

LINC-NIRVANA: Mechanical challenges of the MCAO wavefront sensor

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ABSTRACT

Several multi-conjugate adaptive optics (MCAO) systems using the layer-oriented approach are under construction and will soon be tested at different facilities in several instruments. One of these instruments is LINC-NIRVANA, a Fizeau interferometer for the Large Binocular Telescope (LBT). This instrument uses a ground layer wavefront sensor (GWS) and a combined mid-high layer wavefront sensor (MHWS) with different fields of view (concept of multiple field of view), a 2-6 arcmin annular ring for the GWS and a 2 arcmin diameter central field of view for the MHWS. Both sensors are Pyramid wavefront sensors which optically co-add light from multiple natural guide stars.

The opto-mechanical problems concerning these sensors are related to the fast focal ratio of the beam on the pyramids coupled with the available pixelscale of detectors. This leads to very tight requirements on the moving systems (linear stages) for the star enlargers (SE) used to pick off the light of individual stars.

As there are 40 star enlargers in the overall system, additional efforts were put into the alignment system of the optics of the star enlargers and the reduction in size of the star enlargers to minimize the distance between available guide stars.

Keywords: multi-conjugate adaptive optics, layer-oriented wavefront sensor, pyramid wavefront sensors, star enlargers, linear stages.

1. INTRODUCTION

The pyramid wavefront sensor¹ (PS) is the basic element of the MCAO system for LINC-NIRVANA² a Fizeau interferometer for the LBT³. This system will measure the atmospheric turbulence, using visible light, and will apply signals to deformable mirrors (DMs) to correct near-infrared light sent to the science detector. LINC-NIRVANA uses the layer-oriented approach^{4,5} and is set up to have three different layers in the atmosphere sensed and corrected: the ground layer with the secondary mirrors of the telescope, the mid and high layers through DMs on the optical bench (Fig.1). The performance foreseen is for a moderate correction of 0.3-0.5 Strehl over the central 2' of the field.

Most of the problems linked with flexure are related to the particular environment where the instrument is going to operate. In fact the optical bench, on board of LBT, tilts over while the telescope changes declination, producing a change in the gravity vector.

2. WAVEFRONT SENSORS

There are two mechanical sensor units per arms: the GWS and the MHWS. Each of the GWS units is placed very close to the focal plane and kept cantilevered on the bench. They provide correction signals for the secondary mirrors, that are conjugated to an altitude of 100m. These units have a cylindrical shape for the part where the PSs and their moving devices are settled and for the part where the bearing and the motor is placed. The pupil reimager has the design of a Folded-Smith Camera. The weight of each unit, including mechanics and linear stages is 250kg. The bearing and motor adds an other 100kg, causing particular problems in keeping gravity-induced displacements within tolerance levels while the telescope pointing changes. The GWS uses the light of 12 natural guide stars in an annular field of view (FoV) between 2' and 6' of the F/15 beam. The light is folded to the side through an annular feeding mirror (Fig.2) that allows

the central 2' of the field passing through to the science and high layer channels. The 45° angle of the feeding mirror has to be within 20" accuracy, defined by the optical depth of the focal ratio. The GWS will use the CCD50 128X128 pixels.

The structure containing the stages has a cylinder shape: two annular plates (1m of diameter), where the stages are mounted, are connected with columns to an additional structural ring. This arrangement allows to minimize the dimensions of the overall component, keeping good stiffness characteristics while the cylinder tilts over with the bench. In Fig.4 are shown the results of a FEM for this structure for a change of 60° in the gravity vector. It is possible to notice that the displacement is almost uniform on the plate, causing mostly a uniform shift of the stages placed on it. This shift can be correct through the positioning system of each single SE.

The same problem of flexure due to gravity vector changes rises for the two structures of the MHWS (Fig.3). In this case, it is the height of these structures on the bench and the relative positions of the detectors that makes the design more challenging (Fig 5). One needs to contain the weight of the overall assembly at a reasonable level for the optical bench supporting it, and to minimize use of expensive materials and manufacturing processes. In fact we have used aluminum for every structural component, making the design as easy as possible to produce also with the aim of containing costs.

The box containing the stages has a cubic shape: two square plates (0.5m of diameter) hanging the stages are connected through four triangular columns at the vertexes and eight additional reinforcing flanges are linked on the outer side, designed for giving to the structure a better flexural response.

