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MEGARA, the new intermediate-resolution optical IFU and MOS for GTC: getting ready for the telescope

A. Gil de Paz^{*a}, E. Carrasco^b, J. Gallego^a, J. Iglesias-Páramo^c, R. Cedazo^d, M.L. García Vargas^e, X. Arrillaga^f, J. L. Avilés^b, N. Cardiel^a, M. A. Carrera^f, A. Castillo-Morales^a, E. Castillo-Domínguez^b, J. M. de la Cruz García^a, S. Esteban San Román^a, D. Ferrusca^b, P. Gómez-Álvarez^e, R. Izazaga-Pérez^b, B. Lefort^e, J.A. López-Orozco^a, M. Maldonado^e, I. Martínez-Delgado^e, I. Morales Durán^c, E. Mujica^e, G. Páez^g, S. Pascual^a, A. Pérez-Calpena^e, P. Picazo^a, A. Sánchez-Penim^a, E. Sánchez-Blanco^e, S. Tulloch^e, M. Velázquez^b, J.M. Vílchez^c, J. Zamorano^a, A.L. Aguerri^{h,i}, D. Barrado y Naváscues^j, E. Bertone^b, A. Cava^k, J. Cenarro^l, M. Chávez^b, M. Garcíaⁱ, J. García-Rojas^{h,i}, J. Guichard^b, R. González-Delgado^c, R. Gúzman^m, A. Herrero^{h,i}, N. Huélamo^j, D. H. Hughes^b, J. Jiménez-Vicenteⁿ, C. Kehrig^c, R.A. Marino^{o,a}, I. Márquez^c, J. Masegosa^c, Y. D. Mayya^b, J. Méndez-Abreu^p, M. Mollá^q, C. Muñoz-Tuñón^{h,i}, M. Peimbert^r, P.G. Pérez-González^a, E. Pérez Montero^c, M. Rodríguez^b, J.M. Rodríguez-Espinosa^{h,i}, L. Rodríguez-Merino^b, L. Rodríguez Muñoz^s, D. Rosa-González^b, J. Sánchez-Almeida^{h,i}, C. Sánchez Contreras^j, P. Sánchez-Blázquez^t, F.M. Sánchez Moreno^d, S. F. Sánchez^r, A. Sarajedini^m, S. Silich^b, S. Simón-Díaz^{h,i}, G. Tenorio-Tagle^b, E. Terlevich^b, R. Terlevich^b, S. Torres-Peimbert^r, I. Trujillo^{h,i}, Y. Tsamis^u, O. Vega^b

^aUniversidad Complutense de Madrid (UCM, Spain), ^bInstituto Nacional de Astrofísica, Óptica y Electrónica (INAOE, Mexico), ^cInstituto de Astrofísica de Andalucía (IAA-CSIC, Spain), ^dUniversidad Politécnica de Madrid (UPM, Spain), ^eFRAGMENTAL SLNE (Spain), ^fAVS SL, ^gCentro de Investigaciones en Óptica (Mexico), ^hInstituto de Astrofísica de Canarias (Spain), ⁱUniversidad de La Laguna (Spain), ^jCentro de Astrobiología (Spain), ^kUniversity of Geneva (CH), ^lCentro de Estudios de Física del Cosmos de Aragón (Spain), ^mUniversity of Florida (USA), ⁿUniversidad de Granada (Spain), ^oInstitut für Astronomie, ETH Zurich (Switzerland), ^pUniversity of St. Andrews, ^qCIEMAT (Spain), ^rUniversidad Autónoma de México (Mexico), ^sOsservatorio Astronomico di Padova (Italy), ^tUniversidad Autónoma de Madrid (Spain), ^uDepartment of Physics and Astronomy, University College London (UK)

ABSTRACT

MEGARA (*Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía*) is an optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) designed for the GTC 10.4m telescope in La Palma that is being built by a Consortium led by UCM (Spain) that also includes INAOE (Mexico), IAA-CSIC (Spain), and UPM (Spain). The instrument is currently finishing AIV and will be sent to GTC on November 2016 for its on-sky commissioning on April 2017. The MEGARA IFU fiber bundle (LCB) covers 12.5x11.3 arcsec² with a spaxel size of 0.62 arcsec while the MEGARA MOS mode allows observing up to 92 objects in a region of 3.5x3.5 arcmin² around the IFU.

The IFU and MOS modes of MEGARA will provide identical intermediate-to-high spectral resolutions ($R_{\text{FWHM}} \sim 6,000, 12,000$ and $18,700$, respectively for the low-, mid- and high-resolution Volume Phase Holographic gratings) in the range 3700-9800Å. An x-y mechanism placed at the pseudo-slit position allows (1) exchanging between the two observing modes and (2) focusing the spectrograph for each VPH setup. The spectrograph is a collimator-camera system that has a total of 11 VPHs simultaneously available (out of the 18 VPHs designed and being built) that are placed in the pupil by means of a wheel and an insertion mechanism. The custom-made cryostat hosts a 4kx4k 15- μm CCD. The unique characteristics of MEGARA in terms of throughput and versatility and the unsurpassed collecting area of GTC make of this instrument the most efficient tool to date to analyze astrophysical objects at intermediate spectral resolutions.

In these proceedings we present a summary of the instrument characteristics and the results from the AIV phase. All subsystems have been successfully integrated and the system-level AIV phase is progressing as expected.

Keywords: instrumentation: spectrographs, techniques: spectroscopic, galaxies: Local Group, spiral, kinematics and dynamics, ISM: kinematics and dynamics

*agil@ucm.es; phone +34 91 394 5152; fax +34 91 394 4635; <http://guaix.fis.ucm.es/megara/>

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1. INTRODUCTION

MEGARA (*Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía*) is an intermediate-resolution optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) for the 10.4m GTC telescope.

The MEGARA project started in response to the Announcement of Opportunity for new instrumentation issued by the Spanish public company GRANTECAN S.A. in 2009. After being selected in a competitive Conceptual Design Review in September 2010, the instrument successfully passed its Preliminary (March 2012), Optical Detailed Design (May 2013) and Full Detailed Design Reviews (December 2014). The instrument is currently (June 2016) in Assembly, Integration and Verification (AIV) phase at system level at the *Laboratorio de Instrumentación Científica Avanzada* (LICA) of the Universidad Complutense de Madrid (UCM, Spain). MEGARA will be transported to the 10.4m GTC at the end of November 2016 and it is scheduled to have its on-sky commissioning on April 2017.

In this paper we summarize the main characteristics of the instrument and the results of the AIV phase at the LICA lab.

Section 2 provides an overview of the instrument subsystems. In Section 3 we provide a summary of the scientific objectives that defined the instrument requirements as agreed by the MEGARA Science Team. Sections 4 through 10 describe these subsystems in further detail, including the MEGARA Control System and the project system engineering and management. Section 11 provides more details on the status of system AIV and results of the laboratory tests performed during this phase. We refer the reader to other publications in this volume^{1,2,3,4,5,6,7,8,9,10,11,12} for further details.

2. OVERVIEW

The MEGARA instrument has two well differentiated units, one located at the 10.4m GTC Folded-Cass (FC) focus, where the LCB IFU and the MOS robotic positioners are placed) and another one at the Nasmyth platform, where the MEGARA spectrograph is placed and kept static. The two units are connected by a total of 1267 optical fibers that are grouped in two 40m-long fiber links^{12,13}.

MEGARA offers one IFU mode (also called Large Compact Bundle; LCB hereafter) with 567 hexagonally-shaped spaxels of 0.62 arcsec in size that allow fully covering a contiguous region of 12.5 arcsec x 11.3 arcsec on the sky. A microlens array reimages the telescope pupil coming from each of these spaxels on an identical number of 100 μ m-core fibers. MEGARA also provides a MOS mode with a total of 100 robotic positioners that can patrol a region of 3.5 arcmin x 3.5 arcmin around the IFU bundle. The Fiber-MOS robotic positioners have been designed and built by AVS (Spain). Each positioner has a seven-spaxel microlens array attached to it that, as in the case of the LCB, reimages the pupil on seven 100 μ m-core optical fibers. Eight of these bundles (i.e. 56 fibers) are devoted to the determination of the sky during the observation with the LCB IFU, so only 92 of these positioners (644 fibers) are actually available for MOS observations and will be controlled by the MEGARA Control System.

The two optical-fiber bundles (LCB plus the 8 sky minibundles and the 92 MOS minibundles) reach the MEGARA spectrograph with a two identical curved telecentric pseudo-slits. These pseudo-slits are placed on top of an x-y mechanism that is used both to exchange between the two instrument modes (IFU/MOS) and to focus the instrument as a function of the disperser element being used and of temperature. The MEGARA fiber bundles have been built by SEDI-ATI Fibres-Optiques (France) while the microlens arrays have been manufactured by [aµs] advanced microoptic systems gmbh (Germany). The design of the MEGARA pre-optics has been carried out by Fractal S.L.N.E. (Spain).

The f/1.5 MEGARA spectrograph is a fully-refractive optical system composed by a collimator with 5 lenses (an aspheric singlet and two doublets) and a camera with 7 lenses (three singlets and two doublets) that both form an angle of 68°. The spectrograph design has been done by Fractal S.L.N.E. while its construction was done by INAOE (Mexico). The disperser elements that are placed at the spectrograph pupil are Volume Phase Holographic (VPH) gratings built by Wasatch Photonics. When sandwiched between flat windows alone the MEGARA VPHs yield a spectral resolutions $R_{\text{FWHM}} \sim 6,000$ (these are the so-called LR, low-resolution, VPHs). By means of prisms that are coupled to the flat

windows the MEGARA VPHs reach spectral resolutions ranging between 12,000 (MR, mid-resolution, VPHs) and 18,700 (HR, high-resolution, VPHs). Identical resolutions are reached in the case of the LCB and MOS modes. The VPHs are inserted in the pupil by means of an insertion mechanism that extracts the VPH from a wheel where up to a total of 11 VPHs can be placed (out of the 6 LR + 10 MR + 2 HR = 18 VPHs built; a number of MR VPHs are still being manufactured), both responsibility of AVS (Spain). More details on the MEGARA spectrograph optical and opto-mechanical design and manufacturing are given in this same volume^{2,3,8,9,10,11,14,15,16,17}. The camera focuses the light onto an E2V 231-84 deep-depleted 4kx4k 15- μ m pixels CCD¹⁸ located in a cryostat designed and built by the INAOE^{19,20}.

