The Multiple Field of View Layer Oriented wavefront sensing system of LINC-NIRVANA: two arcminutes of corrected field using solely Natural Guide Stars

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ABSTRACT

LINC-NIRVANA is an infrared camera that will work in Fizeau interferometric way at the Large Binocular Telescope (LBT). It will take advantage of a field corrected from two MCAO systems, one for each arm, based on the Layer Oriented Technique and using solely Natural Guide Stars. For each arm, there will be two wavefront sensors, one conjugated to the Ground and one conjugated to a selectable altitude, ranging from 4 to 15 Km. They will explore different fields of view for the wavefront sensing operations, accordingly to the Multiple Field of View concept, and particularly the inner 2 arcminutes FoV will be used to select the references for the high layer wavefront sensor while the ground one will explore a wider anular field, going from 2 to 6 arcminutes in diameter. The wavefront sensors are under INAF responsibility, and their construction is ongoing in different italian observatories. Here we report on progress, and particularly on the test ongoing in Padova observatory on the Ground Layer Wavefront Sensor.

Keywords: Layer Oriented, Multiple Field of View

1. INTRODUCTION

LINC-NIRVANA is an instrument for the Large Binocular Telescope (LBT), located in Mount Graham, Arizona. It will take advantage of the full resolving power of the telescope baseline (22.8m) thanks to two MCAO systems, one for each arm, providing a 2' corrected FoV. The initial idea[2],[3] to increase the corrected field of view of an instrument using Multi Conjugate Adaptive Optics (MCAO) which generated a number of lab demonstrators[6] and on-sky demonstrators[8],[11] is now turned into reality, since MAD had is successful first light on the sky, both using the Star Oriented (SO) wavefront sensor[9] and the Layer Oriented (LO) one[1] and, even if its purpose was mostly to validate MCAO in the sky, is also producing scientific papers[4],[5],[7],[10],[14].

A couple of MCAO instruments[12],[13] are under construction in this moment, using different approaches for the wavefront sensing operations. LINC-NIRVANA is one of these instruments, the MCAO system of which is based on the LO technique[15],[17]. The latter, in fact, is very promising because of the efficient usage of light, which is somehow extending the limiting magnitude for the WFS reference selection, allowing good sky coverage using solely natural guide stars[16] (this fact has been proved on the sky with MAD, being the limiting magnitude of the LO wavefront sensor about two magnitudes fainter than the one of the SO sensor). We recall here some of the main features of the LO technique, like the optical co-addition of the light at the level of the detectors, the usage of the Pyramid Sensor (PS)[18] (which is more sensitive and thus more efficient than other conventional wavefront sensors like the Shack-Hartmann and the Curvature one[19]) and the independency of the loops driving the deformable mirrors of the system. The Multiple Field of View (MFoV) technique is an improvement of the LO technique, considering to use a wider FoV for the wavefront sensor conjugated to the ground in order to have higher probability to find suitable references, and LINC-NIRVANA will use a system based on this MFoV technique.

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In this article, after recalling the basic principles of the LO and MFoV techniques, we describe the status of the MCAO wavefront sensors for LINC-NIRVANA, being Istituto Nazionale per l'AstroFisica (INAF) responsible of their design and construction through three observatories (Padova, Arcetri and Bologna), with the co-operation of the Max Planck Institute für Astronomie in Heidelberg.

2. LAYER ORIENTED MULTIPLE FIELD OF VIEW

The idea beyond the LO technique is to have the wavefront sensors looking to a certain number of stars simultaneously, superimposing optically the light coming from all these references at the level of the detectors, where an image of the telescope entrance pupil is created. Each wavefront sensor is conjugated to a Deformable Mirror (DM), and each couple detector-DM is conjugated to a certain altitude chosen in order to minimize the residual atmospheric turbulence.
Thus, instead of having one wavefront sensor for each reference star, like in the SO mode, in the LO concept the number of wavefront sensors used in the system is equal to the number of DMs performing the correction.
Of course, to perform this operation one needs to use pupil plane wavefront sensors, like the pyramid or the curvature ones.

