MEGARA Optical Manufacturing Process

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ABSTRACT

MEGARA is the future visible integral-field and multi-object spectrograph for the GTC 10.4-m telescope located in La Palma. INAOE is a member of the MEGARA Consortium and it is in charge of the Optics Manufacturing work package. MEGARA passed the Optics Detailed Design Review in May 2013, and the blanks of the main optics have been already ordered and their manufacturing is in progress. Except for the optical fibers and microlenses, the complete MEGARA optical system will be manufactured in Mexico, shared between the workshops of INAOE and CIO. This includes a field lens, a 5-lenses collimator, a 7-lenses camera and a complete set of volume phase holographic gratings with 36 flat windows and 24 prisms, being all these elements very large and complex. Additionally, the optical tests and the complete assembly of the camera and collimator subsystems will be carried out in Mexico. Here we describe the current status of the optics manufacturinegin the abstract two lines below author names and addresses.

Keywords: spectrographs optics, optical manufacturing, optical testing

1. INTRODUCTION

MEGARA (*Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía*) is an optical Integral-Field Unit (IFU) and Multi-Object Spectrograph designed for the GTC 10.4m telescope in La Palma. The MEGARA consortium is led by the Universidad Complutense de Madrid (UCM) with the partnership of the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), the Instituto de Astrofísica de Andalucía and the Universidad Politécnica de Madrid. INAOE is responsible of the Spectrograph Optics Work Package in collaboration with its Technological Partner the Centro de Investigación en Óptica (CIO). MEGARA is being developed under a contract between GRANTECAN and UCM. The detailed design, construction and AIV phases are now funded and the instrument should be delivered to GTC before the end of 2016.

The instrument offers two IFU-type modes with two different bundles, one covering 12.5 arcsec x 11.3 arcsec with a spaxel size of 0.62 arcsec and another one covering 8.5 arcsec x 6.7 arcsec with a spaxel size of 0.42 arcsec. The multiobject mode will allow observing up to 100 objects in a region of 3.5 arcmin x 3.5 arcmin around the two IFU bundles. Eight of these bundles will be devoted to the determination of the sky during the observations so only 92 of these positioners will be available controlled by the control system. MEGARA will provide intermediate-to-high spectral resolutions. The requirement is $R_{FWHM} \sim 6{,}000$, 12,000 and 18,700, respectively for the different resolution modes: Low (LR), Medium (MR) and High (HR).

The spectrograph, with a fixed geometry between collimator and camera, will provide the angles for each spectral configuration by prisms. Volume phase holographic gratings (VPHs) will be accommodated in the pupil position. Low-

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resolution will be built with simple gratings sandwiched between two flat windows; mid and high resolution units are provided with the gratings sandwiched between two flat windows and glued to symmetric prisms that allow the beam to incide on the VPH in the optimum angle.

The scientific requirements[1] defined the following number of configurations: 6 for LR, 10 for MR and 2 for HR. The optics elements include 1 field lens, 12 lenses of the collimator and camera, 34 flat windows for the VPHs and 24 prisms for the MR and HR spectral configurations, making a total of 71 elements. These optics will be manufactured between INAOE and CIO. The manufacturing of the collimator and camera lenses is in progress. The 24 prisms will be fabricated at INAOE while the 34 flat windows at CIO. CIO is also responsible of the coatings of all the elements, 48 coating depositions will be carry out.

An overview of the MEGARA project is presented by Gil de Paz[1] et al. 2014. Different MEGARA subsystems are discussed by Castillo[2] et al. 2014, Ferrusca[3] et al. 2014, Ortíz[4] et al. 2014, García-Vargas[5] et al. 2014 and Pérez Calpena[6] et al. 2014. In section 2 we present an overview of the Field Lens and the spectrograph optics main characteristics. In section 3 the Optics Manufacturing specifications including the tolerances and some of most relevant tests are described. Section 4 is dedicated to the Coatings and Section 5 is the Summary.

