CCD wavefront sensing system for the ESO Multi-conjugate Adaptive Optics Demonstrator (MAD)

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MAD's mission is to demonstrate the feasibility of Multi-Conjugate Adaptive Optics (MCAO) on the sky as a pre-requisite for the 100-m OWL telescope as well as several 2nd Generation VLT Instruments. It aims at comparing the relative merits of different methods and, therefore, employs alternatively multiple Shack-Hartmann and layer-oriented wavefront sensors requiring 3 and 2 detector units, respectively. The 5 detector heads will be identical and equipped with CCD50 devices from Marconi, which have already been successfully tested with the VLT AO instrument NAOS-CONICA[1] (see also [2]). ESO's standard CCD controller FIERA will be utilized in its new version upgraded to a PCI bus board. Major challenges lie in the very restricted space available for the heads, the low weight allowance on mobile probes, the opto-mechanical coupling, stringent noise requirements in the presence of limited options for cooling and high demands on the frame rates, and the high data transfer rates to the real-time computer. At the same time, as for all VLT instruments, a maximum compatibility with existing hard- and software standards must be maintained. The adopted solutions will be described and discussed.

Introduction

The MAD project aims at demonstrating the Multi-Conjugate Adaptive Optics (MCAO) capabilities by building a prototype to be tested at the VLT visitor focus (UT3). The instrument will use 3 to 8 natural guide stars and laser guide star, so as to achieve a high-Strehl PSF over a field of view of 2' in the K band (Figure 4). Two concepts will be tested with this prototype. The first technique is the Shack Hartmann MCAO that uses an asterism of 3 stars in the visible domain. Each star's wavefront is measured independently with the shack Hartmann method by a high speed CCD camera coupled with an array of microlenses. A global wavefront reconstruction scheme is applied to deformable mirrors (Figure 1). The correction across the field of view can be optimised for specific directions.

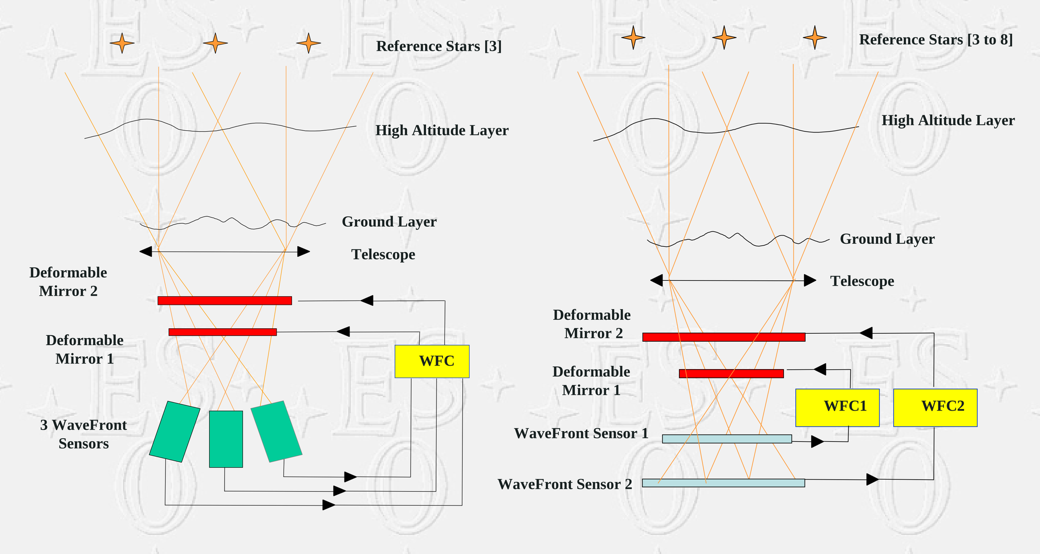

Figure 1 : Left, the Star oriented MCAO, right the layer-oriented MCAO concepts.

The second scheme is called the layer-oriented approach : The wavefront is reconstructed at each altitude independently. Each wavefront CCD sensor is optically coupled to all the others. The pyramid wavefront sensor conceived in 1995, offers a practical and compact solution to the optical design. Layer-oriented AO can also be coupled to laser guide Stars.