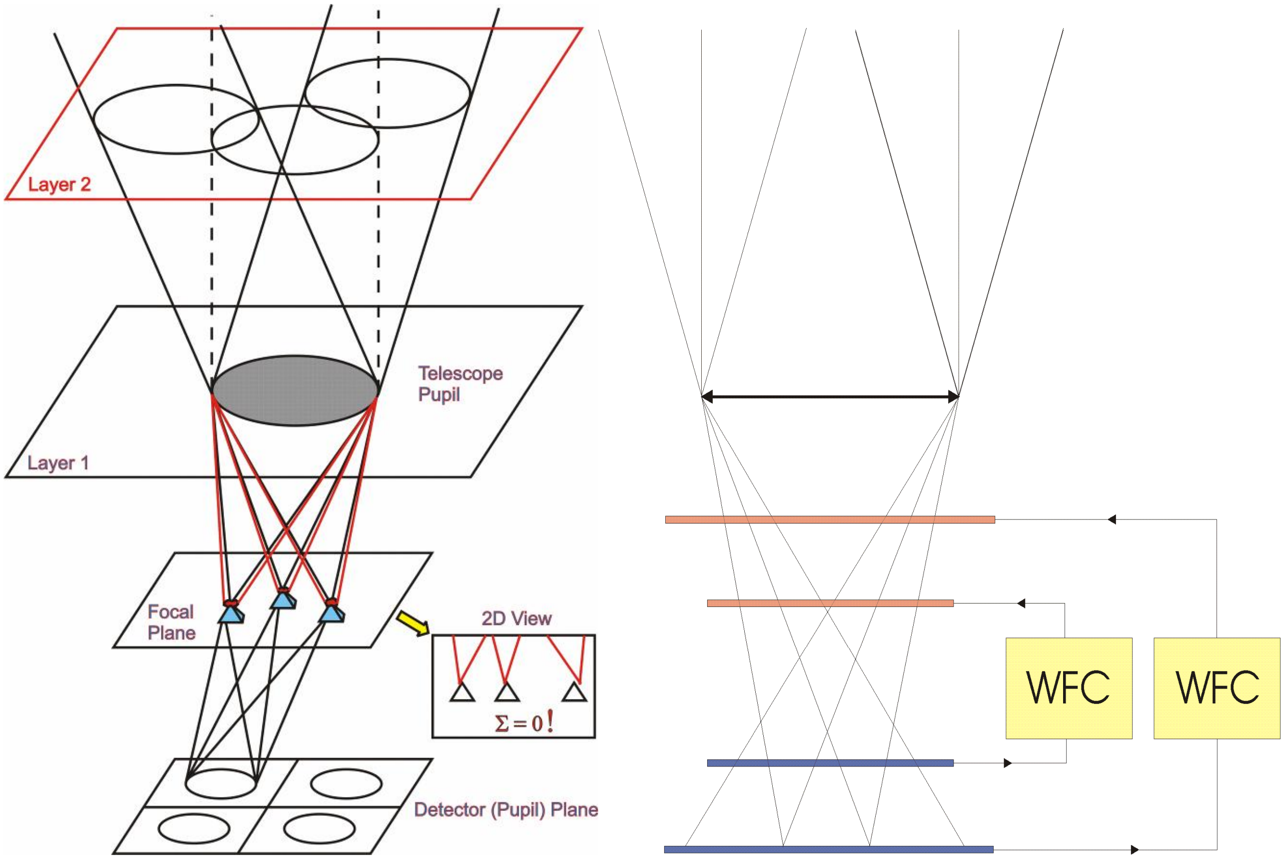


Figure 1: LEFT: the optical co-addition of the light in the L-O technique; RIGHT: the independency of the loops driving the deformable mirrors.

Which are the advantages of the layer oriented technique compared to star oriented systems?

- The optical co-addition of the light (**Figure 1** left side) is of course giving an advantage in term of Signal to Noise Ratio (SNR) compared to the classical SO MCAO, where each detector is looking at a single star: in the latter case in fact the limiting magnitude for each individual WFS remains the same when compared to a classical single star AO system, while in the LO case, above all when considering the ground layer or altitudes close to it, having the light of all the stars superimposed on the pupil, much fainter stars cab be used as references and the limiting magnitude for the WFS is given by the integrated magnitudes of all the stars used

- Being the ground layer quite strong and located very close to he telescope entrance pupil, normally, in a system with 2 DMs one "couple" detector-DM is conjugated to the ground and the second one is conjugated to an intermediate altitude (between 5 and 10 kilometers) close to other powerful turbulent layers. These 2 loops are in fact totally independent from a computational point of view (see **Figure 1** right side), thus simplifying the system in term of required computational power. But the main advantage is that each loop can be tuned in a way to mimic the behavior of the atmosphere at that altitude, meaning that the spatial and temporal sampling performed by the wavefront sensors can be optimized with respect to the relative value of r_0 of that altitude, and this fact can bring a huge advantage in term of photons per sub-aperture on the detectors.
- If, as pupil plane wavefront sensor, the Pyramid one is considered, this means that its high sensitivity can bring to an additional advantage in the limiting magnitude reachable by the WFSs, which is depending on the telescope diameter[19] and, for an 8m class telescope, is of the order of one magnitude (but it can arrive to about two magnitudes in the case of a 40m telescope).

Which are the disadvantages of the layer oriented technique compared to star oriented systems?

- To have two detectors conjugated to different altitudes, there is the need to split the light between the two wavefront sensors; this problem is completely overcome by the MFoV technique, which is described just after.
- Having four pupils to be re-imaged on the detector, and above all for the detector conjugated to high layers, where the projection of the telescope entrance pupil, called meta-pupil, is bigger than on the ground (depending of course on the WFS FoV, on the conjugation altitude and on the desired sampling), the detector size is larger compared to the one of an individual SO WFS.

An evolution of the L-O is called the Multiple Field of View technique, where the idea behind is to use a larger FoV for the detector conjugated to the ground, in a way to increase the probability to find suitable references for the WFS. The loops remain independent and the light is still optically co-added at the level of the detector, so it is basically the LO technique but with the WFSs which are using different fields of view. In **Figure 2** there is a drawing which is explaining the MFoV approach, where the considered FoV of the 2 wavefront sensors are 2' and 6'.

