PERFORMANCE AND RESULTS OF THE NAOS VISIBLE WAVEFRONT SENSOR

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Abstract: The NAOS adaptive optics system was installed in December 2001 on the Nasmyth focus of the ESO VLT. It includes two wavefront sensors: one is working at IR wavelengths, the other at visible wavelengths. This paper describes the NAOS Visible Wave Front Sensor based on a Shack-Hartmann principle. This wavefront sensor unit includes: 1) a continuous flow liquid nitrogen cryostat and a low noise fast readout CCD camera controlled by the ESO new generation CCD system FIERA using a fast frame rate *EEV/Marconi CCD-50*. This 128 x 128 pixels split frame transfer device has a readout noise of 3 e- at 50 kilopixel/sec/port. FIERA provides remotely controlled readout modes with optional binning, windowing and flexible integration time. 2) two remotely exchangeable micro-lens arrays (14x14 and 7x7 micro-lenses) cooled to the CCD temperature (-100 ˚C). The CCD array is directly located in the micro lenses focal plane, only a few millimeters apart without any relay optics. Additional opto-mechanical functions are also provided (atmospheric dispersion compensator, flux level control, field of view limitation). On sky performances of the wavefront sensor are presented. Adaptive Optics corrections was obtained with a reference star as faint as visible magnitude 17. The maximum achievable band-path is 35 Hz at 0 dB for the open loop transfer function.

Key words: CCD, low noise, camera, adaptive optical system, wavefront sensor, Strehl Ratio, microlenses, cryostat.

1. INTRODUCTION

NAOS, fully described in Ref. 1 and Ref. 2, is the Adaptive Optics (AO) system of the ESO Very Large Telescope (see Figure 1). Installed at the Nasmyth focus of the VLT, NAOS is the AO system for CONICA (see Ref. 3), the science infrared camera. NAOS will provide diffraction limited images in the 1-5 µm wavelengths range. NAOS has been designed and manufactured by a French consortium (ONERA, LAOG and Observatoire de Paris).

The deformable mirror with 185 useful actuators compensates the atmospheric disturbance measured by two Shack Hartmann wavefront sensors (WFS), one covering the visible wavelengths and the other covering the infrared. This paper describes the visible wavefront sensor and its CCD camera. NAOS is mounted on the telescope adapter rotator and rotates with the telescope field rotation. Therefore, the structure stiffness of the whole instrument is critical for the final performance of the instrument. The opto-mechanical path of the wavefront sensing channel requires special care to avoid flexure which may highly contribute to an image quality degradation.

The sensitivity of the whole NAOS instrument is highly dependent on the wavefront sensor performance. The visible WFS for NAOS uses a 128x128 pixels low noise CCD fabricated by EEV/Marconi with 16 output ports to allow a high frame rate (up to 500 frames/sec) and low noise (3 e^-).

Figure 1 : NAOS-CONICA mounted on the Yepun telescope (left) and the VLT Platform at Paranal just before the NAOS first light in November 2001 (right).

2. NAOS AND VISIBLE WAVEFRONT SENSOR PRESENTATION

A set of dichroic beam splitters allow to share the NAOS incoming light between the scientific path (CONICA) and the wave-front sensing path. The reflected part of the light is redirected to the wave-front sensors.

A field selector, composed of two parallel mirrors placed in the F/15 beam, chooses the reference star for wavefront sensing apart from the scientific observed object. The description of the field selector is given in Ref. 4. Then a mirror selects the required Shack-Hartmann wavefront sensor, either IR or visible WFS.

The visible wavefront sensor is basically made of a cooled CCD camera including 2 lenslet arrays that can be remotely exchanged and one opto-mechanical bench located at the cryostat outside. The different elements of the visible wavefront sensor are shown in the Figure 2.

