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A calibration source for the ELT AO systems

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ABSTRACT

The paper describes the possible implementation of a calibration source to be installed in the ELT optical train providing a single pass test beam for AO systems calibration. The source could be used by SCAO systems like those of MICADO/MAORY, HARMONI and METIS and to monitor M4 shape and differential pistons. Additional functionalities could be provided in order to use it for LGS based AO systems calibrations like the MCAO system of MAORY/MICADO or the foreseen LTAO system of HARMONI. In this work, we show a straw man optical design for such an on-axis source and describe options to provide off-axis sources to support engineering and commissioning phases of AO systems at the ELT.

Keywords: Extremely Large Telescope, Adaptive Optics, Calibration strategy, Calibration unit

1. INTRODUCTION

The ELT with its 39m diameter will be the largest optical telescope ever built with unsurpassed performances in terms of resolution and sensitivity from ground. The telescope relies on high performing Adaptive Optics as the final step to achieve its goals. It is worldwide recognized that one of the most critical task in bringing an AO system to successful operation on sky right from the beginning is the level of testing and calibrations [2][3] done prior to finally close the loop on sky. Many different successful projects has followed this approach of having a very comprehensive and detailed calibration and verification plan completed in the laboratory before moving to the telescope. This is the case of LBT AO systems FLAO 1 & 2[4], Magellan AO MagAO, the VLT AOF systems GRAAL and GALACSI[1] the planet imagers SPHERE[5] and GPi to mention only a few of them. This approach cannot be easily applied to the AO systems of the ELT like SCAO, LTAO and MCAO under development for the ELT instruments like MAORY/MICADO, HARMONI, and METIS. Among the various difficulties we mention briefly the unavailability of an optical facility to couple the ELT adaptive mirror M4 with ELT AO systems prior to telescope integration. So, at present, all AO system of the ELT will be coupled with M4 directly at the telescope and as baseline closed loop test will be performed directly on sky. Such baseline plan being very ambitious and effective differs significantly from previous experience as shortly reported above. As a risk mitigation strategy the paper presents the study (part of an H2020 EC OPTICON initiative) of a possible optical calibration unit to be deployed at the ELT telescope to perform daytime AO verification and commissioning activities. The ELT optical design is quite favorable in this respect and the studied solution exploit the intermediate focal plane located between M2 and M3. This initial study shows that a simple optical system can provide an on-axis focal plane sources having all the features of the ELT focal plane. The availability of such source is the main ingredient to quickly and safely verify functional and performance requirements for the different ELT SCAO systems. The calibration unit on-axis design can be generalized to provide angularly extended off-axis sources for LGS based AO systems like MAORY MCAO and HARMONY LTAO. Finally such on axis optical unit could be used in a single pass measurement configuration to verify and monitor the optical shape and differential pistons of M4, the main component of any AO systems of the ELT, as detailed by others[6].

2. THE CALIBRATION UNIT OF ARGOS AND ELT UNIT CONCEPT

The current study has been started after discussion in the framework of a JRA1 OPTICON Network having a work package fully dedicated to Adaptive Optics calibration strategy and AIT tools (H2020, OPTICON, CA #730890). The

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network activity started in December 2017 and involves all instrument groups of the ELT namely HARMONI, MICADO, MAORY, METIS, HIRES and MOSAIC. The idea of this Work Package (WP) was to find synergies between the different groups and possibly design common strategies and AIT tools for the test and verifications of the AO system performance and specifications. The WP distributed two questionnaires among the various mentioned group with questions about expected calibration strategy and required AIT tools. For the first item it was clear that the different group have adopted as baseline the current proposition of the ELT namely a system calibration done using pseudo synthetic Interaction Matrices (IM). As pointed out above such technique has been used lately at AOF and is currently still to be explored. For such reason the majority of the considered groups reported that the availability of a calibration source at the telescope would provide a very useful and easy tool for IM acquisition and additionally a reliable method to measure and verify Non Common Path Aberrations (NCPA) between AO WFS and instrument detector. It is interesting to mention here that all SCAO systems of the ELT use pyramid sensors as wavefront sensors (WFS). Such non-linear WFSs will surely benefit from the possibility to measure the NCPA in diffraction-limited conditions. The starting point of the present initial study is the availability of an intermediate focal plane in the ELT optical train. This focal plane is located between M2 and M3. The idea for the calibration unit optical design is to use this intermediate focal plane to inject the required sources NGS and LGS. A similar arrangement has been already realized at the LBT telescope where the calibration unit of the GLAO system ARGOS ([7],[8]) uses the focal plane of the primary mirror (LBT has a Gregorian type optical configuration) to inject NGS and LGS sources. A logical sketch of the ARGOS CalUnit is reported in Fig.1.