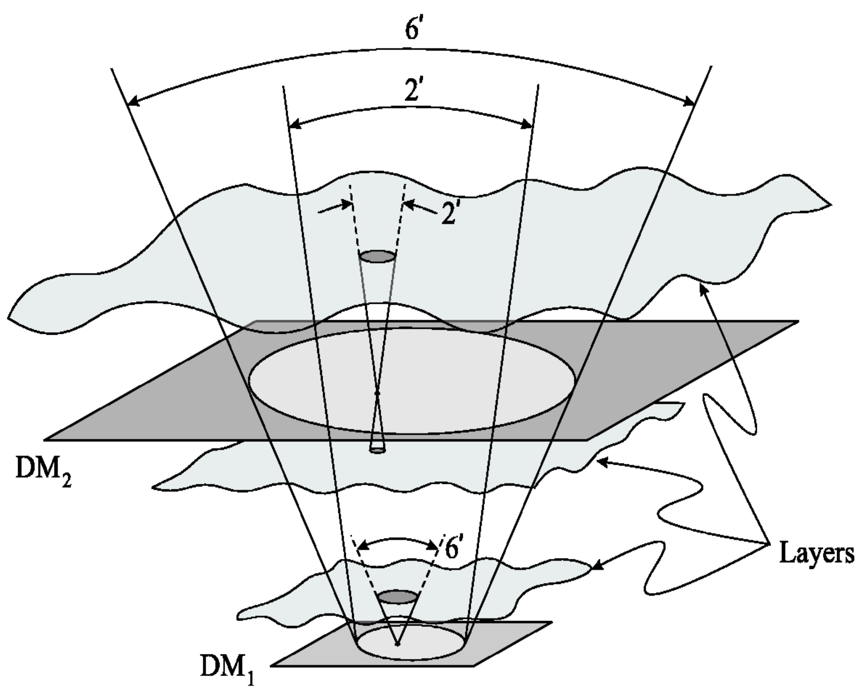


Figure 2: the Multiple Field of View Layer-Oriented technique.

Being the 6' FoV larger in surface of about 6 times than the 2', the internal FoV is used entirely by the high layer WFS while the ground one is using the anular FoV from 2' to 6'. In this way, there is no need of light splitting between the 2 detectors, and thus there is an improvement in term of photons of about a factor 2 on the high layer WFS and of a factor 10 on the ground one when compared to the normal LO approach!
Indeed, we should notice that increasing the FoV of the ground WFS means to decrease its depth of focus, meaning that this technique is working only in those observing sites where the ground turbulence is confined in a thin layer located very close to the ground, which is true for most of the observing sites.
It is clear anyway that, ideally, we should have a way to increase the FoV of a WFS maintaining its capability to be sensitive also to turbulent layers located not only very close to its conjugated altitude, and in the following section we show that this possibility exists.

3. THE LINC-NIRVANA MCAO SYSTEM

The LINC-NIRVANA instrument will have two MCAO systems, one for each arm, that will provide a corrected FoV of 2' to the LINC camera and to the fringe tracker. Each arm has two wavefront sensors, which are described in the following sections: the Ground layer Wavefront Sensor assembled, integrated and tested in Padova observatory, and the Mid High Wavefront Sensor (MHWS), built in Bologna observatory.
In Figure 3 there is an 3-D drawing of the LINC-NIRVANA optical bench, where all the major components are shown.

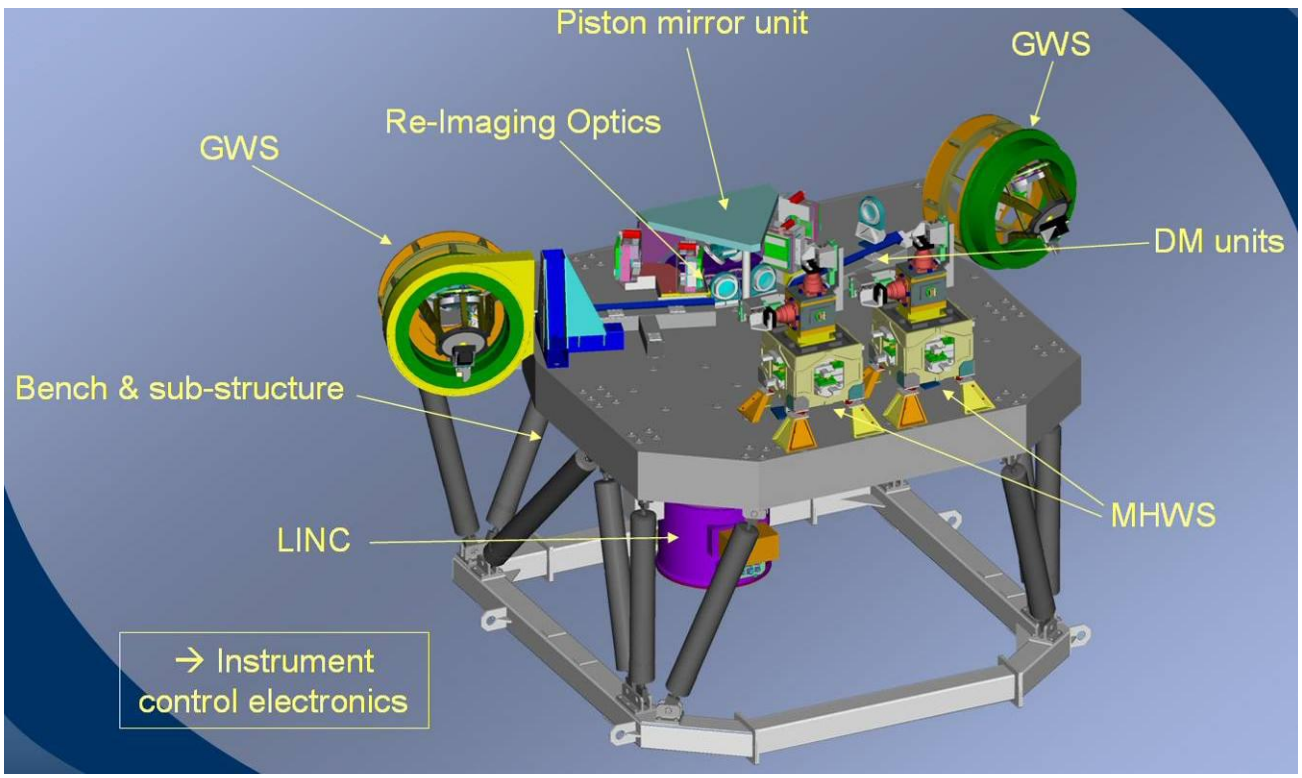


Figure 3: The LINC-NIRVANA optical bench

3.1 THE GROUND LAYER WAVEFRONT SENSOR

The GWS is conjugated to the ground, and it is using the FoV from 2' to 6' in diameter; the light is folded toward the WFS with an anular mirror, which let the central 2' pass through. A maximum of twelve pyramids can be placed in the

FoV in order to pick-up a correspondent number of references to be used by the GWS for the wavefront sensing operations. In front of each pyramid there is a system with two lenses, which has the purpose to enlarge individually the dimension of the reference star on the pyramid pin (thus reducing the pupil size on the detector). Since that in front of each pyramid there is this system with two lenses, which have to move solidly with the pyramid itself, there is a mechanical structure holding these two lenses and the pyramid, which is called Star Enlarger (SE), shown in **Figure 4**.