The different instrument mechanisms (focal-plane cover, Fiber-MOS robotic positioners, pseudo-slit exchange, focus, shutter, and VPH wheel and insertion mechanism), data acquisition (DAS hereafter), monitors and interlocks are all controlled by the MEGARA Control System (MCS), which is fully compliant with the GTC Control System (GCS), which is responsibility of GRANTECAN. More details on the MCS can be found in Section 9 and elsewhere⁸.

The MEGARA System Engineering has provided (and still does) the methodology required for the ensuring the success of a complex system such as MEGARA in a structured and orderly manner. It also minimizing risks and anticipating problems that may arise. Finally, MEGARA includes a detailed management plan that, within a series of managerial parameters, that is currently allowing a successful AIV (Assembly, Integration and Verification) and a timely deliver to GTC while satisfying all instrument and functional requirements. More details on the MEGARA system engineering and management plan are provided in Section 10 and in other publications in this volume²¹.

3. MEGARA SCIENCE

The scientific interests of the MEGARA Science Team can be grouped in two categories, (1) the study of Galactic and extragalactic extended nebulae and (2) the study of numerous compact sources clustered in the sky with intermediate-to-high surface densities. Category (1) includes the study of Planetary Nebulae, nearby galaxies, and the high-redshift IGM and category (2) Galactic open stellar clusters, resolved stellar populations in Local Group galaxies, intermediate-redshift dwarf and starburst galaxies, and high-redshift cluster galaxies. The MEGARA Science Team encompasses researchers with broad range of interests that belong to institutions of all members of the GTC community (Spain, Mexico and UF). This ensures that, as a facility instrument, MEGARA will also serve to the interests of these astronomical communities (see Figure 1 for a summary of the main subjects of interest of our Science Team). More details on the science drivers of the MEGARA instrument have been published elsewhere^{22,23,24,25}.

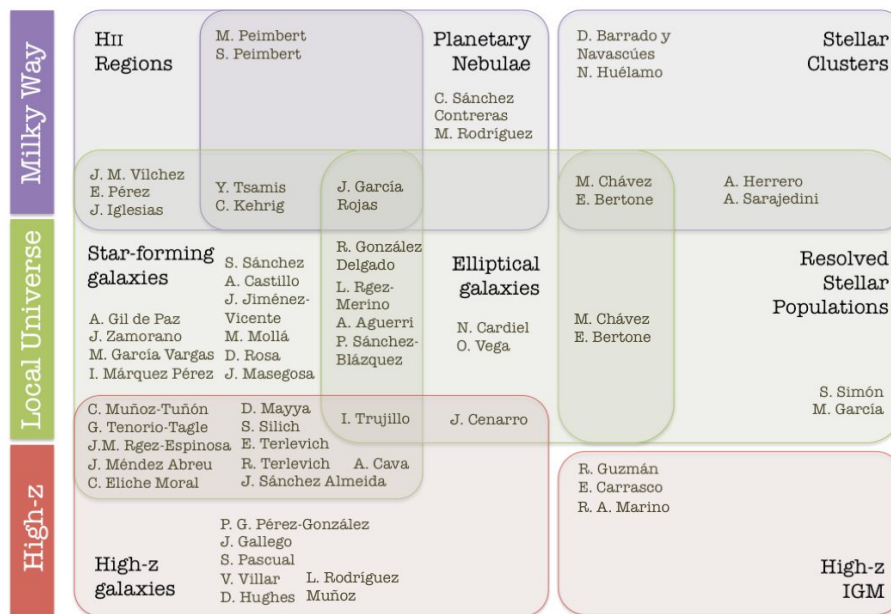


Figure 1. Main scientific interest of the MEGARA Science Team members. These are also the main drivers that are behind the unique capabilities of the MEGARA instrument in terms of efficiency, resolution and versatility.

3.1 IFU Science

MEGARA Galaxy Disks Evolution Survey: Among the study of astrophysical nebulae, our team has a strong interest in the understanding of the evolution of galaxy disks through the analysis of the velocity ellipsoids and the 2D spatial distribution of spectral indices and chemical abundances. Measuring these quantities throughout disks is fundamental to differentiate between the contribution of stellar populations formed in-situ and ex-situ to the present-day properties of disks. This will be done by means of the *MEGARA Galaxy Disks Evolution Survey* (MEGADES hereafter), which constitutes a major part of the planned Guaranteed Time observations with MEGARA. Note that in this context we consider stellar migration as an ex-situ mechanism for the evolution of stellar populations and chemicals in disks.

With this objective in mind we will map with the LCB IFU the central regions and the major and minor axes of a sample of nearby galaxy disks from the DAGAL/S4G sample that has been observed with GALEX and Spitzer²⁶. This sample has been used to characterize the mechanisms that are currently responsible for the evolution of galaxies from the Blue Cloud (a Blue Sequence when UV-IR colors are used) to the Red Sequence²⁷. Prior to the exploitation of the MEGARA observations we have first characterized the spatially-resolved properties (FUV-NUV and NUV-3.6 μ m, environment, nuclear activity, angular momentum, mass/circular velocity) of these galaxies and selected a subset of targets for MEGADES covering the entire range of properties observed. In Figure 2 below we show the observed color vs. surface brightness profiles and the spin (specific angular momentum) and circular velocities derived from the modeling of the light distribution of the disk galaxies in the whole DAGAL/S4G sample^{27,28,29}.

We will use the MEGARA LCB IFU to map the central regions of these galaxies where the presence of massive star formation, nuclear activity or the effects of a bar potential might play a role on the spectrophotometric and chemical evolution of disks. Besides, we will scan the major and minor axes of these galaxies with the LCB, where the IFU would be mainly used as a light bucket, allowing us to reach unprecedented low surface brightness in spectroscopy.

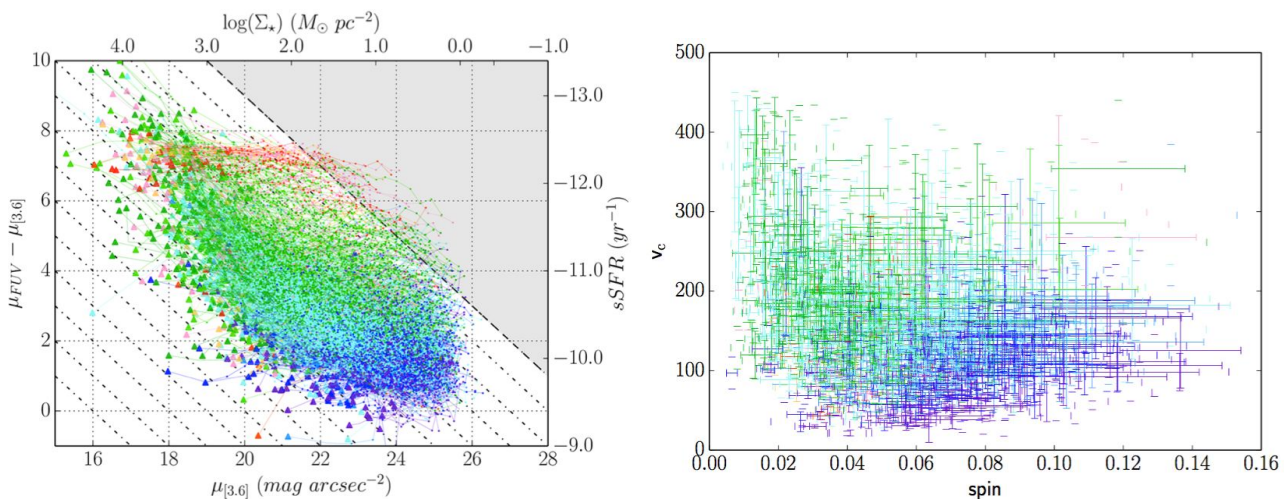


Figure 2: *Left:* FUV-3.6 μ m color versus 3.6 μ m surface brightness for the DAGAL/S4G sample. Each line corresponds to a single galaxy. Profiles are color coded by morphological type (red: E, orange: S0, green/cyan: early-type spirals, blue/magenta: late-type spirals). *Right:* Derived circular velocities and specific angular momenta (spin) of the disks of the spiral galaxies within the DAGAL/SG4 sample using the predictions of chemo-spectrophotometric disk models²⁹.

In addition to this study of the unresolved stellar populations in galaxy disks in the DAGAL/S4G sample, this survey will also include (1) the detailed single-star spectroscopic analysis of the Local Group galaxies M33 and IC 1613 and (2) the study of the chemical abundances of individual HII regions throughout the disks of the DAGAL/S4G sample using the MEGARA MOS mode (see below). Other objectives that the MEGADES dataset will soon allow us to pursue include the study of the interplay between the massive-star formation and the interstellar medium and the long-standing problem of the abundance discrepancies in HII regions and the potential identification and analysis of chemo-dynamical phenomena (see Figure 1 for the Science Team members with interests in this topic).

Finally, other scientific topics that should make extensive use of the MEGARA IFUs are the study of Planetary Nebulae (PNe), the identification and analysis of arcs and highly magnified galaxies in clusters, and the mapping of the high-redshift intergalactic medium (IGM) through the search of rest-frame UV resonant line emission in the blue part of the optical spectrum:

Planetary Nebulae and HII regions: Regarding the study of the PNe we aim at understanding, on one side, the nebular shaping process, which is believed to be driven by the interaction between collimated, fast (i.e. jet-like) winds ejected during the late-AGB or early post-AGB stages and the slow, largely spherical envelopes formed during the previous AGB phase as a result of a heavy mass-loss process. On the other side, we will use the superb efficiency of the MEGARA instrument combined with the large collecting area of GTC to analyze the faint metal recombination lines with an unprecedented combination of depth and spectral resolution so to determine the origin of the discrepancy between the element abundances derived from recombination and collisionally-excited lines and which lines actually provide the most reliable abundances and what method should thus be used to calculate the metallicity of the gas. In this sense, deep LCB observations of proplyds and HH objects in Galactic HII regions would also led some light on the origin of the abundance discrepancy³⁰.

High-redshift IFU observations: We aim to use the MEGARA IFUs to identify and analyze arcs and highly magnified galaxies in clusters. The faint continuum emission and relatively large projected size in the sky of some of these sources make necessary the use of an IFU in order to identify them and for spectroscopically measuring their redshifts, especially when they have been identified in the infrared³¹. Finally, we will also search for redshifted emission of resonant lines in the UV rest-frame such as OVI1033 Å, CIV1550 Å, or Ly α . This search would be done starting from the location of known bright Lyman Alpha Emitters (LAEs) and Lyman Alpha Blobs (LABs). Note that the good blue efficiency of MEGARA allows searching for Ly α emission already at $z > 2$.

