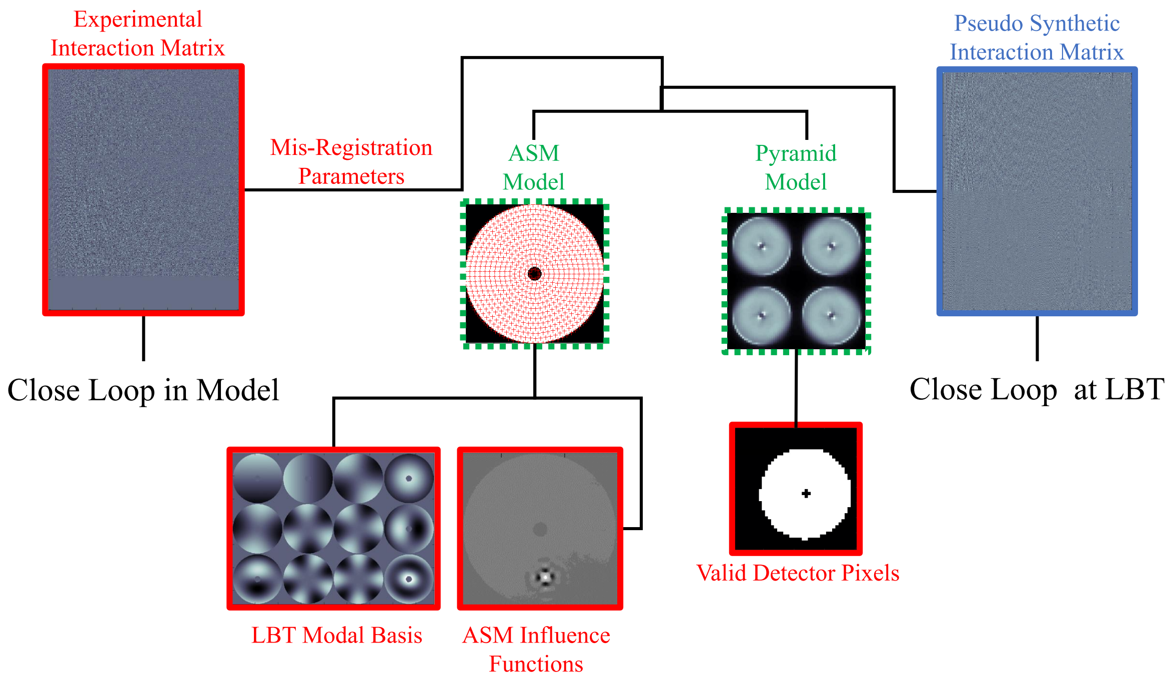

Figure 2: Summary of the model definition. Red lines represent the experimental inputs and green lines the synthetic data.

We make the assumption that the optimal value for the mis-registrations parameters is the iterative minimization of χ_{400} using all the reference signals available. In practice, the shifts and rotation are the most critical parameters to adjust (See Figure 12). Therefore the iterative procedure consisted in setting these parameters first and then adjust the magnification. Two steps were enough to converge to a satisfying estimation of the mis-registrations parameters. The last estimation for each parameter is given in Figure 3. As a final step, we tune the amplitude of the KL modes to minimize the RMS of the residual slopes with respect to the reference Interaction Matrix.

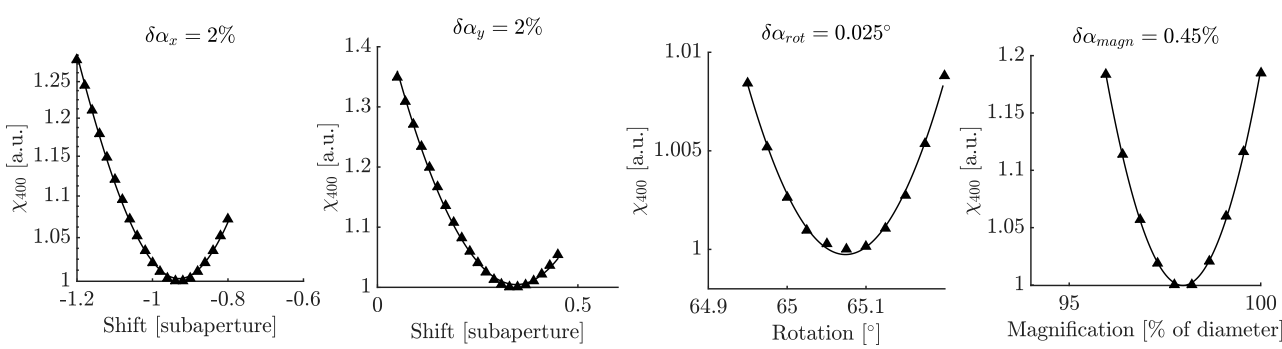

Figure 3: Last estimation of the mis-registrations parameters.