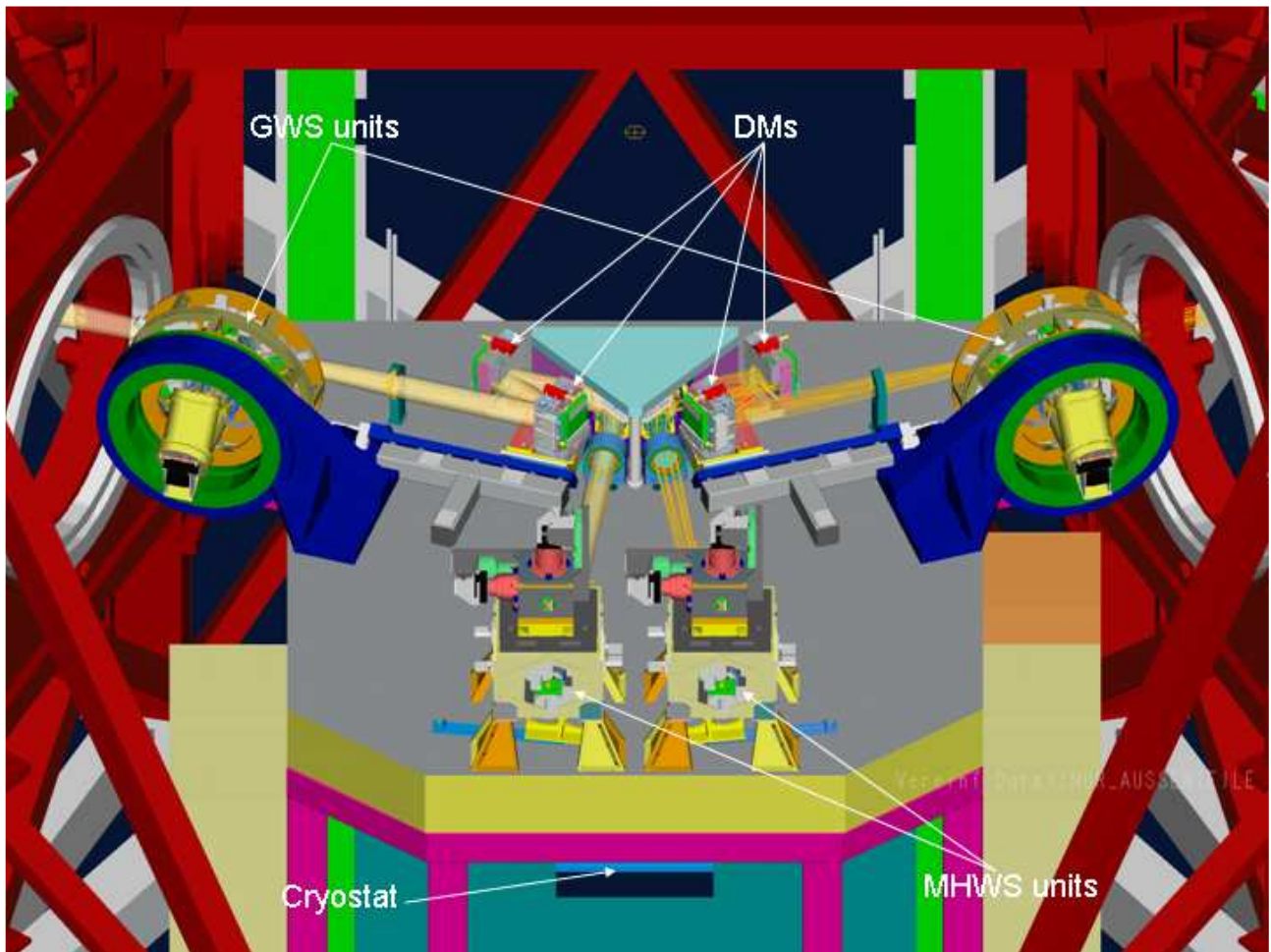


Figure 1. LINC-NIRVANA optical table within the telescope frame at the rear offset bent focal station of LBT.

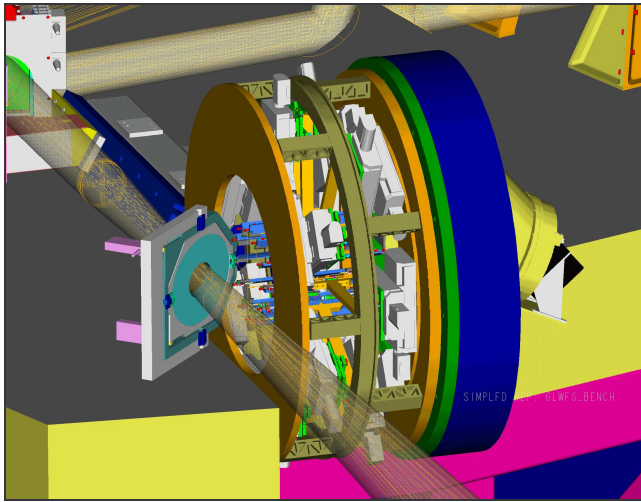


Figure 2. The light of 12 natural guide stars in the 2'-6' annular field is collected by the pyramid mounted on the arms (star enlargers) movable in this field. (GWS)

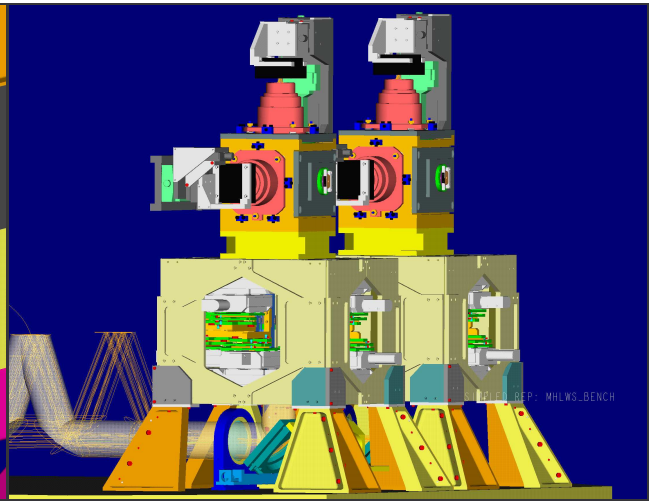


Figure 3. The light of 8 natural guide stars in the 2' field is collected by the pyramid mounted on the 8 arms (star enlargers) movable in this field. (MHWS)

The MHWS sends correction to the DMs on the bench, that could have different conjugation heights between 4 and 15 km. The light in the central 2' field is split by the dichroic in to two channels: the science channel in the cryostat under the bench and the visible channel through the F/20 camera to the WFS. This camera enlarge the diameter of the beam allowing the reference stars selecting devices of the MHWS to be moved and handled in an easier way within the field. Below the sensor, a folding mirror (Fig.3) mounted on linear stage feeds light to the selecting devices and can be replaced with a beam splitter that allows the use of a patrol camera assisting in reference star selection. A CCD39 80X80 pixel will be used for the MHWS.