3.2 MOS Science

MEGADES: With regard to the scientific objectives of MEGADES, we plan to complement the study of nearby disks described above with (1) MOS observations of resolved-stars in Local Group (LG hereafter) galaxies and (2) HII regions in DAGAL/S4G galaxies. For the study of resolved stellar populations in the LG, the inclination, location in the sky and relatively undisturbed morphology makes of the disk of M33 an ideal laboratory to analyze the 2D distribution of single-star abundances and kinematics that could provide further clues on the role of the different processes that shape the photometric, chemical and dynamical evolution of galaxy disks.

The MEGARA Fiber-MOS is designed to study point sources with high number densities (such as RGB stars in LG galaxies) as it allows reaching densities as high as 8 objects per arcmin². This fact along with the short reconfiguration time of Fiber-MOS robotic positioners (<1min; see Section 4) makes of MEGARA a unique tool for the study of large numbers of sources in this kind of targets.

The study of the chemical abundances of individual HII regions throughout the disks of a subset of DAGAL/S4G galaxies using the MEGARA Fiber-MOS will allows us to put further constraints on the relative role of in-situ and ex-situ processes on the chemo-spectrophotometric evolution of galaxy disks^{32,33}.

Other scientific interests of the MEGARA Science Team in the exploitation of the Fiber-MOS include:

Galactic stellar clusters: With the use of the MOS we also aim to study of properties of very low mass stars (and brown dwarfs) in young stellar associations. First, starting from within the Gould Belt and, then, farther away, to the Galactic anticenter and the Perseus Arm. The goal is to put star formation in a galactic perspective and to include the effects of both metallicity and environment. We will also use these observations to re-calibrate the activity-sensitive Ca H+K index with the stellar age for an extended sample of solar analogs in stellar open clusters in the context of the characterization of solar analogs candidates for the future search of Sun-Earth-like planetary systems.

High-redshift MOS observations: There are also multiple interests within the MEGARA Science Team regarding the study of high-redshift galaxies: Intermediate-redshift Blue Compact Dwarf (BCD), clump-cluster, peas and starburst galaxies and high-redshift proto-clusters. In order to address all these topics with maximum efficiency the capability for observing a relatively large number of objects within a small patch of the sky of the MEGARA MOS is a big advantage especially when carrying out studies on cosmological fields that aim to reach the spectroscopic limit.

4. FOLDED-CASSEGRAIN SUBSYSTEMS

The MEGARA Folded-Cassegrain (FC) subsystems include all components that collect and conduct the light from the GTC Folded-Cassegrain F focal plane to the spectrograph entrance. Those elements are (a) a Field Lens to correct from lack of telecentricity of FC-F, thus providing a telecentric focal plane for the microlens arrays, (b) the focal-plane cover that allows obtaining very low cross-talk observations with half the field-of-view (FoV) and the multiplexing of the MEGARA default mode, (c) the microlenses (in the form of microlens arrays) that change the focal number of the telescope allowing a good coupling with fibers (from $f/17$ to $f/3$), (d) the LCB IFU fiber bundle, (e) the Fiber MOS that allows to position 92 minibundles in the focal plane (plus 8 fixed minibundles for the determination of the sky when the LCB is used) and corresponding fiber bundle, (f) the interface plate that supports the LCB IFU in the central area of the focal plane, (g) the FC Rotator Adapter that provides the interface with the GTC FC rotator and (h) the interface between fibers, pseudo-slit plates where fibers are arranged and the Spectrograph entrance. The mechanical design and construction of the FC assembly and the robotic positioners has been done by AVS (Spain), while the optical design of the field lens and the microlenses has been done by Fractal S.L.N.E. (Spain). The microlens arrays and the fiber bundles have been manufactured by SEDI-ATI (France) and [aμs] (Germany), respectively.

Figure 3 below shows different design views and photographs of the FC and the adapter to the GTC FC rotator.

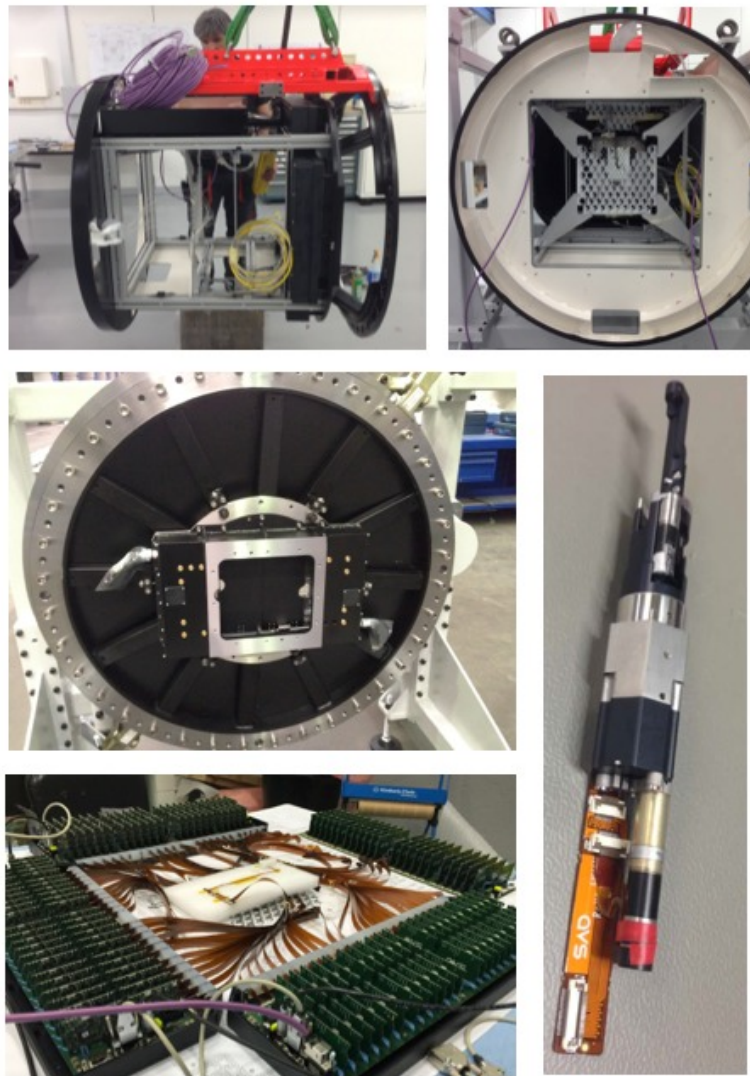


Figure 3. Photographs of the different components of the FC unit during the subsystem AIV.

Following the light path, we first find the field lens. This field lens has been designed to provide a telecentric field for MEGARA since the GTC telescope has the aperture at the secondary mirror. This allows that the opto-mechanical axes of all the fiber bundles will be parallel among them. Thus, the positioners move on a flat surface (the focal plane) with their opto-mechanical axis perpendicular to this surface and the IFU is also placed flat parallel. A small field curvature remains but it is below 0.1 arcsec in the whole FoV. Virtually no power is introduced by this field lens.

After the field lens we have the telescope focal plane where different microlens arrays change the focal ratio from $f/17$ (the value provided by the telescope at FC-F) to $f/3$, a value that allows minimizing focal ratio degradation (FRD) effects during the beam transport within the fibers. MEGARA has two modes, the Integral-Field Unit (IFU) and the Multi-Object Spectrograph (MOS) mode, that correspond to the two fiber bundles of the instrument: Large Compact Bundle (LCB) and Dispersed Bundle or simply Fiber-MOS (see Figure 4), each with a corresponding set of microlenses. In the case of the LCB the square-shaped lens array is composed of 567 lenslets while the Fiber-MOS has 100x seven-lens arrays (only 92x will have their fibers mounted on the MOS pseudo-slit; the other 8 are mounted on the LCB pseudo-slit). The seven lenses in each Fiber-MOS minibundle are hexagonally-shaped/packed and are identical to those of the LCB. The microlens arrays are made of fused-silica with each microlens or lenslet being plano-aspherical with a $ROC=0.844\text{mm}$, $c = -0.9797$ and an aperture of 0.511 mm (designed by Fractal and built by [aus]).

The lenslets that constitute the Large Compact Bundle (LCB) microlens array are arranged on a square area of 12.5 arcsec x 11.3 arcsec and are centered on the optical axis of the instrument. The 92 7-lenslets arrays of the Fiber MOS can be positioned anywhere in the central 3.5 arcmin x 3.5 arcmin around the IFU bundle thanks to the positioner robots (or simply positioners). Note that a total of 8 robotic positioners (orange hexagons in Figure 4) located in the outer edge of the instrument FoV are kept fixed in order to be used for measuring the sky background simultaneously with the observations with the LCB. The layout of the hexagonally-packed/shaped microlens array of the LCB IFUs is also shown in this figure.

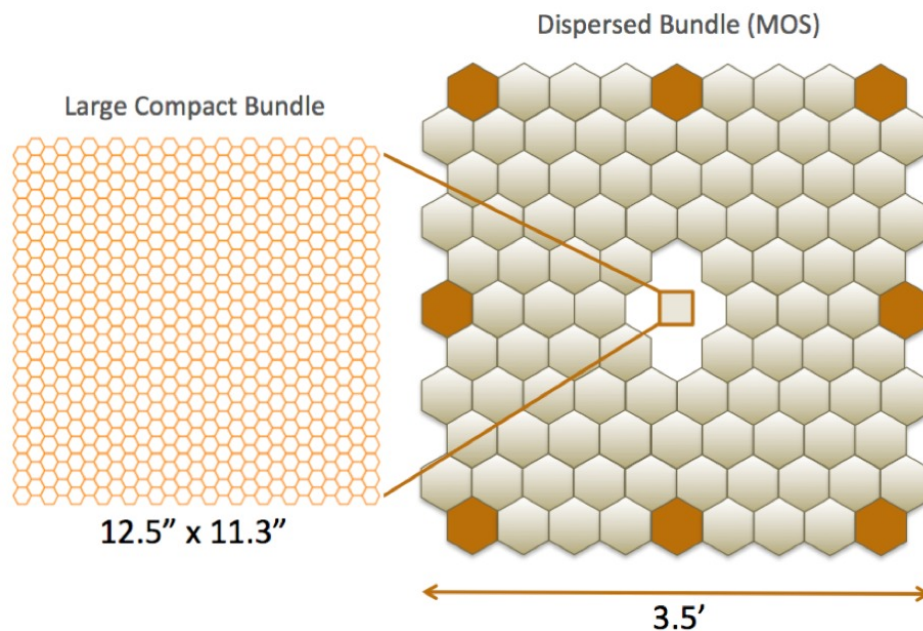


Figure 4. Layout of the LCB and MOS modes of MEGARA.