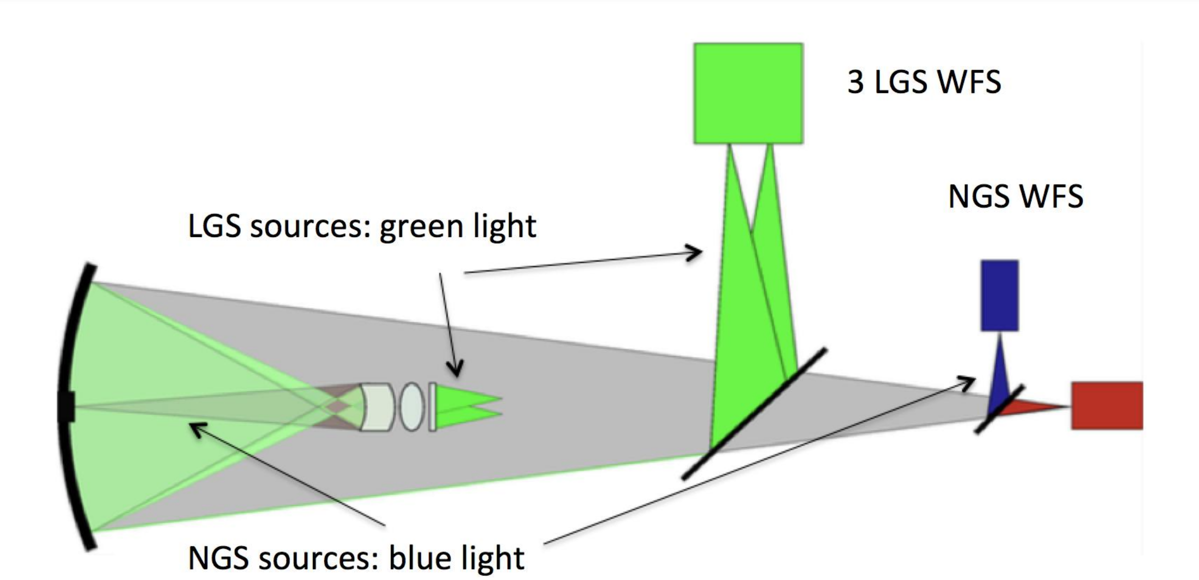

Figure 4: Sketch of the light path and scheme of the calibration method including calibration unit and WFS.

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Figure 1. A schematic diagram of the LBT ARGOS calibration unit showing the different paths of the 3 off-axis LGSs and the on-axis NGS.

As a first comment we report that the calibration unit (hereafter CalUnit) optics is located inside the shadow of M1 obstruction so all the telescope beam is probed by the unit. Secondly we note that the LGS sources are reimaged in the focal plane of the LBT secondary mirror trough some optical elements while the NGS on axis source is generated by placing a fiber in the M2 vertex and refocusing it with the proper F/ by using reflection on the last coated surface of the CalUnit optical element. With such a setup the two kind of sources are reimaged in an almost completely separated manner and can be separately optimized. The ELT CalUnit concept we will detail below assume to place the CalUnit close by the ELT intermediate focal plane and use a similar configuration for NGS and LGS. We note here that the intermediate focal plane of the ELT is positioned very close to the optical surface of M4 the adaptive mirror unit [9]. The F/ of the intermediate focal plane is F/4.4 so to avoid large optical elements we try to stay close to the focal plane. A convenient location for the calibration unit hardware is the interior of M4 in between the M4 hexapod and M4 reference plate. A figure of M4 showing the relevant elements is reported below (courtesy of ADS and MIC).