3.2 Impact of the numbers of reference signals on the parameters estimation

A pseudo-synthetic calibration requires to regularly update the mis-registrations parameters that could evolve during the operations. One possible approach consists in dithering signals on the DM to retrieve their signatures in the WFS space and the corresponding mis-registrations parameters. However, the type and number of signals required is still to be investigated as no clear optimization has been identified yet. In our case, we only have KL modes signals to consider and we could study the impact of the number of modes necessary to align our model.

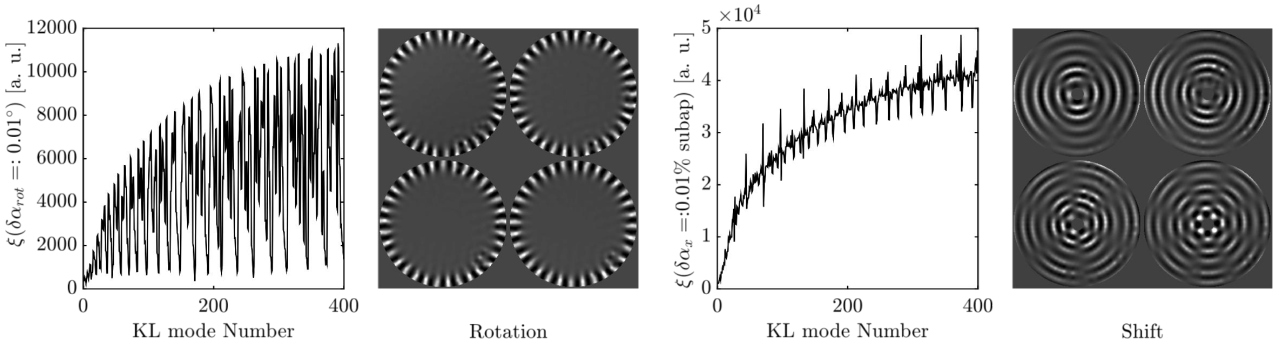

Figure 4: Sensitivity of the KL modes to a rotation (Left) and a shift (Right) displaying the modes with the highest sensitivity.

The first step consists in sorting the KL modes by their sensitivity to a given mis-registration. We define $\xi_j(\alpha_i)$ the sensitivity of the mode j to a mis-registration α_i as the RMSE of the WFS slopes for a step $\delta\alpha_i$:

$$\xi_j(\delta\alpha_i) \triangleq RMSE(Y_j(\alpha_i), Y_j(\alpha_i + \delta\alpha_i) \tag{4}$$

Figure 4 shows that, globally, the sensitivity to a shift increases with the spatial frequency (and thus with the number of the mode) while this evolution is more complex for a rotation. Since the modes mostly have a circular symmetry, this plot can evolve when considering higher values of rotation such as 10, 30 or 45 degrees but we make the assumption that our working point is close enough not to consider these values. In the following of the paper, the modes are ordered according to their sensitivity to the studied mis-registration.

The second step is to quantify the error on the estimation of the parameters as a function of the number of modes N used to minimize χ_N. This work is still on going and we show here only preliminary results for the estimation of the rotation (see Figure 5). This seems to show that the number of modes necessary can be reduced to less than 10 modes. Studying other specific patterns could also provide a gain in speed and SNR but remains to be investigated.

4. MODEL ANALYSIS

4.1 Numerical Validation

4.1.1 Direct Comparison of WFS Signals

The first step consists in comparing the synthetic WFS signals with the experimental ones. This is provided in Figure 6 which shows that both interaction matrices are almost identical, validating the good quality of the model. We can notice however that second order features are missing from the synthetic model signals: in the experimental data, a few subapertures seem to be less illuminated than others, especially close to the central the experimental measurement as evolving a lot between two experimental Interaction Matrices. This is well illustrated in Figure 7. These are thus not reproduced in the simulator as we consider a perfect illumination of the pyramid and taken into account these features in the model is still to be investigated. However, this should not be problematic as the most important feature remains the ASM/WFS registration.