The GTC pupil image is formed at the back surface of each array and is overfilling the fiber core in order to provide an illumination condition as similar as possible to the one given by the Instrument Calibration Module (ICM) and to minimize the impact of either mounting or assembly errors between fibers and microlenses on the flux homogeneity in between fibers. The alignment between the image of the pupil and the fiber core has been verified to be less than $10\mu\text{m}$ for the LCB and for each and every Fiber-MOS minibundle.

Each of the 100 microlens arrays of the MOS mode is held by a robotic positioner (by means of a button; both manufactured by AVS) that moves independently of the rest allowing reconfiguring the entire focal plane in less than one minute of time. The positioning of the fiber minibundle is performed by combining the interpolation of two rotations, which allows covering a circle with a radius of 11.605mm from the center of the positioner (this circle reaches the corners of the hexagon with an E/C of 20.1mm). The fixing of the positioner button to the positioner, which is strong and repetitive, allows the disassembly it from its back in order to facilitate the maintenance of the mechanical and electronics parts. See a photograph of some of the robotic positioners already mounted in the instrument focal plane in Figure 5.

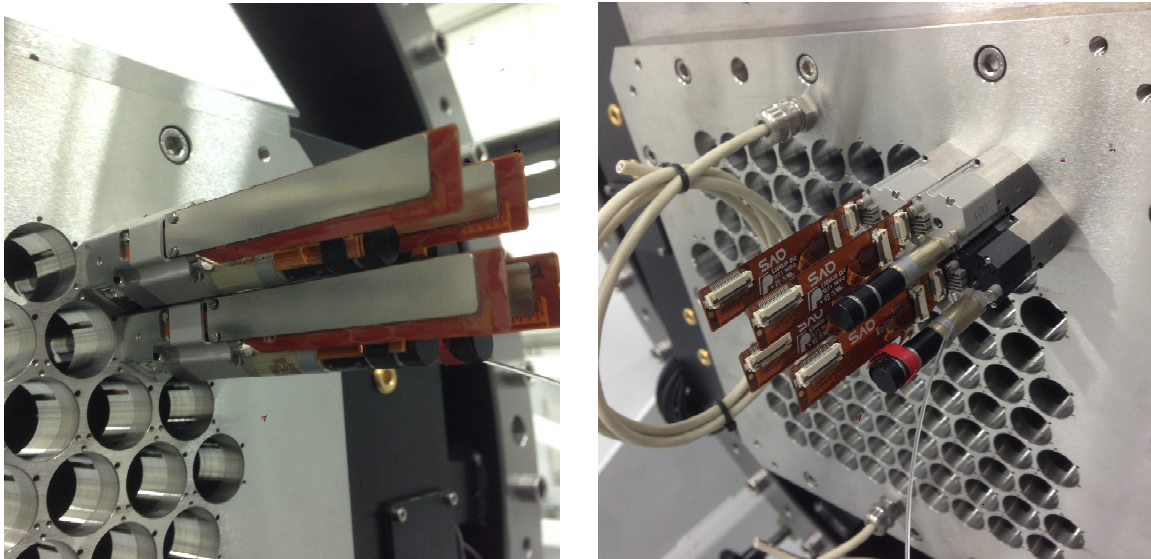


Figure 5. Some Fiber-MOS robotic positioners mounted in the FC assembly of MEGARA (see also Figure 3).

5. FIBER LINK

The fiber cables transport the light from the focal plane to the spectrographs at the pseudo-slit position. The fiber selected is the one from Polymicro FBP 100/140/170; 100 μ m is the core, 140 μ m is the cladding and 170 μ m is the mechanical coating. This fiber has a numerical aperture of 0.2 ± 0.02 (optical angle acceptance and output light angle of the fiber, $\sin(12.71)$). This is a wide broadband fiber and provides a good FRD. More details are provided elsewhere in this volume^{12,13}.

The final length of the fiber link is 40 meters. The MEGARA optical fibers for all three instrument modes will be integrated in sub-units of 7 fibers. Both the LCB sub-units (plus the 8 sub-units coming from the sky positioners that shall be also attached the LCB pseudo-slit) and MOS sub-units are independently covered by two loose tubing (not a tight jacket) made of polyurethane with an external diameter somewhat lower than 40 mm. The routing of the

The fibers at the fiber cable output are arranged in a pseudo-slit configuration (one for each of the two modes and bundles) and placed in front of spectrograph (see Section 6.1).

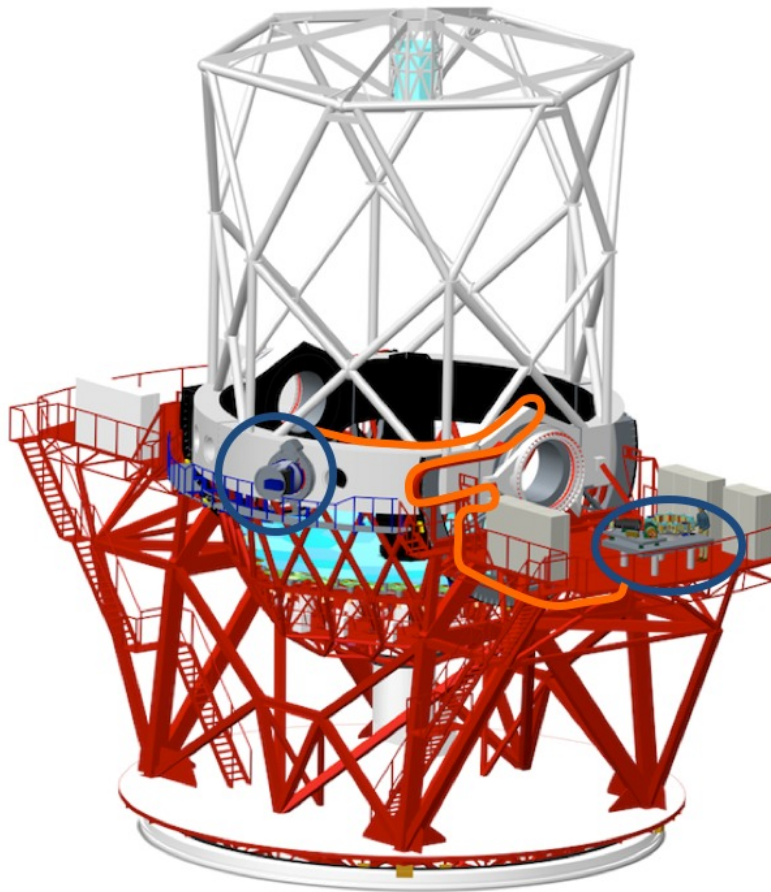


Figure 6: 3D view of the GTC telescope with the MEGARA instrument placed on the FC-F and on the Nasmyth-A platform (encircled in blue) with the fiber bundle routing highlighted in orange.

6. MEGARA SPECTROGRAPH

In Figure 7 we show the 3D view of the detailed design of the MEGARA spectrograph. The positions of the pseudo-slits, the collimator, the VPH in use (located at the instrument pupil), the camera and the cryostat can be easily identified. A major fraction of the area of the MEGARA spectrograph 3m x 2m optical table is occupied by the VPH wheel, where are total of 11 VPHs can be placed. The spectrograph optical and mechanical design has been carried out by Fractal S.L.N.E. while the construction has been done by INAOE (Mexico), including the MR and HR prisms and the flat windows used in all VPH-based disperser elements. The VPH themselves have been manufactured by Wasatch Photonics. The wheel and insertion mechanism have been manufactured by AVS (Spain), expect its control, which has been done by the UCM.

6.1 Pseudo-slits

The optical fibers are mounted on two identical frames (one for each of the pseudo-slits of the two instrument modes, namely LCB and MOS) that follow the curvature of the entrance focal plane ($ROC=1075\text{mm}$) for a total length (tangential to the curve) of 119mm. In order to follow this curvature each frame is split in flat sub-frames (where fibers are attached), called boxes. Each box (of each pseudo-slit) has an integer number of 7-fiber sub-units. The fiber pitch between adjacent fibers within each box is $170\mu\text{m}$ and their optical axes are all parallel since the system is telecentric.

The pseudo-slits are moved using two translation stages mounted on x-y that will allow exchanging the pseudo-slit in use between that of LCB or MOS modes, and also will be used as a focusing mechanism that will be configured in the z-axis for each of these modes and VPH and for a given temperature. The control of mechanisms is responsibility of the UCM.

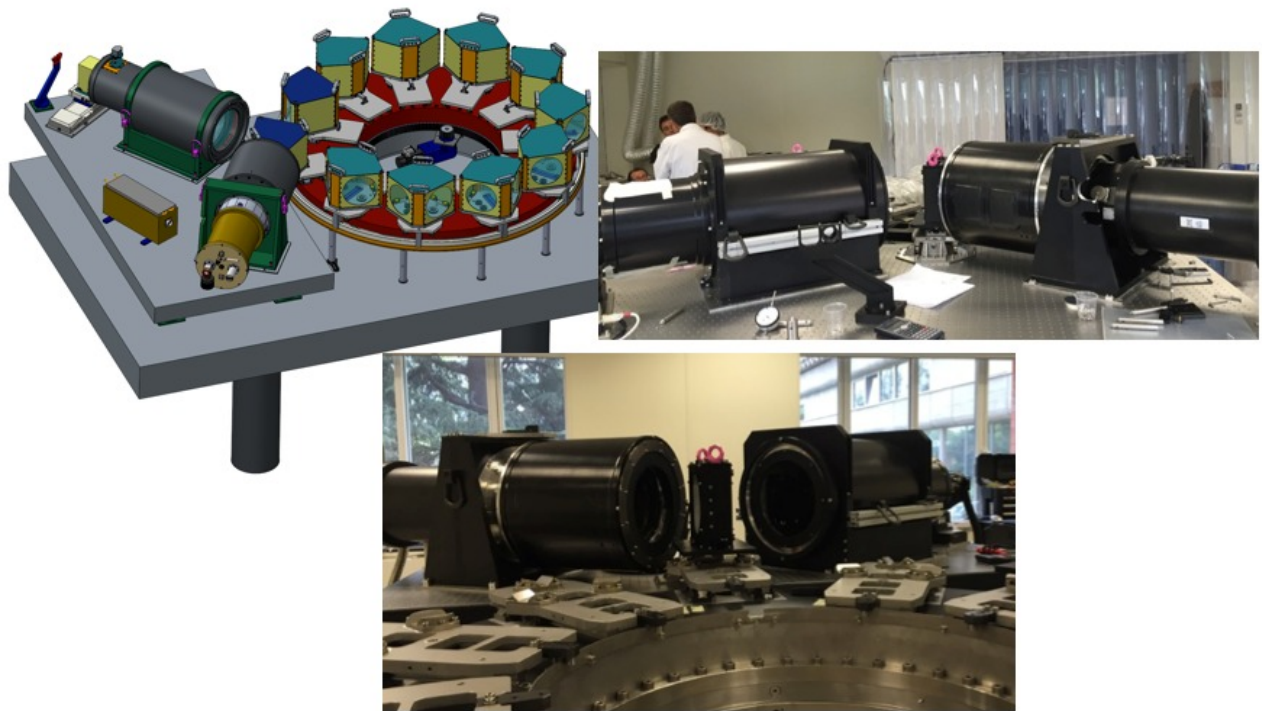


Figure 7. MEGARA Spectrograph: 3D view (*top-left*) and photographs (*top-right* and *bottom*) obtained during AIV.