The goal of the MAD instrument is to determine which approach between the layer-oriented MCAO (LOWFS) and the Shack Hartmann MCAO (SHWFS) is the best for future MCAO systems. MAD is the ESO laboratory and sky tool for MCAO techniques. This is also an important milestone to pass for the design of VLT 2nd generation instruments, towards OWL instruments.

The CCD system concept

As a fast track project, the key word is to re-use as much as possible previous parts and sub systems that have been used for other instruments like NAOS (wavefront sensors) and SINFONI (Optics and deformable mirrors).

The requirements for the CCD system are broken down into 59 items. The system architecture is depicted in Figure 2, and the heads environment in Figure 4.

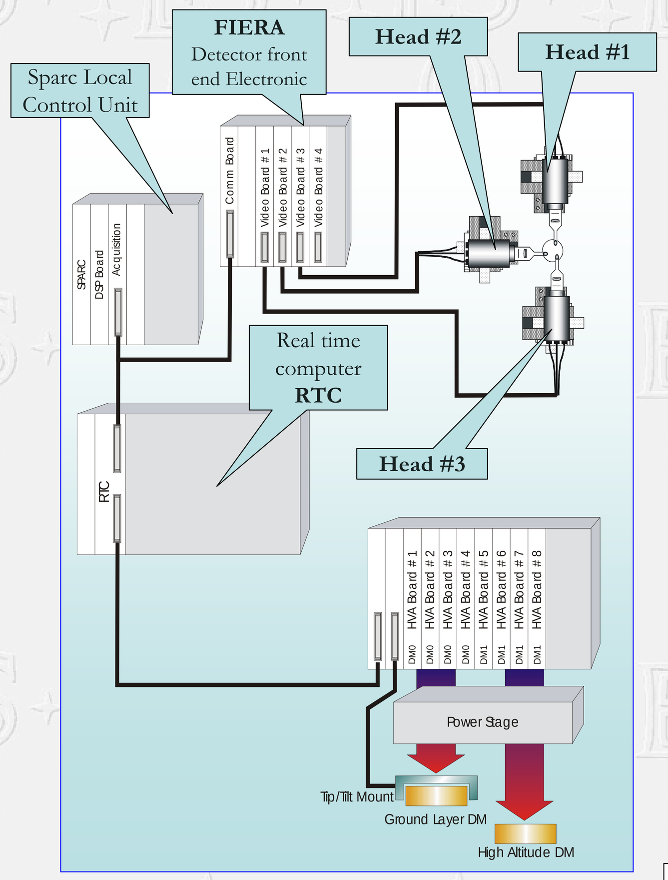

Figure 2 : The overall system architecture (SHWFS). The LOWFS has the same architecture, except that two heads are considered instead of 3.

Main system features :

- 3 CCD heads for SHWFS
- 2 CCD heads for LOWFS
- SHWFS and LOWFS systems are running separately
- Using a single FIERA controller
  - 12 video inputs
- CCD Head must be compact
  - 90x60x40 mm
  - No LN2 cooling
  - Design of new heads
  - Light : 500g
- Mounted on XY stages
  - Find the star to sense the wavefront
  - Cable length and stiffness requirements : soft cables
- Low noise and high speed
- Embedded micro lens array (SHWFS)

All the optical setup is mounted on a table at the VLT Nasmyth platform. The 3 heads for the SHWFS must move on a XY table to pick up a star across a 2' field of view. By contrast, the LOWFS CCD system is attached to its dedicated optics. All the CCD heads need flexible cables for clocks, bias and video that are attached to the FIERA controller.