As an additional information, Figure 8 shows that both model and real system have a similar sensitivity to the KL modes and the same stability with a similar conditioning number and similar eigen Values spectra. The residual differences between both curves can be explained by the fact that the synthetic Interaction Matrix is noise-free, we can then expect that the knee of the eigen values distribution for a higher eigen mode number, which is clearly visible on the plot.

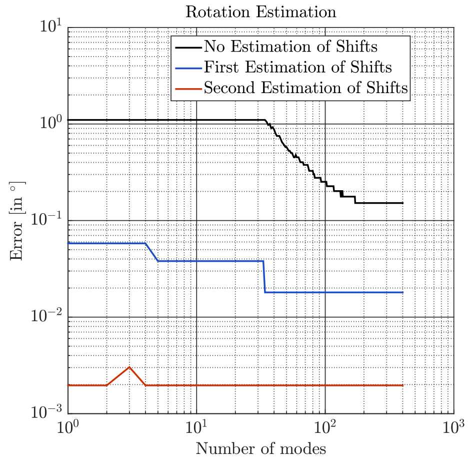

Figure 5: Error on the estimation of the rotation as a function of the number of reference signals used for the identification. In that case the reference is a synthetic Interaction Matrix. The results are given for each step of the alignment procedure: between two estimations of the rotation, both values of shifts are updated.

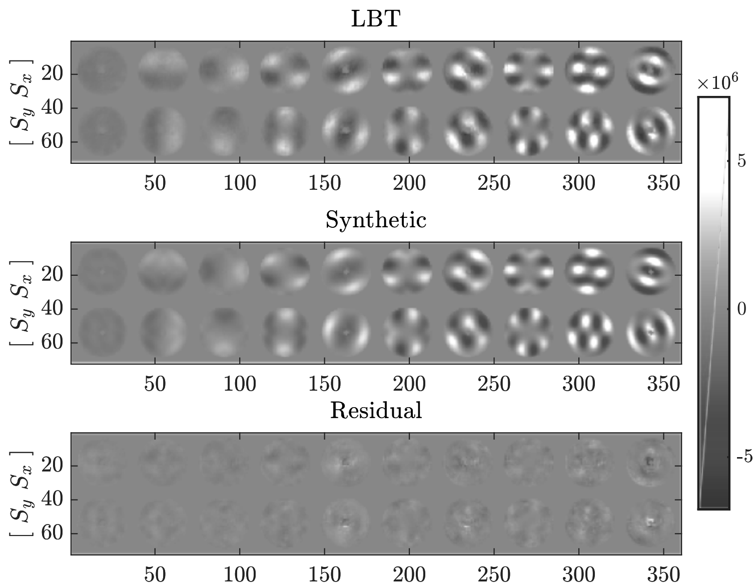

Figure 6: Comparison between synthetic and experimetal WFS Slopes Maps for the uneven KL modes from 1 to 19.

4.1.2 Closed Loop Performance in Simulator

Estimating the quality of a synthetic Interaction Matrix can be complex as this object relies essentially on experimental measurements and on the registration between WFS and DM. Therefore the easiest way consists in testing it in closed loop on the real system to evaluate the AO performance. The first milestone of this work was then to efficiently close the loop of the simulator using the experimental Interaction Matrix from LBT.
This is basically the opposite of our initial goal but it provides already a first indication of the model quality: if an experimental Interaction Matrix can be used to close the loop in simulator, the model should be representative enough of the real system. Figure 9 displays the performance for the same turbulent phase screens with and without aliasing (projecting the turbulence on the modal basis controlled by the DM). We can still see small

