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WORK-PACKAGE (DELIVERABLE NR)

WP6 DEFORMABLE MIRRORS AND THE EST-MCAO PERFORMANCE

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SUMMARY

In this document we report on the analysis of the performances of the EST DM configuration. EST is designed to be equipped with a MCAO system in which the DMs are tilted 45 degree in orthogonal planes. This is done in order to get a polarization-free optical scheme and reduce the instrumental polarization. However, 45 degree tilted DMs represent a non-standard configuration for DMs use, and an accurate evaluation of the performances of the system is needed. To this aim, a specific simulation software was developed to model and study the behaviour of tilted DMs in different conditions.

After describing the simulation software developed for the purpose, we analyse different DM configurations and provide guidelines and recommendations for the EST MCAO design.

The developed software, which extends the well-known PAOLA numerical environment to the simulation of inclined DMs and other allows us to study the impact of inclined DMs on the AO performances in closed-loop conditions. In this regard, we present the results derived from specific simulation that were made to evaluate the variation of the Strehl ratio as a function of different DM inclinations, in different seeing conditions.

Further, we present the results of end-to-end simulations of the effects of the DM inclination on the modal basis representation that were carried out by using a Zeemax model.

The results derived from our study show that the use of a conventional DM with constant spacing of actuators along its two main axes in a tilted configuration is not suitable for the purpose of the EST project. Indeed, the decrease of the overall system performances do not meet the project requirements, with a Strehl ratio decreasing by a factor of at least 50% in best seeing conditions.

For this reason, non-standard DMs with non-isotropic actuator spacing represent the best tradeoff between the system performances and the stringent instrumental polarization requirements of the EST project.

The results from the numerical simulations presented in this document will be verified during the coming months by experimental tests on the optical bench of the AO Laboratory at the INAF Osservatorio Astronomico di Roma.

LIST OF ABBREVIATIONS

DM	Deformable Mirror
AO	Adaptive Optics
WFS	Wavefront sensor
DMSC	Deformable mirror simulation code
EST	European Solar Telescope
PAOLA	Performance of Adaptive Optics for Large Apertures
DMTF	DM transfer function

1. INTRODUCTION

Precise and sensitive polarimetry forms a cornerstone for the EST [4]. This translates into the need of a polarization-free optical design. For this purpose, the EST MCAO system requires the use of DMs in a non-standard configuration. More precisely, the EST preliminary design devised that each DM is inclined 45 degree in orthogonal planes in order to mutually compensate the instrumental polarization [3]. However, this represents a very non-standard setup for the DMs. For this reason, an in-depth analysis of the performances of the DMs in such configuration is specially needed in order to verify its feasibility and identify possible shortcomings (if any).
In this document, we present a preliminary assessment of the performance of tilted DMs as derived from numerical simulations.
Starting from closed loop simulations of a very simple AO system, we study the effect of tilting a DM for several different seeing conditions. To this purpose, we have modified the well-known PAOLA simulation environment [4] to extend its capabilities to the simulation of inclined DMs.
Further, in order to better investigate the performances of tilted DMs and to identify possible solutions, we model the response of the DM as a function of the inclination angle. To this purpose, given the absence of any suitable existing code, we have developed a specific software to simulate the DMTF of tilted DMs.
Finally, we present ZEEMAX end-to-end simulations that were developed to investigate the effects of the DM inclination on the modal basis representation commonly used to control the DM.

This whole section is confusing. I would suggest to remove it. Otherwise, it should be done after the detailed analysis of the mirror and compensating for all effects

2. PAOLA CLOSED LOOP SIMULATIONS

In order to test the effects of a tilted standard DM on the closed loop performances, we simulated a very simple and schematic AO system with the PAOLA simulation code. To do this, we have modified the PAOLA code to include the ability of working with inclined DMs. Although our purpose is to analyze the effect of a tilted DM on the overall performances of a general AO system, we set up typical atmospheric conditions observed at the La Palma observatory, which is one of the proposed observing sites for the EST, to better represent the project case. For this purpose, we have used the La Palma atmospheric daytime turbulence profile measured by [3].
The telescope diameter is set to 4 m. Other simulation parameters can be found in the following:

- ➢ Wavelength: 600 nm
- ➢ Zenith angle: 30 degree
- ➢ WFS equivalent pitch: 8 cm
- ➢ WFS integration time: 1 ms
- ➢ DM actuators: 11 x 11
- ➢ Loop time lag: 1 ms
- ➢ Conjugation height: 0 km
- ➢ Loop gain: 0.5
- ➢ DM type: MEMS