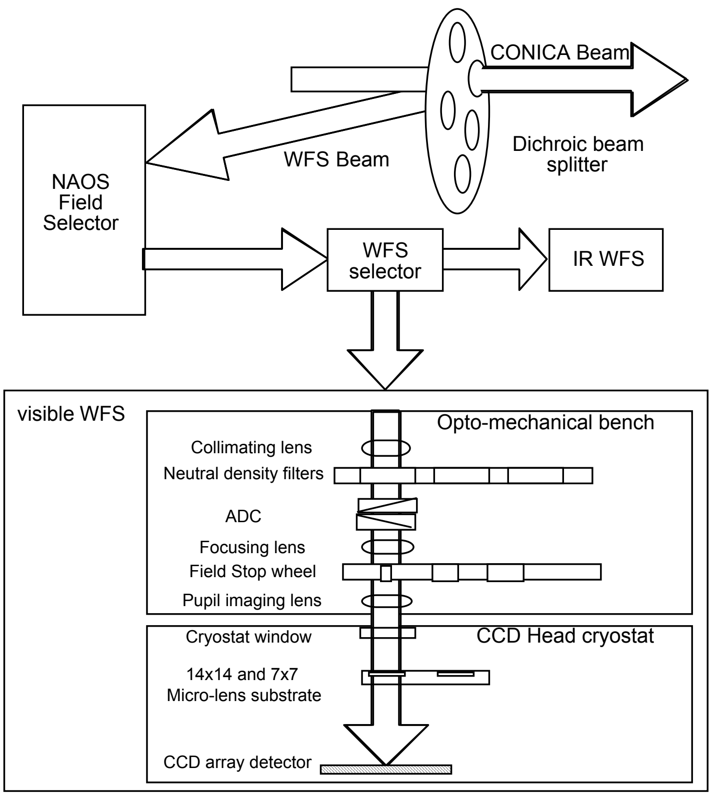


Figure 2: Block diagram of NAOS and of the visible wavefront sensor.

3. THE LOW NOISE READOUT CAMERA

The Visible WFS Detector System (see Ref. 5 and Ref. 6) is split into 3 main parts: the CCD detector, the cryostat and the CCD controller.

3.1 The EEV/Marconi CCD-50 description and architecture

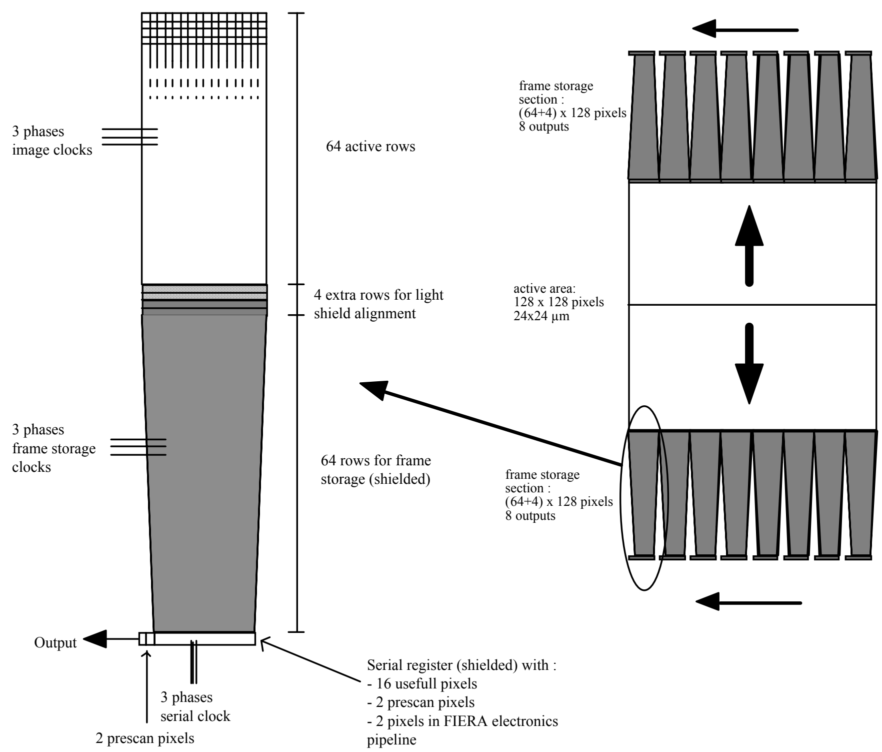


Figure 3: detector architecture of the 128x128 CCD (bottom).