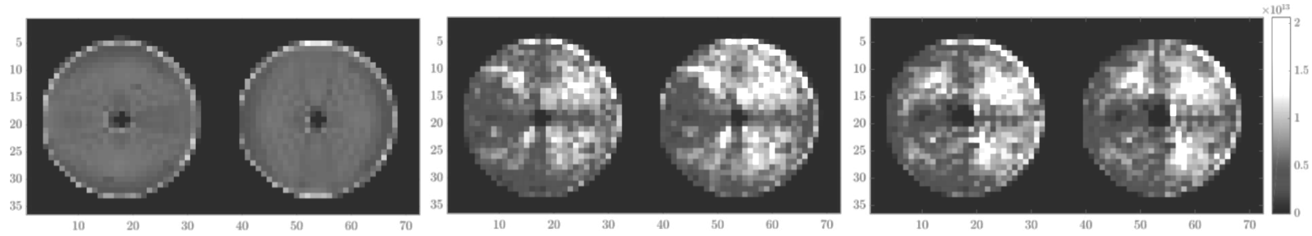

Figure 7: Variance Map of the WFS Slopes over the 400 KL modes using a synthetic Interaction Matrix (Left) and an experimental one from 2016 (Center) and 2017 (Right). In the synthetic case, the ring on the border of the pupil is due to the interpolation errors of the Influence Functions measurements.

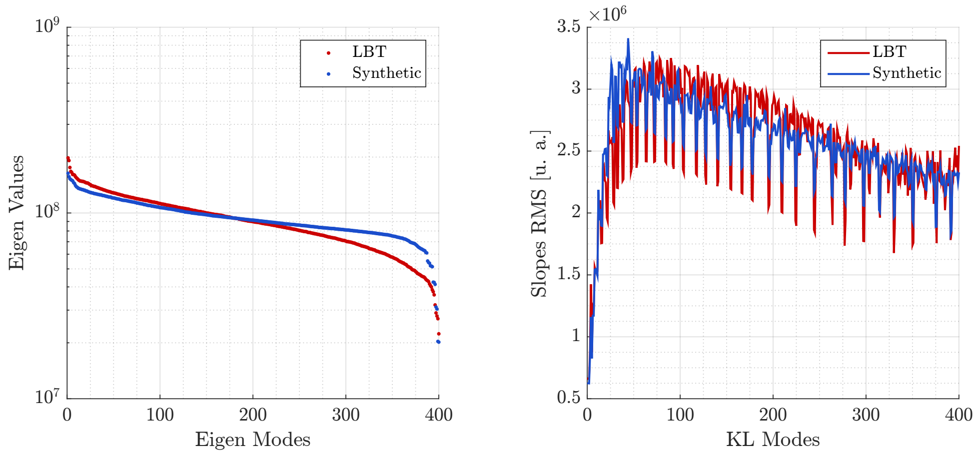

Figure 8: Left: Eigen Values Spectra: Conditioning numbers are 8.1 in the synthetic case and 8.85 in the experimental case. Right: Slopes RMS of both Interaction Matrix for the 400 KL modes showing that the sensitivity of the Pyramid WFS is well reproduced in the simulator.

differences in the performance but globally the correction is equivalent which validates the model quality and pushes to consider the final step of the model validation: an experimental test at the LBT.

4.2 Sensitivity to Mis-Registrations

4.2.1 Characterization of a Mis-Registration,

In presence of large amplitude mis-registrations, some specific moving patterns can be visible displaying the DM actuator position/force map. Here we want to detect the smallest mis-registration possible with respect to the reference Interaction Matrix, effect that would not be visible using the ASM positions. Such signature can however be identified in the residual phase screens that are accessible in simulator.

To be able to isolate this small effect, one needs to consider the error budget that is defined as the sum of all the relevant contributors (fitting,aliasing, temporal error, noise, calibration error and model) to the residual phase variance $\sigma^2_{\Phi_{res}}$:

$$\begin{aligned}\sigma^2_{\Phi_{res}} =&\sigma^2_{\Phi_{fitting}} + \sigma^2_{\Phi_{aliasing}} + \sigma^2_{\Phi_{temporal}} \\ &+ \sigma^2_{\Phi_{noise}} + \sigma^2_{\Phi_{calib}} + \sigma^2_{\Phi_{model}}\end{aligned} \tag{5}$$