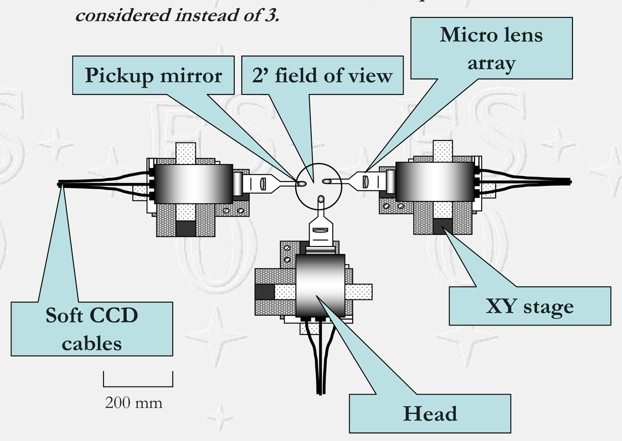

Figure 4 : Close up to the CCD heads, SHWFS configuration

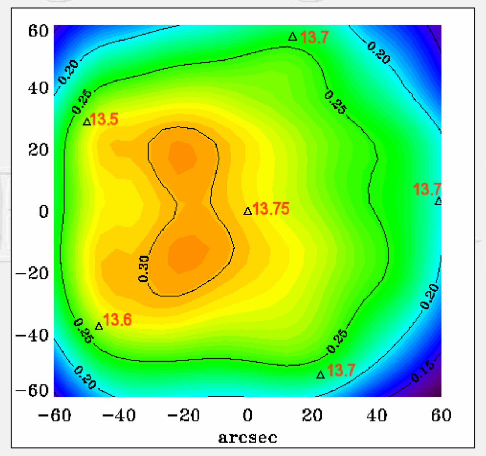

Figure 3 : 2 arcmin field of view with 6 stars : expected Strehl ratio across the field. Star positions (triangles) and magnitudes (red figures) of stars used for MCAO correction. LOWFS system.

The detector

The MAD project is a fast track project, and the CCD procurement is always on the critical path. Since CCD procurement could lead to unacceptable time overhead, it has been decided, as a best trade off, to use a CCD that ESO knows very well. Moreover, ESO has several of them in stock : the Marconi AO CCD50 (Figure 5). This device has already been used for the NAOS project as wavefront sensor and has delivered satisfactory performance.

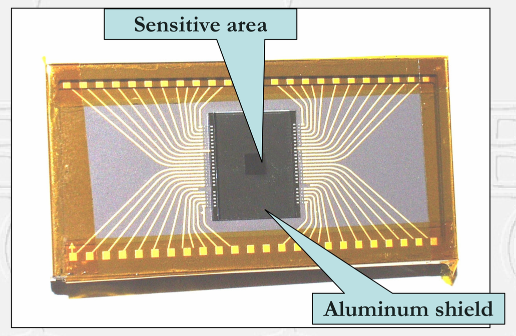

Figure 5 : Marconi CCD 50 device, the package has a size of 60x30 mm

CCD datasheet in a nutshell :

- Marconi AO CCD50, split frame transfer architecture (Figure 6)
- 16 output ports
- 128 x 128 pixels
  - ¼ of photosensitive area (64x64 pixels, 4 ports) used
- Pixel size : 24 µm square
- Wavelength range: 0.45 - 0.90 nm
- Backside illuminated
  - Quantum efficiency: > 25% (30%), peak >70% (80%)
- Readout noise : < 8 (6) e-/pixel @ 500 Hz
- Dark current : < 500 (250) e-/pixel/sec

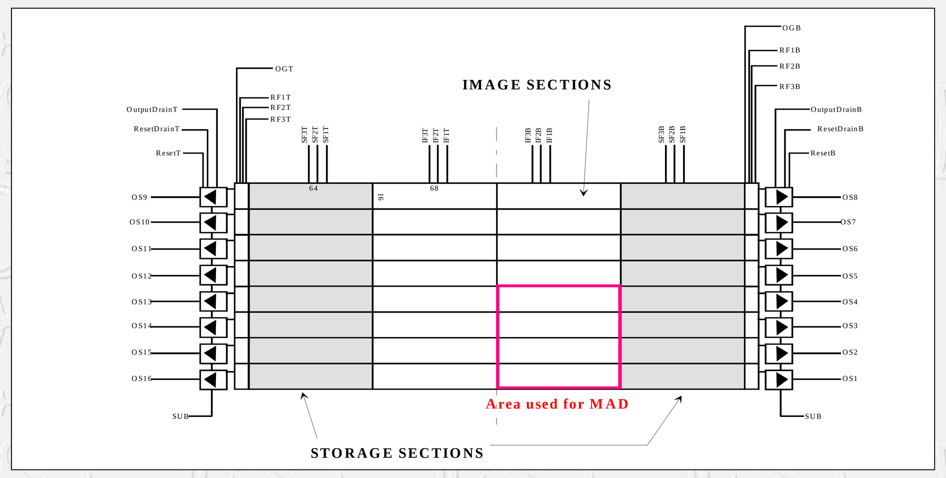

Figure 6 : CCD architecture made of 16 sections of 64x16 pixels

Only 4 of the 16 ports will be used, so ¼ of the useful sensitive surface will be digitized, whereas the rest of the area must be clocked out to avoid charge contamination.

