MEGARA FIBER BUNDLES

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ABSTRACT

MEGARA (Multi Espectrógrafo en GTC de Alta Resolución para Astronomía) is the future optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) for the 10.4-m Gran Telescopio CANARIAS (GTC). MEGARA has three different fiber bundles, the Large Central Bundle covering 12.5 arcsec × 11.3 arcsec on sky, the Small Compact Bundle, of 8.5 arcsec × 6.7 arcsec, and a Fiber MOS positioner system that is able to place up to 100 mini-bundles with 7 fibers each in MOS configuration within a 3.5 arcmin × 3.5 arcmin FOV. The MEGARA focal plane subsystems are located at one of the GTC Folded Cassegrain focal stations. A field lens provides a telecentric focal plane, where the fibers are located. Micro-lenses arrays couple the telescope beam to the collimator focal ratio at the entrance of the fibers. Finally, the fibers, organized in bundles conducted the light from the focal plane to the pseudo-slit plates at the entrance of the MEGARA spectrograph, which shall be located at one of the Nasmyth platforms. This article also summarizes the prototypes already done and describes the set-up that shall be used to integrate fibers and micro-lens and characterize the fiber bundles.

Keywords: MEGARA, integral field unit (IFU), multi-object spectrograoh (MOS), fiber bundles, microlens integration, fiber characterization, fiber positioners, GTC

1. INTRODUCTION

Begin the Introduction two lines below the Keywords. The manuscript should not have headers, footers, or page numbers. It should be in a one-column format. References are often noted in the text[1] and cited at the end of the paper.

MEGARA (Multi Espectrógrafo en GTC de Alta Resolución para Astronomía) is an optical fiber fed spectrograph. The MEGARA focal plane subsystems are located at one of the Folded Cassegrain focal stations of the Spanish 10.4m telescope GTC. Fiber bundles conduct the lights to the spectrograph that will be hosted at one of the Nasmyth platform (see Figure 1). The instrument offers three observing modes: two integral field units (IFUs), the Large Compact Bundle (LCB) and the Small Compact Bundle (SCB), and multi-object spectrograph (MOS) also known as the Dispersed Mode (DM). The LCB and the SCB shall be fed by a 100 µm and 70 µm fiber cores respectively, and accordingly delivering a FOV of 12.5″ × 11.3″ and 8.5″ × 6.7″. While the MOS shall be able to place up to 100 mini-bundles with 7 fibers each (100 µm fiber-core) covering a sky area of 3.5 × 3.5 arcmin^2. The science light will come into the spectrograph from one of the Folded Cassegrain focus (where the LCB, SCB and MOS subsystems are located and telecentrically illuminated with the aims of a field lens), by means of a ~ 40m fiber optic wiring. At the fiber entrance the telescope focal ratio is reduced from F17 to F3 with the aim of a micro-lens array. Subsequently each fiber bundle will be allocated at the spectrograph focal plane forming a smoothly curved pseudo-slit with a radius of curvature of 1075 mm and 110mm long.

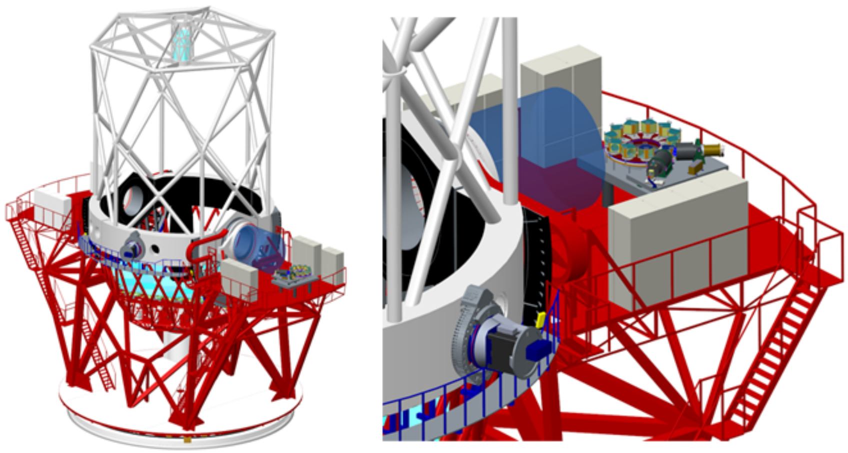


Figure 1: Left hand side shows a perspective of GTC with MEGARA placed at one of the Nasmyth platform while right hand side shows a zoom where the Folded Cassegrain focus and MEGARA on the Nasmyht platform are seen.