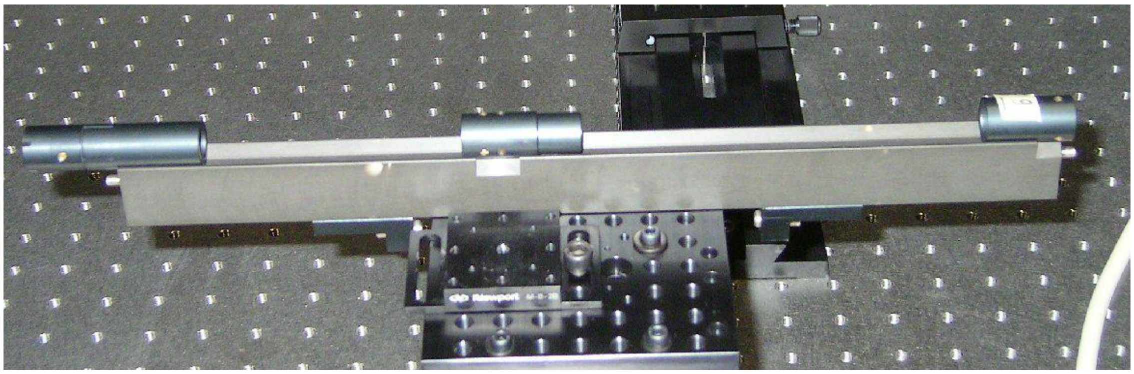


Figure 4: the mechanical structure called star enlarger, holding the two lenses and the Pyramid (on the left side)

The GWS is driving the Adaptive Secondary mirror (672 actuators) of the telescope in order to exploit the correction; a pupil re-imager is then creating 4 images of the pupils on the detector. The pupil re-imager is realized by using an hybrid configuration of mirrors and lenses, as it is shown in **Figure 5**: a first flat mirror (adjustable in tip-tilt) is folding the beam toward a parabolic mirror (adjustable in tip-tilt and centering), which is focusing the beam into a 4 lenses objective (also adjustable in tip-tilt and centering) that finally creates the four pupil images on the detector (adjustable in tip-tilt and, remotely controlled, in centering and focus). The CCD used for the GWS is a 128x128pixel detector.

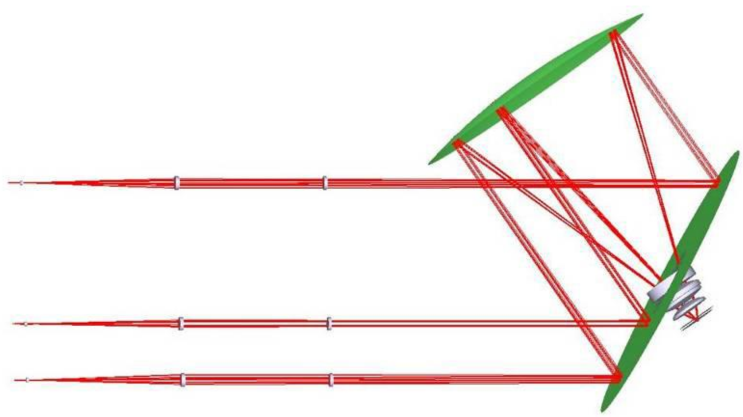


Figure 5: The GWS Optical Design

In Figure 6 the GWS mechanical structure is shown, while in Figure 7 the hybrid pupil re-imager is shown. The lower part of the GWS, where all the linear stages are visible, allows to point a maximum of 12 SE on the selected reference stars, by using a custom made XY table (shown in **Figure 8**) minimizing possible tilt of the pyramids (causing a bad overlap of the pupils on the detector). The upper part is the pupil re-imager, a cross-section of which is shown in **Figure 7**. A solution for the mechanics using a-static leverages has been adopted for the pupil re-imager, which minimizes the flexures at different elevation angle of observation. Clearly visible in **Figure 7** are the flat mirror, the parabolic mirror and the last group of four lenses re-imaging the pupil on the detector.