The heads

The head design has to fulfill requirements of compactness (90x60mm, Figure 7) because of the closeness of the head inside the focal plane. This is not straightforward because the CCD package itself is not a compact one (i.e. 30x60 mm, Figure 5). The heads shall be vacuum tight, and shall include the cooling system and temperature sensors. Micro sub-D connector will be welded to the box to ensure its tightness with respect to moisture.

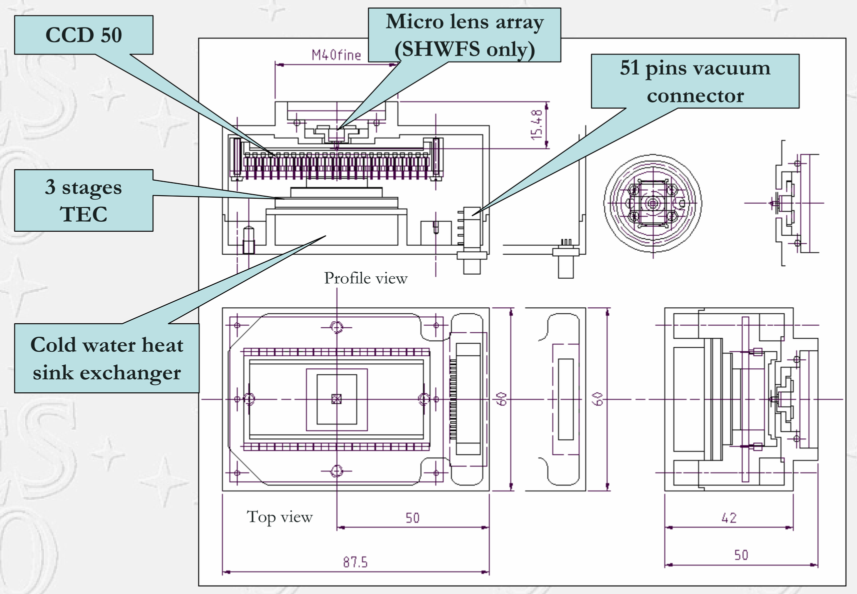

Figure 7 : Preliminary mechanical sketch of the CCD head

The CCD cooling

Design constrains :

- Liquid nitrogen (LN2) cannot be foreseen to cool the CCD (compactness issue)
- The CCD is a non-MPP CCD, thus producing a large amount of dark current (around 500pA/cm^2 at room temperature)
- The noise performance must not be jeopardized by additional dark current shot noise (Figure 8)
- The maximum exposure time is only 40ms using 4x4 binning

It allowed us to use an efficient triple-stage thermoelectric Peltier cooler (Figure 9). The thermal load has been estimated to 1W and requires an open loop Peltier controller able to provide up to 4/5A per head. The heat from the hot Peltier side will be extracted by a cold water heat sink exchanger. Thus, the CCD temperature will mainly depend on the cold water temperature. The water circuit will be provided either by a closed cycle chiller or by the VLT service point connection.

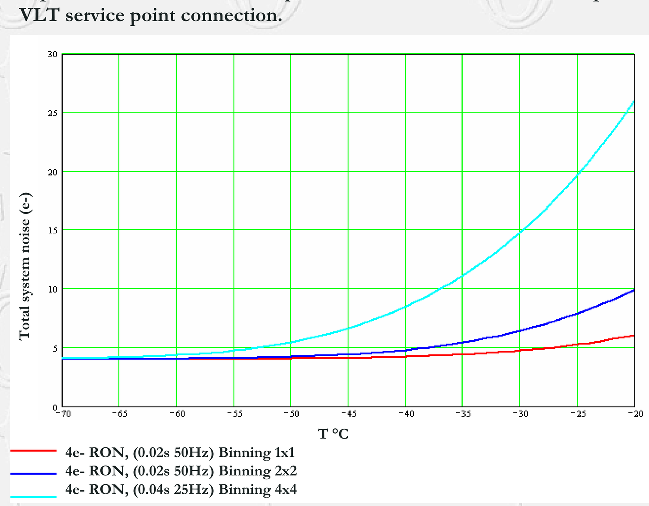

Figure 8 : Overall dark current noise system performance degradation versus operating temperature