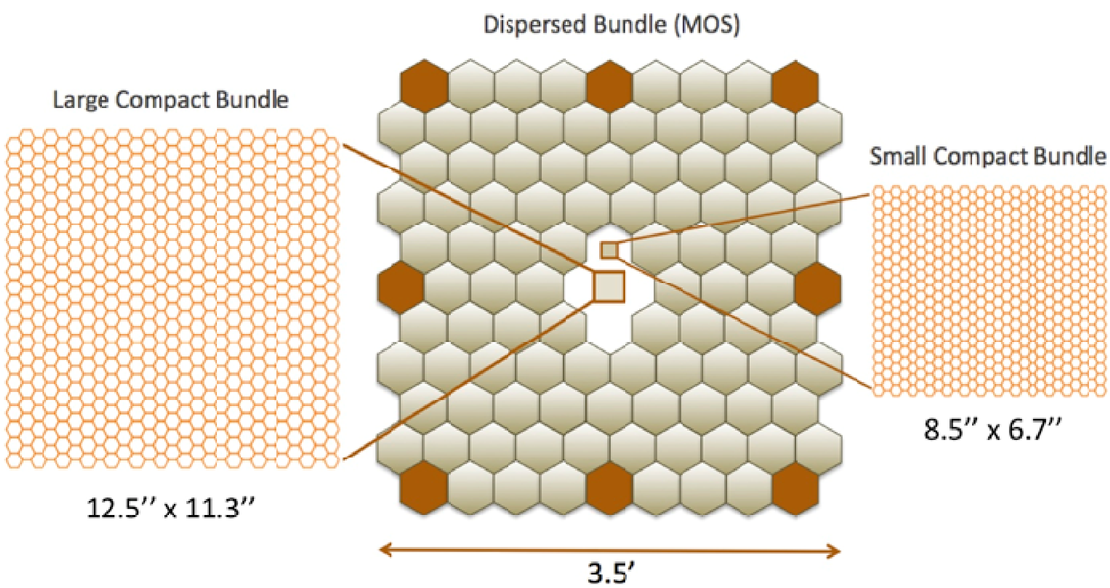


Figure 2: Left hand side shows a perspective of GTC with MEGARA placed at one of the Nasmyth platform while right hand side shows a zoom where the Folded Cassegrain focus and MEGARA on the Nasmyht platform are seen.

MEGARA shall work in the optical range from 3700Å to 9800Å. The spectrograph is an all refractive system[1] (with F3 and F1.5 focal ratios for the collimator and camera respectively) using a set of interchangeable gratings that are based on volume phase hologram gratings (VPHs) placed at the collimated beam (where the pupil of the system is formed). The final set offer three spectroscopy modes: at low, medium and high resolution (accordingly to R_{FWHM} = 6000, 12000, 18700). Finally, the scientific data will be recorded by means of an E2V 4k × 4k detector, with a 15µm pixel size. The main parameters are shown in **Table 1**.

The Universidad Complutense de Madrid (UCM) leads the MEGARA Consortium. The rest of MEGARA Consortium partners is constituted by the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) in Mexico, and the Instituto de Astrofísica de Andalucía (IAA-CSIC) and the Universidad Politécnica de Madrid (UPM) in Spain.

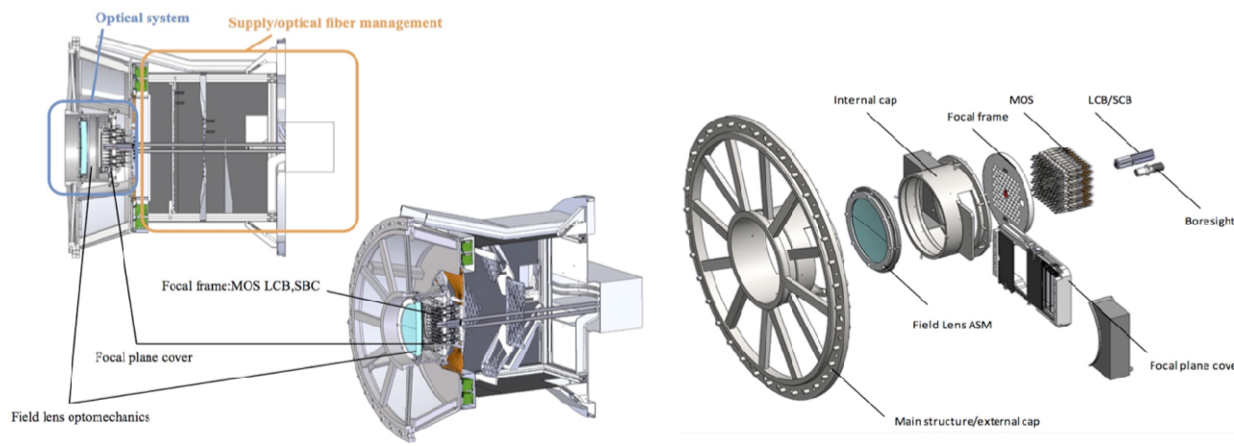
Table 1: Main characteristics of MEGARA LCB and SCB IFUs and MOS modes

PARAMETER		**REQUIREMENTS**		
Telescope		GTC		
Plate Scale		0.82 mm arcsec^{-1}		
Field Lens		D = 260mm		
Microlens		Hexagonal Shape F-ratio transformation from F17 to F3		
Fiber Unit		Holded at Folded Cassegrain focus Field lens for telecentric illumination LCB, SCB, MOS		
		Large Compact Bundle	**Small Compact Bundle**	**MOS Bundle**
Fiber-core		100μm	70μm	100μm
No. of fibers		623	511	644
Spaxel		0.62″	0.42″	0.62″
FOV		12.5″ × 11.3″	8.5″ × 6.7″	3.5′ × 3.5′
$\Delta\lambda$(EED$_{80}$)		4.0 pix	3.48 pix	4.0 pix
$\Delta\lambda$(FWHM)		3.6 pix	3.14 pix	3.6 pix
R	**LR**	6000	7000	6000
	MR	12000	13500	12000
	HR	18700	21500	18700
Pseudo-slit		110 mm long & ROC = 1075mm		
F-ratios		Collimator F3 to camera F1.5		
Pupils size		160 mm		
Gratings		VPHs, 240mm × 190mm (MR, HR), 220mm × 180mm (LR), selectable		
Wavelength coverage		3700Å – 9800Å		
Detector		E2V 1 × 4k × 4k, 15μm pixel size, AR coated		

The MEGARA Science Team includes a line-up expert researchers encompassing different astronomical areas from exoplanets & cool stars to cosmology, going through massive stars, planetary nebula, and nearby galaxies, coming from all the MEGARA consortium institutions and other Spanish and Mexican research centers together the University of Florida (FL).

MEGARA is being developed under contract with GRANTECAN. MEGARA has already delivered the CDR documentation and is ready to enter into manufacturing.