6.2 Collimator

The collimator is $f/3$ and has a focal length of 484.4 mm for a total of 5 lenses (1 singlet and two doublets). The first lens of the collimator is the only aspherical surface of the instrument, which also one of the smallest lenses in the system (140mm diameter; blank diameter 160mm). A shutter is placed right beyond the first collimator lens. The shutter has 3 positions: open, closed & filter, where the order-sorting (OS) filter is placed in the optical path for observations at >7000 Å. In Figure 8 we show the optical design and a photograph of the collimator already built taken during AIV with the pseudo-slit already in place (see also Figure 7 above). All collimator lenses have been built by INAOE (Mexico).

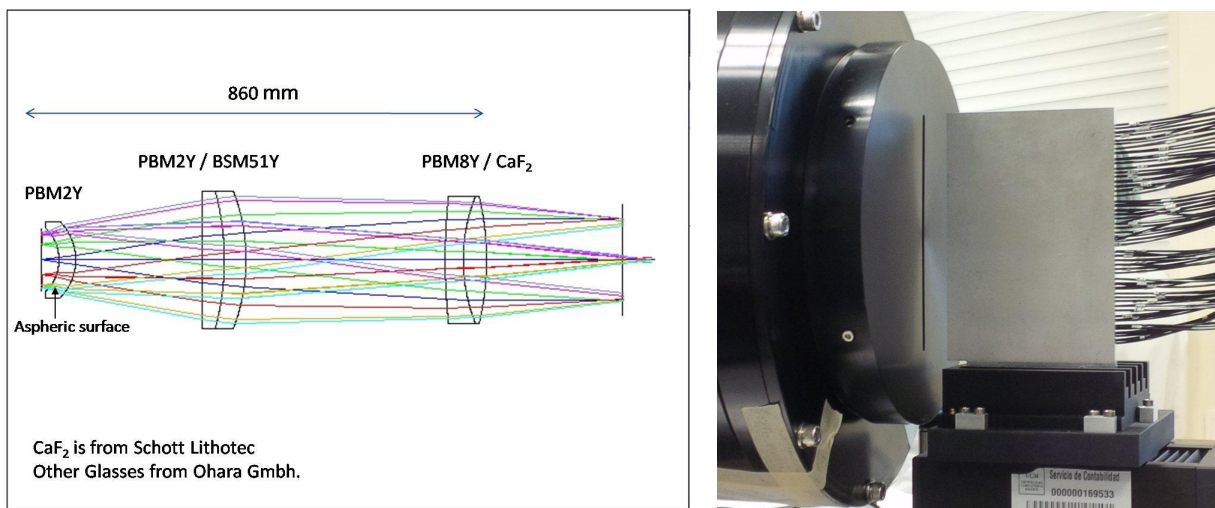


Figure 8. Optical design of the collimator (*left*) and photograph of the pseudo-slit at the collimator entrance (*right*).

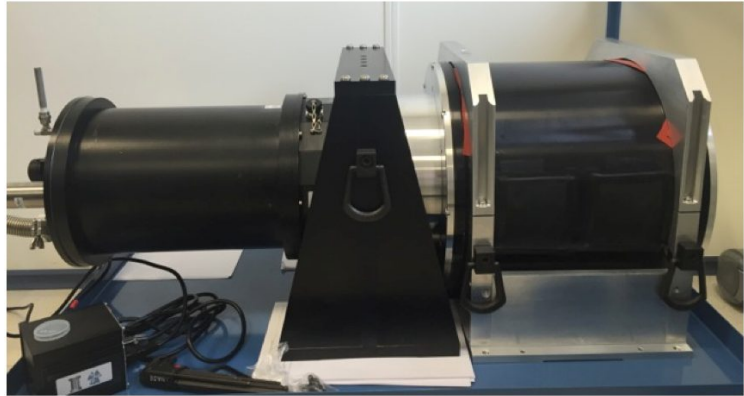
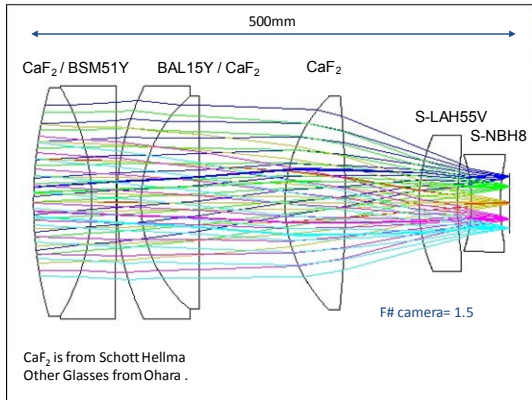


Figure 9. Optical design of the camera (*left*) and photograph of the camera already integrated with the cryostat and ready for system AIV at LICA-UCM (*right*).

6.3 Camera

The camera of the MEGARA spectrograph is an $f/1.5$ system with a focal length of 245.9 mm. Two doublets and 3 singlets compose the camera as can be seen in Figure 9. The image field is 61.4mm x 61.4mm that covers the 4k x 4k 15- μ m pixels of the CCD231-84 by E2V (UK). The last lens also acts as window for the cryostat. As shown in Figure 7, the angle between the collimator and the camera is fixed to 68°. Details on the optical design are given in other publications^{2,3,9,15,16,17}. All camera lenses have been manufactured at INAOE (Mexico).

Table 1. MEGARA VPHs. The resolution, $R_{FWHM} = \lambda / \Delta\lambda_{FWHM}$, is derived from the FWHM ($\Delta\lambda_{FWHM}$) of the 1D spectra. These numbers are identical for the LCB IFU and MOS modes (see also Figure 10).

	VPH Name	Setup	R_{FWHM}	$\lambda_1 - \lambda_2$ Å	λ_c Å	$\Delta\lambda$ (@ λ_c) Å	Δv km/s	lin res Å/pix
1	VPH405-LR	LR-U	6028	3653 – 4386	4051	0.672	50	0.17
2	VPH480-LR	LR-B	6059	4332 – 5196	4800	0.792	49	0.20
3	VPH570-LR	LR-V	6080	5143 – 6164	5695	0.937	49	0.23
4	VPH675-LR	LR-R	6099	6094 – 7300	6747	1.106	49	0.28
5	VPH799-LR	LR-I	6110	7220 – 8646	7991	1.308	49	0.33
6	VPH890-LR	LR-Z	6117	8043 - 9630	8900	1.455	49	0.36
7	VPH410-MR	MR-U	12602	3917 - 4277	4104	0.326	24	0.08
8	VPH443-MR	MR-UB	12370	4225 – 4621	4431	0.358	24	0.09
9	VPH481-MR	MR-B	12178	4586 – 5024	4814	0.395	25	0.10
10	VPH521-MR	MR-G	12035	4963 – 5443	5213	0.433	25	0.11
11	VPH567-MR	MR-V	11916	5393 – 5919	5667	0.476	25	0.11
12	VPH617-MR	MR-VR	11825	5869 – 6447	6170	0.522	25	0.13
13	VPH656-MR	MR-R	11768	6241 – 6859	6563	0.558	25	0.14
14	VPH712-MR	MR-RI	11707	6764 – 7437	7115	0.608	26	0.15
15	VPH777-MR	MR-I	11654	7382 – 8120	7767	0.666	26	0.17
16	VPH926-MR	MR-Z	11638	8800 - 9686	9262	0.796	26	0.20
17	VPH665-HR	HR-R	18700	6445 - 6837	6646	0.355	16	0.09
18	VPH863-HR	HR-I	18701	8372 - 8882	8634	0.462	16	0.12

6.4 VPHs

The pupil, which is the location of the VPH gratings, has a 160mm free diameter. Different types of pupil elements (all of them based on VPH-type gratings) can be accommodated in the pupil position. The spectral resolutions of MEGARA

in terms of $R_{\text{EED80}} (\lambda/\Delta\lambda_{\text{EED80}})$ are $\sim 5,500$, $10,000$ and $17,000$ (respectively for LR, MR and HR VPHs). When expressed in terms of the FWHM of unresolved lines in the extracted (1D) spectra the spectral resolution these numbers become $R_{\text{FWHM}} \sim 6,000$ (low resolution; LR), $R_{\text{FWHM}} \sim 12,000$ (mid-resolution; MR) and $R_{\text{FWHM}} \sim 18,700$ (high resolution; HR). With regard to the wavelength coverage, MEGARA offers full optical coverage with the LR VPHs ($R_{\text{FWHM}} \sim 6,000$) alone or with the MR VPHs ($R_{\text{FWHM}} \sim 12,000$) combined. In Figure 10 we show the coverage in terms of wavelength and spectral resolution of the different spectral setups available in MEGARA.

In the case of the highest resolution mode (HR VPHs), the incident angles are so high that the use of single monolithic prisms implies very large prisms and a small amount of vignetting of $\sim 10\text{-}19\%$, depending on wavelength. In the case of the MR VPHs we found that the standard Kogenik method was yielding very low efficiencies in one of the polarizations, so we use the HD manufacturing technology patented by Wasatch Photonics instead, as this allowed recovering rather flat and high efficiency curves in both polarizations. In addition to the broad-band coatings of the collimator and camera lenses the *Centro de Investigaciones en Óptica* (CIO, Mexico) has also designed specific narrow-band coatings for the VPHs windows and prisms.