The CCD used in the NAOS project was manufactured by EEV/Marconi based on a contract with ESO.

This CCD is a split frame transfer CCD with a light sensitive area of 128x128 pixels and a pixel size of 24 µm. The 2 storage sections are light shielded. Additional 4 rows on each storage section compensates if the light shield is misaligned. The charge is shifted to each 8 output amplifiers on the bottom and top side. Therefore, the CCD is partitioned into 16 sections with one amplifier per section (see Figure 3).

A subsection of the CCD with 16 x 64 pixels of the image zone, the corresponding storage section and the serial register are also shown on this figure. All of these sections of the CCD are clocked in exactly the same way. Because of the lenslet array configuration (14x14 or 7x7 sub-apertures), only 14 of the 16 CCD outputs are used for NAOS.

3.2 The FIERA CCD Controller

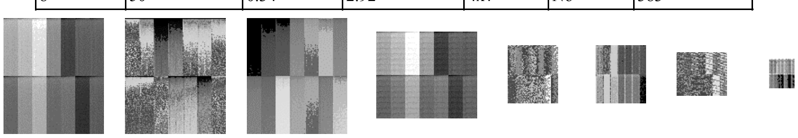
3.2.1 Presentation

ESO has built an universal CCD controller able to drive a variety of "new generation" CCD. This system is called FIERA (Fast Imager Electronic Readout Assembly). The requirements for the FIERA CCD Controller are briefly summarized hereafter:

- System noise negligible compared to the readout noise of the CCD amplifier.
- x2 and x4 binning capability, windowing capability
- Up to 2 Mpixel/sec operation
- 16 simultaneous video outputs can be managed. On NAOS, we use 14 A/D converters 16 bits/1 MHz
- Cross-talk between channels of the CCD controller must be negligible - less than 1 bit or less than the CCD readout noise.

3.2.2 The CCD readout modes and noise performances :

Mode Number	Pixel rate (kpixels/s)	Gain (adu/e-)	Measured Noise (e-)	Binning	Windowing	Max Frame Rate (Hz)
1	280	0.34	3.9	1x1	No	209
2	635	0.33	5.4	1x1	No	444
3	635	2.1	6.9	1x1	No	444
4	280	0.35	3.9	1x1	6x6	277
5	50	0.34	2.9	2x2	No	136
6	280	0.36	4.3	2x2	No	587
7	50	0.34	2.98	2x2	6x6	133
8	50	0.34	2.92	4x4	No	383



Mode 1 Mode 2 Mode 3 Mode 4 Mode 5 Mode 6 Mode 7 Mode 8

Table 1: List of readout modes for the NAOS visible wave-front sensor and readout noise performance measured on the VLT telescope. CCD dark images are also shown.

Each readout mode defines the following parameters: windowing, binning, conversion gain (in e-/adu) and frame rate. We need several readout mode for the following reasons:

- we have to match the readout mode with the micro-lens array configuration (7x7 or 14x14 micro-lenses).
- the readout noise has a strong impact on the NAOS performance in terms of sky coverage. Because the readout noise decreases with the pixel frequency, the CCD readout is designed to skip the unused pixel, either by binning or by windowing. Then the pixel frequency can be reduced. Table 1 shows the list of readout modes that are effectively used in NAOS. Also shown in this table is the noise performance of the CCD camera measured on the VLT telescope, demonstrating the very low noise with this system.