2. OPTICS OVERVIEW

2.1 Field Lens

A field lens was designed to provide a telecentric field for MEGARA. With the field lens 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[1].

Table 1.Field lens characteristics

Field Lens characteristics					
Element	Material	R1 (mm)	R2 (mm)	Central Thickness (mm)	Edge ∅ (mm)
Field Lens	Fused Silica	-214.6	-1731.8	30.0	274

2.2 The spectrograph

MEGARA spectrograph has a fully refractive optical system. It is composed by a pseudo-slit, where fibers are placed simulating a long slit 119mm length and with a ROC of 1075mm. The pseudo-slits will be moved for exchanging the pseudo-slit in use between the different modes, and also will be used as a focusing mechanism that will be configured in the z-axis for each of these modes and VPHs. Following the light path we find then the collimator, which is composed by 5 lenses. The first lens of the collimator is the only aspherical surface of the instrument. The pupil has 160mm free diameter and it is the location for the VPHs. Once the beam passes through the grating it goes to the camera composed by two doublets and 3 singlets that focuses the light onto the detector.

The collimator is composed by an aspheric singlet and two doublets as seen in Figure 1. It has a focal length 484.4 mm -at 632.8nm- and f-ratio equal to 3.03. The main characteristics of the optical elements are summarized in Tables 1 and 2. The camera is composed by two doublets and 3 singlets as shown in Figure 1. Its focal length is 246.86 at 632.8nm with a f-ratio of 1.54. The image field is 61.4mm x 61.4mm covering 4K x 4K pixels to maximize the spectral coverage throughout the detector. The complete specification of the optical elements are summarized in Table 3. A detailed description of the spectrograph design and performance can be found in Carrasco[7] et al. 2011.

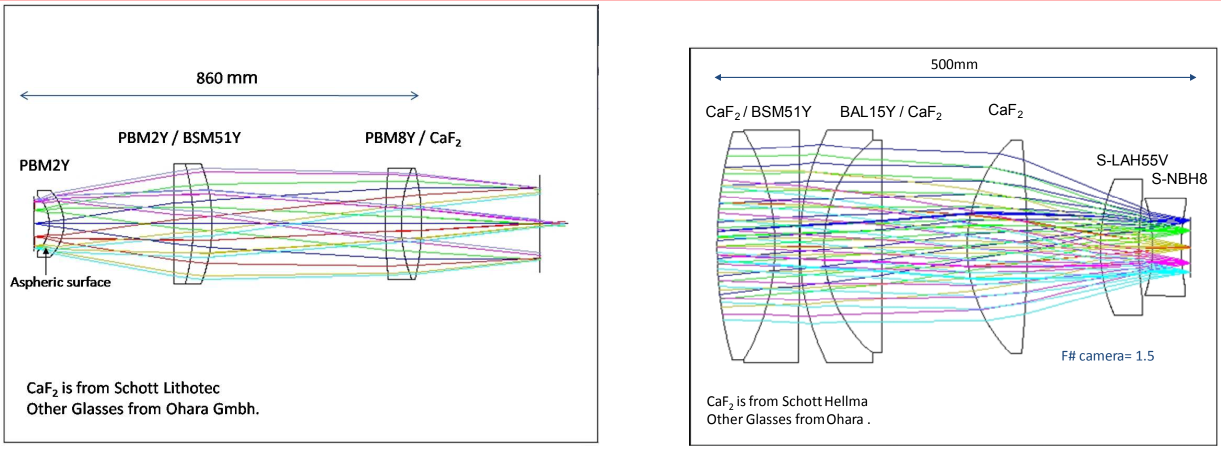

Figure 1. Layout of the MEGARA main optics. Left: the collimator is formed by an aspheric lens and two doublets. Right: the camera is composed by two doublets and three singlets. The drawigns are not in scale as the diameters of the collimator doublets are larger than those of the camera.

Table 2. Collimator optics parameters. The largest diameter is 272 mm.