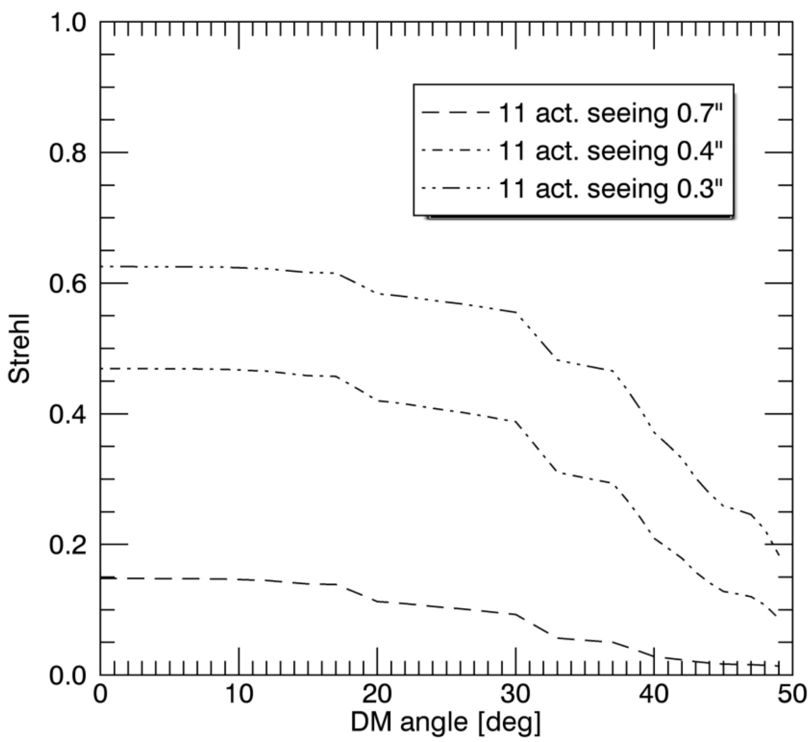
These represent a simplified scheme for the analysis of the overall effect of the tilt of a DM on the performance of an AO system. For this reason, these parameters are kept fixed and several simulation runs are performed by only varying the angle of tilt of the DM. This is done for different seeing angles from 0.3 arcsec to 0.7 arcsec, which correspond to excellent to medium seeing conditions, respectively.

It is worth noting here that our purpose is only to study the effect of tilted DMs on the overall performances of the AO system, not to simulate the EST MCAO system. For this reason, we have chosen a very schematic AO configuration, in order to keep the simulation setup as simple as possible and to focus on effects of the DM tilt only.

The results of these simulations are shown in Fig. 1. The impact of the DM inclination on the Strehl ratio achieved by the AO system is rather constant only for a limited range of inclination angles (<20 degree). For larger values of the inclination angle, the Strehl ratio drops remarkably, with a severe decrease of the performances of the system.

This can be better seen in Fig. 2, where we plot the variation of the Strehl with respect to the DM conventional configuration (no tilt).

The obtained results show that the relative variation of the Strehl ratio as a function of the DM tilt depends of the seeing conditions. The worse the seeing conditions the steepest the decrease of the Strehl ratio as a function of the DM inclination. Indeed, while for 0.3 arcsec seeing the decrease of the performances at 45 degree DM tilt is of the order of 50%, it can be as large as 90% in the case of 0.7 arcsec seeing. It is worth noting that the decrease of the Strehl ratio is a non-linear function of the DM tilt.



mcv
1. We need 50x50 actuators
2.For a pupil DM, why is there a difference?
3. Details about the code and implementation are needed
4. How does it deal with an effective illumination?

Fig. 1: Strehl vs DM tilt angle for different seeing conditions.

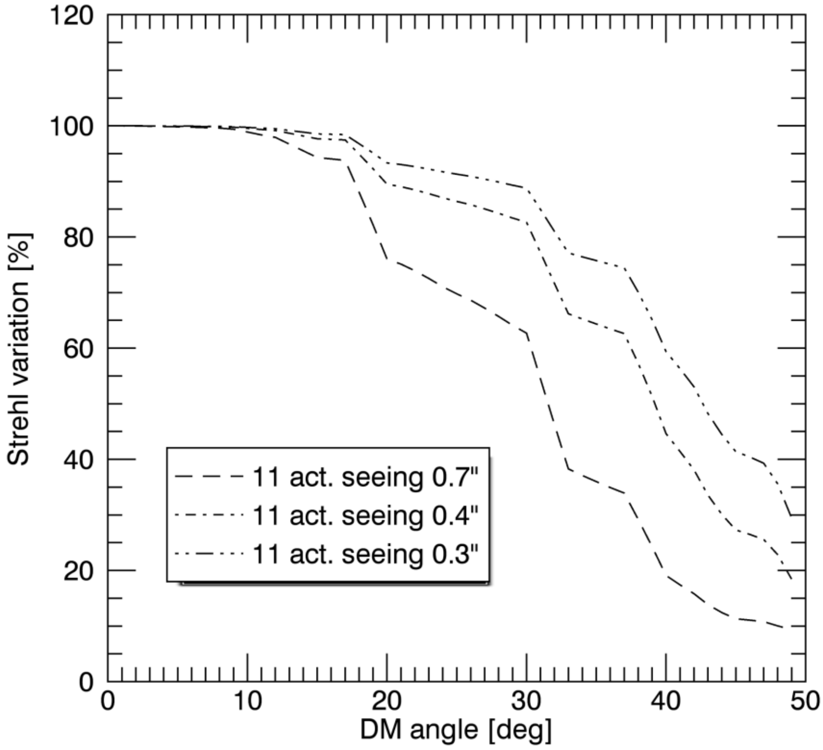


Fig. 2: Relative variation of the Strehl ratio as a function of the DM tilt, for different seeing conditions.