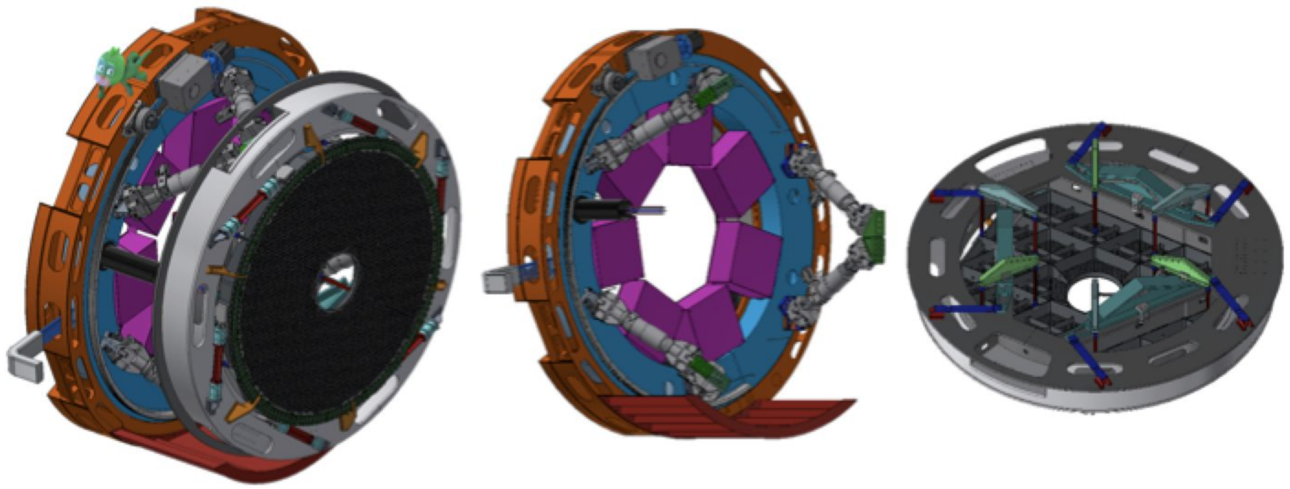


Figure 2. A figure of M4 unit (left) and its two main parts hexapod platform (center) and reference and optical surface (right). The CalUnit hardware can be located in between (a) and (b).

The option to place the calibration unit in such position inside M4 has been discussed preliminary with ADS and MIC, (the two companies producing the M4 unit) and no showstopper has been found for such option. Of curse a more in detail study need to be done to find the best arrangement in terms of accessibility and maintainability of the M4 unit. With these considerations in mind we developed an optical design for the ELT calibration unit able to provide NGS and LGS reference star with the proper F/ and focal plane position as showed schematically in the figure below.

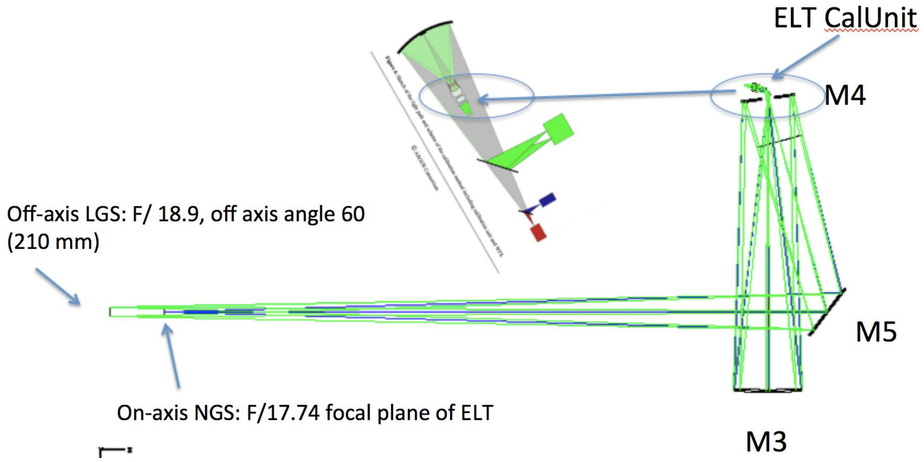


Figure 3. The sources arrangement produced by the considered CalUnit. Diffraction limited on-axis NGS and extended off-axis sources (60 arcsecond) LGS are generated at the final ELT focal plane.

3. THE NGS SOURCE OPTICAL PATH

In the case of the NGS source we consider an elliptical surface to reimage a source fiber into the intermediate focal plane with the correct F/. A close-up of the design is reported in the figure below. Theby reference fiber is placed in the center of the mirror that fold the light on the ELT optical axis. The considered elliptical surface has a radius of curvature of 1456mm and a conic constant of 0.332. The mirror diameter is 380mm. The on axis final PSF produced by this optical set-up is diffraction limited with a wavefront rms of 10nm. The wavefront map and achieved PSF are reported in the figure below.