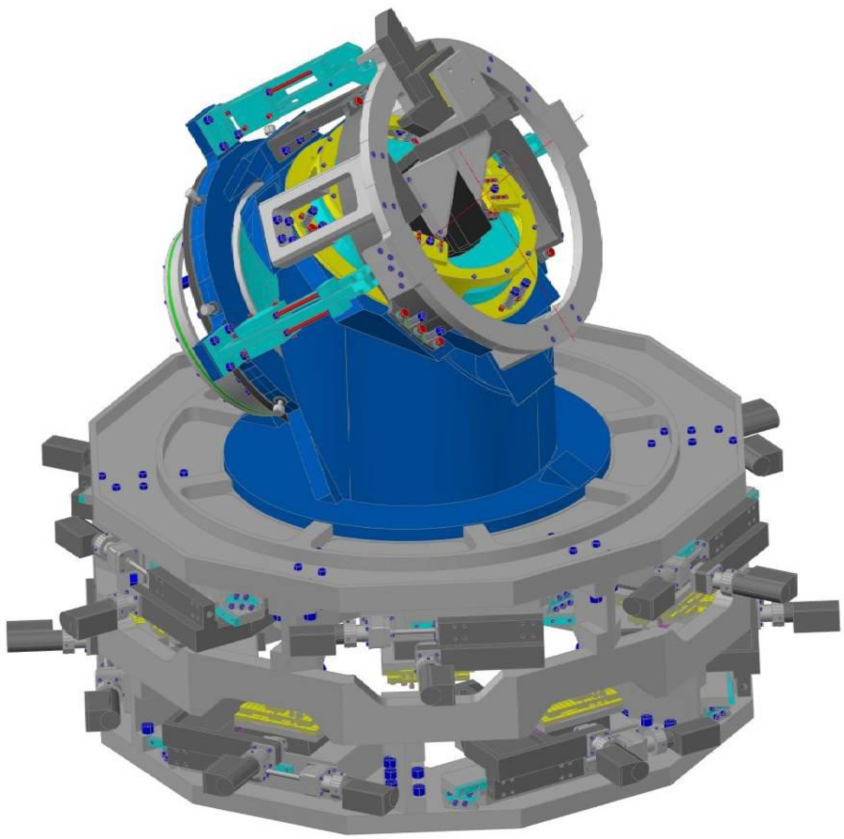


Figure 6: the Ground Layer wavefront sensor

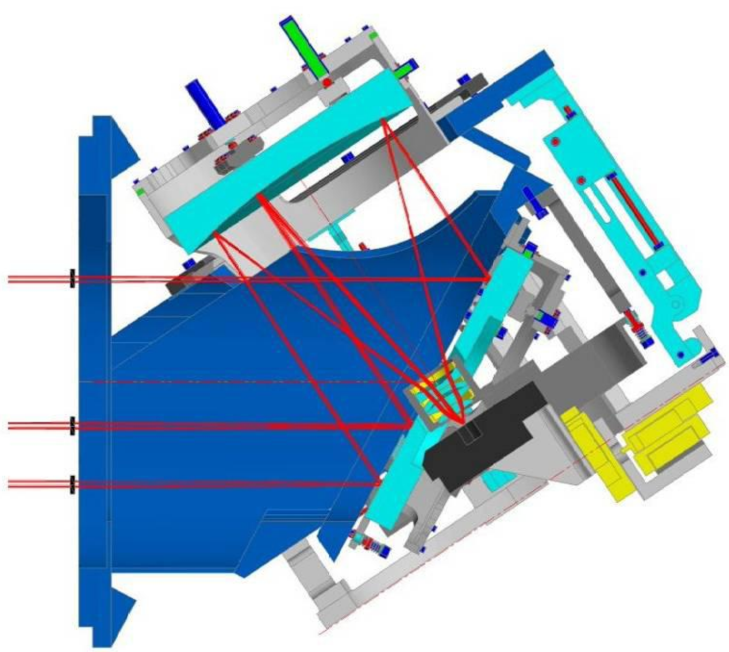


Figure 7: The pupil re-imager of the GWS

The status of the GWS is that all the optics has been delivered to Padova, while the mechanics is partially delivered (all the SE). Several tests have been performed or are undergoing on the individual components and subsystems, such as the pyramids (all the vertex angle have been measured), the linear stages (extensive tests have been performed on the prototype to characterize pitch and roll at different working temperatures), the detectors (tests are undergoing to see the chip homogeneity and the RoN at different integration times) and the AIT of the 12 SE is on-going in these days.

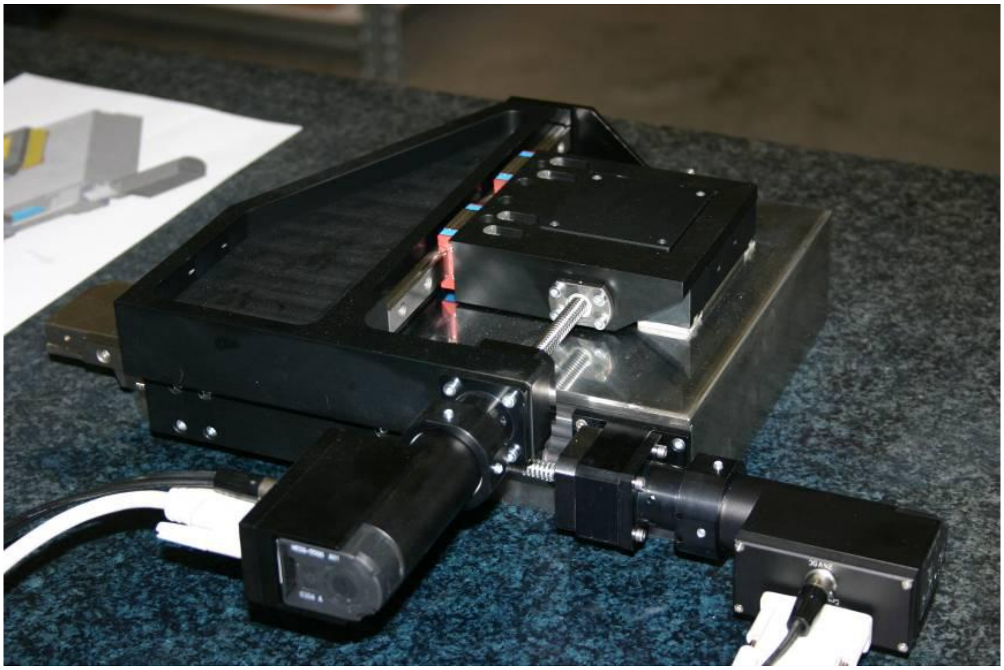
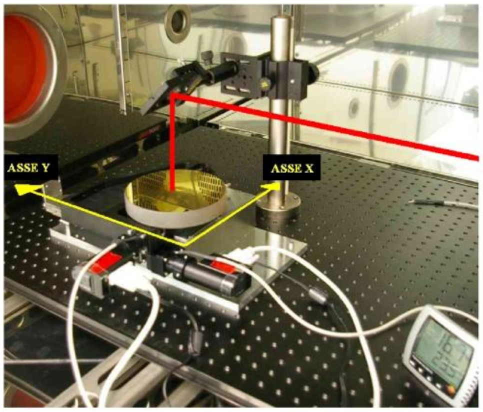


Figure 8: the custom made XY table, keeping controlled (<20”) pitch and roll of the moving part in a temperature range from -15 to 20 degrees.