3. DMSC: THE EST DMS SIMULATION CODE

Several complex AO/MCAO simulation codes are nowadays publicly available to study and evaluate the performances of different MCAO systems (e.g. CAOS, YORICK-YAO). Although these codes can simulate and model very different MCAO configurations (e.g. GLAO, SCAO, MOAO, LGS), as far as we know, they cannot handle the presence of tilted DMs in a straightforward manner, and with the accuracy needed to characterize the EST MCAO configuration. Indeed, tilted DMs constitute a very non-common configuration, especially in astronomical applications. Besides, EST is the first astronomical telescope with a built-in polarization-free MCAO system, integrated into the light path.
For the above reasons, it turned out that existing simulation codes were not best suited to our purpose and, in particular, to study the response of the DM for different angle of inclination and different actuator geometries. Our choice was therefore to develop a specific code from scratch, in order to include all the characteristics needed for the modelling of the EST MCAO configuration. This code (hereafter DMSC) is an analytic code written in IDL language.
The main capabilities and features of the code are listed in what follows, and are specific to the simulation and characterization of tilted DMs:

• user-defined non-isotropic actuator maps;
• modeling DMs tilted on two axes simultaneously;
• selectable actuator coupling;
• non-linear actuator response.

The above DMSC features allow the study of a series of different options. Among the many, it is worth mentioning that the analysis of the effects of the actuator coupling, and of the asymmetric actuator distributions to partially compensate for the asymmetric spatial sampling of the pupil, represents the main goals of our work.

In the following we describe a very simple DM configuration with uniform circular distribution of actuators; this configuration is used to study the first order effects of tilting a DM. Then we investigate the performances of a more realistic DM configuration with an elliptic distribution of actuators.

3.1 DM ACTUATORS MAP

The main feature of DMSC resides in the ability of working with DMs with asymmetric actuator maps and their effective projection onto the pupil plane, and of studying different actuator couplings.
Indeed, in the presence of a tilted DM with isotropic distribution of actuators, the effective spatial density of actuators depends on the tilt angle. In other words, the effective density of actuators on the pupil plane reflects the amount of inclination of the DM. For this reason, a partial compensation of the actuator spacing along one axis might be necessary. DMSC is designed to integrate these features and provide the end-user with the necessary flexibility to study different actuator configurations. In Figs. 3 and 4 we show two examples of actuator maps with different actuator densities and distributions, as modelled by the code.

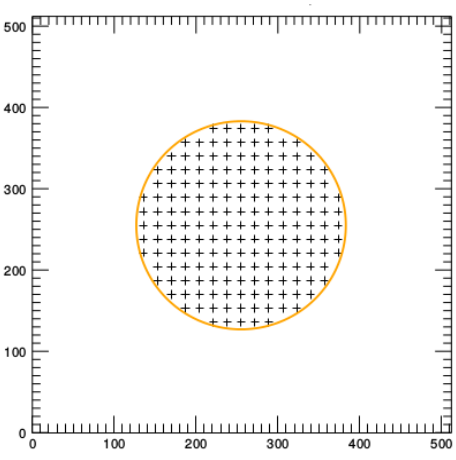


Fig. 3: Example of actuator map for non-tilted DM.

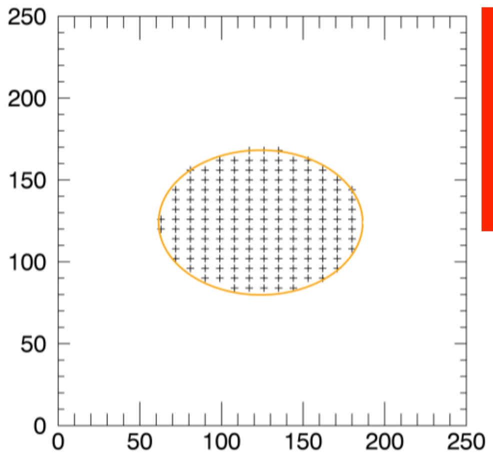


Fig. 4: Example of actuator map for a 45 degree DM with an overdensity of actuators along one axis.

I never understood this figure.
If the mirror is rotated in one axis,
why does the size changes in
the both axis?

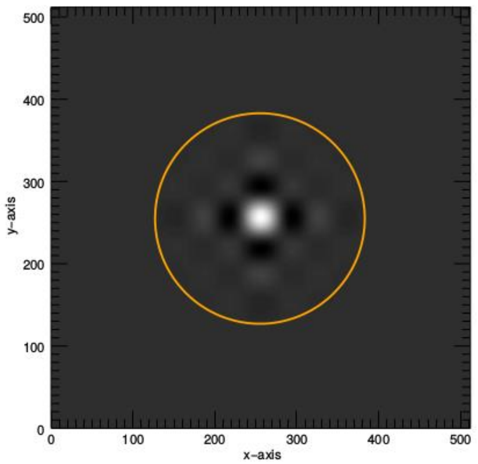


Fig. 5: DM spatial response for a non-tilted DM with 8 × 8 actuators with 0.2 spatial coupling. The yellow circle represents the edge of the mirror effective area whose physical diameter is 2 cm.