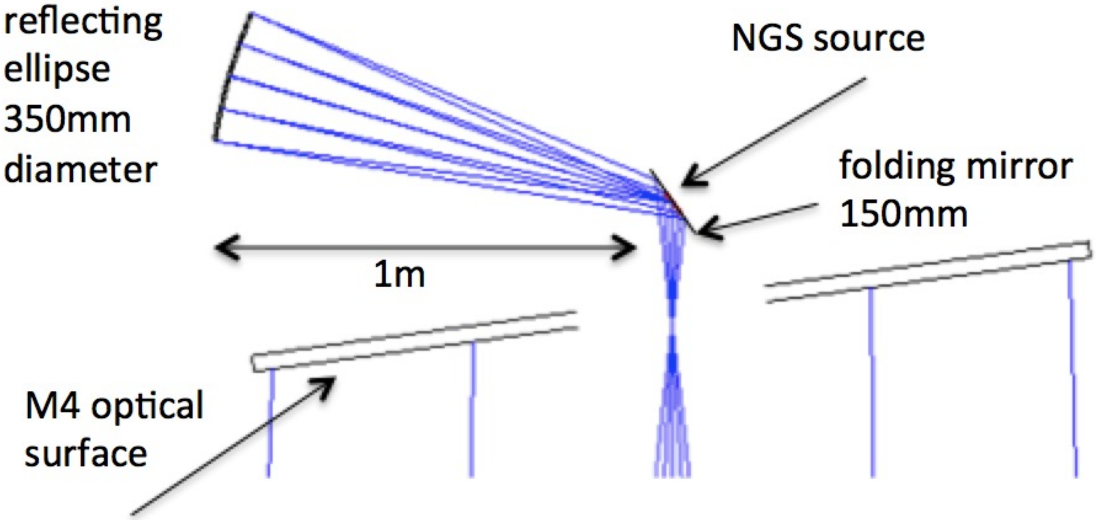
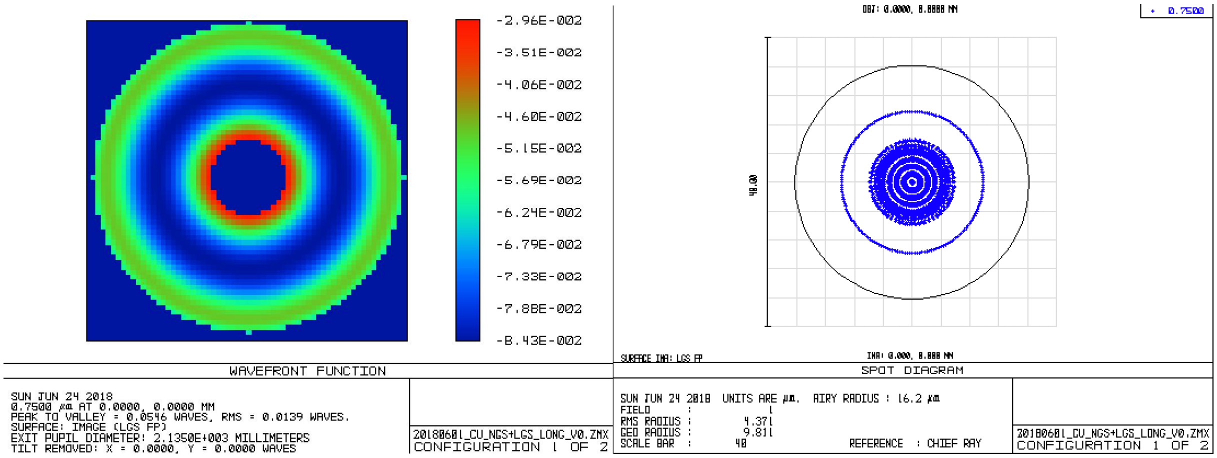


Figure 4. The optical arrangement to generate the NGS. A reference fiber is placed at the folding mirror surface.



