This report aims to present the adaptive optics simulator based upon the data provided by the European Southern Observatory.

In accordance to the physical system, the basic elements for the simulator are the Turbulence Generator, the Wave-front Sensor, the Control Unit Block and the Deformable Mirror.

A modular approach to the problem is given and its implementation is developed recurring to a numeric calculus simulator.
This work was supervised by Aníbal Coimbra Matos and Maria Inês Carvalho, to whom we wish to thank.
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GLOSSARY

**AO** Adaptive Optics

**AOS** Adaptive Optics Simulator

**DM** Deformable Mirror

**ESO** European Southern Observatory

**HVA** High Voltage Amplifier

**TG** Turbulence Generator

**WFS** Wave-front sensor
Adaptive Optics Simulator

I Introduction

Adaptive Optics [AO] is a set of techniques for the enhancement of ground-based astronomical observation.

The need of such systems arises from the atmospheric turbulence. For ground located telescopes the atmospheric turbulence introduces aberrations in incoming light wave-fronts, causing degradation on the optical diffraction limit. This limit has the form:

\[ \vartheta \sim \frac{\lambda}{D} \]

The effects of atmospheric turbulence may be divided in two parts with different strength: image motion (or tip-tilt) being 87% of the wave-front variance, and image blur (or high-order wave-front distortion) being 13% of the variance. Image motion is by far the largest effect to be corrected.

A standard measure of the optical strength of turbulence is Fried's parameter \( r_0 \), the distance over which the optical phase distortion has a mean-square value of 1 rad\(^2\) at \( \lambda = 0.5 \mu m \). For good observing sites \( r_0 \approx 20 – 30 cm \). This value represents the diameter of a seeing disk on the telescope mirror (\( r_0 \) is always greater than \( \vartheta \)).

Figure 1 – Atmospheric temperature gradient.
The European Southern Observatory [ESO] is undertaking a set of procedures in order to develop an advanced adaptive optics system to improve optical resolution. This work exploits data from ESO physical facilities, to improve control methods and algorithms.

1.1 Document synopsis

Most contents of this work consist of theoretical investigation about basic elements/modules for the construction of an adaptive optics simulator.

The simulator is divided in five different components:
1. Atmospheric turbulence generator;
2. Wave-front sensor;
3. Control unit;
4. High frequency amplifier;
5. Deformable mirror.

Chapter II introduces AOS by means of its requirements, describing the main techniques to sense and control the aberrations in incoming WF.

In Chapter III is given a theoretical description of each of the modules stated above and presented the implementation procedures followed. A Kalman Filter is described, its use justified and its implementation, with reference to standard texts, developed.

Chapter IV presents the AOS graphical user interface and a step-by-step procedure to use the simulator.

Chapter V shows relevant results for a specific example.

II AO System overview

1 Procedure and objectives

To achieve the light theoretical diffraction limit the optical effects of atmospheric turbulence must be eliminated. AO systems attempt to eliminate these phase variations by varying the optical path length between the aperture and the sensing instrument (Figure 2).

![Figure 2– Conceptual functioning of deformable mirrors](image)
The optical path length is modified by measuring the variation via WF sensors and modifying the shape of the DM and the tip-tilt mirror. To accomplish this objective, the design frequently consist of surfaces which have equal and opposite aberration contributions, so that the distorted incoming WF is corrected, resulting in null distortion.

The headline of the adaptive optics procedure is as follows (See Figure 3):
1. Measurement of the details of blurring from "guide star" near the object to be observed;
2. Calculation (on a computer) of the shape to apply to a deformable mirror to correct blurring;
3. Activation of the DM to correct incoming WF.

Simulation of AO systems permit to analyze their performance as well as to predict the performance of different algorithms and components.

Next generation telescopes at ESO will be using part of the results obtained and improved by meaning of such simulators.

2 AO architectures

There are two different types of architectures to measure atmospheric turbulence: star-oriented and layer-oriented. The former is used in Classic AO systems and the later in multiconjugate AO systems (MCAO). MCAO techniques are intended to achieve full
compensation over wide fields of view to which it is necessary to employ three-dimensional WF compensation.