Pyramid	$\bar{\beta}$		Pyramid	$\bar{\beta}$	
F2	0°.566305 = 33′58”.7		F21	0°.566704 = 34′00”.1	
F3	0°.566848 = 34′00”.6		F22	0°.565116 = 33′54”.4	*
F4	0°.566427 = 33′59”.1		F24	0°.566020 = 33′57”.8	*
F6	0°.567989 = 34′04”.8		F25	0°.566082 = 33′57”.9	
F7	0°.567232 = 33′02”.0		F26	0°.566576 = 33′59”.7	
F8	0°.566931 = 34′01”.0		F27	0°.566268 = 33′58”.6	
F9	0°.565709 = 33′56”.6		F28	0°.565850 = 33′57”.1	*
F12	0°.564764 = 33′35”.1	*	F30	0°.566915 = 34′00”.9	*
F13	0°.565777 = 33′56”.8		F31	0°.566610 = 33′59”.8	*
F14	0°.564824 = 33′53”.4		F32	0°.566919 = 34′00”.9	
F15	0°.565812 = 33′56”.9		F33	0°.566025 = 33′57”.7	
F16	0°.564905 = 33′53”.7		F34	0°.565951 = 33′57”.4	
F17	0°.565778 = 33′56”.9		F35	0°.566438 = 33′59”.2	*
F18	0°.565301 = 33′55”.1		F36	0°.565954 = 33′57”.4	
F19	0°.565580 = 33′56”.1		F37	0°.566028 = 33′57”.7	*

Figure 9: the setup used to test the Pyramids vertex angle (right side) and the table summarizing the results (left side).



Stage	Temperature	PtV tip-tilt	Tip-tilt linear deviation
PI	26°C	19.1"	3.7"
PI	15°C	14.0"	3.4"
PI	5°C	20.2"	4.9"
PI	−5°C (first)	24.0"	6.4"
PI	−5°C (second)	45.6"	8.4"
PI	−15°C	46.2"	9.7"
Tomelleri	15°C	16.7"	2.7"
Tomelleri	5°C	20.8"	4.3"
Tomelleri	−5°C	11.6"	2.6"
Tomelleri	−15°C	7.6"	2.2"

Figure 10: the setup used to test the XY positioning table to control the tip-tilt introduced when positioning the SE on the WFS reference stars (left side) and the table summarizing the results (right side). These test have been performed in Heidelberg, where a temperature controlled laboratory was available, to check the system behavior in the telescope temperature operating range.

Figure 11: one SE mounted on the optical bench during its integration phase.

3.2 THE MID-HIGH LAYER WAVEFRONT SENSOR

The MHWS is instead conjugated to an altitude that can vary from 4 to 15 Km, in order to optimize its correction, which is actuated by a Xinetics Deformable Mirror (DM), based on 349 piezo-stack actuators which is mounted on-board the optical bench. Following the LO scheme, the DM has to be conjugated to the same altitude to which the WFS is conjugated. The MHWS is using the visible part of the central 2' FoV, and a maximum of eight pyramids can be positioned in such a FoV in order to select the suitable references for the wavefront sensor. The light is then sent to a 6 lenses pupil re-imager which creates four pupil images on the detector, an 80x80pixel CCD. In **Figure 12** a cross section of the MHWS is visible.