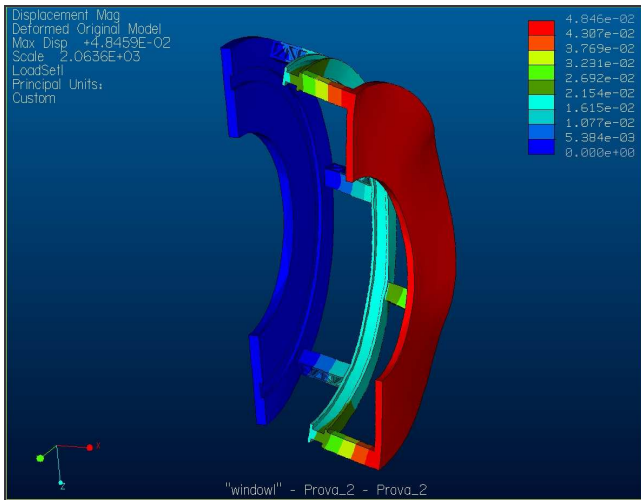


Figure 4. FEM of the cylinder structure containing the stages of the GWS. The cantilevered plate has an almost uniform displacement.

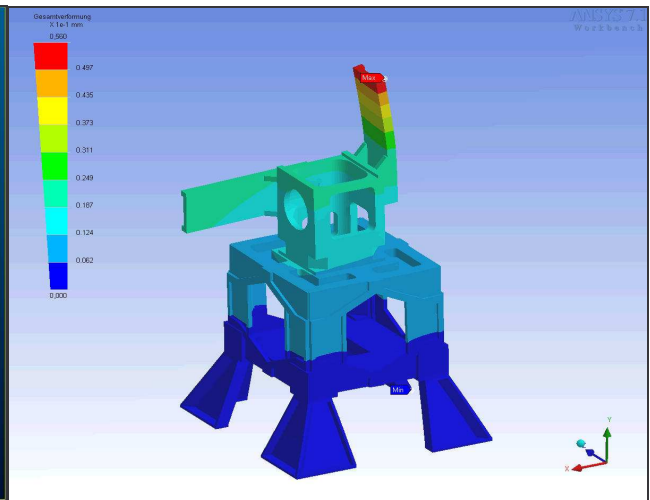


Figure 5. FEM of the structure of the MHWS. The most critical part is the supporting flange for the CCD placed in the upper region of the sensor.

3. STAR ENLARGERS

The devices used to select guide stars are called star enlargers (SEs). They are the basic mechanical items of both sensors. Each GWS unit can select 12 stars with 12 SE, while one MHWS has only 8 SEs to select up to 8 stars, this resumes in altogether 40 SEs for the entire instrument. Each SE exists out of a mechanical arm with the optics mounted on it and 2 crossed linear stages for x-y movement of this arm in the field (Fig.7). The dimensions of the SE unit are slightly different for the MHWS and the GWS resulting out of the different focal ratios they are fed with: F/15 for the GWS and F/20 for the MHWS respectively. The purpose of the SE is to enlarge the spot of the star on the tip of the pyramid without enlarging the overall field. The concept for only two SEs is depicted in Fig.6 and extensively described in different papers^{1,4,5}.

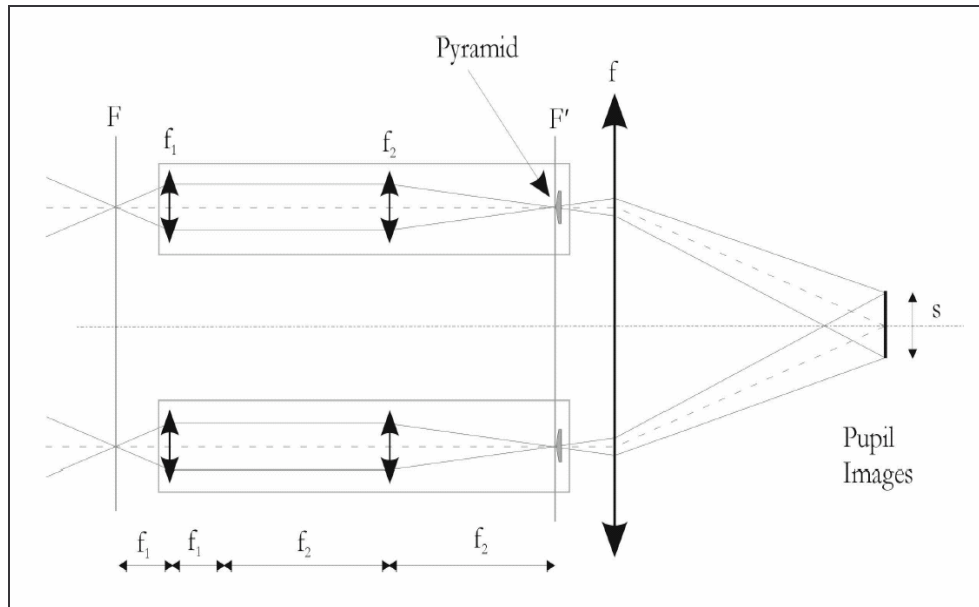


Figure 6. Schematic of the star enlargers. The incoming F/20 beam ($F=F/20$ focal plane) gets enlarged to a F/225 beam on the tip of the pyramid ($F'=F/225$ focal plane). An objective re-images the pupils with the size $s=f/F'$. The two achromatic doublets in the star enlarger have focal distances $f_1=14$ and $f_2=157.5$.