Section 2 briefly outlines the MEGARA focal plane subsystems, while Section 3 describes the set-ups design elaborated to perform several tests and verification task over the micro-lens array and fibers. Finally, Section 4 gives the details of the set-ups developed to verify the fibers bundles and to glue the micro-lens arrays to the fibers.



Folded Cassegrain Adapter Section — Folded Cassegrain Adapter optical components exploded view

Figure 3: Section of the Folded Cassegrain subsystems assembly and a exploded view of the optical components.

2. FOCAL PLANE UNITS

All these subsystems are found at the Folded Cassegrain rotator adapter, a structure that fixes and positions the different optical subsystems of the focal plane at the Folded Cassegrain focus station including the field lens, the focal plane cover, the positioners and the IFUs[2]. Figure 3 shows a section of the Folded Cassegrain subsystems assembly and a exploded view of the optical components. The optical and electrical cable management subsystems, which are in charge of routing optical and electrical cables to the Folded Cassegrain rotator, are also included within the adapter.

The MEGARA Folded Cassegrain adapter support the following subsystems:

- The field lens shall correct the lack of telecentricity of the GTC focal station providing a field curvature below 0.1 in the whole FOV.
- The focal plane cover shall allow occulting part of the fibers (LCB and MOS) for performing null-cross-talk observations. A Focal-Plane Cover would be used so to allow removing the light coming from one every two consecutive fibers (or sets of fibers) at the corresponding pseudo-slit. In the case of the LCB this implies arranging the fibers so two consecutive fibers will come from different halves of the FOV. Regarding the MOS the decision was that all seven fibers from each MOS would be placed together in the pseudo-slit (to minimize inter-positioner cross-talk between the central – brightest – fiber of each positioner) but that adjacent sets of 7-fiber would come, again, from different halves of the FOV. In the case of the SCB, as the separation between adjacent fibers (170mm) at the pseudo-slit relative to the fiber-core size (70mm) is significantly larger than in the case of the LCB and MOS, we did not find necessary to include that functionality. Figure 4 shows the simulated spatial profiles obtained in the CCD for three adjacent positioners on the pseudo-slit.
- The 2D refractive micro-lens arrays (see Figure 5) shall couple the science light at the telescope focal plane into the fibers, defining the FOV and adapting F# from F17 to F3 to minimize FRD. The micro-lens arrays are arranged in different arrays for each mode following a hexagonal geometry to maximize the area to be cover. The spaxel size shall be fixed to 0.62″ for LCB and MOS and 0.42″ for SCB.
- The Fiber MOS shall consist of 100 robotic positioners (8 of them for LCB sky subtraction). Each fiber mini-bundle patrols a circular area of diameter Φ23.21 mm thanks to the two rotations provided by the positioner robot. Finally, the fibers bundles shall be routed through the Folded Cassegrain rotator cable wrap; the elevation ring and the elevation rotator cable wrap up to reach the spectrograph at the Nasmyth platform. At the spectrograph entrance, each bundle shall be arranged in a row at the pseudo-slit, which shall be divided in boxes to simulate the focal plane curvature at the spectrograph entrance (ROC 1075mm, size 110mm).

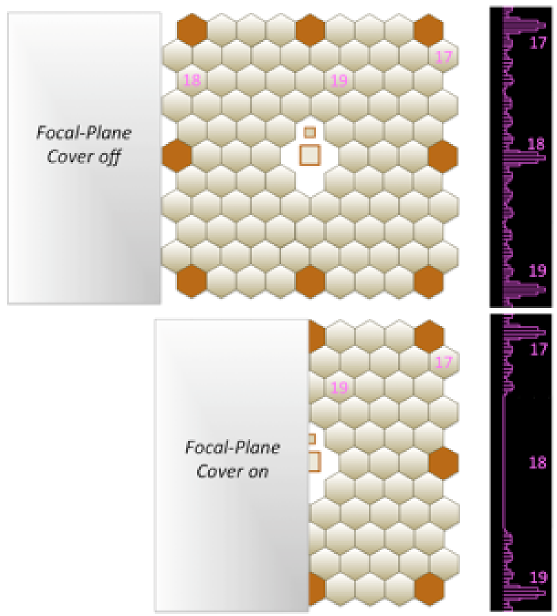


Figure 4: MEGARA footprint with the Focal-Plane Cover off (default mode) and on (for demanding null-cross-talk observations). The corresponding simulated spatial profiles obtained in the CCD for three adjacent positioners on the pseudo-slit (numbers 17, 18, 19) are shown in the right.

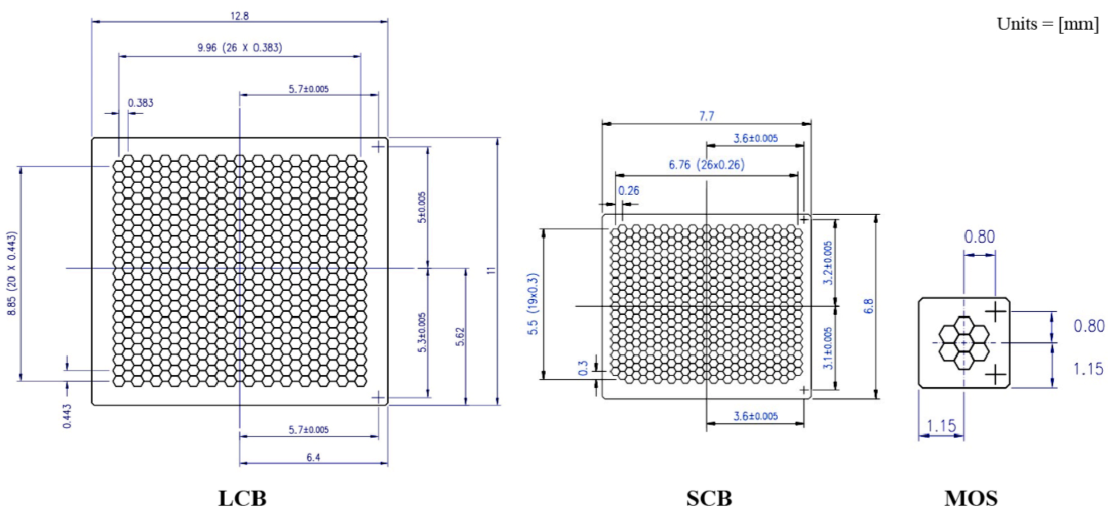


Figure 5: Lenslet distribution for the LCB, SCB and MOS button fiber bundles respectively.