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SUN JUN 24 2018
0.7500 µm AT 0.0000, 0.0000 MM
PEAK TO VALLEY = 0.0546 WAVES, RMS = 0.0139 WAVES.
SURFACE: IMAGE (LGS FP)
EXIT PUPIL DIAMETER: 2.1350E+003 MILLIMETERS
TILT REMOVED: X = 0.0000, Y = 0.0000 WAVES
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20180601_CU_NGS+LGS_LONG_V0.ZMX
CONFIGURATION 1 OF 2
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SUN JUN 24 2018  UNITS ARE µm.  AIRY RADIUS : 16.2 µm
FIELD      :          1
RMS RADIUS :      4.371
GEO RADIUS :      9.811
SCALE BAR  :     40                REFERENCE  : CHIEF RAY
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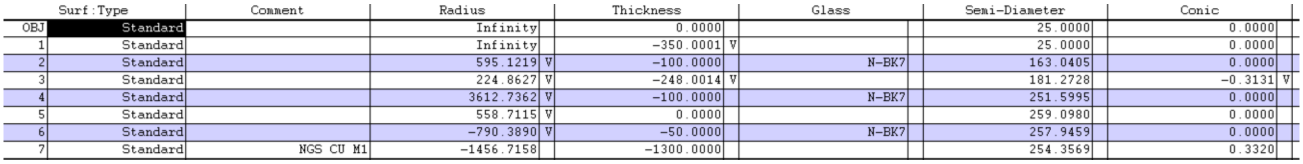
20180601_CU_NGS+LGS_LONG_V0.ZMX
CONFIGURATION 1 OF 2
```

Figure 5. The achieved NGS wavefront and PSF at the final focal plane of the ELT.

The elliptical surface has been selected with a long radius of curvature to be able to place the ellipse out from the M4 area where accessibility is required to reach some of the critical components of M4. We will show later in the paper that by reducing this distance a more compact optical design can be achieved. We note here that a similar set-up has been proposed in [6] to calibrate the differential piston and influence functions on M4. This set-up could be implemented with the proposed calibration unit. To this aim part of the on axis beam should be derived before the elliptical surface and combined interferometrically at the final ELT focal plane with the reference source beam.

4. THE LGS SOURCES OPTICAL PATH

To implement off-axis LGS sources we take advantage of the different operating wavelengths of NGS and LGS, the last one monochromatic) as in the ARGOS CalUnit. We use a lens objective to refocus LGS sources to the intermediate focal plan and then to the final LGS focal plane 2492 mm from the NGS focal plane. This is the final focal plane for the LGS sources in the ELT when the LGS source is located at 100km of altitude above the telescope. We report in the table below the main parameters of the considered lenses.



	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic
OBJ	Standard		Infinity	0.0000		25.0000	0.0000
1	Standard		Infinity	-350.0001 V		25.0000	0.0000
2	Standard		595.1219 V	-100.0000	N-BK7	163.0405	0.0000
3	Standard		224.8627 V	-248.0014 V		181.2728	-0.3131 V
4	Standard		3612.7362 V	-100.0000	N-BK7	251.5995	0.0000
5	Standard		558.7115 V	0.0000		259.0980	0.0000
6	Standard		-790.3890 V	-50.0000	N-BK7	257.9459	0.0000
7	Standard	NGS CU M1	-1456.7158	-1300.0000		254.3569	0.3320

Table 1. A table reporting the main parameters of the reimaging optics used for the LGS path.