3.3 Cryostat flexures

The specifications concerning the cryostat flexures when the system is rotated are very strict. Flexure tests were performed using a rotating table allowing a full 360° rotation to simulate the NAOS adapter rotation during the astronomical observations on the telescope.

Cryostat flexures as low as 2 microns (peak to peak for one complete turn) of the inner part of the cryostat compared to the outer part was measured and 0.1 microns in the same conditions for the micro-lenses displacement compared to the CCD, demonstrating a remarkable stiffness of the cryostat and of the micro-lens arrays exchange mechanism (see Ref. 6).

3.4 Lenslet array alignment

The 2 lenslet arrays are aligned with respect to the CCD with the following specifications :

- X and Y lenslet location (CCD) accuracy : 2 µm
- parallelism CCD/lenslet array : 2 µm from one side of the lenslet to the other

An image of the aligned spots obtained at cold temperature with the 2 lenslet arrays is shown in the Figure 4. From these images, we computed the location of each spot by measuring the centroid of each spot and hence we deduced the overall lenslet alignment accuracy in location and parallelism.

The two lenslet arrays can be exchanged at cold temperature with a re-positioning precision of 2 µm (RMS).

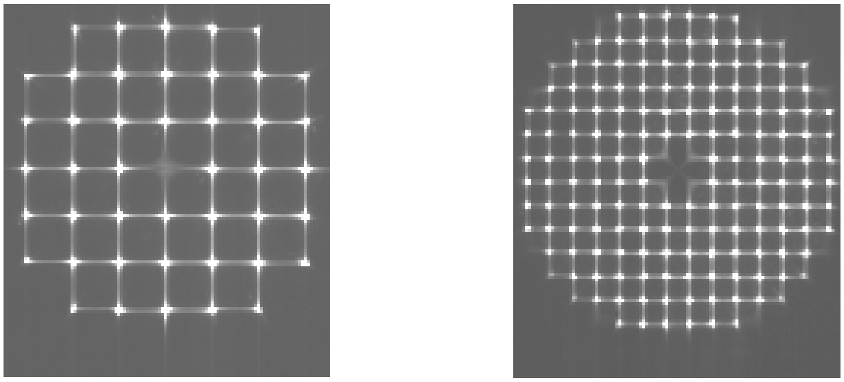


Figure 4: (right) image of the spots with the 14x14 lenslet array at cold temperature, micro-lenses aligned; (left) same image with the 7x7 lenslet array.

4. RESULTS ON THE VLT TELESCOPE

NAOS, including all its subsystems like the visible wavefront sensor, was installed on the VLT *Yepun* telescope unit by mid-november 2001, as well as the scientific infrared camera CONICA. NAOS and CONICA obtained their first light on the VLT by November 25th 2001 during the first commissioning period. The excellent performances of NAOS and of the visible wavefront sensor allows very high Strehl ratio as it is shown in the Figure 5 :

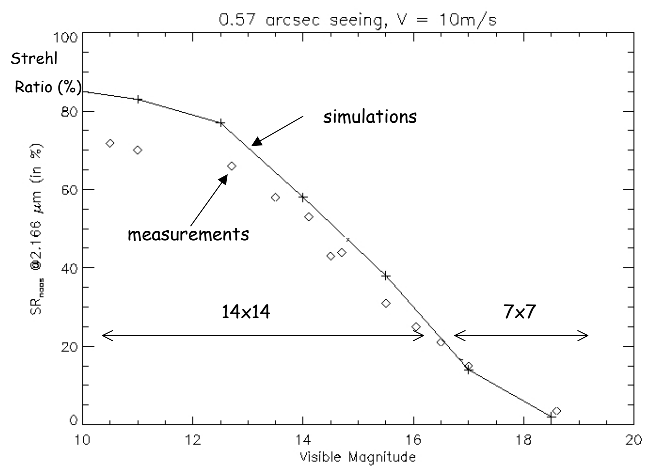


Figure 5: Strehl Ratio of NAOS and CONICA using the visible wavefront sensor. Simulations and measurement in the laboratory are shown at the same time in the figure, as well as the micro-lenses configuration (7x7 or 14x14). The seeing was 0.57 arsec, the wind speed 10 m/s,

and the Strehl Ratio is measured using a narrow band filter at 2.166 µm with the CONICA science camera.