Collimator Optical Elements. (*) Cemented doublets.					
Element	Material	R1 (mm)	R2 (mm)	Central Thickness (mm)	Edge ∅ (mm)
COLL S-1	PBM2Y	-91.0 (x)	-113.3	35.0	155.0
COLL D-2*	PBM2Y	flat	-728.1	35.0	272.0
COLL D-3*	BSM51Y	- 728.1	-398.8	35.0	272.0
COLL D-4*	PBM8Y	+1259.9	+344.5	25.0	260.0
COLL D-5*	CaF_2	+344.5	-542.5	45.0	250.0

Table 3. Coefficients of the collimator aspheric element.

Aspheric Coefficient	R^4	R^6
Values (mm)	-2.611×10^{-8}	-1.600×10^{-11}

Table 4. Camera optics main parameters.. The largest diameter is 240 mm

Camera Optical Elements. (*) Cemented doublets.					
Element	Material	R1 (mm)	R2 (mm)	Central Thickness (mm)	Edge ∅ (mm)
CAM D-1*	CaF_2	+435.9	-231.7	60.0	236.0
CAM D-2*	BSM51Y	-231.7	Flat	25.0	240.0
CAM D-3*	BAL15Y	+269.2	+145.1	25.0	240.0
CAM D-4*	CaF_2	+145.1	Flat	60.0	220.0
CAM S-5	CaF_2	+156	-1143	62.0	220.0
CAM S-6	S-LAH55V	+176.4	365.8	40.0	140.0
CAM S-7	S-NBH8	-162.5	219.5	30.0	110.0

The pupil size is 160 mm. Given the fixed geometry of 68º between collimator and camera, the angles for each spectral configuration will be provided by prisms. The VPHs will be accommodated at the pupil position. Low-resolution units will be built with simple VPHs sandwiched between two flat windows. Mid and high resolution units will be provided with the gratings sandwiched between two flat windows glued to symmetric prisms that allow the beam to incide on the VPH in the optimum angle. The expected resolutions expressed as $R_{FWHM}=\lambda/\Delta\lambda_{FWHM}$ are presented in table 5. The corresponding central wavelengths and velocity resolution are presented by Gil de Paz[1] et al 2014. Figure 2 shows a layout of the different MEGARA resolution modes.

Table 5. MEGARA VPHs. The resolution, $R_{FWHM}=\lambda/\Delta\lambda_{FWHM}$, is derived from the FWHM ($\Delta\lambda_{FWHM}$) of the 1D spectra and the case of the LCB IFU and MOS modes (see also Figure 9). The angle of incidence (AOI) specified for the coatings, the clear aperture of each element and the prisms apex are included.

VPH Name	Setup	R_{FWHM}	Coating λ_1-λ_2 (nm)	Coating AOI (°)	Aperture (mm x mm)	Prism apex (°)
VPH405-LR	LR-U	6028	365.3 – 438.6	34	170 x 210	Flat
VPH480-LR	LR-B	6059	433.2 – 519.6	34	170 x 210	Flat
VPH570-LR	LR-V	6080	514.3 – 616.4	34	170 x 210	Flat
VPH675-LR	LR-R	6099	609.4 – 730.0	34	170 x 210	Flat
VPH799-LR	LR-I	6110	722.0 – 864.6	34	170 x 210	Flat
VPH890-LR	LR-Z	6117	804.3 – 963.0	34	170 x 210	Flat
VPH410-MR	MR-U	12602	391.7 – 427.7	10.5	180 x 220	44.00
VPH443-MR	MR-UB	12370	422.5 – 462.1	10.5	180 x 220	44.00
VPH481-MR	MR-B	12178	458.6 – 502.4	10.5	180 x 220	44.00
VPH521-MR	MR-G	12035	496.3 – 544.3	10.5	180 x 220	44.00
VPH567-MR	MR-V	11916	539.3 – 591.9	10.5	180 x 220	44.00
VPH617-MR	MR-VR	11825	5869 – 6447	10.5	180 x 220	44.00
VPH656-MR	MR-R	11768	624.1 – 685.9	10.5	180 x 220	44.00
VPH712-MR	MR-RI	11707	676.4 – 743.7	10.5	180 x 220	44.00
VPH777-MR	MR-I	11654	738.2 – 812.0	10.5	180 x 220	44.00
VPH926-MR	MR-Z	11638	880.0 – 968.6	10.5	180 x 220	44.00
VPH665-HR	HR-R	18700	644.5 – 683.7	34.0	180 x 220	67.86
VPH863-HR	HR-I	18701	837.2 – 888.2	34.7	180 x 220	68.61