2.1 Large Compact Bundle

The LCB (**Figure 5**) is an IFU bundle compound of 567 fibers (100 µm fiber-core, spaxel 0.62″) delivering a FOV of 12.5″ × 11.3″ near the optical axis of the instrument plus 8 positioner robots (orange hexagons in Figure 2) located in the outer edge of the instrument FOV that let simultaneously sky background measurements. The LCB IFU is an ideally tool suited for the study of individual compact objects under average seeing conditions and for absolute flux-calibration purposes when the MOS mode is used. When the object under study is larger than 8-10 arcsec the use of the LCB is preferred over the SCB given the improved sky subtraction yield by the former under those conditions. The power resolutions found by the LCB are R ~ 6000, 12000, and 18700 (see Table 1).

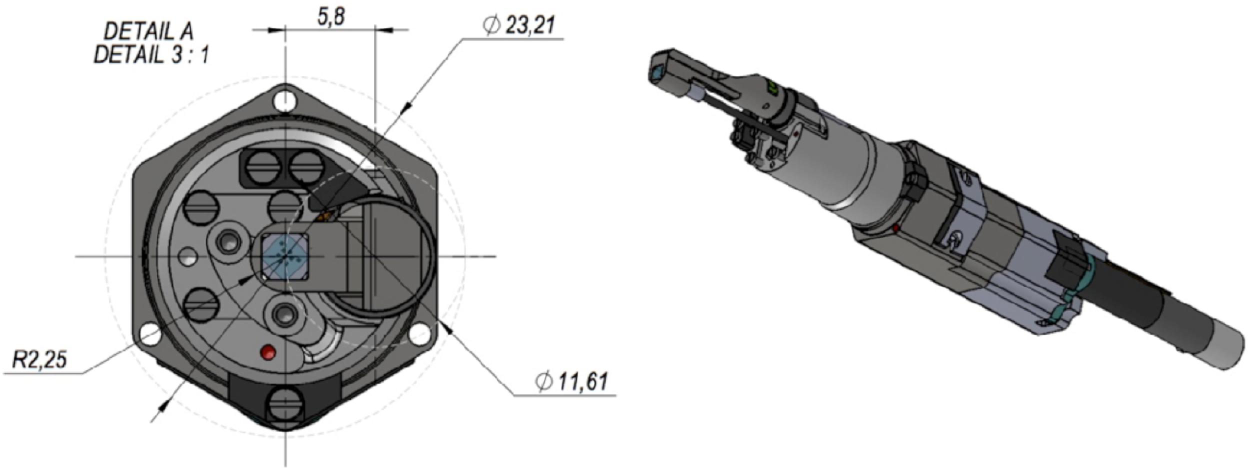


Figure 6: Image of the robotic positioner of MEGARA MOS.

2.2 Small Compact Bundle

The SCB is composed by 511 fibers (see **Figure 5**, 70 µm core, spaxel 0.42″) distributed in a square image area of 8.5″ × 6.7″, whose center is offset approximately 19 arcsec from the center of the LCB. Given its better spatial resolution, and poorer spectral sampling, in order to not lose any information in the vicinity of bright point sources this bundle has a more stringent requirement for the maximum cross talk allowed on the detector. A gap of 170 µm is used in the pseudo-slit of all modes. Otherwise, taking into account the relation between fiber core and external diameter, a factor ~ 2.5× the core size is obtained at the SCB while ~1.7× the core size is used at the LCB and MOS. When SCB is used a power resolution of 7000, 13500 and 21500 are reached (see Table 1).

2.3 MOS Bundle

The Fiber MOS (**Figure 5**) is composed by 100 robotic positioners (see **Figure 6**) and allows placing 92 seven-fiber mini-bundles (8 of them are devoted for LCB sky subtraction) anywhere in the 3.5 × 3.5 arcmin^2 FOV. The distance between two adjacent positioners centers is 20.1mm. Each positioner patrols a circular area with a diameter of 23.21mm by combining the interpolations of two rotations provided by the positioner robot. The positioner was designed and manufactured by AVS while the mini-bundle was integrated by SEDI. The behavior of the prototype positioner rotations (R1 and R2) was well characterized fulfilling the radius, flatness, parallelism, eccentricity and tilt requirements, providing a high repeatability and position accuracy.

3. FIBER TESTS AND VERIFICATION SET-UPS

Throughout this section we will introduce the proposed opto-mechanical units for fiber micro-lens coupling and the MOS fiber-bundle characterization, before the final integration at the telescope. The whole verification system to be discussed is composed by the following units:

3.1 Illumination System at F17/F3

The concept of this unit is based on the need of a system that illuminates properly the MOS fibers before and after gluing the array. This will let to measure and check the micro-lens fiber attachment behavior, measuring the transmission of the fibers illuminating these ones at F3 (before being glued to the lenslets) and the micro-lens fiber transmission illuminating the arrangement at F17. The purpose with this system is to identify any broken or anomalous fiber of the complete bundle.