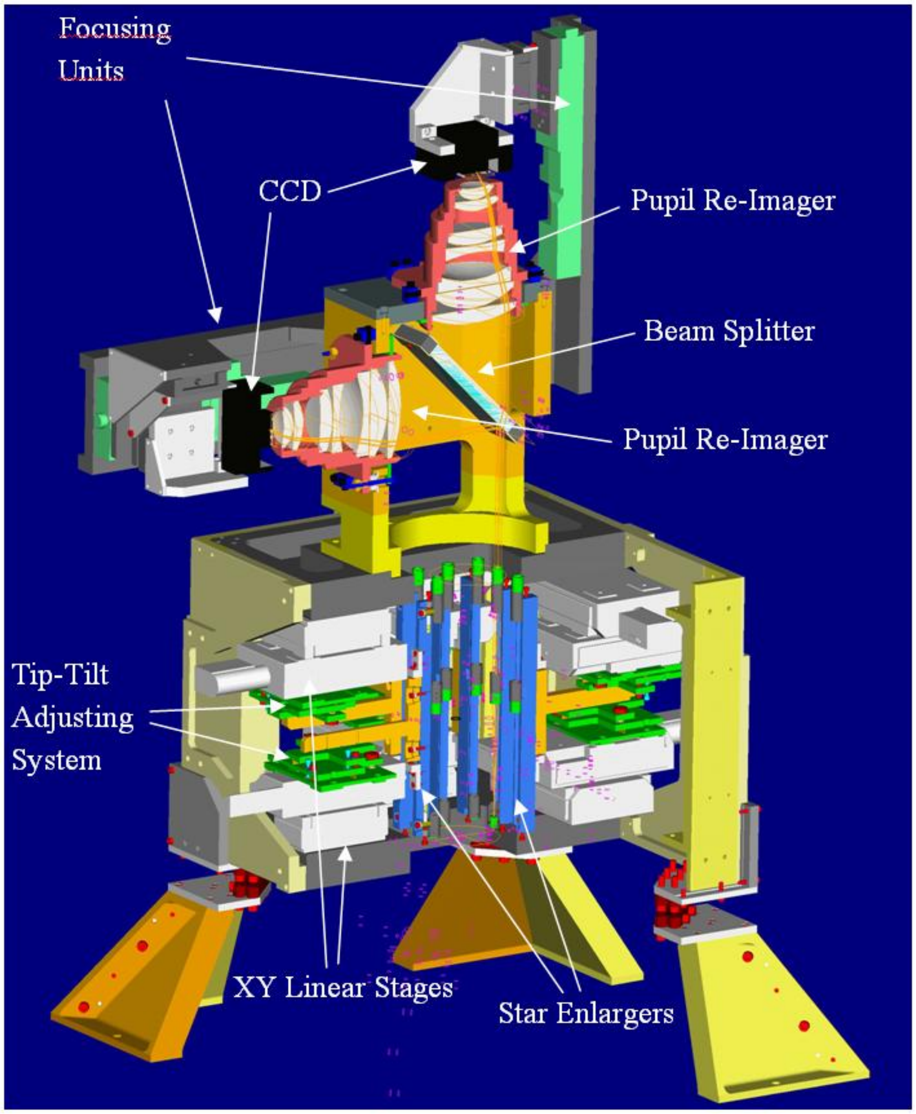


Figure 12: the Mid High Wavefront Sensor

The integration of the first MHWS in the astronomical observatory of Bologna has been successfully completed, and the system has been delivered to Heidelberg, where it is being integrated nowadays in an optical bench to perform close loop tests of the MCAO system. Concerning the second MHWS, all the opto-mechanical parts are ready, and the assembly of the sensor should start soon.

4. CONCLUSIONS

The four Layer Oriented Multiple Field of View wavefront sensors are in their integration phases in the Italian INAF observatories of Padova and Bologna. Their constructions is carried out in co-operation with the Max-Planck Institute of Heidelberg, where for example the tests on the linear stages have been performed, the tip-tilt stages for the star enlargers alignment have been designed and built and the mechanical drawings of the MHWS have been carried out. The first MHWS wavefront sensor is ready (**Figure 13**) and delivered to Heidelberg, where close loop test are planned for this year. This means that, by the end of 2008, there might be in Heidelberg a full MCAO system mounted on an optical bench testing a single arm of the final NIRVANA system. The first GWS is on its AIT phase in Padova, and it should be ready by the beginning of 2009.

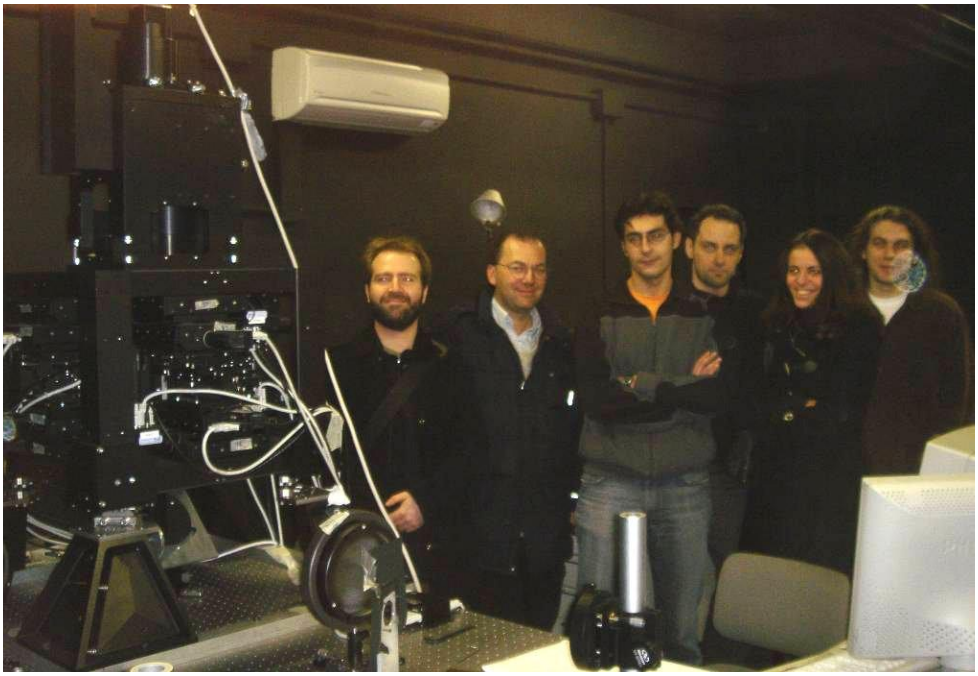


Figure 13: a photo of the MHWS mounted on the optical bench in Bologna observatory, during the acceptance tests.

REFERENCES

[1] Arcidiacono C., Lombini M., Ragazzoni R., Farinato J., Diolaiti E., Baruffolo A., Bagnara P., Gentile G., Schreiber L., Marchetti E., Kolb J., Tordo S., Donaldson R., Soenke C., Oberti S., Fedrigo E., Fernet E., Hubin N., "Layer Oriented wavefront sensor for MAD on sky operations", *SPIE Proc*., this conference (2008).

[2] Beckers J. M., "Increasing the size of the isoplanatic patch size with multiconjugate adaptive optics", in *ESO conference on Very Large Telescopes and their instrumentation*, *M.-H. Hulrich ed*., pp. 693 (1988)

[3] Beckers J. M., "Detailed compensation of atmospheric seeing using multiconjugate adaptive optics", *SPIE Proc.* **1114**, pp. 215-217 (1989).