The achieved result is shown in Fig.6 below where we report the LGS and NGS beam arrangements together with the achieved spot in the final focal plane for the off-axis source. Note that the final source is generated at 60 arcsecond off axis with the correct F/ 18. The linear distance from the axis is 210mm.

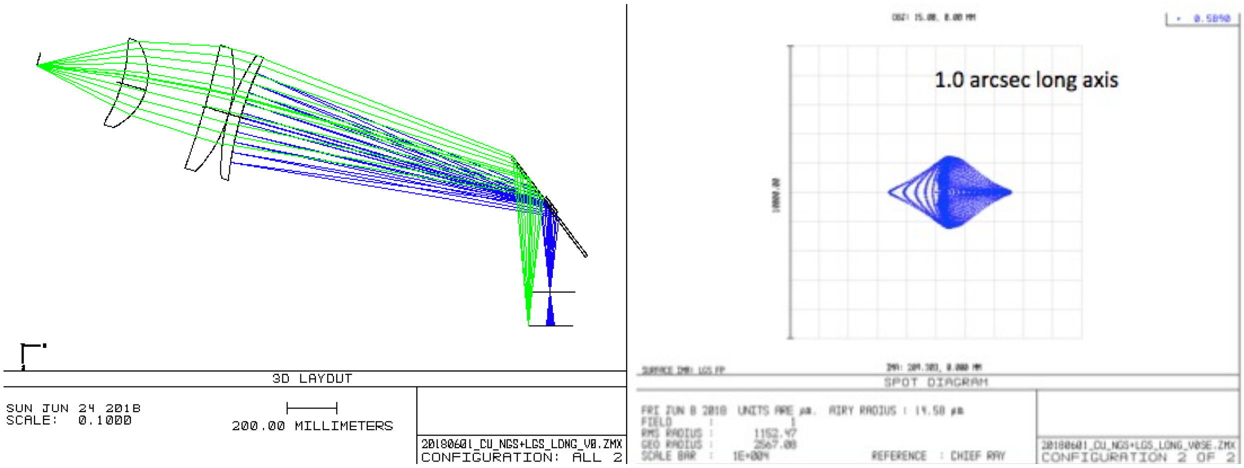


Figure 6. The reimaging optics that generates the LGS spot at the proper focal plane and with proper F/. The back surface of the final meniscus is an elliptic surface with a polychromatic reflective coating that provides the NGS source.

The PSF of the LGS beam is not diffraction limited but this is not relevant in this case because the LGS image is an extended object of a few arcescond size or more. For comparison we show in the figure below the image of a top hat fiber of 0.5 mm diameter. The image is an almost round object of 2 arcsecond diameter, surely a good representative object for the LGS WFS having a pixel scale of the order of 1 arcsec. We note here in passing that the CalUnit of ARGOS uses an hologram in the refractive part of the reimaging optics to control the wavefront aberrations of the LGS beams. Such hologram could be designed and added in this case to control the aberration of the off axis sources if required.

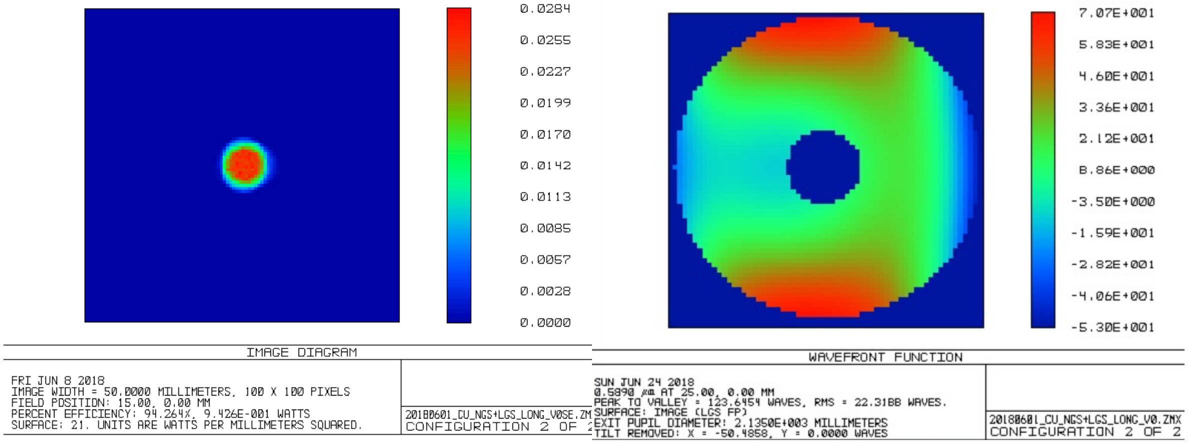


Figure 7 An image (left) of the final image of an object of 0.5mm placed in the input focal plane of the reimaging optics. On the right the corresponding wavefront. In this case wavefront quality is 6um rms and maximum derivative is 1.4 arcsecond.

The wavefront rms achieved by the current design is quite large and equal to abut 6um rms. The important aspect to consider here is the wavefront derivative on each subaperture of the LGS SH sensor. Considering 80x80 subapertures (a typical number for the ELT LGS systems like those for HARMONI or MAORY) we find a maximum local slope per subapertures of 1.4 arcsec. The number is not large with respect to the SH FoV anticipated to be larger than 10 arcsec and with respect to the pixel scale of 1 arcsec. However these slopes could be a problem for the measurements of NCPA being a pattern to be removed. As we will show in the next section a shorter design does better in this respect so we leave the design as is and consider that it should be revised in a second development phase if required. As a final note we mention that the designed system do not create a system pupil. However we can introduce an entrance pupil placing a diaphragm on the first lens surface. This diaphragm is reimaged at about 10m distance from the exit pupil of the ELT optical train. This translates in the fact that the chief rays angle at the final focal plane is not currently the correct one. We consider that adding another optical elements allows the optical system to generate proper F/ and sources with the correct pupil position. The design of this last optical system is still to be developed but should not present particular difficulties.