2.1 Classic AO

**Star-Oriented Wave-front Sensing:** The atmospheric turbulence is depicted at one target and the whole disturbance introduced along the atmosphere is represented in it. The use of many of such sensors (directed to different anisoplanatic areas) creates a multiple star wave-front sensor.

2.2 Multiconjugate AO

**Layer-Oriented Wave-front Sensing:** This technique consists of assigning multiple detectors to different altitudes, assuming the turbulence can be separated into different layers (whose interference is larger), and sense the turbulence present at the altitudes chosen. In order to collect the information relative to each altitude there must be an extra process that can be implemented either optically or numerically.

2.2.1 Reconstruction Techniques

The reconstruction of the wave-front from the data gathered can be accomplished in two different ways:

1. **Globally:** Taking all the data at once from all the WF sensors and reconstruct the WF at the altitude of interest.

2. **Locally:** Taking the data coming from a single altitude and with that information drive directly the mirror that is affect to it.

---

Figure 4 – Local and Global Reconstruction
2.2.2 Control Strategies

Control strategies permit to combine all the possibilities between the reconstruction technique and the sensing architecture, giving a large spectrum of tests that can be implemented.

3 Modules

The conceptual scheme of the modules needed to simulate an AO system and their relations are depicted in Figure 5.

Figure 5 - relation between modules

Each of the modules is described below.

4 Atmospheric Turbulence Generator

4.1 Overview

The turbulence simulator aims to recreate the atmospheric turbulence by means of its mathematical description.

Turbulence has its origins in temperature fluctuations in small patches of air that cause changes in the index of refraction (like many little lenses), causing light rays to be refracted many times (by small amounts). When these rays arrive to a telescope they are no longer parallel and hence can't be focused to a point.

In the AOS the distorted WF is injected in the curvature sensor and thereafter in the control loop in order to be compensated, ideally resulting in null phase.

The mathematical description of the phenomena is widely known. In the present case Kolmogoroff turbulence profile was used, which defines the structure function for the phase fluctuations as:
Equation 4-1

\[ D_\phi = 2\left[ (\Phi^2 (r_1)) - (\Phi(r_1)\Phi(r_1 + r)) \right] \]

Equation 4-2 describes the atmospheric turbulence in a base of Zernike polynomials, whose modes are orthonormal:

\[ \Phi = \sum_i \alpha_i Z_i \]

Equation 4-2

Equation 4-3 and Equation 4-4 give the complete formulae for the Zernike polynomials.

\[ Z_{\text{even}_j} = \sqrt{l+1}R^m_l(r) \sqrt{2} \cos(m\theta) \]
\[ Z_{\text{odd}_j} = \sqrt{l+1}R^m_l(r) \sqrt{2} \sin(m\theta) \]
\[ Z_j = \sqrt{l+1}R^0_l(r) \]

m ≠ 0
m = 0

Equation 4-3

Where:

\[ R^m_l(r) = \sum_{s=0}^{l-m} \frac{(-1)^s(l-s)!}{s![(l+m)/2-s][(l-m)/2-s]} r^{l-2s} \]

Equation 4-4

The values of \( l \) must be always integral and satisfy: \( m \leq l, l - m = \text{even} \), where \( m \) is the azimuthal frequency, \( l \) the radial degree and \( j \) the mode ordering number as function of \( m \) and \( l \). Kolmogoroff spectrum of turbulence is represented by Zernike polynomials, used to describe many different problems as thermal and optical effects (The first 10 modes are presented in Figure 21). A complete description of Zernike modes is given in [3].

The development of a Zernike polynomial representation of Kolmogoroff spectrum of turbulence permits to analytically calculate the aberrations introduced in light rays crossing terrestrial atmosphere.

With this representation it is intended to simulate atmospheric turbulence and develop a complete reference model to foresee and control the behaviour of the DM. However there is a limitation to the use of Zernike polynomials: The first mode, known as the piston, cannot be used in reproducing atmospheric turbulence[3].