The SEs are arranged around the field as close as possible to each other, trying to leave enough space for the movement. This problem is particularly important for the GWS where 12 SEs instead of 8, with a travel range of 100mm instead of 50mm, have to be fit. The stages are commercially available from Physik Instrumente. They are provided with an incremental encoder and an on-board amplifier. The 8 stages of the MHWS are arranged in a square box 500mm large, while the 12 stages of the GWS are placed in a cylindrical case of 1000mm in diameter, that rotates during observations. For this reason the supporting structures of the GWS are more sensitive to flexure due to gravity vector changes. Finite element analysis were performed for the most critical parts, as the support (Fig.8). First verification of the system will be done with the Single Arm Experiment⁶ before the commissioning of the instrument.

The optics of the SEs for the GWS are only slightly different from the one of the MHWS. Each SE has three optical elements: two achromatic doublets, 6 and 12.7 mm in diameter respectively, and a pyramid 12 mm in diameter. A constraint in designing the barrels for these optical elements was that the outer diameter must not exceed 16mm. They are mounted in three different barrels on a V-groove support (Fig.7 left) and have a different adjusting system for alignment purposes. There are requirements on the alignment of the system and other for the operation of the sensor.

Alignment requirements are on:

- focus of the full assembly ($< 0.1\text{mm}$)
- focus of each single optical element (tunable)

- de-center of each single optical element (tunable)
- tip-tilt of each single optical element ($\pm 30'$ first lens; $\pm 15'$ second lens; $\pm 1^\circ$ pyramid)
- tip-tilt of the full assembly ($< 20\mu\text{rad}$ adjustable)

Operational requirements are on:

- tip-tilt of the full assembly due to gravity changes ($< 30 \mu\text{rad}$)
- wobble of the stage during movement ($< 50 \mu\text{rad}$)
- minimum incremental motion of the stage ($< 0.1 \mu\text{m}$)

The alignment requirements are to be fulfilled when the optics get assembled; the operational requirements are to be fulfilled during the observation, while the sensor and/or the single SE need to be moved.

To accomplish the alignment requirements with proper accuracy we designed different adjustment systems. With that we could simplify the alignment process which is quite important by the great number of SE to be assembled. Experiences with the MAD instrument aboard VLT⁷ were taken and the existing design was worked over. A prototype was built to test the improvements (Fig. 7 right).

The SE are re-imaging four pupils which are superimposed on the detector. An imperfect superimposition of the pupils will cause a blurring and introduce an artificial wavefront error. A simulation of the optical impact of blurring (Fig. 9) shows that a wavefront error of 40nm corresponds to a blur of 0.4 sub-apertures. This value is considered as the lower limit to reach the requested performance in strehl ratio for the overall instrument. A blurring of 0.4 of the dimensions of a sub-aperture corresponds to $75\mu\text{rad}$ differential tip-tilt between the SE. As several different components can introduce tip-tilt it has to take care that the sum of all the misplacements don't exceed this value.

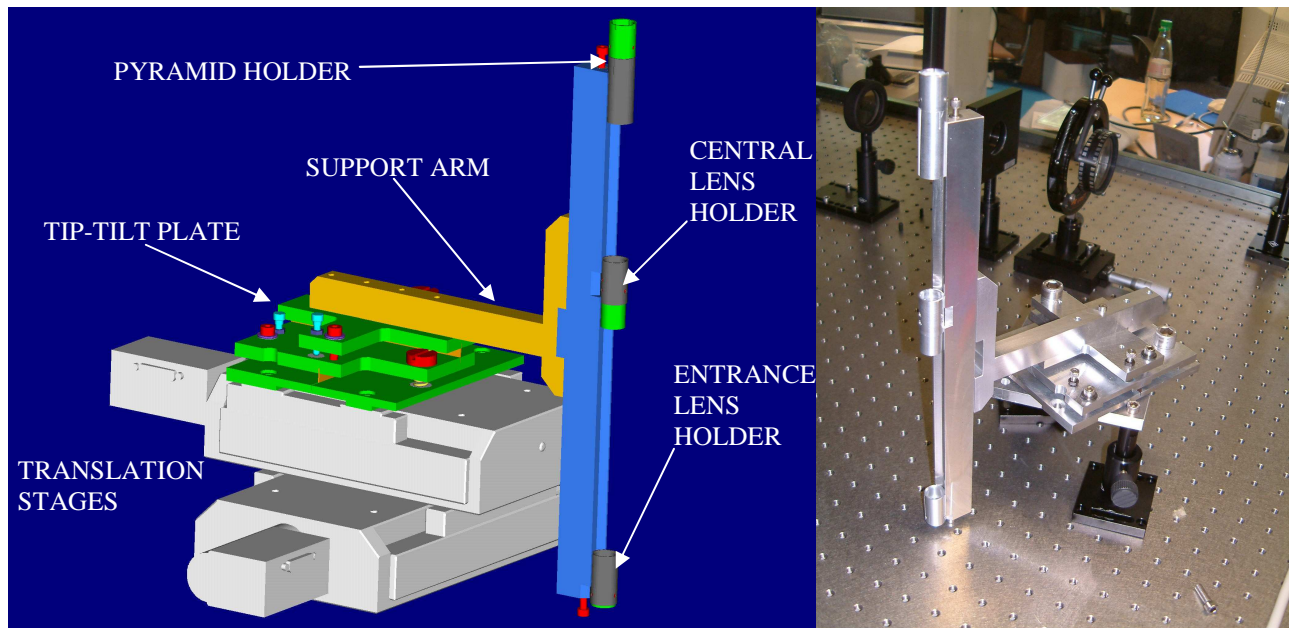


Figure 7. *Left:* single SE unit, with two PI motorized linear stages for positioning, tip-tilt plate for adjusting, support arm (180mm long for the MHWS and 280mm long for the GWS) and V-groove support 300mm long. *Right:* prototype of the SE and of the tip-tilt plate assembled together in the laboratory.