5. THE SHORT NGS AND LGS CALIBRATION UNIT

The idea of this second set-up is to study the performances of the above considered optical system when the refractive group is allowed to stay closer to the telescope optical axis. This will require some additional consideration about the placement inside M4 but it provides better performance with smaller size optics as shown below. Details of the optical design for this option are given below in Tab.2 and Fig.8.

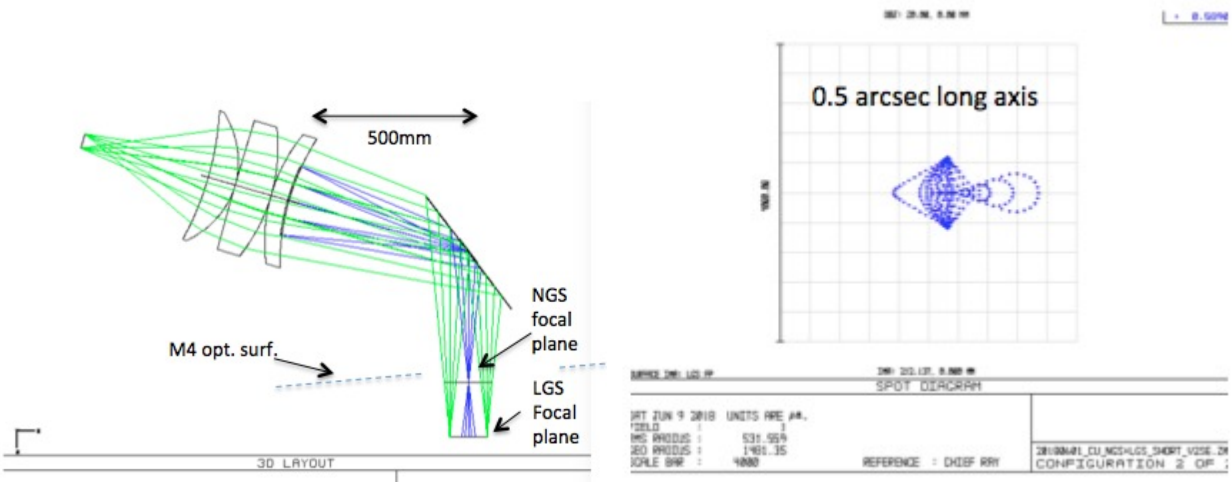


Figure 8. The optical set-up when the refractive optics is allowed to be closer to the optical axis in tis case the distance between the last lens and the folding mirror is 500mm. on the left the achieved PSF in the case of the LGS source. The NGS elliptical surface is readjusted to provide the same quality as for the long set-up.

The quality of the LGS spot is improved and we retain the same quality of the NGS source bay changing the ellipse radius of curvature.

Surf:Type		Radius	Thickness	Glass	Semi-Diameter	Conic
OBJ	Standard	Infinity	0.0000		20.0000	0.0000
1	Standard	Infinity	-350.0000 V		20.0000	0.0000
2*	Standard	813.0220 V	-75.0000	N-BK7	180.0000 U	0.0000
3*	Standard	219.4568 V	0.0000		180.0000 U	-0.3656 V
4*	Standard	-8309.1478 V	-100.0000	N-BK7	180.0000 U	0.0000
5*	Standard	468.7689 V	0.0000		180.0000 U	0.0000
6*	Standard	-449.3522 V	-50.0000	N-BK7	180.0000 U	0.0000
7*	Standard	-631.3951	-500.0000		180.0000 U	0.3363

Table 2. A table reporting the main parameters of the reimaging optics used for the LGS path when the refractive optics group is placed at 500mm distance from the folding mirror.

Placing the lenses group closer to the optical axis enables to reduce their size that is now smaller than 360mm. We note here that the weight of such lenses should be around 10kg each. We show below the image of a top hat fiber and the corresponding wavefront in the considered case. The obtained image is a round disk of 2 arcsecond with a fiber size of 0.7mm. The achieved wavefront quality is now 1.5um rms and the maximum slopes considering 80x80 subapertures SH is of 0.2 arcseconds that we consider acceptable in terms of loss of dynamic range of the WFS.

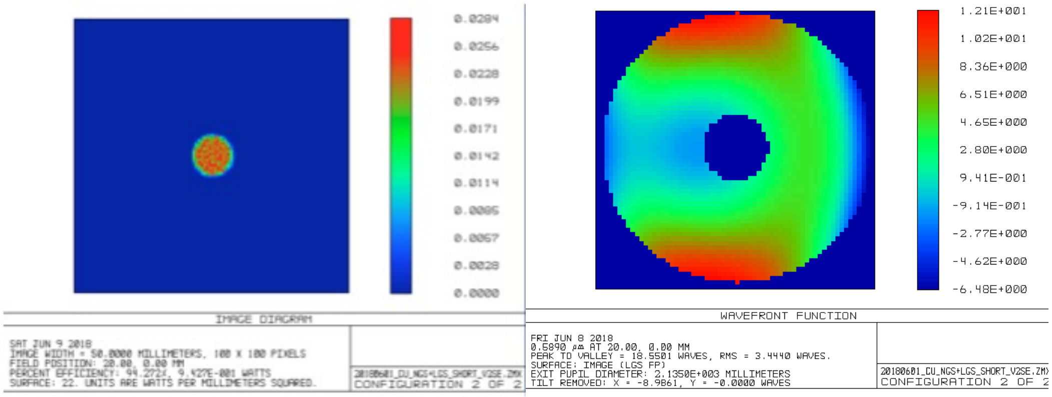


Figure 9. An image of the final image of an object of 0.7mm placed in the input focal plane of the reimaging optics. On the left the corresponding wavefront. In this last case the wavefront quality is 1.5um rms and maximum derivative is 0.2 arcsec.