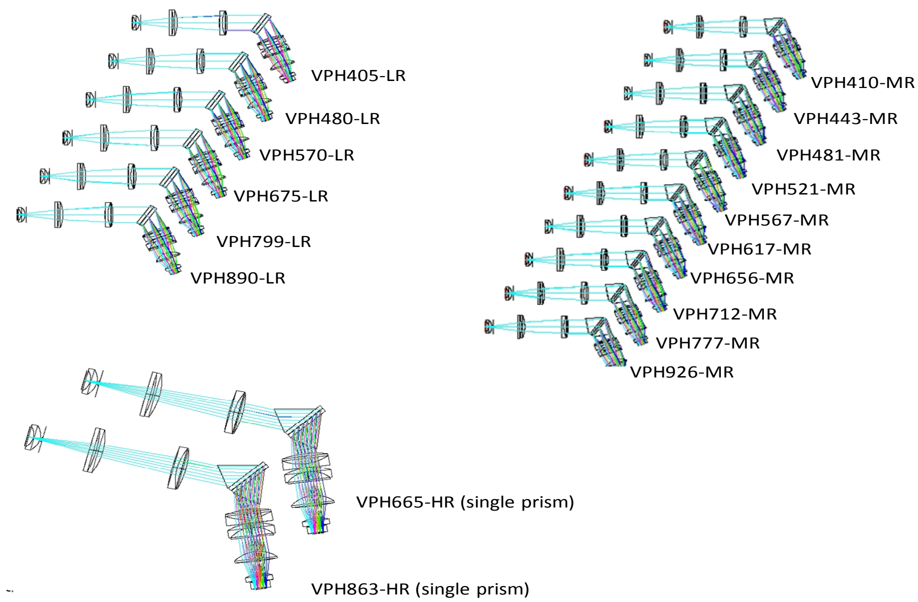

Figure 2. This configuration keeps the angle between the collimator and camera fixed at 68°. The low resolution mode LR uses at pupil a VPH grating sandwiched between two flat window. The different angles on the hologram needed for the different spectral MR and HR resolutions are obtained by sandwiching the holograms between two prisms.

3. OPTICS MANUFACTURING

3.1 Main optics and field lens specifications and tolerances

The optics specifications are considered high precision given the diameters, the tolerances and the materials, in particular CaF2 and BSM51Y. The main parameters with the corresponding tolerances are Edge diameter (Edge ∅) in mm, Radius of curvature (RoC) in mm, Surface figure at λ=0.632 nm in fringes, Scratch and Dig according to MIL 13830, and Wedge in arcmin. S1 and S2 refer to the lens first and second surface respectively, considering that the light travels from left to right according to the optical design. Table 6 presents the specifications for the Field Lens and the collimator and camera elements. Table 7 shows the corresponding parameters for the aspheric collimator lens COLL-S1. A detailed analysis of the manufacturing tolerances is presented in Ortiz[4] et al., 2014.

INAOE and CIO have the infrastructure and human resources required to manufacture and to test all the elements of MEGARA spectrograph optics[8] to achieve the high precision specifications. Both insitutions have developed jointly a detailed manufacturing[9] and testing plan[10] to fulfill the schedule established in the MEGARA Managment Plan. All collimator and camera blanks have been already procured from OHARA and are being polished at INAOE and CIO. An example of the interferograms produced for each surface of each element, in this case for SI of COLL-D4, is shown in Figure 3.