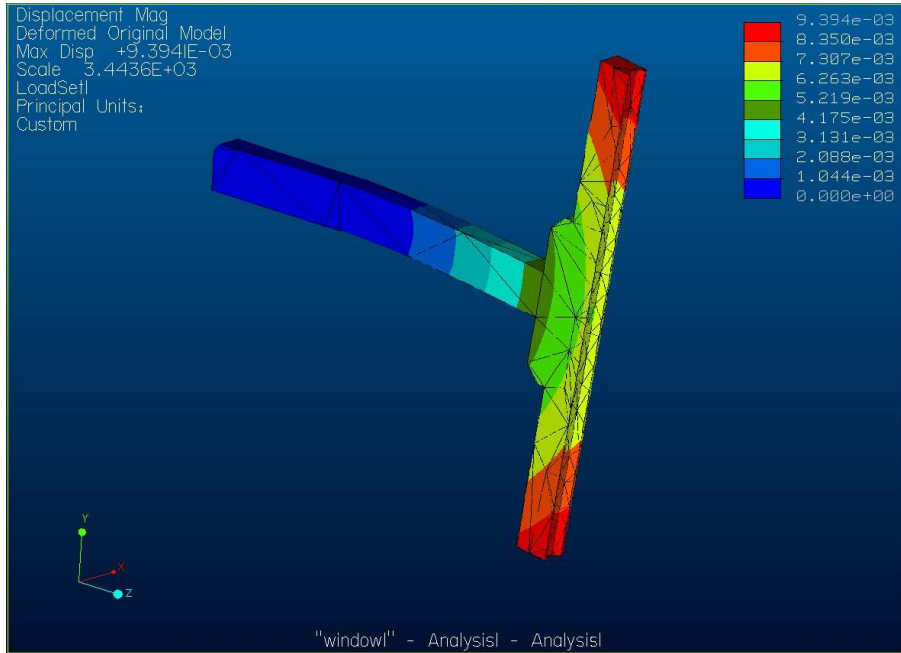


Figure 8. Results of a finite element analysis performed for the support of the SE, showing displacements due to gravity vector changes.

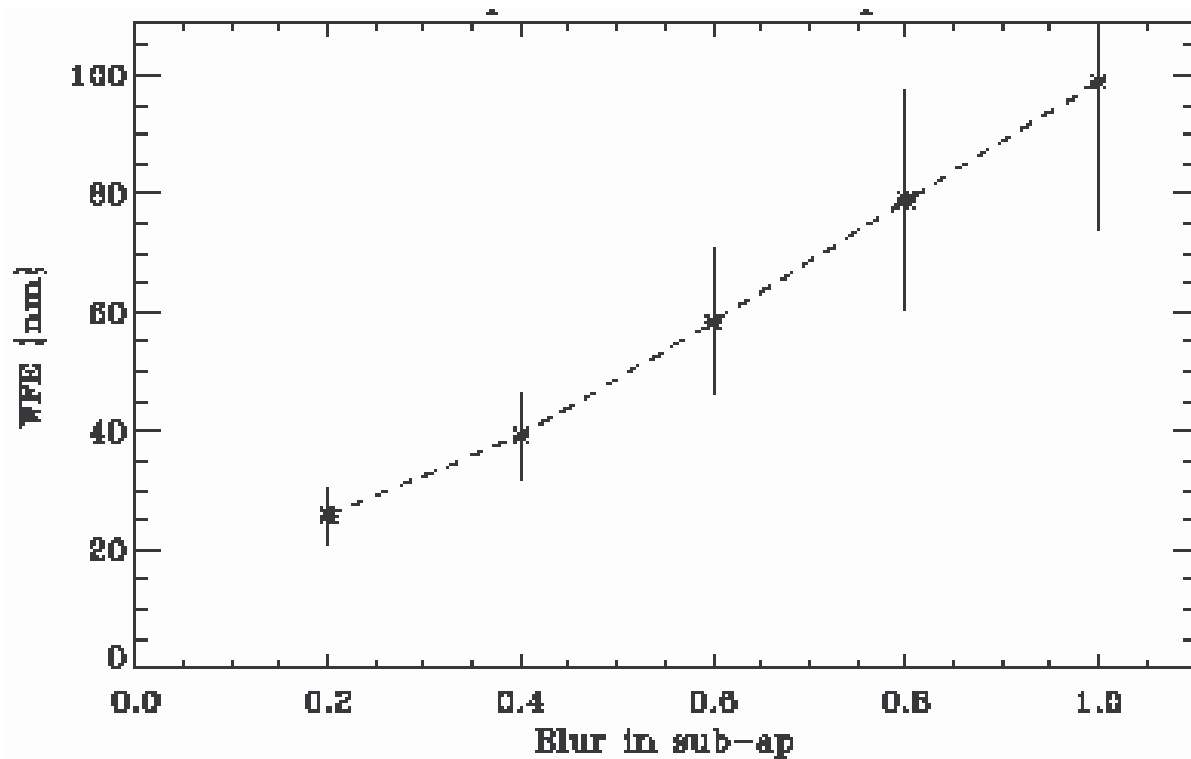


Figure 9. Simulation performances of the wavefront correction system as a function of the blur in sub-aperture of the superimposed spots coming from different SEs. WFE stands for wavefront error.

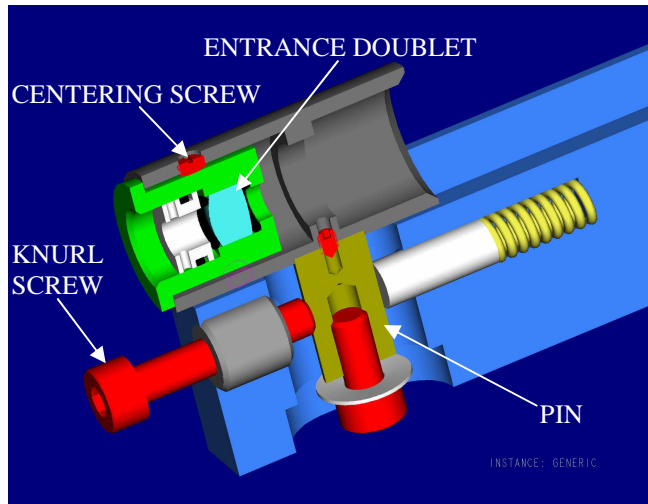


Figure 10. Holder of the entrance doublet, 6mm diameter.