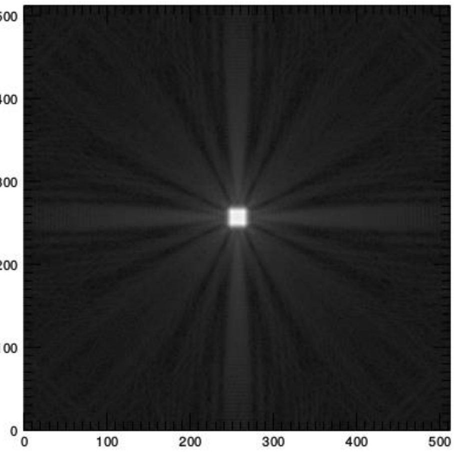


Fig. 6: DMTF for a non-tilted DM with 8 × 8 actuators with 0.2 spatial coupling. Note that the cutoff frequency is the same for both axes.

3.2 DM SPATIAL RESPONSE AND SPATIAL TRANSFER FUNCTION

As already mentioned, the first step of our analysis is represented by the numerical modelling of the DM spatial response for different mirror configurations (actuator spacing, inclination angle,...).

The DM spatial transfer function (DMTF) is given by the Fourier transform of the DM spatial response (Roddier, 1999). This is in turn defined by the projection of the Dirac impulse onto the influence function basis I:

$$\gamma_{DM} = \sum_{i=1}^{N} p_i I_i(\mathbf{r}).$$

where $i=1,...,N$, and N is the number of actuators.

The coefficients p_i are computed from the minimization of the quadratic distance between the impulse and its projection,

Define symbols in the equation

$$\mathbf{p} = S^{-1} \cdot \mathbf{b}$$

In doing this, the DM influence function I, of the actuator i, is modelled by a Gaussian of the form:

$$I = \exp(\log(A_{CLP}) * ((x)^2 + (y)^2)),$$

where A_{CLP} is a coefficient representing the amount of actuator coupling, and x and y are the spatial coordinates in the DM space. Different DMs have different influence functions,

and different actuator couplings that depend on the mirror technology (piezo DM, MEMS,...). However, [1] has shown that a Gaussian function can be regarded as a good approximation of the real influence function, at least as far as the linear regime is considered. It has to be stressed that the influence function is also projected onto the pupil in order to take into account the DM tilt.
The DMTF is then obtained by Fourier transforming the DM spatial response as obtained by shifting the influence function at the location of each actuator of the mirror.

The DMTF represents the response in the Fourier space (the spatial frequency space) of the DM. In other words it represents the spectrum of spatial frequencies which are corrected by the DM. This spectrum is characterized by the lowest corrected frequency given by the mirror diameter d ($v_0 = 1/d$), and a cutoff imposed by the actuator pitch A_{pitch} ($v_{cutoff} = 1/2 \cdot A_{pitch}$). In the presence of an effective non-isotropic distribution of actuators on the pupil given by either intrinsic overdensity of actuators along one axis, or a tilt of the mirror, there will be a different cut-off frequency for each of the two axes. This is one of the fundamental aspect of the use of tilted DMs and represents one of the focal points of our analysis.

In Figs. 5 and 6 we show the DM spatial response and the DMTF respectively, for a non-tilted DM with *8* actuators per axis (same actuator spacing for both axes). The physical dimension of the DM is *2* cm.
It is worth noting that, given the isotropic spatial effective distribution of the actuators as seen from the telescope pupil, the cutoff frequency is the same for both axes (the DMTF is symmetric). We also note that the DM spatial response is symmetric for the same reason. In this work we focus on the asymmetries of the DMTF and the DM spatial response to the tilt of the DM. In addition, in the following sections, we also analyse the impact of different actuator spatial couplings on the DMTF and DM response, as a function of the mirror tilt and actuator pitch. To this regard, in Fig. 7 we show an example of response function of a DM (13 actuators per axis) with elliptic distribution of actuators.