The unit is compound of an illumination stage, which is composed of (1) a cavity with a halogen illumination source plus

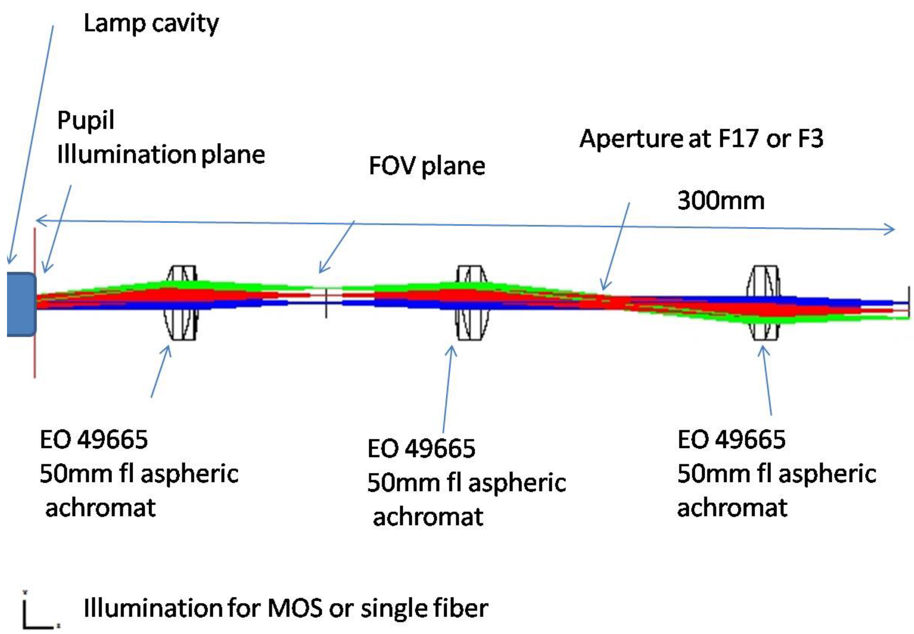


Figure 7: Optical design and trade-off of the F17/F3 illumination unit.

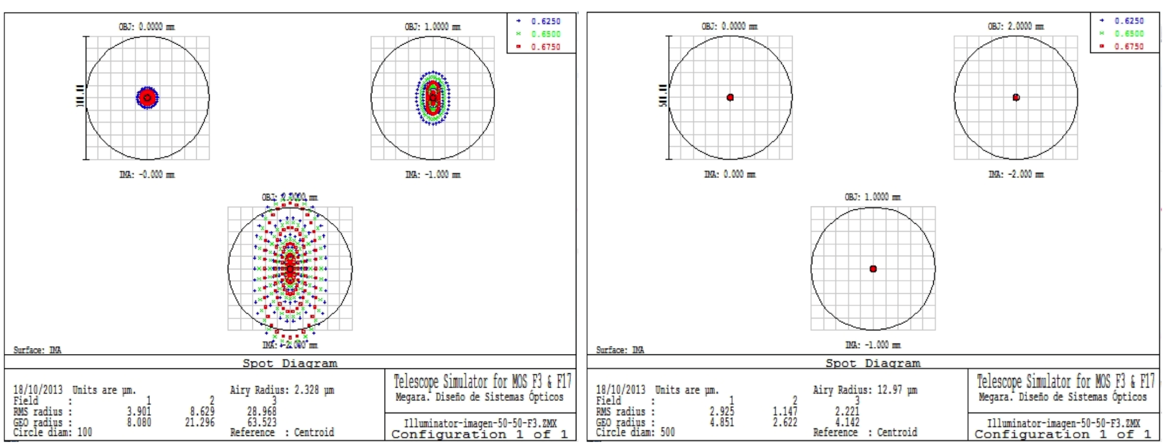


Figure 8: Left hand side image quality provided by the system when is illuminating the nude fiber at F3. The fiber core is 100µm, while right hand side shows the image quality over an area of 500µm, when the micro-lens is illuminated at F17.

a 50 mm FL doublet that provide a uniform pupil and FOV respectively (at this position a selectable aperture is available in case we illuminate a nude fiber or a lens let) and (2) a 1:1 image relay system made with two 50mm FL doublets and an aperture diaphragm that provides the illuminated area onto the fiber entrance at the required F number. Aspherics are used to allow high F number values. **Figure 7** shows the optical layout of the illumination system.

The image quality analysis shows that nude fibers (before being glued to the micro-lens) must be centered in the FOV in order to have a good image quality. See Figure 8. As it can be seen the image quality is good enough to reproduce the fiber-core size (100µm) and the micro-lens aperture size (511 ± 2 µm).

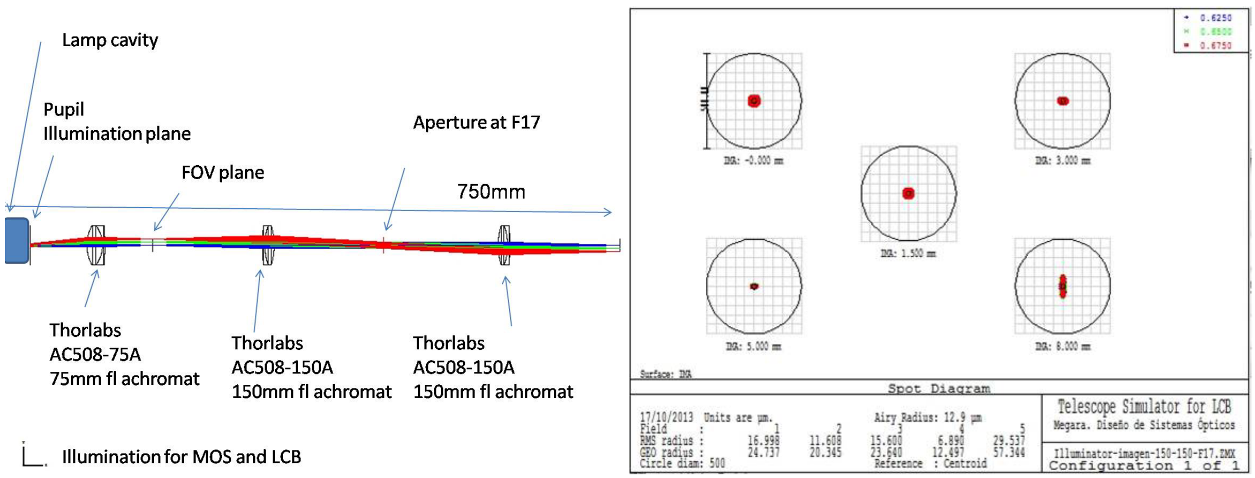


Figure 9: Optical layout of the telescope simulator unit together the image quality results shown in the spot diagram.