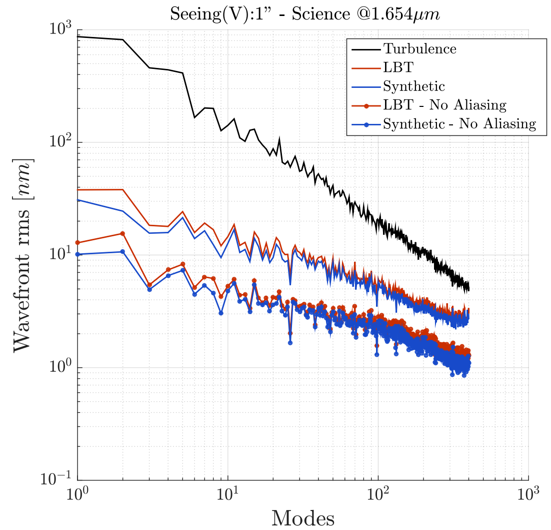

Figure 9: Comparison of Closed Loop performance in simulator. The correction is almost identical and confirms the good quality of the synthetic model and its alignment.

We are only interested in $\sigma^2_{\Phi_{model}}$ and we can cancel out some terms of the error budget: $\sigma^2_{\Phi_{noise}}$ can be disabled and the turbulence phase can be projected on the modal basis controlled by the ASM to get rid of the fitting and aliasing effects. Moreover, for the purpose of the model alignment, it can be interesting to close the loop of the model on a static phase screen getting rid of the temporal delay and any effect related to the wind direction. That way, in presence of eventual mis-registrations between the model and the reference Interaction Matrix, some specific moving patterns are visible in the residual phase screen. These patterns are a direct signature of the mis-registration type as illustrated in Figure 10 where we can clearly see how the correction is mis-applied.

In the case of a shift, one will see fringes moving in the direction of the corresponding shift. Superposing the actuators coordinates and the corresponding average patterns shows that both are extremely correlated. This makes sense as a shift will impact all the subapertures equally. However, in the case of a rotation, the residual phase screens displays a rotating pattern that corresponds to a mode controlled in the Interaction Matrix. These modes correspond actually to the most sensitive modes identified in Figure 4.

These features could be useful for the model alignment purpose. Once that the mis-registrations parameters are correctly set, the patterns disappear and second order model errors, already identified in Figure 7, become visible. The corresponding impact on the closed loop (see Figure 11) is a second order effects and will not impact the performance. This however confirms the good alignment of the model.

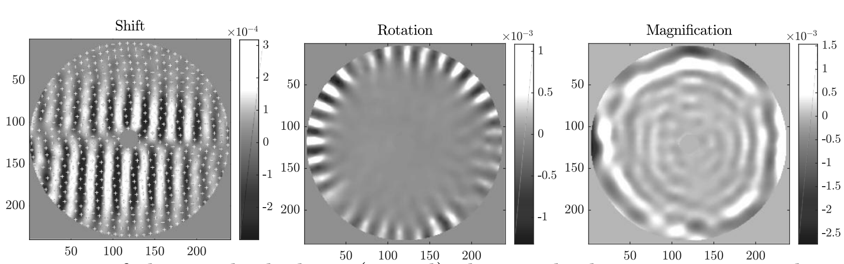

Figure 10: Typical patterns of the residual phase (in rad) closing the loop on a static phase screen for different types of mis-registrations. Left: shift of 20 % of a subaperture superpozing the actuators coordinates, Middle: Rotation of 0.5 °, Right: magnification of 98 % of the pupil.

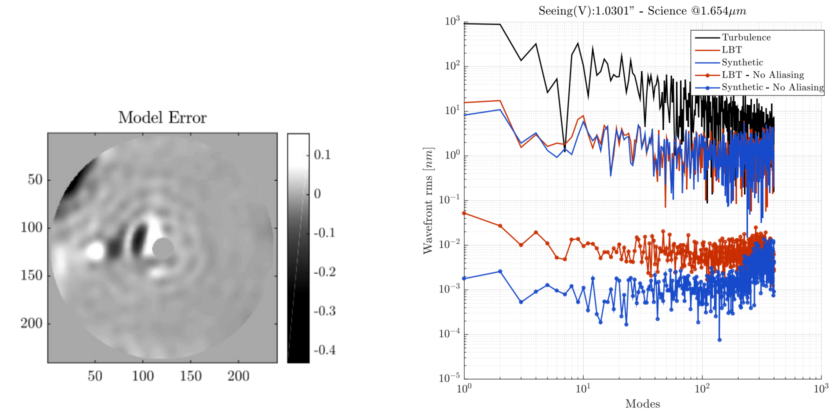

Figure 11: Left: Residual Phase Screen closing the loop on a static pattern with the experimental Interaction Matrix in the simulator. The patterns visible correspond to the model errors identified in Figure 7. Right: Corresponding Modal PSD showing that these errors are negligible and that the model is correctly aligned.

