# Comparison of different adaptive optic systems involving the same mirror

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More and more applications need a high precision controlled wavefront. A lot of scientists declare that λ/10 PV is now the objective for their beam quality. An adaptive closed loop has been designed with the aim of correcting wavefront with a maximum error of λ/10.

Such a performance can be realized by using a mirror which is capable to control its shape with this accuracy and using a wavefront sensor with this same absolute accuracy. A 16x16 Hartmann-Shack sensor has been used to control a 48 piezo actuators mirror. The static wavefront has been corrected with an accuracy better than λ/10 PV. By controlling curvature on the mirror, we obtain a precision of λ/5 PV.

The results obtained 5 years ago with another wavefront sensor and the same mirror will be compared with these last results showing that a good wavefront sensor is the key in high precision adaptive close loop. Moreover, we will show that this same mirror has been controlled using an interferometer. The results are less good than those obtained with the 16x16 Hartmann-Shack sensor.

The best solutions for controlling adaptive mirror and the timing performance obtained on a PC will be discussed. Using an atmospheric perturbations simulator, we measured the shape of the focusing point with long exposure duration. The gain on the Strehl Ratio will be presented.

## 1 Overview

Since 1998, Imagine Optic sell Shack-Hartmann WaveFront Sensors (WFS) as standard products. They are used in Laser characterization, for lens testing …etc…

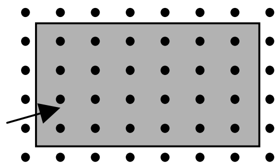
Early 2001, a customer asked for an adaptive optic (AO) system involving a CILAS mirror and our wavefront sensors. Afterall, we discovered that this mirror was involved in many AO systems before. We decided to compare the results obtained by people using this mirror.

After a description of the mirror, we will review the results obtained by CILAS while controlling the fabrication of the mirror, we will describe the first closed loop made. Then, we will discuss the setup we chose and the results we obtained using one of our wavefront sensors.

## 2 The CILAS mirror : SAM 48

This mirror was manufactured by the CILAS company in 1995 for the CEA (the French atomic commission). It was bought for the SILVA project, its aim is the uranium isotopes separation by laser.

This mirror is a 8 by 6 push-pull piezo-electric actuators, the pitch between actuators is 9.5mm. The applied voltage ranges from –400V to +400V. A cooling system was designed in order to use this mirror with high power laser.



### *2.1 The tests at CILAS*

The sensitivity of the actuators

A Digital Analog Converter (DAC) board is plugged in a PC. A sine function is applied to a channel. A high voltage power amplifier is used to apply +/- 100 V to the mirror. A mechanical sensor measure the movement of the surface of the mirror exactly in the center of the actuator.

The Sine function is used in order to decrease the measurement noise.

When an average is done on all the actuators, a sensitivity of **3.94 nm/V** is measured.

The dispersion on all the actuators is about **+/- 5% PV.**

The influence of the neighborhood actuators

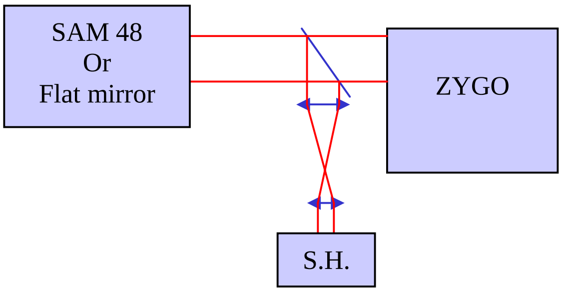
The same setup is used in order to measure the influence function. The mechanical sensor is placed not only in front the actuator, but also in front of the nearest actuators.
Let us suppose that the movement of the controlled actuator is 100%.
The movement of the **8 nearest actuators is 35 %.**
The movement of the **other actuators is below 5 %.**
These figures show that the influence function is narrow. A comparison can be done with bimorph mirror : when an actuator is controlled in the center of the mirror, all the shape of the bimorph mirror change.

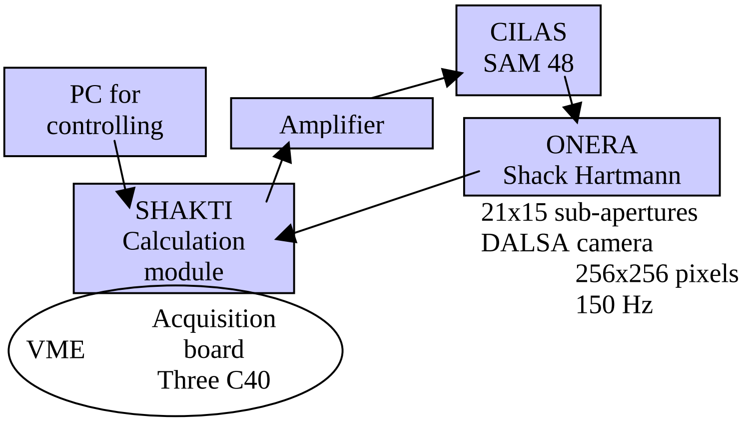
The flatness of the mirror at 0V

A ZYGO interferometer is used to measure the flatness of the mirror.
The shape of the mirror is almost only curvature with **0.5 micron Pic to Valley** (PV).
When this mirror was manufactured, all the influence functions were saved using the interferometer, but no closed loop was used to measure the best flatness of this mirror.