Requirements :

- Spec : < 500e- /pix_bin1x1/sec
  - Reached at -27°C
- Goal : ~250e-/pix_bin1x1/sec
  - Reached at -32°C
  - Desired : -45°C
- Needs moderate vacuum inside the head (0.1-0.01mb)

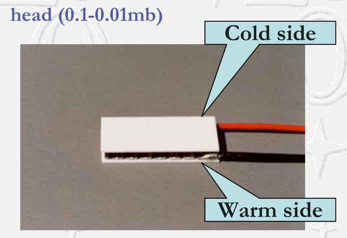

Figure 9 : Single TEC Peltier cooler module, compact and cheap.

If the floor intrinsic system noise is 4e-, at a frame rate of 50hz, binning 2x2, an operating CCD temperature of -35°C is required to prevent dark shot noise from becoming dominant. The temperature is -50°C for a readout rate of 25hz at binning 4x4. The increase of system noise has a direct impact on the ability to use fainter stars and/or achieve acceptable Strehl ratios. So, the operating CCD temperature needs to be at lowest as possible.

The readout modes and system expected performance

The frame rate defines the exposure time because of the CCD frame transfer architecture. This frame rate is defined by a software parameter that is entered by the user. Nevertheless, for the highest frame rates, this is limited by the readout time of a given subframe at a given binning. The best trade-off has to be found between the readout noise, binning, frame rate and pixel frequency as shown in Table 1.

It must be noted, that, using binning 1x1, 1068 pixels must be read out per port, using binning 2x2, 272 pixels and using binning 4x4, 68 pixels. The frame shift frequency is 6250 Hz (160µs).

500 Hz	400 Hz	200 Hz	100 Hz	50 Hz	25 Hz	← Frame rate
< 7 e- 600kpx/s	< 6.5 e- 600kpx/s	< 4.5 e- 300kpx/s	< 4.5 e- 300kpx/s	< 4.5 e- 300kpx/s	NA	*Binning 1 × 1*
< 4.5 e- 300kpx/s	< 4.5 e- 300kpx/s	< 4.5 e- 300kpx/s	< 4.5 e- 300kpx/s	< 4.5 e- 300kpx/s	NA	*Binning 2 × 2*
NA	< 3.5 e- 50kpx/s	< 3.5 e- 50kpx/s	< 3.5 e- 50kpx/s	< 3.5 e- 50kpx/s	< 3.5 e- 50kpx/s	*Binning 4 × 4*

Table 1 : Expected performance according to readout noise (green in e-) and serial register pixel readout speed (red in kilo-pixel per second). This does not include dark current shot noise contribution.

The noise figures are based on the experience gained with the NAOS CCD system. This means that three readout frequencies will be used to satisfy the requirements : 50 kpx/s, 300 kpx/s and 600 kpx/s. The frame rate is defined as the combination of frame shift, pixel readout time and idle time defined by the user, as shown in Figure 10. This scheme defines a synchronous readout of the 3 SHWFS CCDs

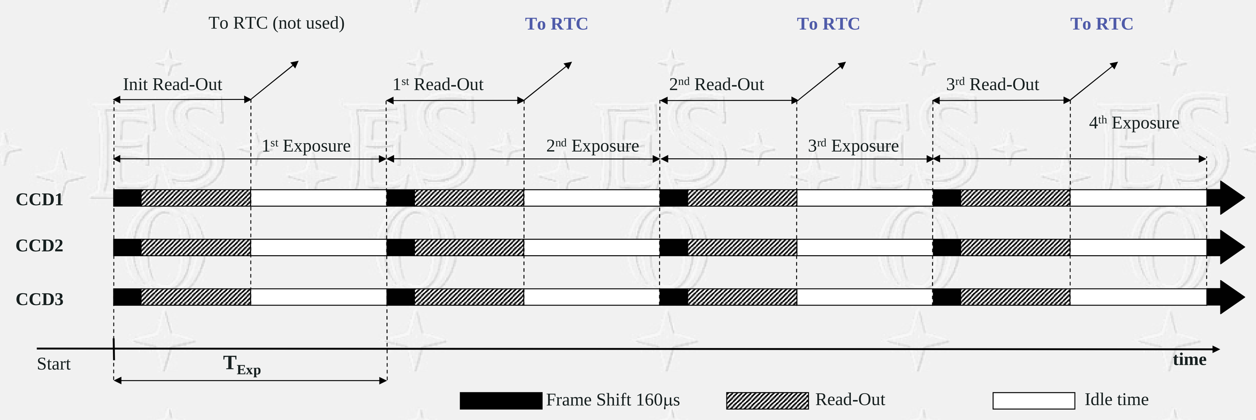

Figure 10 : SHWFS CCDs readout sequence, horizontal scale is time, the first frame will not be used by the real time computer (RTC)