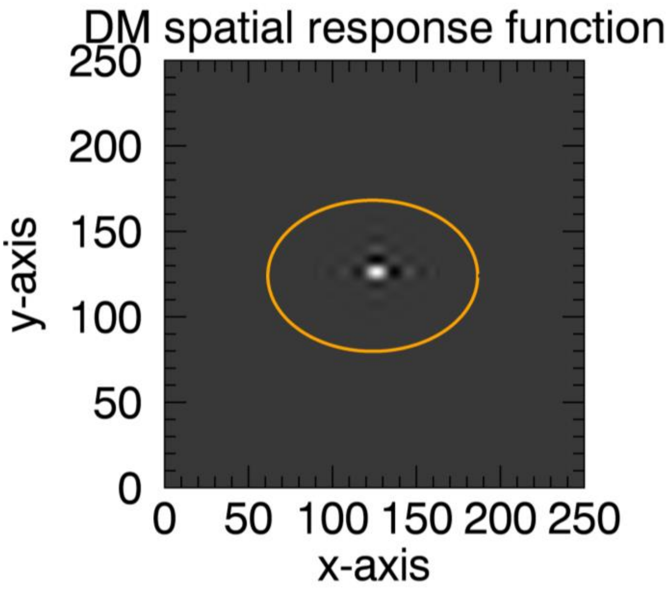
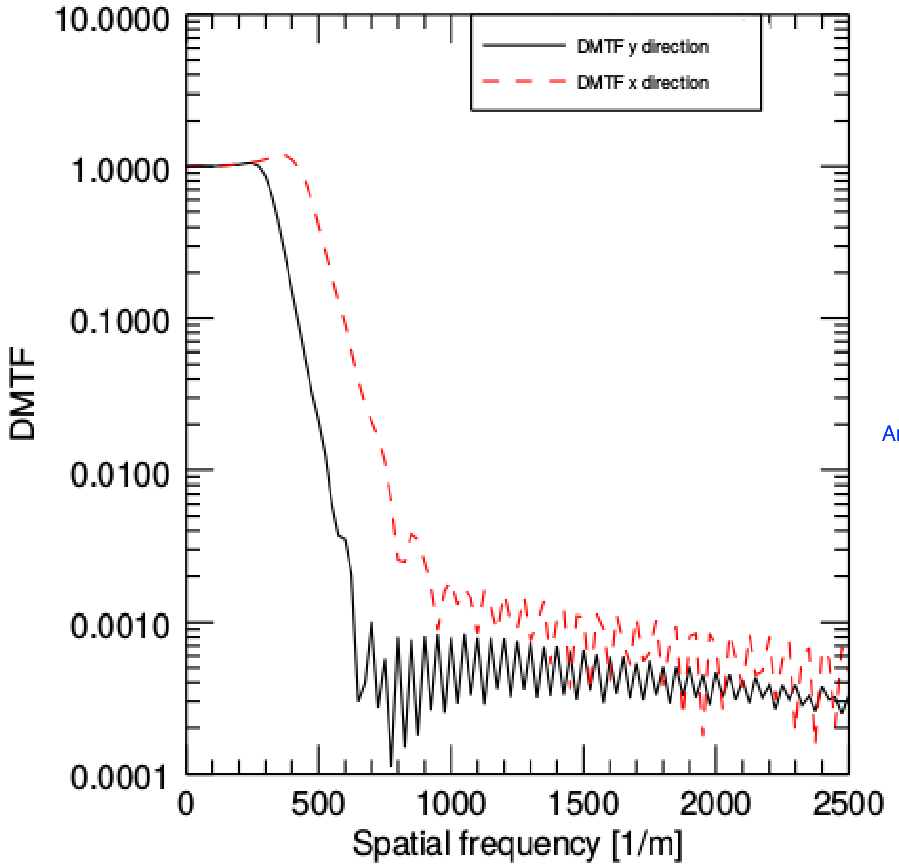


Fig. 7: DM response for a not tilted DM with elliptic distribution of actuators.

4. ANALYSIS OF THE 45 DEGREE TILTED DM FOR THE EST MCAO SYSTEM

In this section we investigate the EST DMs configuration with tilted DMs. More in particular, we study two different cases: a standard DM with uniform distribution of actuators tilted by 45 degree and corresponding to the case investigated in the closed loop PAOLA simulations presented above, and a non-standard custom DM with increased density of actuators along one direction. In addition we analyse the effect of different actuator couplings.



Are these fluctuations numerical?

Fig. 8: DMTF along different directions for case 1.

4.1 CASE 1: STANDARD DM TILTED BY 45 DEGREE

As already mentioned, the effect of tilting a DM with respect to one of its axis translates into a different density (pitch) of the actuators along the two main axes, as seen from the pupil plane just before the DM. In other words, there exist a different effective pitch and, therefore, a different cutoff frequency depending on the geometrical axis considered. In the following we will consider a simple standard DM inclined by 45 degree (rotation axis oriented along the y-axis direction) and with the same physical pitch along the two main axes (same physical spacing of the actuators along the x- and y-axis). The DM inclination results in a elliptic pupil with overdense actuators along the y-axis direction, and then a different cutoff frequency.

In Fig. 8 we show the DMTF of this system. Due to the overdense spacing of the actuators as seen from the pupil, the cutoff frequency along the x-axis is larger than for the y-axis. This can be seen by the elongation of the DMTF along the x-axis direction. It is worth remarking here that, for the purpose of our study, it is not required to use specifications of off-the-shelf DMs, as our aim is to investigate the global effects of using different technical solutions instead of investigating the fine details of a precise DM configuration.
After looking at these results one could think that it is convenient to use tilted DMs as the cutoff frequency along one direction is larger. However, there is a price to pay for this increase of cutoff frequency that resides in the non-linear effects and actuator coupling. In order to show this, in Fig. 8 we plot the DMTF along different directions. While the cutoff frequency increases along the x-axis, there is also a substantial increase of the high-frequency tail of the transmission function which eventually results in an amplification of the noise. In addition, we also observe a larger overshooting of the DMTF in proximity of the cutoff frequency.

Actuator coupling: why is this a problem?
Non-linearity: this is not addressed here. Why mentioning it?