4.2 Atmospheric turbulence model: the Auto-regressive model

Le Roux [2] presents the auto-regressive model for the evolution of the atmospheric turbulence, where the distorted phase is represented by:

---

1 A technique normally used is to develop the control of this mode separately.
\[ \phi_{n+1} = F[\phi_n, \phi_{n-1}, \phi_{n-2}, \ldots, \phi_{n-k}] + v_{n+1} \]

Equation 4-5

\[ \phi \] is the vector composed by the coefficients of the phase distortion in the Zernike basis, \( n \) is the discrete time index and \( v \) is a random process associated with the turbulence.

The first order model (AR1, with \( k=1 \)) is expressed by:

\[ \phi_{n+1}^{\text{tur}} = A_{\text{tur}}^{\text{tur}} \phi_{n}^{\text{tur}} + v_{n+1}^{\text{tur}} \]

Equation 4-6

Considering a bounded overall energy, the variance of the turbulence is given by:

\[ C_{\phi^{\text{tur}}} = A_{\text{tur}}^{T} C_{\phi^{\text{tur}}} A_{\text{tur}} + C_{v} \]

Equation 4-7

and if \( C_{\phi^{\text{tur}}} \) is taken as the Kolmogoroff covariance matrix:

\[ C_{v} = C_{\text{Kol}} - A_{\text{tur}}^{T} C_{\text{Kol}} A_{\text{tur}} \]

Equation 4-8

For the turbulent mode \( i \) the Equation 4-6 becomes:

\[ \phi_{n+1}^{\text{tur},i} = \sum_{j} A_{\text{tur}} (i, j) \phi_{n}^{\text{tur},j} + v_{n+1}^{(i)} \]

Equation 4-9

with the diagonal coefficients \( A(i,i) \) given by:

\[ a^{(r)} = \exp(-T_{c}^{(r)}) \approx \exp(-0.3(r + 1)V / D) \]

Equation 4-10

and null elements elsewhere.

### 4.3 Implementation Procedure

Figure 6 shows the implementation of the atmospheric turbulence introduced in the system with Kolmogoroff covariance. Three different sections are identified by dash-boxes.

The first section produces a perturbation signal with covariance given by Equation 4-8.

The second section permits to choose which Zernike modes affect the output. This feature was introduced since the power associated to each mode decreases enormously with its order affecting the way higher modes are visualized in the WF. The matrix Zer_Select \((i,i)\) elements must be either 1 to be visualized or 0 otherwise.

The third section corresponds to the first term of Equation 4-6, performing a basic loop with one unit delay. The sample time must be less than the period of coherence of turbulence – a few milliseconds. Tests were made with 1ms but, in order to correspond to ESO
requirements, a model with \( \frac{1}{2100Hz} \) shall be implemented. This has to be with the frequency of the WFS membrane, explained hereafter.

The autoregressive turbulence model is hence implemented.

---

5 Wave-front sensor

5.1 Overview

There are many different ways of measuring an optical wave-front. Many techniques, however, do not suit adaptive optics requirements once they are either bandwidth limited or use coherent beams as reference. The two techniques most commonly employed are the Shack-Hartmann sensor [5, pp 33] and the curvature sensor. It is only briefly presented the curvature sensor once this is the technique used in sensing wave-fronts in the AOS.

5.2 Curvature sensors

Curvature sensors consist of the measurement in extra-focal planes of the WF intensity. The intensities are measured at planes either side of the focal point. Roddier shown
that these intensities are proportional to local curvature, and hence the sensor output signal \( S(r) \) is [5]:

\[
S(r) = \frac{I_2(r) - I_1(r)}{I_2(r) + I_1(r)} = \frac{f(f-l)}{2l} \left[ \frac{\partial}{\partial n} \Phi \left( \frac{f}{l} r \right) \delta_c + \nabla^2 \Phi \left( \frac{f}{l} r \right) \right]
\]

Equation 5-1

where \( f \) is the focal distance, \( l \) the distance from measurement planes to focal plane, \( I_1 \) the pre-focal intensity and \( I_2 \) the post-focal intensity.