The flexure of the SE arm was explored with a finite element analysis (Fig.8). It can cause a tip-tilt of up to $30\mu\text{rad}$. The wobble is defined through pitch, yaw and roll, parameters one gets with the datasheet of any commercially available translation stage. However, the minimum amount of pitch, yaw and roll is strongly related to width of the stage and the kind of bearing the stage uses. It was quite difficult to find a company fulfilling our specification of less than $50\mu\text{rad}$ to each of this parameters.

Figure 7 is showing one star enlarger with the cross mounted translation stage. The entrance doublet and the pyramid holder are mounted at the opposite ends of the support arm, both provided with a refocusing system (Fig.10-12). The central lens holder is glued onto the

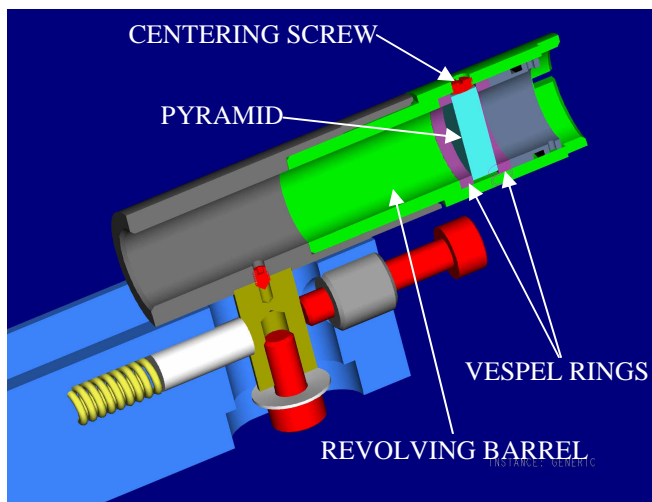


Figure 12. Pyramid of 12mm in holder of 16 mm in diameter.

To reduce the static tip-tilt introduced by misalignment of the SE a tip-tilt plate was designed which is mounted on the translation stage holding the SE. With this tip-tilt plate the differential tip-tilt can be minimized. The unit permits to adjust the tip-tilt angle with a sensitivity of $10\mu\text{rad}$ over 1mm travel range. This is accomplished through a pair of crossed elastic plates bent by fine screws which are counterbalanced by preloading springs. The two movements are completely decoupled. A prototype of this unit, custom made, has already been realized and tested.

The first two requirements on operations also concern the issue of tip-tilt. The arm of the SE can introduce tip-tilt through flexure and the stages can introduce tip-tilt because of bad straightness and flatness which can be seen as wobble while moving the stages.

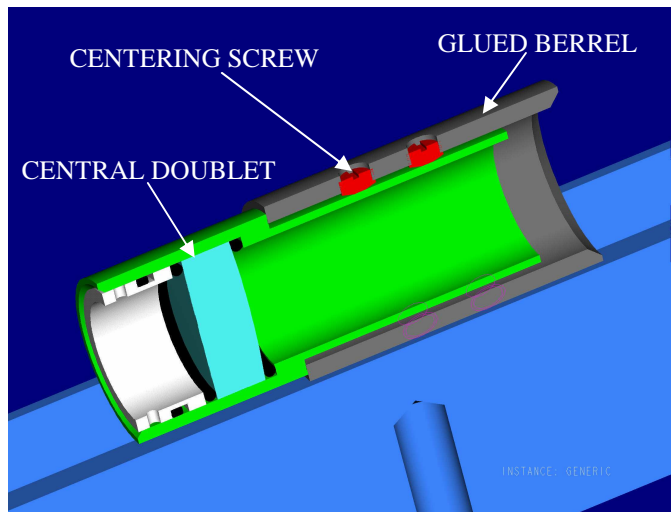


Figure 11. Central lens holder with a 12.7mm doublet.

support arm (Fig.11) after being aligned and therefore it defines the fix point of the system. The holders are connected to the support by a pin inserted in an elongated hole. The focus adjustment is preloaded with a washer spring placed on the back of the support. The refocusing is possible unlocking the securing screw and turning, by hand, the knurl screw.

The first and second lenses are mounted with o-rings and axial locking in inner barrels that can be centered using three fine thread screws placed at 120° . The wall thickness of the barrel for the central lens is very small and the precision is very tight, but they don't need special and expensive manufacturing processes.

The pyramids of each star enlarger have to be aligned rotationally one to each other to avoid an azimuthal

blurring of the four pupils on the detector. Therefore the pyramid holder exists out of two parts, an inner and an outer barrel. The inner barrel is inserted with a small clearance into the outer barrel, just tight enough to keep position, but able to be rotated. The centering of the pyramid is performed also with three screws at 120° distance, pushing directly on the pyramid bounds. Such a system has to be chosen because there is not enough space to insert a further adjustment barrel if the specified 16mm outer diameter should be kept. The pyramid is clamped between two rings of Vespel^{®*} in order to allow a smooth movement while it is going to be centered.