4.2 CASE 1: DM WITH A DIFFERENT PITCH OF THE ACTUATORS ALONG ONE AXIS

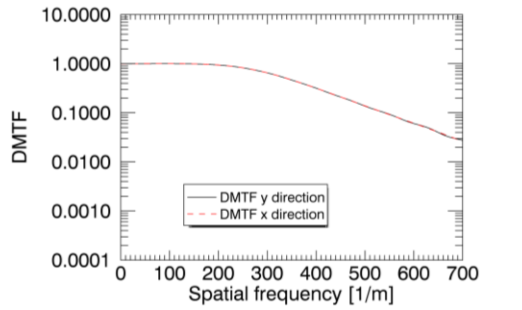
If you want to compare with the original mirror, you should separate the actuators in the x-direction. What you are doing is increasing the coupling between actuators in the y-direction

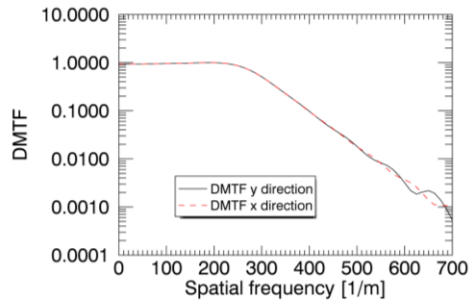
In order to take into account the projection effects on the apparent pitch and on the cutoff frequency of an inclined deformable mirror, one possibility is represented by the adoption of an elliptic distribution of actuators with a different pitch along the two main axes. This is done to compensate for the increased apparent density of actuator along the inclination axis and to match the two cutoff frequencies. In particular, for an inclination angle equal to 45 degree along the x-axis, it is necessary to increase the density of actuators in the y-direction by a factor of approx. 1.4 (see Fig. 4). This configuration corresponds to a custom-made DM. The DMTF along the two main axes of the mirror for such configuration is shown in Fig. 9a. In this case we have considered a DM with a usable diameter of 2 cm and with 13 actuators per axis, and a very small coupling (1%). The different pitch of the actuators along the two axes of the mirror allows us to completely recover the projection effects and the apparent reduction of the actuator spacing along the direction of inclination. No significant difference is observed between the two response functions along the two axes of the mirror.

4.3 EFFECTS OF THE ACTUATOR COUPLING

In order to investigate the impact of different actuator couplings on the response function of the DM, we studied the DMTF for different values of the coupling.
In Fig. 9 we plot the DMTFs for four different actuator spatial couplings: 1%, 10%, 15%, and 20%. As can be seen, a different interactuator coupling has a large impact on the high frequency attenuation, and the dynamic range of the DM. In particular, the larger the coupling, the larger the difference of the DMTFs for the two axes.
We note that the range of interactuator coupling explored here (up to ~20%) corresponds to realistic values of a typical membrane mirror; see for example:
http://www.bmc.bostonmicromachines.com/pdf/Multi-DM.pdf
With an interactuator coupling of 10%, significant differences are already seen in the very high spatial frequency tail of the response. These differences become even more apparent when the intercoupling reaches values of the order of 20%. In this case, the response function for frequencies above the cutoff results to be significantly different for the two axes. In addition, it is important to note that the high frequency attenuation is smaller for the axis corresponding to the direction of inclination of the mirror, where projection effects take place.

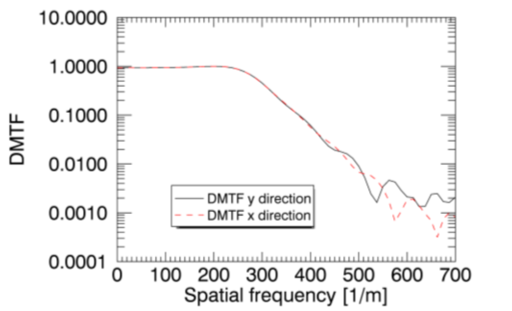
Is this numerical noise?
A Gaussian is smooth. Why does the DMTF show wiggles?

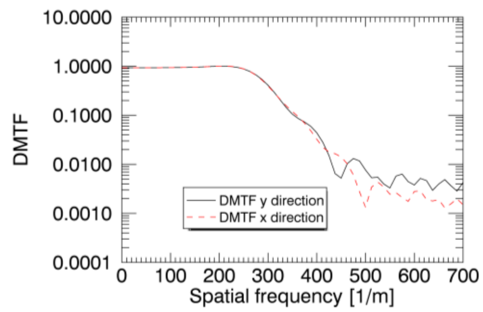




a) b)

If modified to separate actuators instead of putting them closer,
x-axis should behave better (more separated actuators)





c) d)

Fig. 9: DMTF of a DM with elliptic distribution of actuators along the two main axes for different values of the actuator coupling: a) 1%, b) 10%, c) 15%, d) 20% coupling, respectively .

5. ZEMAX ANALYSIS OF MODAL CROSS-TALKS ON TILTED DMS

A full different analysis of the effects of modal control on tilted DMs was performed by using a simple ZEMAX model for a tilted DM. This is to verify how much the Zernike modal base loses its orthogonality and develops cross-talks between its modal components, once a collimated beam is reflected off a deformable tilted surface.
The results obtained from this analysis are particularly relevant for the modal control of the DM that will be further investigated during the coming months by experimental tests on the optical bench.
The schematic model of Fig. 10 is relaying a focal plane F1 trough a DM and compares the Zernike modes retrieved at the reflected (conjugated) image plane F2. Here it is possible to analyze different situations vs the DM tilt angle:

1. The DM is *always flat* and modes (aberrations) are injected at F1.
2. Modes are injected at the DM plane modifying the SAG of the DM mirror surface adding "standard" Zernike polynomials over its flat surface.
3. Modes present in F1 are compensated using the SAG of the DM surface modulated by a linear combination of "standard" Zernike polynomials.