The technique used to produce the two focal planes consists of the movement of a membrane at the frequency referred (2.1kHz).

The first term in Equation 5-1 represents the boundary conditions, which take the form of an impulse around the edge of the optical pupil.

In polar coordinates the Laplacian is given by:

\[
\nabla \Phi^2 = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial \Phi}{\partial r} \right] + \frac{1}{r^2} \frac{\partial^2 \Phi}{\partial \theta^2}
\]

Equation 5-2

5.3 Sensor Measurements
The phase found for each sensor, whose spatial structure is similar to that of the DM is computed considering the Laplacian overall integral for the incoming wave-front. This is accomplished considering the internal functioning of the sensor itself\(^2\): curvature sensors capture light photons within a restrict area, affecting the resulting measurement, which cannot be considered with respect to radius \( r \) but to the overall intensity captured in the segmented area. It is latter the comparison between the intensities measured at each side of the membrane that indicates the curvature. The measurement of wave-front curvature is taken along a sensor segment and not only at a specific point (for example the central one), resulting:

\[
\psi_i = \int_A S(r) dA \quad \text{for each segment } i.
\]

Equation 5-3

5.4 Implementation procedure

Laplacian computation is simplified since Zernike polynomials can be written in the form:

\[
Z_j = f(r).g(\theta)
\]

Equation 5-4

\[
\nabla^2 Z_j = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial}{\partial r} (f(r).g(\theta)) \right] + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} (f(r).g(\theta))
\]

Equation 5-5

Where \( g(\theta) \) is \( \cos(m\theta) \) or \( \sin(m\theta) \).

After the development of the derivative terms, and aggregating common terms results:

\[
\nabla^2 Z_j = g(\theta).\tilde{f}(r)
\]

Equation 5-6

with:

\[
\tilde{f}(r) = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial f(r)}{\partial r} \right) - \frac{m^2}{r^2} f(r)
\]

Equation 5-7

\( m \) is the azimuthal frequency of the Zernike polynomials.

The integration of the local curvature associated with \( Z_j \) along the sensor segment \( i \) has the form:

\[ However, this method has as assumption that there is no scintillation – which is, the sum of the pre-focal and the post-focal intensities is held constant.
\[
M_{i,j} = \int_{\theta_{i,j}}^{\theta_{i,j}} \int_{r_{i,j}}^{r_{i,j}} \left( \nabla^2 Z_j + \frac{\partial Z_j}{\partial r} \delta(r - R) \right) r \partial r \partial \theta
\]

Equation 5-8

where \( \theta_{i,j} < \theta < \theta_{i,j} \) and \( r_{i,j} < r < r_{i,j} \) define the boundaries of the segment \( i \) and \( R \) the pupil radius of the curvature sensor.

The first term is:

\[
\int_{\theta_{i,j}}^{\theta_{i,j}} \int_{r_{i,j}}^{r_{i,j}} g(\theta) \delta \theta \int r \cdot f(r) \partial r
\]

Equation 5-9

The second term is:

\[
\int_{\theta_{i,j}}^{\theta_{i,j}} \int_{r_{i,j}}^{r_{i,j}} \left( \partial Z_j \frac{\delta(r - R)}{\partial r} \right) r \partial r \partial \theta
\]

Equation 5-10

which is equal to:

\[
\begin{cases} 
\int_{\theta_{i,j}}^{\theta_{i,j}} \left. \frac{\partial Z_j}{\partial r} \right|_{r=R} \partial \theta, & \text{for } R \in \left[ r_{i,j}, r_{i,j} \right] \\
0, & \text{otherwise}
\end{cases}
\]

Equation 5-11

The output of the curvature sensor, \( \Psi \), can then be obtained by multiplying the matrix \( M \), whose lines are mirror segments and columns the coefficient for curvature for each Zernike mode, by the coefficients of the turbulence in the Zernike basis:

\[ \Psi = M \Phi \]

Equation 5-12

In order to implement a realistic control approach an intermediate computation shall be introduced so that the control is done in sensors’ measurements space. This is accomplished recurring to an interaction matrix whose columns correspond to the signal sensed at a single element when a known value is applied recursively to each DM sector. This interaction matrix permits as well to objectively inspect the actuation influence in each sensor. One uses consequently a matrix with dimensions [number of DM segments x number of sensors].
Figure 9 – Visualization of the interaction matrix used.