3.2 Telescope simulator

GTC is a F17 telescope therefore this unit allows illuminating any array from that of the MOS to the LCB at this F-number to perform its characterization. It will be used with the array already glued. As the previous system, the simulator consists of two subsystems. An illumination stage with a halogen that provides a uniform pupil and a 75 mm FL doublet that provides a uniform FOV. At this position a selectable aperture is available in case we illuminate a lenslet or a full array. And a 1:1 image relay system made with two 150mm FL doublets and an aperture diaphragm that provides the illuminated area at F17 onto the fiber entrance. An optical layout and a spot diagram of the system are shown in Figure 9.

3.3 NF and FF units

We refer to near field (NF) as the photometrical distribution of the light on the surface of the fiber output end, while the far field (FF) is the angular distribution of the light of the output fiber beam. This unit will allow us to tests both NF and FF of the fibers and the simultaneous measurement of the optical properties of at least 7 fibers (a complete MOS unit or button, see Figure 10) or any fiber with a cladding/core ratio 170/100 (in the case of the SCB, the FF cannot be measured unless some changes are done).

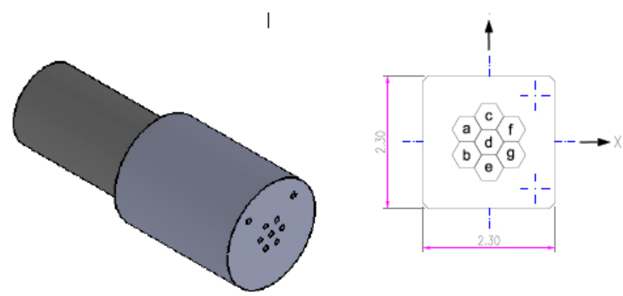


Figure 10: Image of a fiber MOS unit or button showing its 7 hexagonal fibers distribution.

There are no large variations regarding spectral behavior in the fibers aside from those due the intrinsic FS fiber material. Thus, by measuring the FRD in a single point across the spectrum will allow checking and characterizing the overall spectral performance. Therefore, we will use this unit in a short wavelength range.

The FF and NF lines share the first doublet of the design and they are split with a corner cube as shown in Figure 11. Two CCDs will be required, one for each line. In order to give a clear explanation of each line, these are described separately. We have used 1/3″ standard size detectors to guarantee that the images can be accommodated.

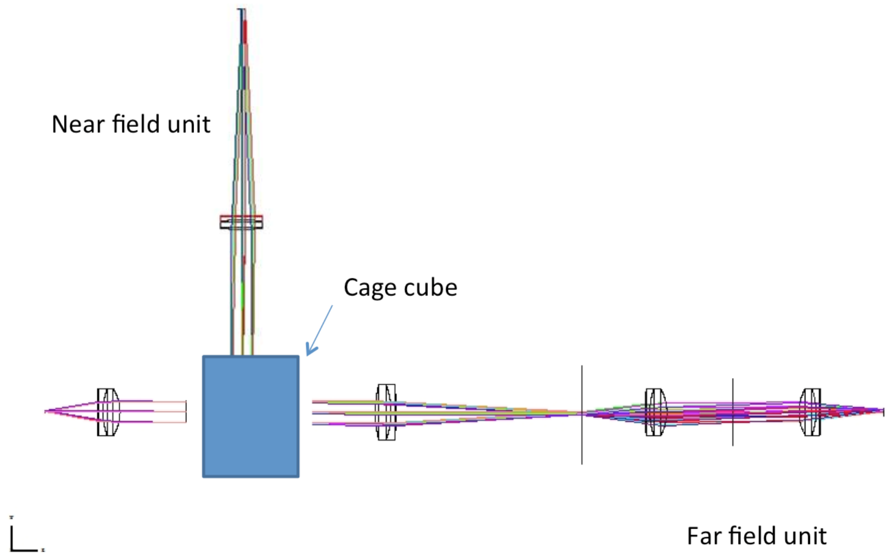


Figure 11: Layout of the Near Field and Far Field unit.

The NF unit works as a relay system providing a 3.57 magnification of a MOS unit onto the detector (see Figure 12). The first lens is a wide FOV achromatic aspheric doublet that improves the image quality for high NA angles (fiber F3 exit), while the aperture stop (11.7mm) is limiting the beam at F3 (flux seen by MEGARA collimator). This unit is intended to measure the flux at this aperture.

The FF unit has been designed around an existing micro-lens array that allows measuring simultaneously the far-field fibers of a MOS unit (7 fibers). For that purpose, a pupil plane is imaged onto the detector. It basically contains three functional stages as shown in Figure 12. (1) a 1:2.85 image relay that lets the fiber surface to be imaged onto a lenslet array with a pitch of 480 µm. (2) A lenslet array that creates an image of the FF of the fiber in a pupil. The array focal length has been chosen to avoid overlapping of the pupil images. (3) And finally, a 1:1 image relay where the pupil plane is transported to the detector plane. The FF line will let to characterize the complete fiber FRD.