4. EXPANDING THE TECHNIQUE TO A 20M CLASS TELESCOPE

In the present configuration the wavefront sensors have to face the typical challenges of an 8m class telescope. LINC-NIRVANA combines the beams from the two 8.4m primary mirrors for Fizeau interferometry in the near-infrared. The beam combination could also be done in the visible and be used for wavefront sensing. In this case we would face the problems of a 20 to 30m class telescope for the wavefront sensor design. Figure 13 shows a layout of how such an arrangement could look like for LINC-NIRVANA. As can be seen in this layout several components are missing, for example the GWS and the IR-cryostat. It clearly stands out that the camera feeding the wavefront sensor has much larger dimension while the sensor itself looks simplified.

The design, made as a study for LINC-NIRVANA, appears like a camera folded twice over the bench, almost 6 meters long, forming an F/60 focal plane at the entrance of the wavefront sensor. 16 SE were set to sense the light of the same amount of different natural guide stars in a field of 2'. In a F/60 focal plane such field has a diameter of 300mm, three times the diameter of the present focal plane in the MHWS. The larger diameter forces to increase the length of the supporting arms of a SE and the travel range of the stages as well as the overall dimensions of the wavefront sensors. I.e. the diameter of the central doublet in a SE will increase from 12.7mm to 35mm and the size of the pyramid will rise from 12mm to 30mm.

Studying the performances of the system it was found that the motion stage requirements for the SEs were much more demanding than for the current design presented in the previous chapter. The tip-tilt allowed, for example, during the movement of the stage (in term of pitch, roll and yaw) should not exceed 10μrad, 5 times better than what we have seen is required for the stages that we are going to use in our instrument. This requirement is too tight for commercially available products, at least for linear stages having normal roller bearings. It could be reached with stages using air-bearing, but there were many doubts about the stiffness of the overall moving assembly made up of such a kind of stages due to the particular operating environment on LBT, where the gravity vector is not fixed. Concerning this particular problem we have examined the possibility of having a custom made design for this stages. We received a promising design from an Italian company that would meet the requirements (Fig.14). The movement of the plate of this translation system would not have been performed through roller bearings but with a table preloaded and sliding on a grinded plane.

5. CONCLUSIONS

The mechanical requirements for the opto-mechanical design of the pyramid wavefront sensor aboard of LBT are in some cases certainly very tight, but still in the range of capabilities of a specialized workshop, without extremely sophisticated manufacturing processes and particularly expensive materials. The available pixelscale of the selected detectors doesn't allow these requirements to be relaxed.

From the experience gained in designing the initial instrument concept we can also argue that opto-mechanical problems for a sensor much more demanding, like that for a 20-30m telescope, could be overcome with more engineering efforts coupled with a good knowledge of the industrial capability.

ACKNOWLEDGMENTS

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* material patented by Du Pond

REFERENCES

1. R. Ragazzoni *et al.*, "Pupil plane wavefront sensing with an oscillating prism", *Journal of Modern Optics* **43**, p. 289, 1996.
2. *Preliminary Design Review of LINC-NIRVANA*, 2003. Available at www.mpia.de/LINC/Files/PDR.pdf.
3. J. M. Hill and P. Salinari, "Large Binocular Telescope project", **5489**, SPIE, June 2004.
4. R. Ragazzoni *et al.*, *ESO proc.* **57**, p.175, 1999a.
5. R. Ragazzoni *et al.*, *A&A* **396**, "Multiple field of view layer-oriented adaptive optics. Nearly whole sky coverage on 8m class telescope and beyond", p.731, 2002.
6. S. Egner *et al.*, "LINC-NIRVANA: the single arm MCAO experiment", **5490**, SPIE, June 2004.
7. M. Lombini *et al.*, "Assembly, integration, and test of the layer-oriented wavefront sensor for MAD", **5490**, SPIE, June 2004.