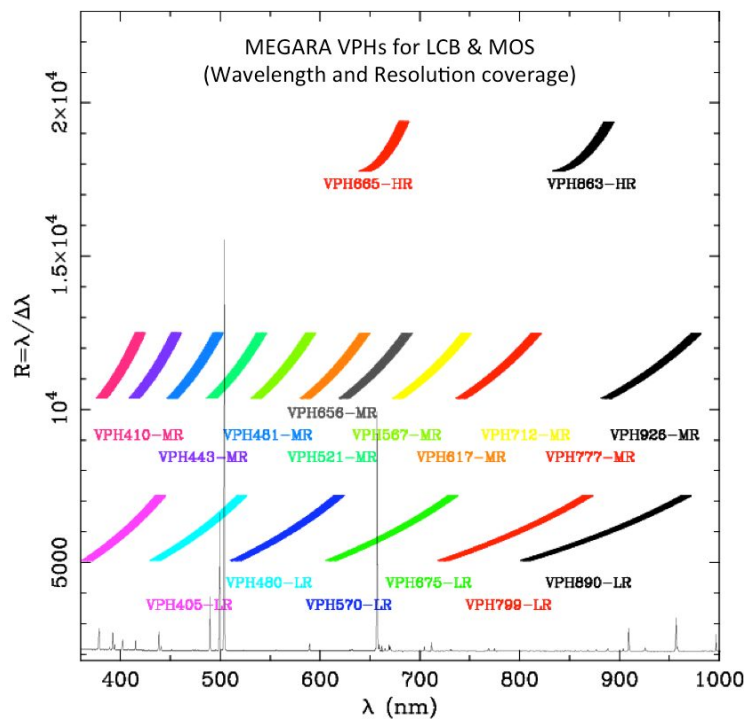


Figure 10. Coverage of the MEGARA VPHs in resolving power (R_{FWHM}) and wavelength for either the LCB IFU and MOS modes ($100\mu\text{m}$ -core fibers). Note that, due to the use of VPHs, the spectral resolution changes across the detector, which spans an angle of $\pm 7.2^\circ$ from the pupil, although this variation is always within $\pm 20\%$.

In Figure 11 we show a flat-field (halogen lamp) and an arc (ThNe) image both taken during the system AIV phase using the LR-V VPH. The analysis of the images obtained shows that the instrument fulfills all requirements in terms of image quality, throughput, stability and cross-talk. In this image the position along the pseudo-slit is shown along the y-axis and wavelength is oriented along the x-axis with wavelength increasing from right to left.

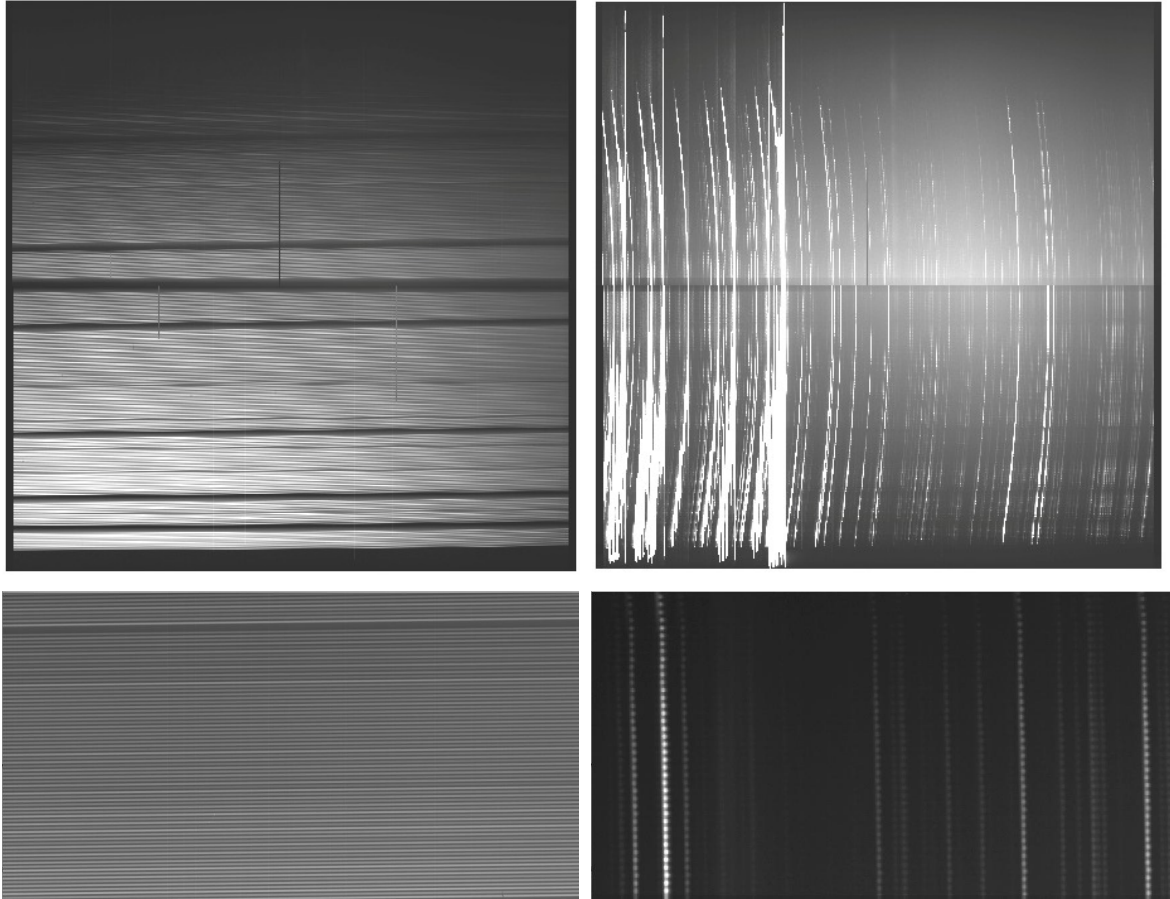


Figure 11. Flat-field (halogen; *left*) and arc images (*right*) taken during the system AIV phase along with the corresponding zoomed-in views of the images. These images have been taken with the LR-V VPH and the engineering-grade CCD.

7. CRYOSTAT

The selected cryogenic device to harbor the CCD detector for the MEGARA spectrograph is a liquid nitrogen open-cycle cryostat. This LN₂ open-cycle cryostat was designed by the INAOE astronomical instrumentation group. It offers modular stages for easy assembly and testing. The cryostat mounting is horizontal and it is designed to be kept static, as well as the other MEGARA spectrograph components. The complete cryostat assembly consists of two main parts: the dewar back and the CCD Head (see Figure 12).

The dewar back (or main body) serves as vacuum jacket and contains the liquid nitrogen tank; it also has on the rear part the liquid nitrogen fill tube, an electrical port for temperature monitor and two vacuum ports. Aluminum is the primary material for the vacuum jackets; aluminum alloys offer a good structural choice, easy manufacturability (compared with stainless steel), have reduced the costs of fabrication and weight but it also offers a lower degassing rate and the hydrogen permeation rate than steel. The LN₂ tank is made of stainless steel (which has low thermal conductivity). The filling tube has a bellow system, which helps to reduce thermal loading on the cryogenics. Cold plate will be made of gold plated OFHC copper to increase thermal conductivity.

The CCD Head is assembled on top of the main body and will contain the CCD detector and its associated electronics; it will contain two electrical ports to read-out the signals from the detector. CCD supports will be made of low thermal

conductivity materials (G10, nylon or Teflon). The CCD detector is thermally connected to the LN2 tank through a high purity free oxygen copper strap, which can be adjusted to give the desired operating temperature for the detector (~150K). The last lens of the MEGARA spectrograph serves as a vacuum window. The CCD head mechanical module can be disassembled completely from the cryostat main body for easy handling and integration and verification of CCD components. More information of the detailed design of the MEGARA cryostat is given elsewhere^{1,19,20}.

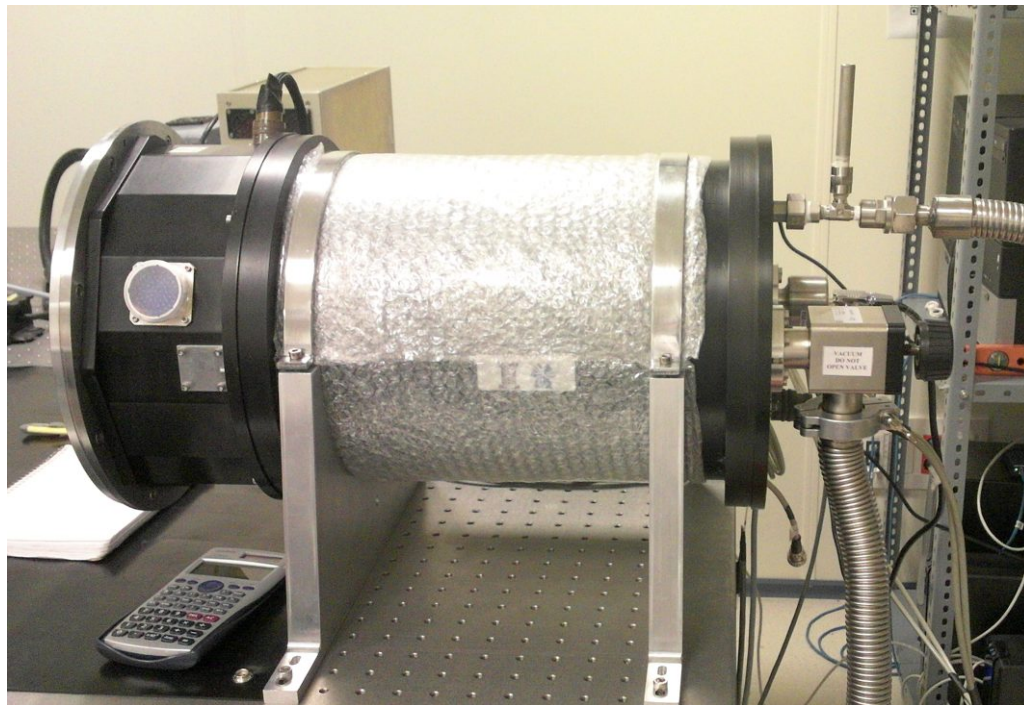
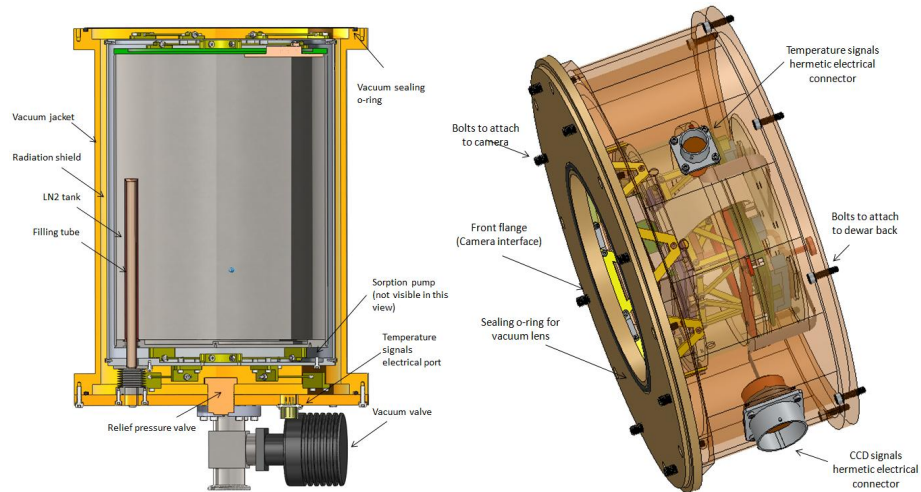


Figure 12. *Top-Left:* Cryostat dewar back 3D design view. *Top-Right:* CCD Head. *Bottom:* Photograph of the MEGARA cryostat ready for being attached to the instrument camera (see also Figure 9 for a photograph of the camera-cryostat assembly ready for system AIV).