Table 6. MEGARA lenses specifications and corresponding tolerances.

Element	Material	Edge ∅ (mm) -0.015	Thickness (mm)	RoC (mm) S1	RoC (mm) S2	Fringes @ λ=0.632 nm S1/S2	S/D S1-S2	Wedge (arcmin)
Field	F. Silica	274	30.0 ± 0.1	-214.6 ± 2	-1731.8 ± 2	0.25/0.25	20/10-20/10	2
COLL-S1	PBM2Y	155	35.0 ± 0.15	-97 ± 0.1	-113.3 ± 0.1	0.25/0.25	40/20-20/10	2
COLL-D2	PBM2Y	272	35.0 ± 0.15	FLAT	-728.1 ± 1	0.5/1	20/10-40/20	2
COLL-D3	BSM51Y	272	35.0 ± 0.15	-728.1 ± 1	-398.8 ± 0.4	1/0.5	20/10-40/20	2
COLL-D4	PBM8Y	260	48.5 ± 0.15	+1259.9 ± 2	+344.5 ± 0.5	0.5/1	40/20-20/10	2
COLL-D5	CaF2	250	45.0 ± 0.15	+344.5 ± 0.5	-542.5 ± 0.5	0.5/2	60/40-40/20	2
CAM-D1	CaF2	236	60.0 ± 0.10	+435.9 ± 0.4	-231.7 ± 0.2	0.5/1	40/20-60/40	2
CAM-D2	BSM51Y	240	25.0 ± 0.1	-231.7 ± 0.2	FLAT	1/0.5	40/20-20/10	2
CAM-D3	BAL15Y	240	25.0 ± 0.1	+269.2 ± 0.2	+145.1 ± 0.1	0.5/1	20/10-40/20	2
CAM-D4	CaF2	220	60.0 ± 0.1	+145.1 ± 0.1	FLAT	1/0.5	40/20-40/20	2
CAM-S5	CaF2	220	62.0 ± 0.1	+156 ± 0.1	-1143 ± 0.8	0.5//0.5	40/20-40/20	2
CAM-S6	S-LAH55	140	40.0 ± 0.1	+176.4 ± 0.2	+365.8 ± 0.3	0.5/0.5	20/10-20/10	2
CAM-S7	S-NBH8	110	30.0 ± 0.1	-162.5 ± 0.2	+219.5 ± 0.2	0.25/0.25	20/10-20/10	2