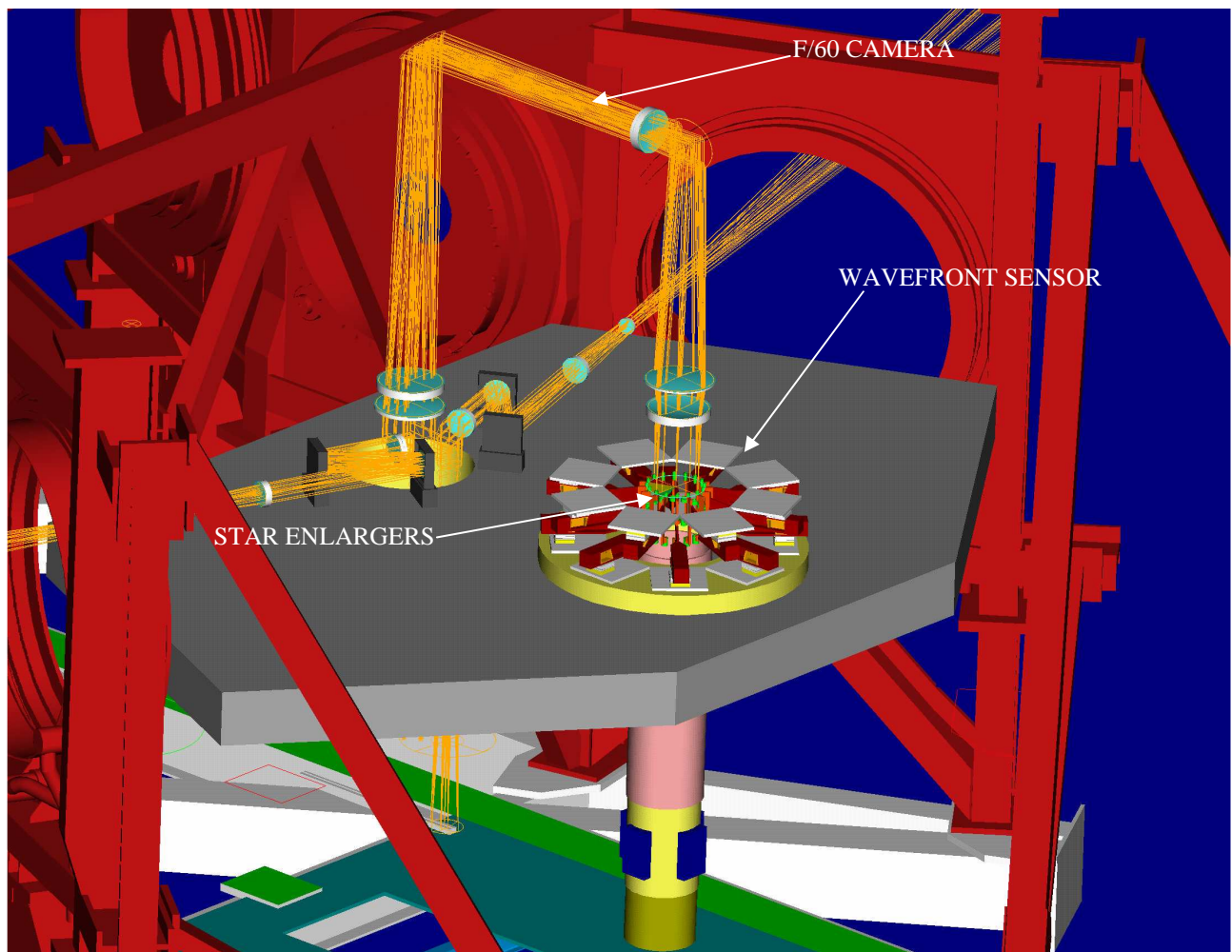


Figure 13. Outline of a 20-30m telescope wavefront sensor based on a design study for LINC-NIRVANA.

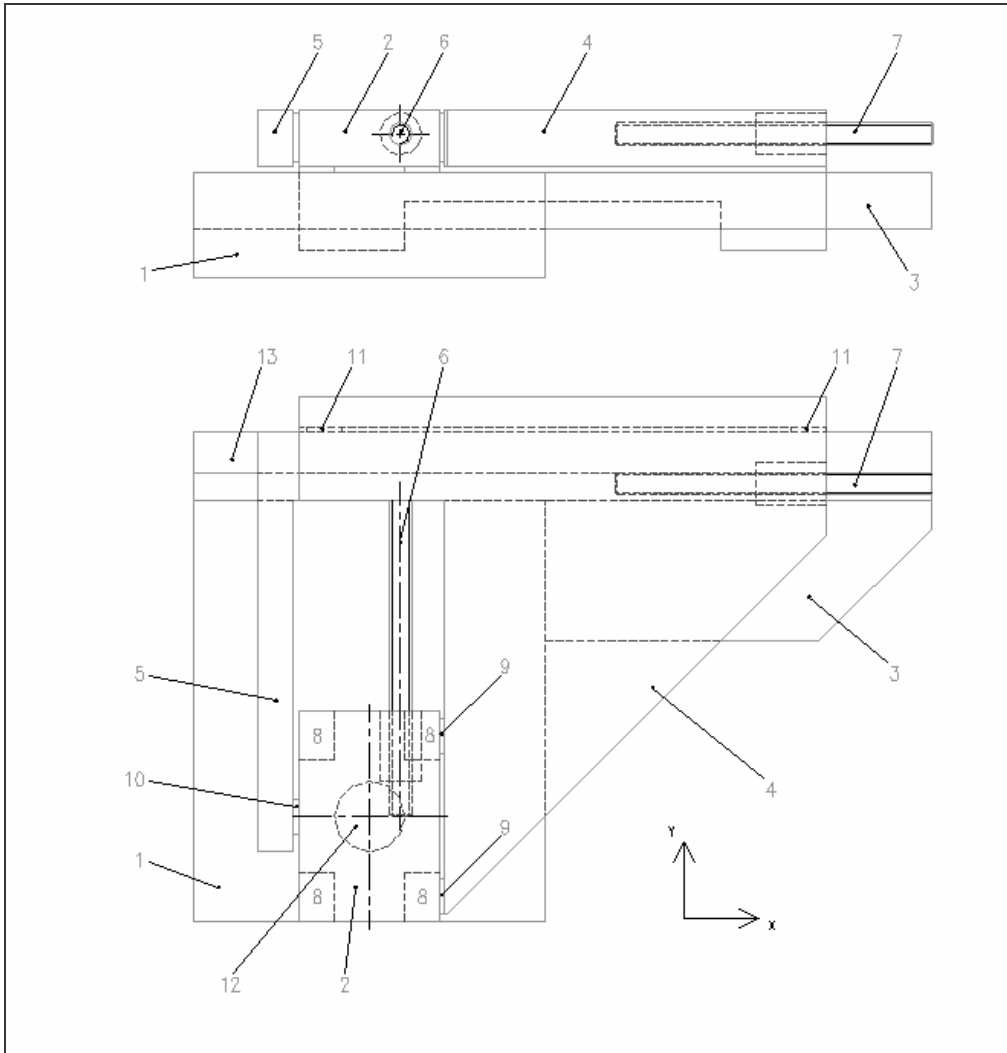


Figure 14. Ultra precision translation stages from Studio Tecnico Tomelleri s.a.s. The table 2 is preloaded by the electromagnet 12 and the pads 8 against the base 1, realized in chromium-plated steel. The structure 3, fixed to the base, has the slide 13 on which moves along the axis x the square 4, driven by the screw 7. The square moves on the slides 13 by the two pads 11, preloaded by the pad 14. The square has an accurate slide, against which the table has two pads 9 preloaded by the pad 10 and the bending of the item 5. With the screw 6 the table is driven along the y axis. All the screw have solutions in order to load the table only along the axis, avoiding stray load or torque against the table.