4.2.2 Impact on the performance

For an AO system with Shack Hartmann WFS, the common rule is not to exceed an mis-registration of 10 % of a subaperture. This result has to be taken carefully as the sensitivity to a mis-registration will depends on the DM geometry and on the number and type of modes controlled in the Interaction Matrix. Using our model of Pyramid WFS and ASM with circular geometry, we could simulate the impact of each type of mis-registrations in terms of Strehl Ratio. The results are presented in Figure 12 and show that the rotation and the shift are the most critical parameters while the impact of a magnification becomes problematic when controlling a high number of modes only.

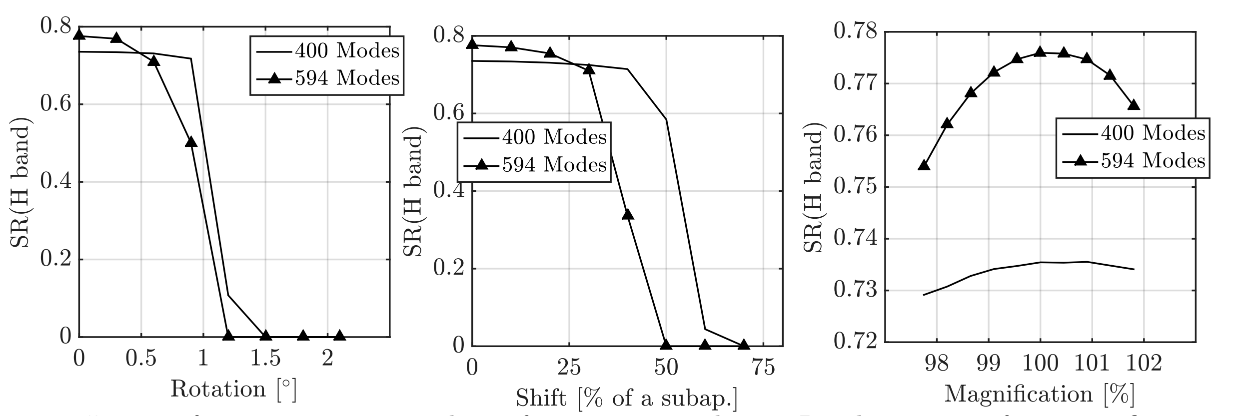

Figure 12: Impact of mis-registrations on the performance in simulation. Results are given for two configurations, controlling 400 and the maximum number, 594 modes.

5. CONCLUSION AND PERSPECTIVES

We could develop a synthetic model of the LBT AO system, focusing on the ASM and Pyramid WFS. We could identify the ingredients required from the telescope: Modal basis, ASM influence functions, WFS geometry and valid subapertures and the key elements : the mis-registrations parameters. Concerning this last element, we established an iterative alignment procedure to calibrate the mis-registrations between the ASM and the WFS using WFS signals.

The synthetic model has then been intensely validated against experimental data in simulator. The first milestone of this study was to close the AO loop in simulator using the experimental Interaction Matrix, and obtain equivalent AO correction, confirming the good quality of the model.

Moreover, we could study the sensitivity of the KL modes to the different types of mis-registrations and quantify the impact on the performance for a system in the LBT configuration. We are also currently studying the cost of reducing the number of reference signals on the estimation of the mis-registrations parameters. Preliminary results show that only a few well-chosen signals can be enough to align the model.

The model seems now ready to be tested on the real system for experimental validation. This should be possible using day-time test at LBT, controlling the telescope in remote. If possible, we will also study experimentally the sensitivity of the model to mis-registrations errors. Another interesting test would be to retrieve a few calibration signals on-sky and try to align the model from it. This would be complimentary to the analysis of number of modes required as it will provide information on the SNR of the on-sky signals required to get a satisfying estimation of the mis-registrations parameters.

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