[4] Bono G., Calamida A., Corsi C. E., Stetson P. B., Marchetti E., Amico P., Prada Moroni P. G., Ferraro I., Iannicola G., Monelli M., Buonanno R., Caputo F., Dall'Ora M., Degl'Innocenti S., D'Odorico S., Freyhammer L. M., Koester D., Nonino M., Piersimoni A. M., Pulone L., Romaniello M., "MAD@VLT: Deep into the Madding Crowd of Omega Centauri", in *ESO conference "Science with the VLT in the ELT era"* (2008).

[5] Bouy H., Kolb J., Marchetti E., Martín E. L., Huélamo N., Barrado Y Navascués D., "Multi-conjugate adaptive optics images of the Trapezium cluster", A&A **477**, 681 (2008).

[6] Farinato J., Ragazzoni R., Diolaiti E., Vernet-Viard E., Baruffolo A., Arcidiacono C., Ghedina A., Cecconi M., Rossettini P., Tomelleri R., Crimi G., Ghigo M., "Layer oriented adaptive optics: from drawings to metal", *SPIE Proc.* **4839**, 588-599 (2003).

[7] Gullieuszik, M., Greggio, L., Held, E. V., Moretti, A., Arcidiacono, C., Bagnara, P., Baruffolo, A., Diolaiti, E., Falomo, R., Farinato, J., Lombini, M., Ragazzoni, R., Brast, R., Donaldson, R., Kolb, J., Marchetti, E., Tordo, S., "Resolving Stellar Populations outside the Local Group: MAD observations of UKS2323-326", A&A, 483, L5 (2008).

[8] Marchetti E., Hubin N., Fedrigo E., Brynnel J., Delabre B., Donaldson R., Franza F., Conan R., Le Louarn M., Cavadore C., Balestra A., Baade D., Lison J.-L., Gilmozzi R., Monnet G., Ragazzoni R., Arcidiacono C., Baruffolo A., Diolaiti E., Farinato J., Viard E., Butler D., Hippler S., Amorim A., "MAD the ESO multi-conjugate adaptive optics demonstrator", *SPIE Proc.* **4839**, 317-328 (2003).

[9] Marchetti E., Brast R., Delabre B., Donaldson R., Fedrigo E., Frank C., Hubin N., Kolb J., Lizon J.-L., Oberti S., Reiss R., Soenke C., Tordo S., Baruffolo A., Bagnara P., Amorim A., Lima J., "MAD on sky results in star-oriented mode ", *SPIE Proc.*, this conference (2008).

[10] Mignani R. P., Falomo R., Moretti A., Treves A., Turolla R., Sartore N., Zane S., Arcidiacono C., Lombini M., Farinato J., Baruffolo A., Ragazzoni R., Marchetti E., "Observations of Isolated Neutron Stars with the ESO Multi-Conjugate Adaptive Optics Demonstrator", A&A, accepted (2008).
[11] Vernet Viard E., Ragazzoni R., Arcidiacono C., Baruffolo A., Diolaiti E., Farinato J., Fedrigo E., Marchetti E., Falomo R., Esposito S., Carbillet M., Verinaud C., "Layer-oriented wavefront sensor for MAD: status and progress report", *SPIE Proc*. **4839**, 344 (2003)
[12] Ellerbroek B., Rigaut F., Bauman B., Boyer C., Browne S., Buchroeder R., Catone J. W., Clark P., d'Orgeville C., Gavel D. T., Herriot G., Hunten M. R., James E., Kibblewhite E. J., McKinnie I. T., Murray J. T., Rabaud D., Saddlemyer L. K., Sebag J., Stillburn J., Telle J. M., Veran J-P., "Multiconjugate adaptive optics for Gemini-South", *SPIE Proc*. **4839**, 55-66 (2003).
[13] Herbst T., Ragazzoni R., Andersen D., Boehnhardt H., Bizenberger P., Eckart A., Gaessler W., Rix H.-W., Rohloff R.-R., Salinari P., Soci R., Straubmeier C., Xu W., "LINC-NIRVANA: a Fizeau beam combiner for the Large Binocular Telescope", *SPIE Proc*. **4838**, 456-465 (2003).
[14] Ragazzoni R., Almomany Y., Arcidiacono C., Falomo R., Farinato J., Gullieuszik M., Diolaiti E., Lombini M., Moretti A., Piotto G., Marchetti E., Donaldson R., Turolla R., "Layer Oriented: science with MAD and beyond", *SPIE Proc*., this conference (2008).
[15] Ragazzoni, R., Diolaiti, E., Farinato, J., Fedrigo, E., Marchetti, E., Tordi, M., Kirkman, D., "Multiple Field of View Layer Oriented Adaptive Optics. Nearly whole sky coverage on 8 m class telescopes and beyond", A&A **396**, 731 (2002).
[16] Ragazzoni R., "Adaptive optics for giants telescopes: NGS vs. LGS", in *ESO Proceedings of the Bäckaskog Workshop on Extremely large Telescopes,* **57**, 175-180, (2000).
[17] Ragazzoni R., Farinato J. and Marchetti E., "Adaptive optics for 100-m-class telescopes: new challenges require new solutions", *Proc. SPIE* **4007**, 1076-1087 (2000).
[18] Ragazzoni R., "Pupil plane wave front sensing with an oscillating prism", *J. of Mod. Opt.* **43**, 289-293 (1996).
[19] Ragazzoni R., Farinato J., "Sensitivity of a pyramidic wavefront sensor in closed loop adaptive optics", *A&A* **350**, L23-L26 (1999).