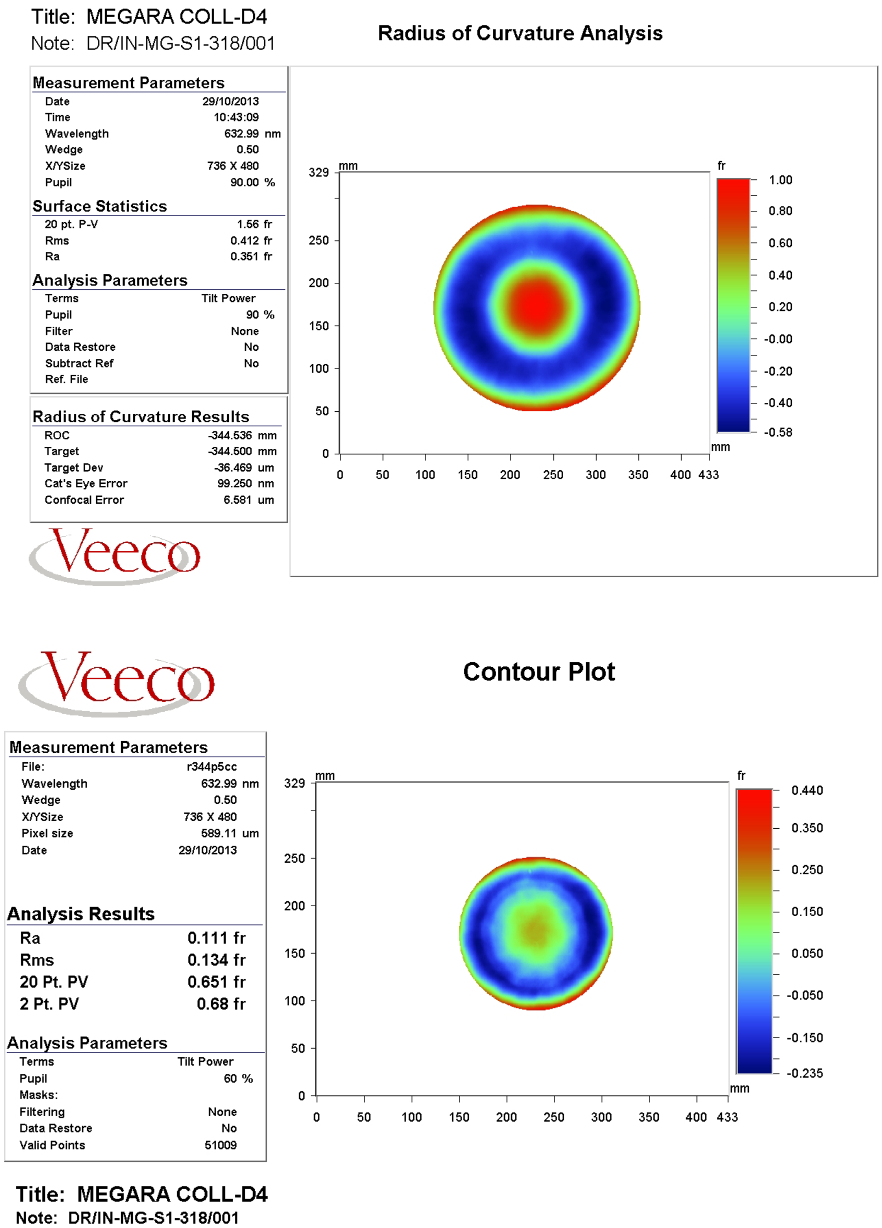

Figure 3. An example of the interferograms obtained for each optical surface. In this case the results are for surface S1 of COLL-D4.

The aspheric surface of COLL-S1 will be tested via a Computer Generated Hologram design by Diffraction International (www.diffraction.com). Given the tolerances in the asphericity coefficients, shown in Table 7, this company carried out a standard sensitivity analysis. They perturbed the coefficients individually by 1%. The manufacturing tolerances are larger than the pertubartions applied to their CGH design. The experimental set-up for this test is shown in Figure 4.

Table 7. Coefficients of the collimator aspheric element COLL-S1

Aspheric Coefficient	R^4	R^6
Values (mm)	-2.611×10^{-8}	-1.600×10^{-11}
Tolerance (mm)	$\pm 7.7 \times 10^{-10}$	$\pm 2.14 \times 10^{-13}$