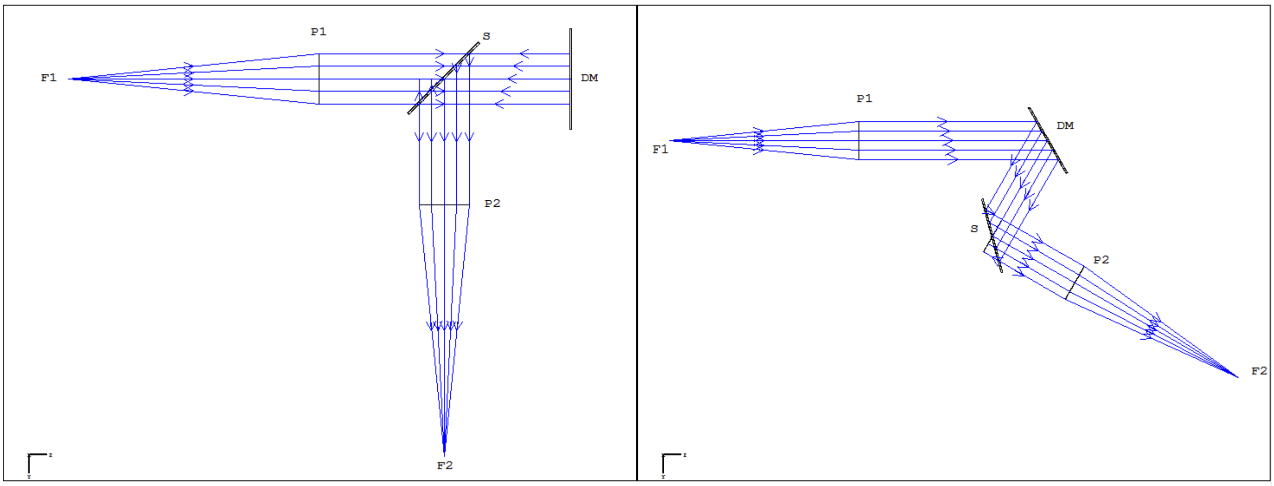


Fig. 10: A virtual test bench in ZEMAX for a tilted DM. Left; configuration standard at 90 degree of incidence angle. Right: The same at 30 degree of tilt.

The S surface is an "always flat" mirror used only to keep the F2 plane out of the system also at reflection angles close to 90 degree; it has the only function to make the layout more readable.
For "standard" Zernike polynomial we refer to Zernike polynomials normalized over the pupil surface.

5.1 VERIFICATION OF THE ZEMAX MODEL FOR THE FLAT DM CASE

First, we verify the accuracy of our ZEMAX model, by showing how aberrations injected at F1 (by means of a Zernike phase surface after P1) and estimated at F2 are unaffected by the flat DM at all the angles between 0 and 45 degree. The aberration used in this test is Z7 (coma). Results estimated at F2 vs tilt angle are summarized in the following table.

Angle	Z1	Z2	Z3	Z4	Z5	Z6	Z7	8Z	Z9	Z10	Z11	Z12	Z13	Z14	Z15
0°	0	0	**1.1**	0	0	0	**-0.1**	0	0	0	0	0	0	0	0
15°	0	0	**1.1**	0	0	0	**-0.1**	0	0	0	0	0	0	0	0
30°	0	0	**1.1**	0	0	0	**-0.1**	0	0	0	0	0	0	0	0
35°	0	0	**1.1**	0	0	0	**-0.1**	0	0	0	0	0	0	0	0
45°	0	0	**1.1**	0	0	0	**-0.1**	0	0	0	0	0	0	0	0

We still don't understand why tilt appears here

The Z3 value of 1.1 is due to the asymmetry of the injected Coma that is retrieved as a combination of Coma and chief ray tilt by the Zemax wavefront analyzer. As expected, the values of aberrations at F2 are independent of the DM tilt angle.

5.2 NEW ABERRATIONS INDUCED BY A NO-FLAT TILTED DM

Then, we show how a no-flat tilted surface induces cross-talks between Zernike modes, when the incidence angle is departing from 0. The aberration is injected modifying the SAG of the DM, by means of the Zemax Grid SAG tool. The DM surface is modified by adding a 0.1 µm of Z7 (coma) to the flat surface of the DM. The wavefront decomposition at F2 shows the reciprocal influence of Z7 and Z3 as a function of the DM tilt. The obtained results are summarized in the following table; yellow highlighted cells show the cross-talk effects.