6. A FIRST MECHANICAL SKETCH OF CAL UNIT INSIDE M4

As mentioned above we considered placing the calibration unit inside the m4 unit in between the hexapod assembly and the reference body. Two figures of the M4 unit showing the space allocated for the optical beams are reported below.

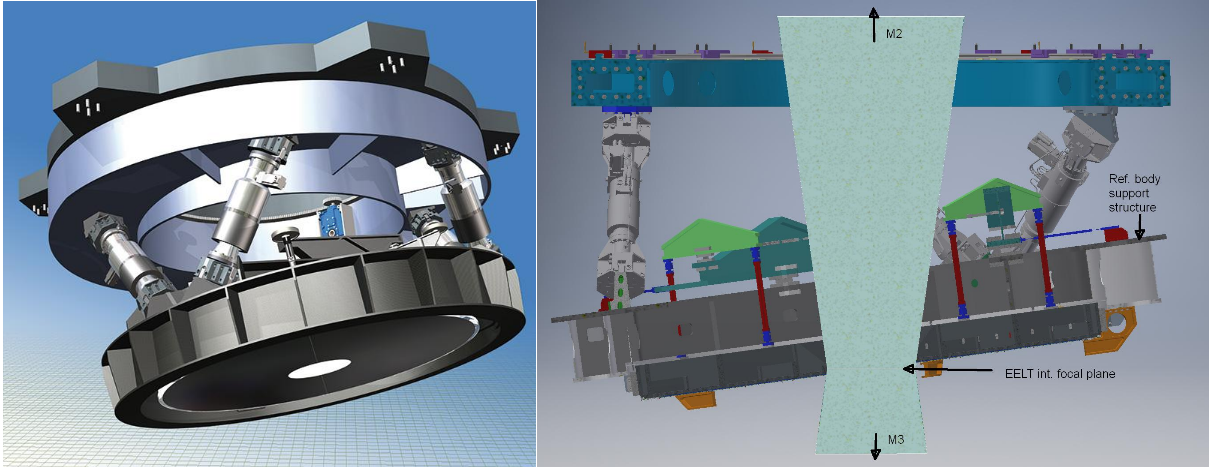


Figure 10. Two figures of the M4 units. The right panel shows the available space for the optical beams.

The folding mirror of the considered calibration unit has been designed to stay inside the central free space where the telescope optical beam is passing. In the image below a first sketch of a possible placement of the calibration unit (surfaces in white) is reported. In Fig.11 we reported the elliptical surface of the NGS optical path and the folding mirror placed inside the optical beams volume. In this configuration the folding mirror has to be repositioned before telescope operation in order not to vignette the optical beams. As mentioned above such positioning of the unit has been preventively discussed with ADS and MIC without encountering showstoppers. In any case the progress towards a detailed design will necessarily need to review the placement of the unit in more details.

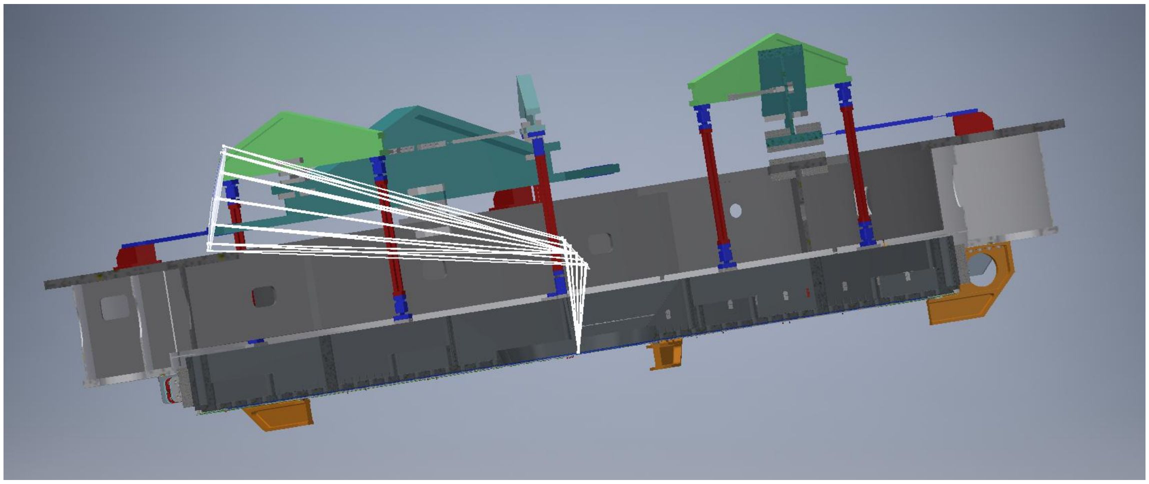


Figure 11. The arrangement of the elliptical surface inside the M4 unit. The floding mirror has to be retracted when the telescope is in operation.

We conclude by saying that the refractive optics that stays behind the elliptical surface do not need to be removed for telescope operations.

CONCLUSION

We have shown in this paper the feasibility of a calibration unit for the adaptive optics systems of the ELT that uses the intermediate focal plane of the telescope. The considered unit resembles the so called CalUnit of the LBT/ARGOS system[7] and is able to produce an on axis polychromatic diffraction limited source (within a FoV of 15 arcseconds) with an overall wavefront error of 10nm rms. At the same time the unit is able to provide off-axis laser guide star reference sources 1 arcminute off axis with a spot size of about 2 arcsecond diameter. The wavefront quality of such sources is lower (1.5 um wavefront rms) but the maximum derivative on an 80x80 subaperture wavefront sensor is 0.2 arcsec so not impacting the dynamic range of the sensor. The design has to be improved to provide a pupil stop in the proper place. Finally the use of a hologram plate in the transmitted beam would improve the LGS wavefront and possibly shape the wavefront to consider telescope off-axis aberrations. We believe that such a unit would be a very useful tools during AIV phase of all the ELT AO systems at the telescope.

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