Figure 10 – Interaction matrix.
Here the pattern is depicted in three dimensions. It is possible to identify lines where the interaction is stronger. These lines correspond to adjacent segments.

The diagonal (squares in blue) show that a signal applied to an actuator affects practically only the sensor it is associated with.
6 Control Loop

6.1 Control Unit

6.1.1 Objective

The control unit is intended to compensate the atmospheric turbulence, causing the phase error (defined as the difference between the incoming WF and the corrected WF) to be attenuated and to achieve a null value at the end of each iteration period. It must be remarked that the discrete implementation procedure, referred below, has a delay of two iteration periods: the first corresponding to sensing the distorted WF and the second to compute the new electric voltage to apply to the DM, just before another measurement takes place. This fact imposes special conceptual attention and justifies the use of predictive instruments as the turbulence generator or the Kalman filtering.
6.1.2 Control method

The control method used in compensating WF distortions can be either accomplished considering a modal compensation algorithm [6] or considering the compensation of the WF curvature as sensed at each mirror segment – zonal control.

The Adaptive Optics Simulator uses the second approach, being the control voltages computed in order to attenuate the curvature in each of the sixty deformable mirror segments for which it as been designed. This option was considered since the decomposition of wavefront surface as sensed in 60 different elements in Zernike polynomials would require the transformation of measurements space back to Zernike modes space. However, optimal algorithms may oblige to the introduction of control compensation of Zernike modes [7].

6.2 High Voltage Amplifier

The High Voltage Amplifier is intended to amplify low-voltage signals at the output of the Control Unit to levels which permit the actuation of the DM itself. Its model was created because at the frequencies of the closed-loop its dynamic presented already a valuable influence that could not be neglected.

6.3 Deformable mirror

Deformable Mirrors (DM) are the most common and suitable group of phase controllers for AO systems.

In general, a physical force is applied to a reflecting surface which causes the DM surface to reshape, which permits exactly to change the optical path length.

There are many different DM. For instance, DM with baseplate or DM without it. The former can use segments or a continuous facesheet. The later are known as bimorph DM.

6.3.1 Bimorph deformable mirrors

The use of this specific type of DM is nowadays very common. Its principle of functioning consists of two passive layers glued to a piezoelectric material. When an electrical voltage is applied the material expands or retracts parallel to the passive layers. This causes a bending moment responsible for the reshaping of the DM.

This device has many attractive features: 1. It has a continuous facesheet; 2. it is a modal device and therefore suited to low-order applications; 3. it is not a power-consuming device when compared to other equivalent systems.
6.3.2 Spatial structure

The spatial structure is proportionally the same as that used for the WF sensor. This allows sensing the WF correction imprinted by one DM actuator (which basically results in the interaction matrix stated above).

6.4 Discrete space-state model

The control unit was conceived in discrete time, since all the control will be implemented in digital form using a RTC.

Since the DM and the HVA dynamics are naturally described in continuous time it will be necessary to obtain their discrete time equivalents. For a general state-space continuous time system:

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
Y &= Cx + Du
\end{align*}
\]

Equation 6-1

The correspondent discrete time model is:

\[
\begin{align*}
[x[k+1] &= \Phi x[k] + \Gamma u[k] \\
y[k] &= Cx[k] + Du[k]
\end{align*}
\]

Equation 6-2

With:

\[
\Phi = e^{At}
\]

\[
\Gamma = \int_{0}^{T} e^{At} \cdot Bdt
\]

Equation 6-3

The complete derivation of the corresponding discrete space-state model can be found at [12].