Angle	Z1	Z2	Z3	Z4	Z5	Z6	Z7	8Z	Z9	Z10	Z11	Z12	Z13	Z14	Z15
0°	0	0	**1.1**	0	0	0	**-0.1**	0	0	0	0	0	0	0	0
15°	0	0	**1.0**	0	0	0	**-0.1**	0	0	0	0	0	0	0	0
30°	0	0	**1.0**	0	0	0	**-0.1**	0	0	0	0	0	0	0	0
35°	0	0	**0.9**	0	0	0	**-0.2**	0	0	0	0	0	0	0	0
45°	0	0	**0.8**	0	0	0	**-0.2**	0	0	0	0	0	0	0	0

If the aberration is introduced in the circular Zernike basis, it is OK that the projection produces cross-talk to other Zernikes. What it you introduce coma in the "elliptical Zernike basis"?

For the not-tilted DM the Z3 value of 1.1 is interpreted as due to the asymmetry of the injected Coma that is retrieved as a combination of Coma and chief ray tilt by the Zemax wavefront analyzer. This offset was already found with a non-tilted flat DM, and represents the reference value of our analysis here. As the tilt of the DM increases, the cross-talk changes. In addition to cross-talks (Z3 in this case), the value itself of the injected Z7, as read from F2, changes and it is dependent on the DM tilt angle. The effect becomes evident starting from 15 degree tilt.

5.3 ABERRATIONS REMOVAL AT DM BY ZERNIKE SAG

Further, we show how tilted DM may remove an aberration using different combination of mode. The initial aberration is injected at F1 (by means of a Zernike phase surface after P1) and recovered modifying the shape of the DM by means of the Zemax Grid SAG surface placed at the surface DM. Wavefront aberrations estimation is taken at F2. The test aberration used is Z7 (coma). The following table shows the values of aberration used to correct the beam vs angle; yellow highlighted cells show the needed correction to be added to the expected one.

Angle	Z1	Z2	Z3	Z4	Z5	Z6	Z7	8Z	Z9	Z10	Z11	Z12	Z13	Z14	Z15
0°	0	0	0	0	0	0	**3.16**	0	0	0	0	0	0	0	0
15°	0	0	**-0.5**	0	0	0	**3.0**	0	**0.15**	0	0	0	0	0	0
30°	0	0	**-1.8**	0	0	0	**2.5**	0	**0.7**	0	0	0	0	0	0
35°	0	0	**-2.2**	0	0	0	**2.4**	0	**0.8**	0	0	0	0	0	0
45°	0	0	**-3.4**	0	0	0	**2.0**	0	**1.15**	0	0	0	0	0	0

The input aberration is Z7 (coma) and the 0.316 µm of the same Z7 at the DM was sharp correcting (at 0 degree) without the help of other modes as expected. Instead, the loss of orthogonality of the standard Zernike base implies, when the DM is tilted, the use of Z3 and Z9 or suggest the use of a different and more efficient "custom" modal bases as discussed earlier in this report.
The above results show that the DM inclination can inject specific modal cross-talks that depend on the inclination angle. These cross-talks can play a significant role in the modal control of the mirror and their accurate calibration has to be accounted for on the wavefront sensor side. To this regard, specific laboratory tests will be performed during the coming months to verify the numerical results obtained so far and identify possible countermeasures.

This only shows the coupling between the circular Zernike basis and the elliptical basis

6. CONCLUSIONS

In this document, we have analysed the response of DM as a function of the tilt angle as obtained from numerical models.

The closed loop numerical simulations carried out in our study show a severe decrease of the AO performance when a generic standard DM is employed with a tilted set-up. This is particularly the case for tilt angles larger than 20 degree. Indeed, the loss of Strehl ratio is significant, and can be of the order of 50% for a 45 degree tilt. Moreover, this loss of performances largely depends on the seeing conditions. The better the seeing, the larger the decrease of the Strehl ratio. This underlines the importance of an accurate evaluation of the response of DMs when employed with large tilt angles.

Tilted DMs present a different response depending on the spatial direction considered. This issue reflects in a different cut-off frequency along the main axes. While the same response for the two main axis of the DM is desirable for practical reasons, the exact match of the two transfer functions it is difficult to be achieved when the actuator inter-coupling is larger than 10%. In addition, a large actuator coupling results in an intrinsic decrease of the dynamic range of the DM. This is the case for both directions. However, in the direction of the inclination, a smaller attenuation of the high frequencies above the cutoff is also seen.

All in all, a custom-made DM with elliptic distribution of actuators appears a promising configuration for the EST MCAO, at least for matching the cut-off frequencies of the DMTF in the two axes. However, large differences are found in the very high frequency tail of the simulated response functions, and a precise evaluation of their possible impact on the overall performances of the system is needed. This is especially the case when the actuator inter-coupling increases. To this regard, specific laboratory tests will be carried out during the coming months to assess the impact of these expected differences on the wavefront correction, and to verify the results from the numerical models obtained so far.
However, since the fitting error was found not to depend on the actuator inter-coupling [6], we expect that the inter-coupling will play a limited role on the overall performances of the tested system. Indeed, it was already shown [6] that the fitting error only depends on the actuator geometry and pitch. Nevertheless, the effects of DM inclination on the fitting error will be carefully analysed also by the planned tests.

Finally, we have also shown that a tilted DM can introduce specific cross-talks between different modes used for its control and the wavefront sensing. In particular, we have shown that the induced cross-talk depends on the angle of tilt. This effect needs to be carefully taken into account when estimating the interaction matrix used to drive the mirror starting from the wavefront sensor measurements.

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