At low visible magnitude, Strehl Ratio up to 70% can be obtained, whereas close-loop AO operation was demonstrated with natural guide star as faint as magnitude 17, as shown in the Figure 6. These two properties (High Strehl ratio and close-loop with very faint stars) demonstrate the remarkable qualities of the NAOS visible wavefront sensor and of its CCD camera.

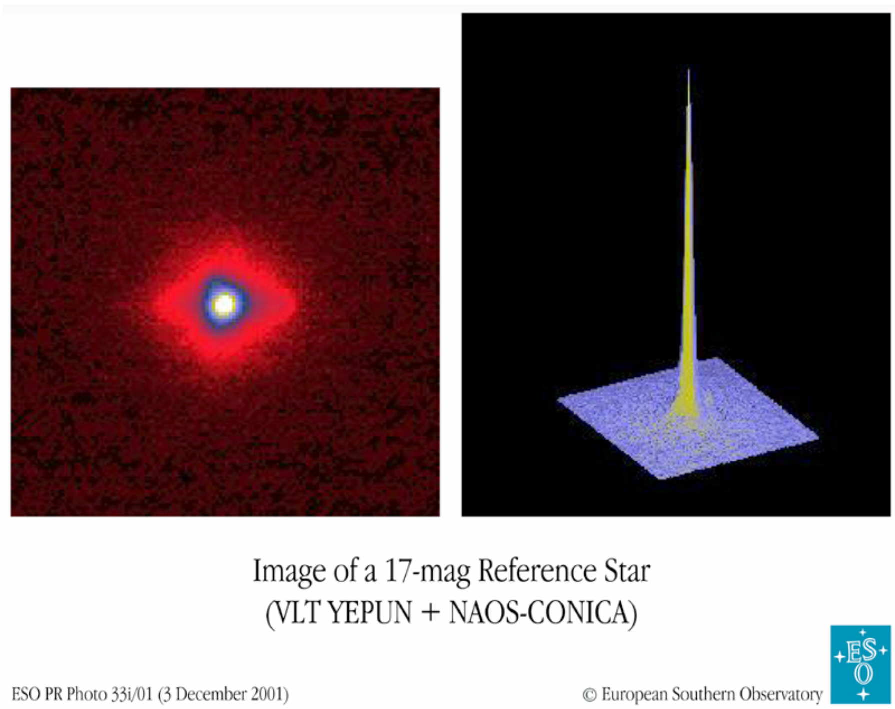


Figure 6: with the visible wavewront sensor, NAOS was able to close the loop using a 17-magnitude reference star just one week after the NAOS first light on the VLT (November 25, 2001).

The maximum achievable band-path is 35 Hz at 0 db for the open loop transfer function. This was measured in the laboratory using readout modes at 444 Hz corresponding to the lowest magnitudes of the Figure 5.

5. CONCLUSION

The NAOS visible wavefront sensor, based on the Shack-Hartmann principle, was built in a strong collaboration between the ESO Optical

Detector Team, the Observatory of Grenoble and ONERA. It demonstrated excellent performances due to the simultaneous qualities of the EEV/Marconi CCD chip, of the ESO/FIERA camera and the mechanical stiffness. Despite of the possibility to exchange remotely the 2 lenslet arrays on the sky inside the cryostat at cold temperature, the mechanical properties of the wavefront sensor in term of stiffness and re-positioning accuracy are remarkable. Also the possibility to obtain a very low readout noise with fast frame rates gives the NAOS AO system the possibility to have high Strehl ratios and closing the loop with very faint reference stars increasing the sky coverage with visible natural guide stars. NAOS will be offered to the astronomical community by autumn 2002.

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