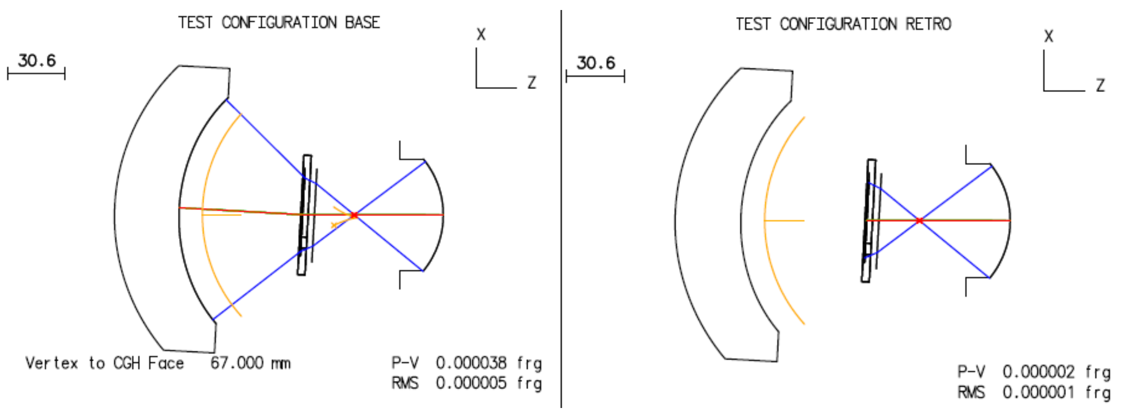

Figure 4. Testing set-up for COLL-S1 aspheric surface. Left: the aspheric surface will be tested in reflection and at normal incidence. The CGH null will be located at the diverging spherical test wavefront from our ZYGO interferometer. Right: the CGH null incorportes a retro-reflective feature for the CGH-to-interferometer alignment.

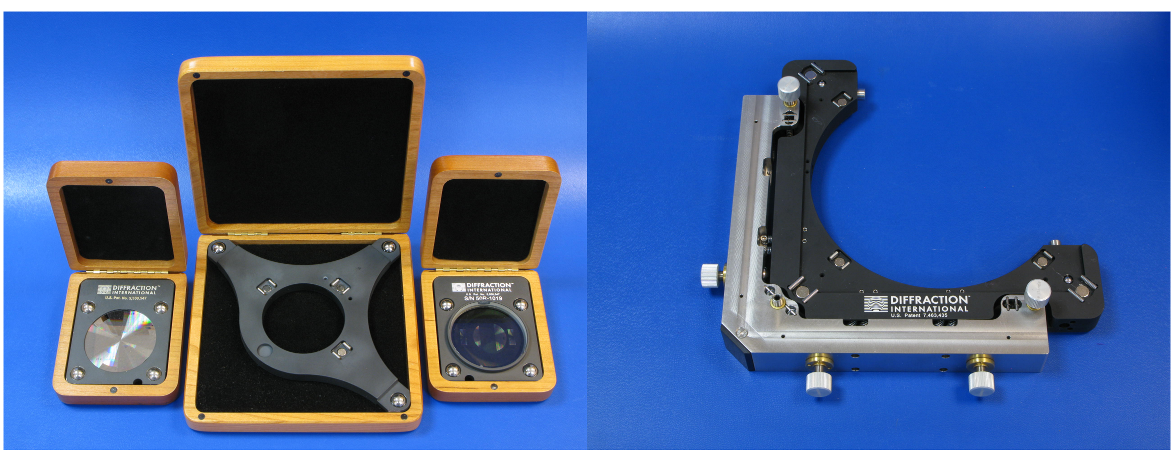

Figure 5. Left: custom phase CGH, mount and alignment CGH. Right: 6-axis positioner.

3.2 Pupil elements specifications and tolerances

The specifications and tolerances for the pupil elements are shown in Table 8 for the windows and in Table 9 for the the prisms. The 36 flat windows for the pupil elements will be manufacture from OHARA SK1300 Fused Silica.. Given the specifications the pupil elements are also considered as high precision optics. Aditionally, there are several risks during the manufacturing process given the weight of the prisms, the equally heavy tools and mounts involved. The blanks for LR-Z, MR-U and HR-R windows have been procured and are polishing at CIO, see Figure 5. At INAOE the polishing of HR-R and MR-U BK7 dummy prisms is in progress.

Table 8. Windows specifications and tolerances.

Element Windows (#)	Material	Length (mm)	Width (mm)	Thick (mm)	Fringes @ λ=0.632 nm S1/S2	S/D S1-S2	Wedge (arcmin)
LR (12)	F.Silica	220±0.2	180±0.2	30±0.1	0.5/1	40/20-60/40	1
MR (20)	F. Silica	240±0.2	190 ±0.2	20±0.1	0.5/1	60/40-60/40	1
HR (4)	F. Silica	240±0.2	190 ±0.2	20±0.1	1/1	60/40-60/40	1

Table 9. MR and HR prisms specifications and tolerances.