## 2.2 *The adaptive optic closed loop by the CEA*

The SAM48 is placed in front of a ZYGO interferometer, A telescope and a beam splitter are used to adjust the size of the beam for the he WFS. The pupil conjugaison (surface of the mirror / microlenses array) is also adjusted.





The WFS is a 21 x 15 subpupils Shack-Hartmann. The slopes of the wavefront and the voltages are calculated by processors boards based on a VME structure.

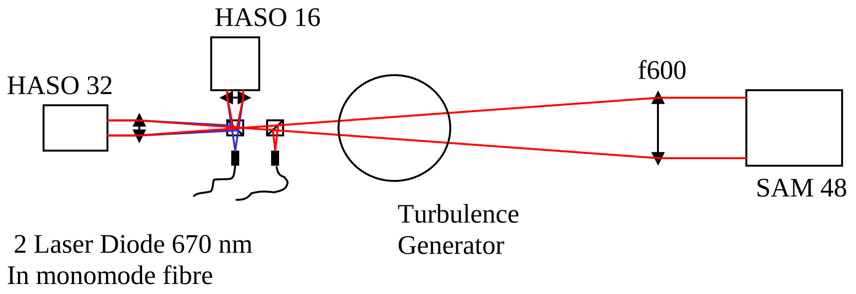
With this setup, the following results were obtained :
Best flatness of the mirror : **60nm PV**
Cutting frequency : **3Hz**

- The flatness of the mirror is quite good but the residual of the wavefront is almost only curvature which is a very low spatial frequency. This result could not be explained at this time : it was not possible to know why the mirror could not adjust its shape to correct curvature. The scientists assumed that the WFS or the closed loop software were responsible of this error.
- The low cutting frequency was forecasted and the scientists proposed to increase the number of processors and decrease the size of the CCD in order to increase the cutting frequency. Finally, this upgrade was abandoned because of the difficulties to upgrade the VME structure.

They decided to change the WFS and chose an Imagine Optic one. In order to simplify the structure, they asked us to build a closed loop on a PC.

# 3 The Imagine Optic closed loop

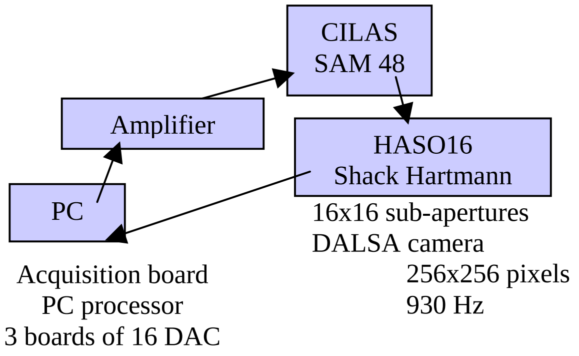
## 3.1 Adaptive optics components



For the WFS, we chose the HASO16 which is a 16x16 microlenses Shack-Hartmann WFS based on 256x256 pixels CAD6 DALSA camera. This WFS is a standard product at Imagine Optic. A fibered laser diode, a beam splitter and a lens are used to light the mirror. The beam travels through the same lens, through the beam splitter and is collimated by a small lens to finally light the HASO16.
To analyze the beam, we use another beam splitter, another lens and another standard WFS : the HASO32, which is a 32x32 microlenses based on 512x512 pixels CAD8 DALSA camera. This WFS have an accuracy in measuring wavefront better than $\lambda/100$ rms. Its spatial resolution is twice better than the WFS used to close the loop. Its maximum speed is 77 Hz.
The reference beam comes from another fibered laser diode, at the focus point of the two small lens near the two WFS.

This setup allows us to acquire the same reference for the two WFS. The aim of the closed loop is then to have the best point after the turbulence generator and not the flattest mirror as possible.
A soldering iron is used to make atmospheric turbulence on the beam. Its position under a converging beam allows us to adjust the spatial frequency of the turbulence in the pupil by translating the soldering iron along the beam.

## 3.2 Computing environment



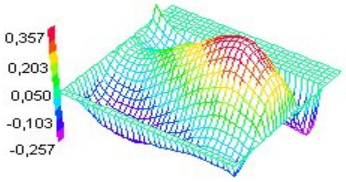
In order to decrease the cost and the system complexity, we decided to use a single PII 800 MHz processor of a PC under Windows NT.