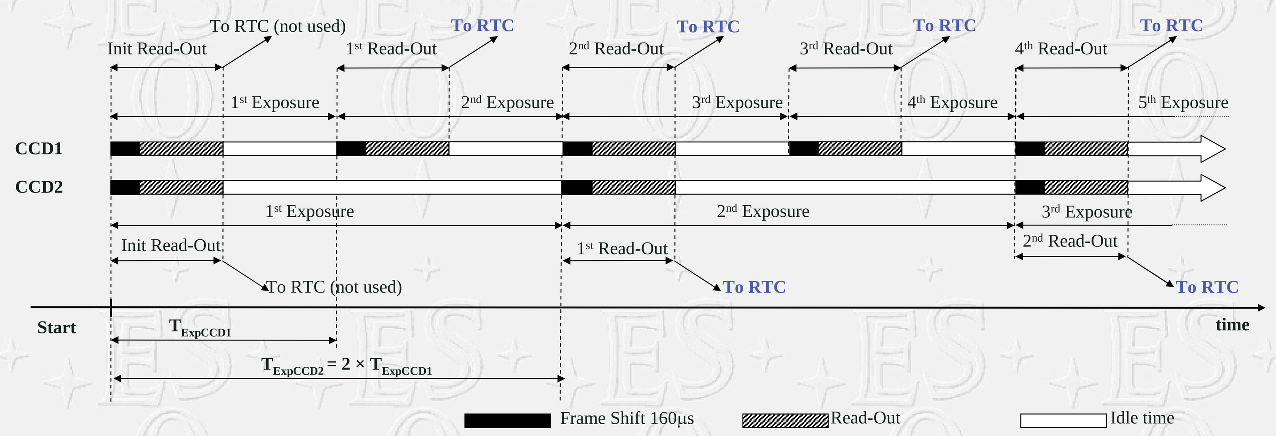

*Figure 11 : Readout sequence for the 2 LOWFS CCDs, horizontal scale is time. This scheme results in TexpCCD1=N*TexpCCD2 where here N=2*

Concerning the LOWFS, the readout scheme can also be synchronous like the SHWFS. Nevertheless, to overcome large brightness differences of stars on CCD1 and CCD2, the frame rate of CCD1 can be a multiple of CCD2, where the frame rate multiple can be 1 (synchronous), 2 and 4 (Figure 11). Minor FIERA software modifications have to be undertaken to handle this specific new readout mode.

The challenges

- Design of light and compact head
- Cooling with TEC
  - keep dark current shot noise as low as possible
  - CCD in vacuum
- One common FIERA System (Figure 12)
  - 12 video inputs
  - RTC interfacing with the new PCI FIERA board
  - Synchronization and exposure time being a multiple from a CCD to another
- Cable stiffness requirement
  - Imposes intermediate soft cables connected to head and preamp
  - 51 signals to carry, EMC potential issues
- Cable length
  - Critical at preamp level
  - avoid noise pick-up

Figure 12 : 16 video channel FIERA front electronic CCD system

The planning

- Q2 2002 — *light* MCAO demonstrator MRR (Manufacturing Readiness Review)
- Q2 2002 — 2k x 2k IR camera *light* PDR
- Q3 2002 — 2k x 2k IR camera *light* FDR
- Q1 2003 — MAD lab AIT with AO IR test camera
- Q2 2003 — MAD CCD system delivery for integration
- Q3 2003 — 2k x 2k IR camera Acceptance Europe
- Q3 2003 — MAD first light + 2k x 2k camera
- Q4 2003 — MAD second observing period
- Q1 2004 — MAD third and fourth observing period

[1] : *Performances and results of the NAOS visible wavefront sensor*, P.Feautrier and all [2] : *CCD based curvature wavefront sensor for adaptive optics - laboratory results*, Dorn and al.