8. CCD DETECTOR

The MEGARA detector is a 231-84-0-E74 model CCD device from E2V (UK). The CCD measures $4096 \times 4112 \times 15\mu\text{m}$ pixels and has four outputs. To reduce electronic cross-talk the detector is read using only 2 amplifiers (see Figure 11). There are several variants of this device but the one integrated in MEGARA is the Deep-Depletion Silicon version with the Astro Multi-2 AR coating. This is the best suited one for the wide wavelength coverage, good efficiency and low-fringing requirements of MEGARA. Our CCD delivers $<3e^-$ read noise and has excellent QE across almost the whole visible spectrum (see Figure 13). In Figure 14 we show the overall system efficiency for this CCD and the final throughput for the different VPHs built for MEGARA.

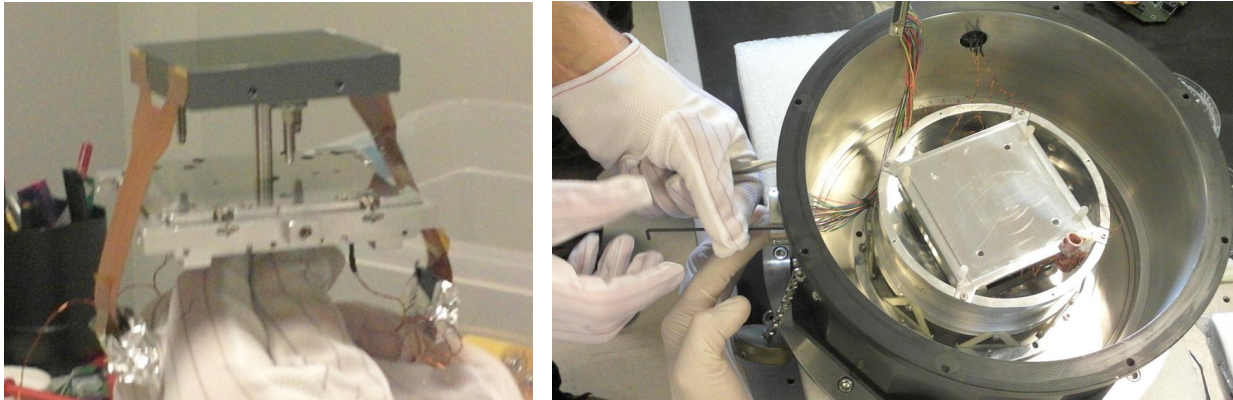


Figure 13. Mounting of the engineering CCD at the UCM clean room. Reassembly of the CCD Head after the installation of the engineering CCD. A more detailed description of all the activities being carried out at the LICA-UCM facilities in the context of MEGARA can be found elsewhere³⁴.

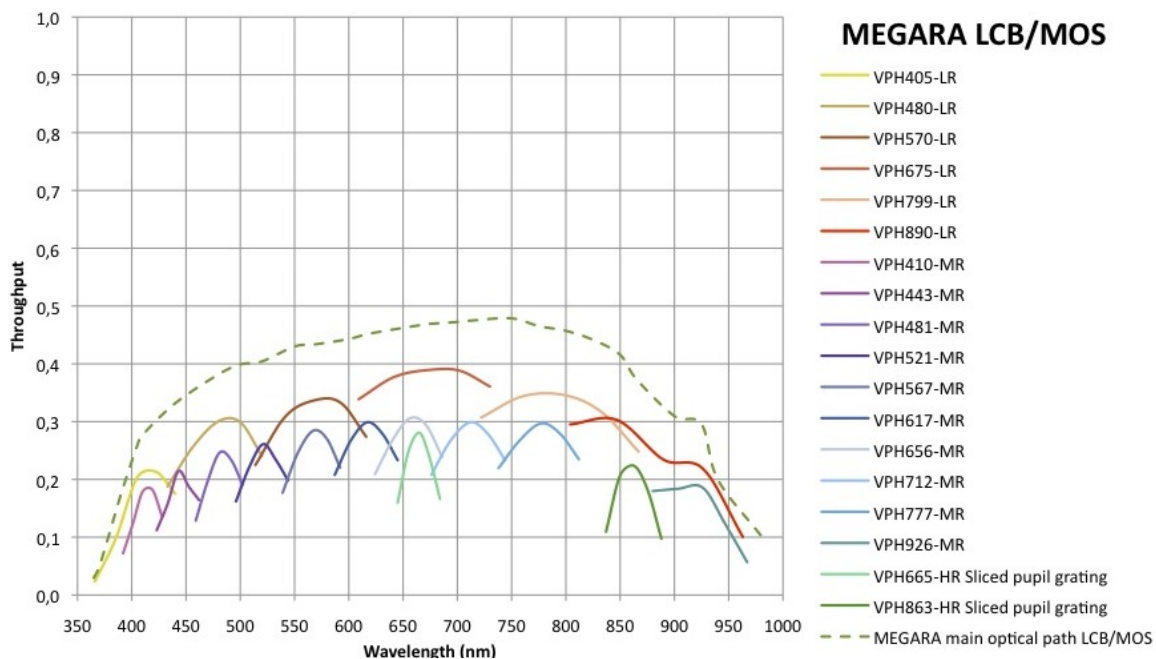


Figure 14. System overall efficiency with no VPH and with the different VPHs designed and built for MEGARA.

The CCD has a thickness of 15 ± 0.01 mm and contains three mounting bolts to ensure tight thermal contact with the base plate. Figure 12 also shows a lateral view of the CCD and PCB at the CCD Head.

9. MEGARA CONTROL WORK PACKAGE

The main component of the instrument Control Work Package is the MEGARA Control System (MCS), which includes the hardware (H/W) and software (S/W) components required to use the instrument and to integrate it with the GTC Control System (GCS)^{7,35} following the standards defined by GRANTECAN.

The MEGARA Control Work Package also includes the design and development of the S/W tools that have been developed by the MEGARA Consortium to facilitate the preparation of the observing programs and the exploitation of the data provided by MEGARA. These tools, also called Science community tools, are fundamental to maximize the scientific return of the instrument to the GTC community. Most of these tools are grouped under the MEGARA Observing Preparation Software Suite (MOPSS)³⁶ and include: The Exposure Time Calculator (ETC)⁶, the Fiber MOS Assignment Tool (FMAT)⁵ and the Fiber MOS Positioning Tool (FMPT)⁴, the last two being responsibility of the IAA-CSIC (Spain). Finally, the Control Work Package also includes MEGARA Data Reduction Pipeline³⁷, which has been developed by UCM.

9.1 MCS Software

MEGARA Control System provides the capabilities to move the different mechanisms of the instrument, to read the CCD detector (DAS) and all routines needed to run the GTC Inspector Panels and Sequencer strategies for MEGARA.

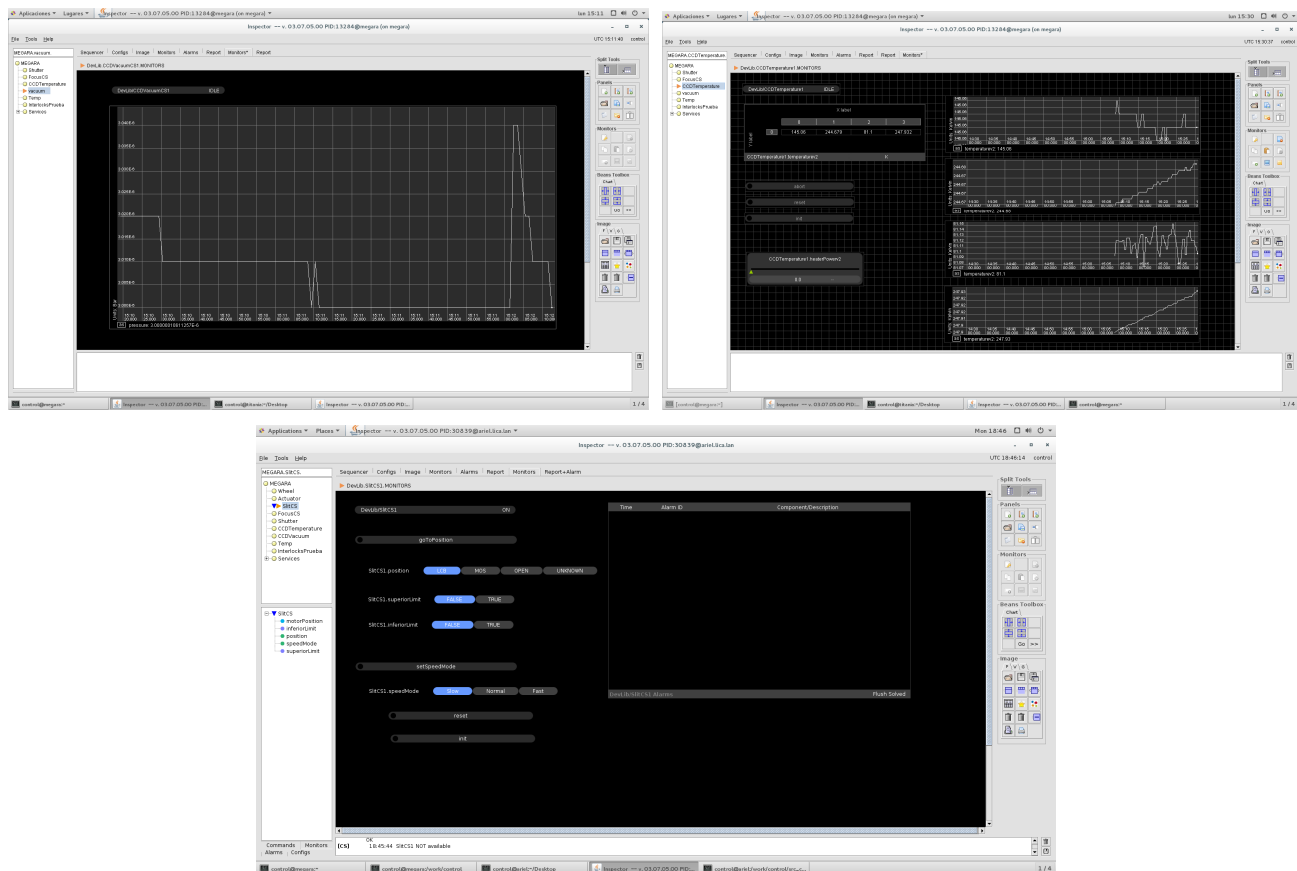


Figure 15. GTC Inspector Panels of the cryostat vacuum (*top-left*) and CCD temperature (*top-right*) monitors and of the pseudo-slit mechanism (*bottom*).