We reached a frequency of 300 Hz while acquiring the image, calculating the slopes and applying the voltages.

## 3.3 Spatial AO system performance

First, in order to measure the quality of the closed loop, the turbulence generator is switched off. A reference is acquired. A response matrix is acquired by pushing and pulling each actuators of the mirror. This matrix is then inverted by a SVD decomposition to obtain the command matrix. When the loop is closed, this command matrix is used with the local slopes given by the HASO16 to obtain voltages.

**0 V applied**

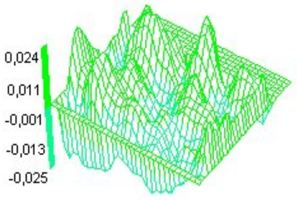


PV = 600 nm
+ 800 nm curvature

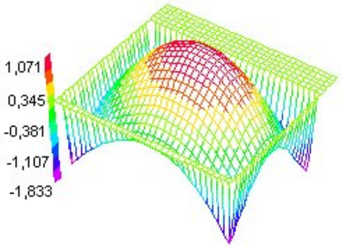
<u>These results are given by the HASO32.</u>

The mirror adjusts its shape with an accuracy of 25nm PV. About 1.5 micron of curvature and astigmatism are corrected.

**The loop is closed**



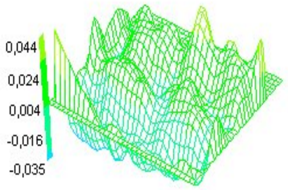
**PV = 50 nm**



PV : 3 microns

The reference is defocused.

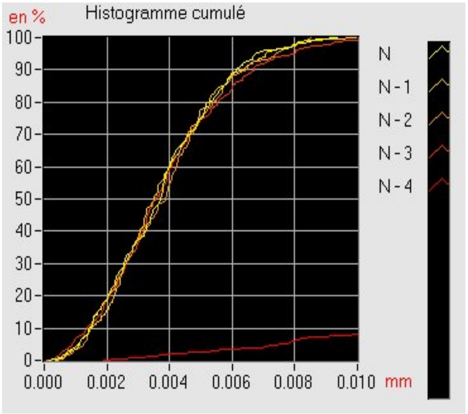
The mirror adjusts its shape with an accuracy of 40nm PV. About 3 microns of curvature are corrected.



**PV : 80 nm**

This result shows that the mirror manage to adjust its shape with an accuracy of 25nm PV without any low spatial frequency in the residuals. Because the HASO16 measures wavefront with an accuracy of 50nm PV, the loop can be closed with this same accuracy.
The CILAS SAM48 is confirmed to be an excellent mirror.

## 3.4 *The number of steps needed to reach the reference*



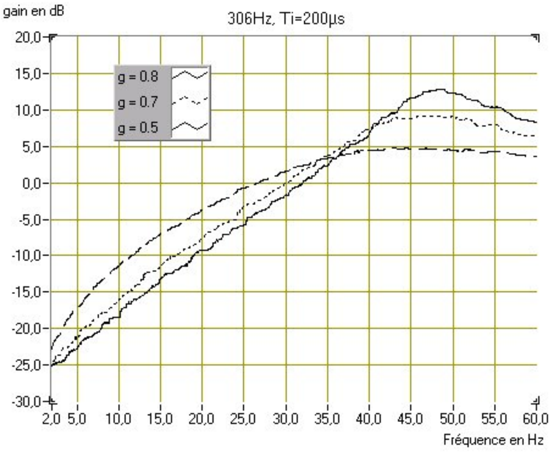
This graph represents the enclosed energy (in %) for a increasing radius (in mm) of the focus point. These curves are calculated from the local slopes measured by the HASO32 during the five firsts steps of the loop.
The curve at the bottom represents the enclosed energy measured before the first correction. The next four measurements are exactly at the same place showing **that the reference is reached after only ONE STEP**.

These measurements were made after slowing down the loop to be stable with a gain value of 1 (the applied voltages are exactly those calculated).

## 3.5 *Timing AO system performance*

This graph shows the rejection bandwidth of the atmospheric turbulence. Three curves are drawn for three different gains of the loop. The frequency is 300 Hz.

**The cutting frequency is 32 Hz** with a maximum gain of 0.8 before unstability.



# 4 Summary

We show that a good wavefront sensor is the key of high performance close loop. It is now possible to reach the reference with only one step, and to control mirror with an accuracy of 25 nm PV on its shape.
The performance of the PC processors are now enough to include such processor in adaptive optic systems. A cutting frequency of 32 Hz was reached with a 16x16 microlenses WFS and a 48 actuators mirror.
Another wavefront sensor with a higher resolution than that one used to control the mirror, is a perfect tool to analyze and characterize a closed loop (in time and space domain)

# 5 Acknowledgments

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