An aperture stop of 23mm gives the maximum field reached by the FF module, before images can overlap themselves. It corresponds to a degradation of up to F1.5. The aim of this aperture is to guarantee that there is no FRD or that this is under control during the array gluing process. This aperture is different from the one shown in Figure 12.

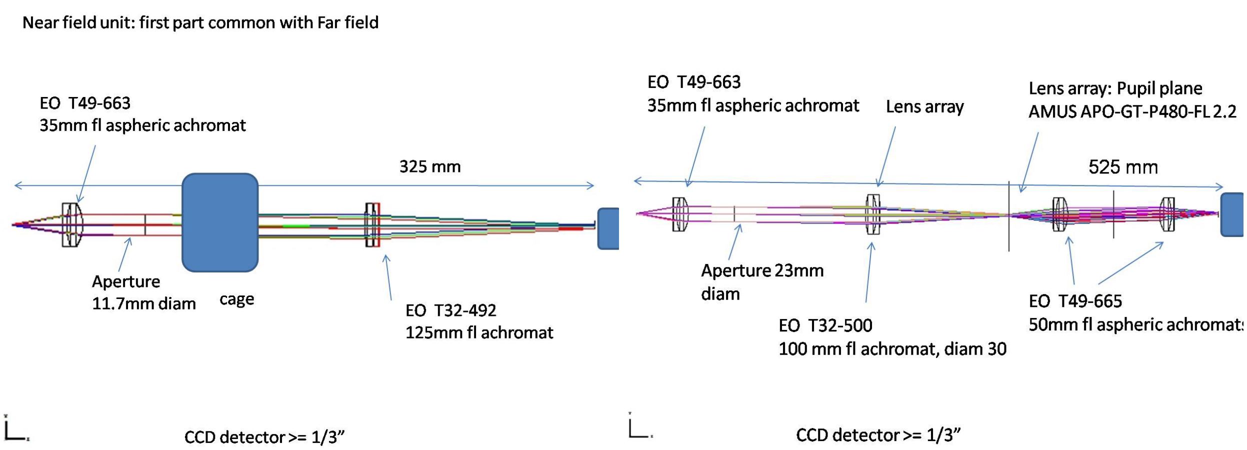


Figure 12: Left hand side shows the optical layout of the NF unit and the right hand side shows the FF unit.

3.4 Gluing Station

This system arise from the needs of a tool to manipulate the arrays during their positioning and gluing process onto the fiber button, and it is composed of a holder base able to grasp the fiber to be glued and allowing to move the fiber button with the following *Rx, Ry, Rz* and *x, y, z* degrees of freedom. And an illumination and imaging system mounted vertically over the holder base and a hosting lenslet array allowing *Rx* and *Ry* adjustments.

This illumination system is based in the telescope simulator unit described in the previous section for sizes up to the LCB area (see Figure 9), existing one functional difference: this unit will not only illuminate the array surface but will also provide a return image (with the aid of a beamsplitter) of the array onto a detector that will monitor and let us to control all the gluing process. A 1/3″ CCD will image the full MOS while in the case of the LCB mounting proccess, a larger detector shall be installed. Figure 13 shows the optical layout of this system.

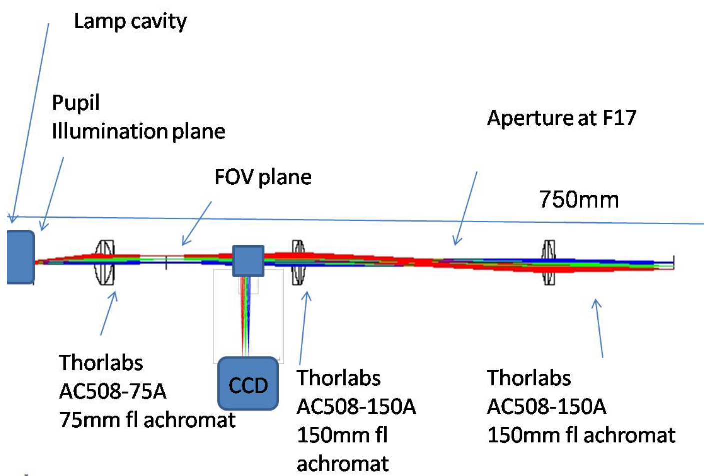


Figure 13:Optical layout of the gluing station unit.

3.5 M2 simulator

In the previous sections we have described the units needed for characterizing the bundles fiber to fiber and/or the mini-bundle button but if we want to characterize the behavior of the entire MOS subsystem, that is, checking the functioning of all the buttons at once, we need a different system. This is a plate that will simulate the M2 mirror of GTC. The need and aim of this unit is to provide a telescope simulator with a FOV that matches that of the GTC. In this way the entire MOS area (3.5 × 3.5 arcmin^2) can be uniformly illuminated. The design contains several light sources (LEDs) distributed at different positions across the plate that can be switched on individually (see Figure 14). This plate will be installed in front of the pre-optics unit of the instrument (Folded Cassegrain subsystems) at a distance of 18m.

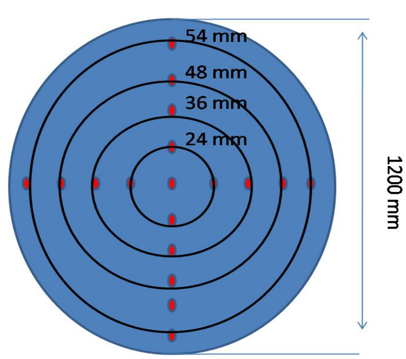


Figure 14: M2 plate with the LED distribution on it.