The MEGARA Mechanisms Control System is composed by a set of devices that represents the different MEGARA components. These components (i.e., focal-plane cover, pseudo-slit, focusing, shutter, grating exchange mechanisms, Fiber MOS positioners, detector, etc.) receive the positioning demands requested by the user in the Observing blocks and provide the data, monitors and alarms that are generated to the GCS. In Figure 15 we show some screen captures of the GTC Inspector Panels for the vacuum and CCD temperature monitors and the control of the pseudo-slit mechanism.

9.2 Science Community tools

MEGARA Science Community Tools are stand-alone applications that have been developed by the MEGARA Consortium to facilitate the preparation of the observing programs and the reduction of the data obtained with the instrument. They include:

- The MEGARA Observing Preparation Software Suite (MOPSS) tools that will soon assist observers to optimally plan their observations. The MOPSS is composed by the Exposure Time Calculator, the Image Simulator, and the Fiber-MOS Positioning tool.
 - The MEGARA Exposure Time Calculator⁶ simulates the signal-to-noise (S/N) ratio that will be obtained for the continuum and a spectral line as a function of wavelength for a specific target (with a given SED) given the exposure time, the MEGARA setup, and the atmospheric conditions.
 - The MEGARA Image Simulator that simulates data frames of any idealized distribution of sources in the sky in the same way that they will be soon observed by MEGARA for a given setup. The Simulator returns a MEGARA frame in FITS format with the simulated spectra corresponding to the projection of each spaxel on the detector plane, including the expected sky contribution and the effects inherent to the observation (bias, flat, geometrical distortion, non-linear dispersion, crosstalk, differential atmospheric refraction), as well as its row stacked spectra frame.
 - The Fiber MOS Assignment (FMAT)⁵ and Positioning (FMPT)⁴ tools that determine the optimal assignment of the 92 positioners used in the MOS mode and the sequence of motion of the robotic positioners, respectively, for an input list of source coordinates in the 3.5x3.5 arcmin². The objective here is to cover as many sources as possible and provide in which order must be the positioners be moved to avoid collisions among adjacent ones while minimizing the configuration time.
- The MEGARA Data Reduction Pipeline (DRP) supplies the users with data corrected from instrument signatures, which can be used at different stages of data acquisition and analysis. These data are expressed calibrated physical units, which then allow directly performing the scientific analysis, without the need of additional data processing. The user is able to modify the predefined parameters of the DRP so to customize data processing.

9.3 MCS Hardware

The MEGARA control system hardware is (physically and logically) divided into two separated parts: The Control cabinet, which gathers all the workstation and interface to the GTC control system and the Power Cabinet that gathers all the power electronic, mainly DC motor drivers and power supplies. Both cabinets are equipped with an AC panel that provides a filtered 230V AC to the cabinets (see Figure 16).

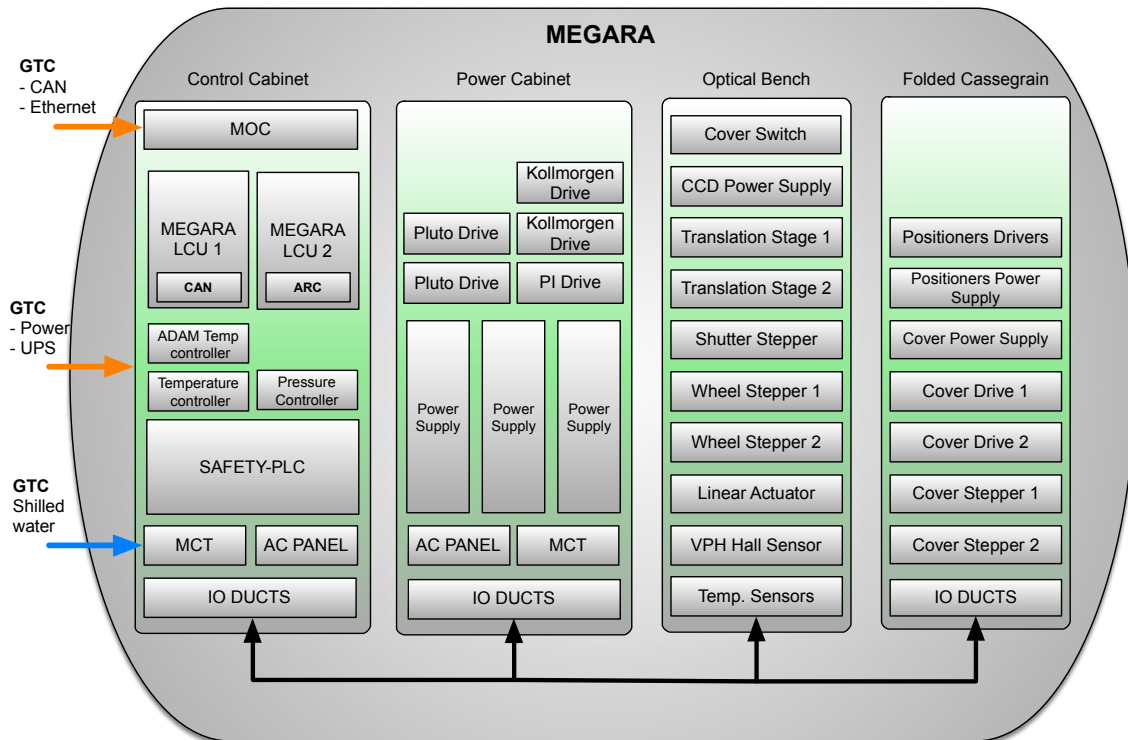


Figure 16. MEGARA Control System hardware overview.

10. SYSTEM ENGINEERING AND MANAGEMENT PLAN

The main tasks that are carried out as part of the Systems Engineering activities within the MEGARA project are:

- Implementing the requirements engineering, which aims to: ensure that the initial requirements are correctly interpreting user needs; generate, monitor and maintain a coherent set of specifications at different levels of the system and ensure traceability between subsystem and system requirements and specifications.
- Performing system analysis, resolve requirement conflicts, carry out trade-off, develop and use simulation models, analyze project risks and perform RAMS analysis.
- Defining and maintaining system configuration (define Product Tree and Interface Table).
- Preparing and executing the Integration and Verification Plan.
- Developing the Operation and Maintenance Plan.

This System Engineering Plan has been developed for the complete system life cycle, from conceptual design to the final instrument acceptance in GTC. The activities are reviewed at the end of each phase in order to add the needed details to the activities (WBS) to be performed in the following phase.

The *Final* MEGARA Management Plan aims at fitting all the managerial parameters listed below. This Management Plan is based on the final contracts for the detailed design, construction, assembly, integration, verification (AIV) and commissioning of MEGARA signed on April 28th and May 5th 2014 between GRANTECAN S.A. and the UCM²¹.

10.1 Leadership

The UCM, as leader institution and responsible for many MEGARA work packages, is committing their best resources both scientifically, managerial and engineering, and also putting the needed energy to develop MEGARA and making

MEGARA to become a workhorse instrument for the GTC and a reference instrument in the large telescope league. UCM also commits to give the PI and the team the needed support and stability to be able to do their work over the project life.

The MEGARA Consortium, formed by UCM, INAOE, IAA and UPM, has been firmly established with a Letter of Agreement and Commitment (LoAC) signed back in 2011 by the representatives from each institution. This LoAC has been recently updated (January 2016) on the view of the final construction contract signed with GRANTECAN S.A. All partners have given MEGARA project the highest priority and have devoted the best resources and facilities for its development.

10.2 Scope

MEGARA-as-contracted has a MOS mode with 92 positioners, plus 8 fixed positioners for sky subtraction placed in the same pseudo-slit as the LCB fibers. The LCB and MOS modes cannot operate simultaneously since MEGARA has one spectrograph, although the exchange between the two modes is very fast (seconds) since all the bundles share the same mechanism. MEGARA shall be equipped with 18 pupil elements (6 LR, 10 MR and 2 HR), 11 of them simultaneously mounted on the spectrograph. Exchanging between the 11 elements mounted on the spectrograph wheel can be done in less than one minute of time.

MEGARA is now going through Assembly, Integration and Verification phase with no major risks either shop-stoppers and will all tests having been passed successfully and all technical and scientific requirements being met to date.

10.3 Schedule

The laboratory acceptance is scheduled for September 2016. The delivery to the observatory will take place on November 2016 with the installation being currently for December 2016. Finally, the on-sky commissioning of the instrument should take place before the end of April 2017.

10.4 Budget

This is a co-funded project by GRANTECAN and by the MEGARA Consortium (UCM, INAOE, IAA-CSIC, UPM). The total project budget adding the money and the in-kind contribution converted to € is 11.8 M€, with 6.5 million euros being money, including a contingency of ~0.43 M€. The rest is in-kind contribution of the Consortium (~5.3 M€). This amount corresponds to 45% of the total project budget. Should we convert this money into Guaranteed Time (GT) according to GRANTECAN conversion (220 hours per million euros), the equivalent GT should be 1166 hours. Despite the fact that the Announcement of Opportunity issued by GRANTECAN on 2009 offered an envelope of 660 hours (well below the equivalent to 1166 hours quoted above), the GT finally awarded to the MEGARA team was only 301 hours.

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