Both the DM and the HVA dynamics will be modelled as first order systems with a -3dB bandwidth of 5 kHz, with independent channels. The control loop runs at frequencies around 1 kHz.

6.5 Implementation Procedure

For a continuous model in the form:
the equivalent continuous model is

\[
\dot{x} = -px + pu
\]

\[
y = x
\]

Equation 6-5

Where \( y \) is the output, \( u \) the input, \( x \) the vector state with dimension 60 and \( p = 2\pi 5 \times 10^3 \).

It is finally found the complete discrete model to be:

\[
\Phi = e^{-pT} \cdot I \quad \Gamma = 1 - e^{-pT} \cdot I
\]

\[
C = I \quad D = 0
\]

With \( I \) the Identity matrix with dimensions [60x60]

The coefficients found were kept as part of a simulation ------ Introduce the corresponding bode plots to justify the option taken.

For further information refer to [9, pp 20] and [10].

6.5.1 Control Unit
6.5.2 High Voltage Amplifier

Figure 14: HVA block implementation and parameters

6.5.3 The Deformable Mirror

Figure 15: DM block implementation and parameters
7 The Kalman Filter

7.1 Objective

The Kalman filtering was implemented in order to enhance the performance of the Adaptive Optics Simulator. Its use is based upon the need to foresee the atmospheric turbulence evolution in at least two iteration periods, one for the sensor acquisition and another to the control actuation. For the moment this feature is not implemented. The present work focuses to attain a functioning model.

7.2 Implementation Procedure

For the Kalman filter the following expressions were used [2, pp 60 to 63]:

\[
\hat{X}_{n/n} = \hat{X}_{n/n-1} + H_n (Y_n - D\hat{X}_{n/n-1})
\]

Equation 7-1

\[
C_{n/n} = C_{n/n-1} - C_{n/n-1} D^T (DC_{n/n-1} D^T + C_{obs})^{-1} DC_{n/n-1}
\]

Equation 7-2

\[
H_n = C_{n/n-1} D^T (DC_{n/n-1} D^T + C_{obs})^{-1}
\]

Equation 7-3

\[
\hat{X}_{n/n-1} = AX_{n-1/n-1}
\]

Equation 7-4

\[
C_{n/n-1} = AC_{n-1/n-1} A^T + C_{KOL}
\]

Equation 7-5
Figure 16: Kalman filter – main system

Figure 17: Subsystem 1 block diagram
III  Simulator usage

In order to have a more pleasant interface to the simulator a graphical user interface was developed.
Figure 20 shows its graphical aspect.
1 Simulator description

The simulator consists of two separate groups. The “Initial Conditions” and the “Simulation Parameters”. They are described below.

1.1 Initial conditions

In this group the user is asked to define the conditions of simulation. These conditions must strictly be set before the simulation takes place. They correspond to physical parameters on which the simulation is based upon, that have precedence with respect to the “Simulation Parameters”.
1.2 Simulation parameters

These user-defined parameters affect the simulations itself. AO Simulator V1.0 enables to configure Turbulence Generator, Observation Noise and Control Unit parameters. Next version will permit to configure many more parameters.

2 Simulator usage

By default when the user starts the AO Simulator V1.0 has the most common values fulfilled in the fields. Any change is automatically updated.

2.1 Steps for the simulation

The user must follow these three steps correctly:
1. Set Initial Conditions;
2. Simulate;
3. Use the plot feature.

After the completion of these three steps the order on which the commands are used is indifferent.

IV Simulation results

1 Parameters of the Turbulence generator

10 Zernike modes
V/D =2Hz
DM Segments: 60
Zernikes Selection: all

Figure 21 – First 10 Zernike modes
If one takes a close look to the z coordinate scale it is possible to perceive the decrease of power associated to each mode, according to Equation 4-10.
Figure 26: Simulation without Kalman filter

Figure 27: Simulation with the Kalman filter
V References


10. ESO - Very Large Telescope – Electronics, DM Control [VLT-TRE-ESO-15600-2271]