4. VERIFICATIONS AND PLANING TESTS VERIFICATION

In this section we describe the verification tests that will be applied to the fiber bundles before its final implementation. For the correct application of the tests and in order to avoid or limit the risks during their manipulation we will carry out some tests with a mini-bundle prototype that will be manufactured from the same fiber batch than the final system. This preventive step will let to ensure the opto-mechanical set-up and check the process in order to deliver a guideline that minimizes the handling of the final bundles that shall be integrated at the telescope. The mini-bundle prototype shall be MOS mini-bundle prototype (i.e., composed by 7 fibers and attached to a MOS button, see Figure 10)

Consequently we propose basically three tasks of verification or tests during the fiber-link integration:

- Fiber quality. In this line we will perform several tests focus on the status of the fibers as:
    1. Identifying the broken fibers or “death fibers”, illuminating the button uniformly and detecting where the light is not transmitted.
    2. The verification of the polished end surface of the fibers for checking that no cosmetics defects are found acquiring images of the pseudo-slit output (previously illuminated uniformly) and verifying the fibers exit looking for any irregularity and/or scratches produced during the polishing process.
    3. Study of the relative fibers transmission comparing the flux measured at the fibers exit relative to that measured with the support of a calibrated photodiode.
    4. To measure the absolute spectral response and to quantify the FRD behavior comparing the flux measured of the NF image of the fibers relative to their accordingly FF images. The flux ratio between each pair of images will provide the fiber transmission at F3. In fact both transmission values for the NF and FF should be very close.
- Array gluing. The arrays will be glued onto the fibers using the gluing unit as well as the NF/FF unit. Therefore in this line we will proceed as follows: we shall perform the micro-lens fiber join mounting the fiber button on the base plate previously illuminated and xyz adjusted and tilted to bring the button centered into the camera FOV. Taking real time images of the fiber exit with the NF/FF unit will guarantee a correct alignment before the glue between the micro-lens and the fiber be finally cured. During the UV-curing process a real time transmission and FF status will be reported in order to detect the maximum transmission. Each MOS button with its lens array will be reported with a NF/FF image at the slit exit. The differential FRD between fibers in the same mini-bundle will be reported.
- Final fiber-link transmission report. The final assembled fiber will be tested to compute the transmitted light of the full joint at one spectral point and within an F3 cone (the accepted cone angle by the collimator). For this task we will make use of the NF/FF unit as well as the illumination unit set at F17. In these lines we are expecting to perform the following tests.
    1. To obtain the final fiber link absolute transmission. At this point a F17 illumination will be projected into the NF/FF unit acquiring two images of the NF with and without the fiber-link. The flux of the seven images will be integrated in the NF image. The transmitted flux of an input signal (flat hat) will be measured at a determined wavelength, as the ratio between both measurements. This measurement will include the losses due to the lenslets boundaries. Note that this would depend on the input image profile, as we would get close to the lens boundaries.
    2. To verify the slit metrology testing the front profile of the-pseudo slit to guarantee the curvature replica with the support of an indicator.
    3. To check the fiber-link integrity, i.e., verifying that all LCB and MOS fibers are correctly illuminated and right positioned at the pseudo-slit. Illuminating the fibers from the pseudo-slit face we will be able to image the LCB or MOS front side, identifying if any fiber is not well illuminated. Also, we can illuminate fiber by fiber from the pseudo-slit side and take a series of images to assure that each fiber in the pseudo-slit correspond to the right position in the focal plane bundle according to their respective arrangement.

4. To check the Integration of the optical components at the Folded-Cassegrain assembly. The objective of this task is to assemble the MEGARA Folded-Cassegrain optical components (which includes the fiber bundles and the field lens) at the Folded-Cassegrain mechanics assembly provided by AVS. The mechanical and electronic components that part of the MEGARA Folded-Cassegrain subsystems will have been previously integrated at AVS. AVS will also manufacture a structure to which the Folded-Cassegrain rotator adapter will be fixed. The Folded-Cassegrain subsystems will be mounted on this frame and the whole assembly delivered to us.

5. To verify the MEGARA Folded-Cassegrain system test. In this test we will perform several checks as to generate a pupil image and verify that this is found at the position of the MOS, to look for any quantitative intensity variation among fibers and identify any misalignment (if exist) of the axis of any robotic positioner. For that, we will use the M2 mirror simulator placed at 18m from the pre-optics unit, which includes all Folded-Cassegrain subsystems already assembled. By moving the M2 simulator the pre-optics unit will be aligned with the alignment telescope available in the Fiber- MOS frame (the central LED will be on for this purpose), taking images of the MOS and LCB slits. All functional fibers should have even illumination, otherwise this would indicate that a heavy misalignment is present. At this step, the positioners will be commanded at different positions to verify that the pupil is aligned in the fiber core at every positioner position, switching on the LEDs increasing the distance from the M2 simulator center to characterize the pointing of the pupil in the fiber core. With this, the dynamical alignment of each positioner will be reported with the foreseen transmission homogeneity between different MOS. and also corrections in the positioners plate could be performed in case of an unexpected severe misalignment be found.

5. SUMMARY

MEGARA is the future optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) for the 10.4-m Gran Telescopio CANARIAS (GTC). MEGARA has three different fiber bundles, the Large Central Bundle, the Small Compact Bundle, and a Fiber MOS positioner system. The MEGARA focal plane subsystems are located at one of the GTC Folded Cassegrain focal stations, providing a telecentric illumination to all the focal plane subsystems with the aid of a field lens. A configuration of hexagonal lenslet array let the different fibers arrangement to be illuminated from F17 to F3, thus minimizing the impact of the focal ratio degradation. The bundles transport the light from the Folded Cassegrain to one of the Nasmyth platforms at the focal plane of the pseudo-slit that feeds the spectrograph.

Several set-ups have been developed in order to perform several tests and verification tasks over the micro-lens and fibers, as the study of the transmission, the quantification of the FRD and/or other cosmetics defects that could influence in the final efficiency of the spectrograph. This includes a gluing station for the construction of the final fiber-link.

REFERENCES

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