Element Prisms (#)	Material	Length (mm)	Width (mm)	Fringes λ=0.632 nm S1/S2	S/D S1-S2	Apex angle (°)
MR (20)	PBM2Y	240±0.2	190 ±0.2	0.5/1	40/20-60/40	44±0.016
HR-R (2)	PBM2Y	210±0.2	190 ±0.2	0.5/1	40/20-60/40	67.87±0.016
HR-I (2)	PBM2Y	210±0.2	190 ±0.2	0.5/1	40/20-60/40	68.81±0.016

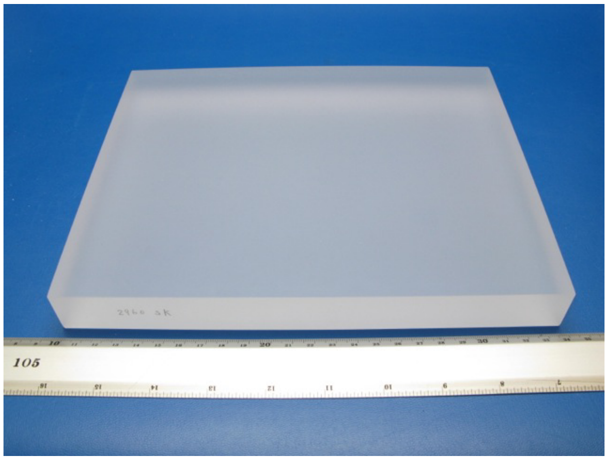
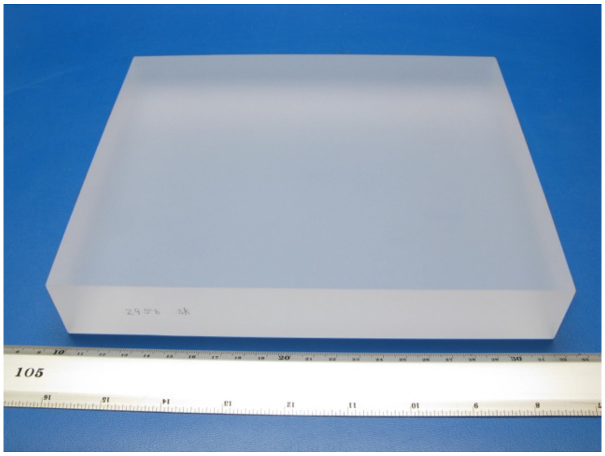

Figure 6. Left: blank for one MR-U window. Right: blank for one LR-Z window. Being polishing at CIO.

4. COATINGS

4.1 Field Lens and Main Optics coatings specifications

The antireflection (AR) coating specifications for the Fiel Lens and the Main Optics are presented in table 10. These elements required a Broad-Band antireflecion coating to cover all the visible wavelenght interval i.e. $\Delta\lambda$=370-980 nm with a reflectivity R < 1.3% in the complete range. To optimize the spectrograph throughput, the AR coatings are specified at a mean angle of incidence (AOI) for surface S1 and surface S2 of each lens. The interface surfaces between doublets do not required coatings as the optical cement will provide an optical match between the glasses.

Table 10. Field lens and main optics coating specifications.

Element	Substrate	Mean AOI for AR coating $\Delta\lambda$=370-980 nm; R < 1.3% Left surface (S1)	Mean AOI for AR coating $\Delta\lambda$=370-980 nm; R < 1.3% Right Surface (S2)
Field Lens	Fused Silica	2°	2.8°
COLL-S1	PBM2Y	21.2°	17.1°
COLL-D2	PBM2Y	4.9°	No coating
COLL-D3	BSM51Y	8.5°	No coating
COLL-D4	PBM8Y	4.5°	No coating
COLL-D5	CaF2	No coating	7.3°
CAM-D1	CaF2	10.8°	No coating
CAM-D2	BSM51Y	No coating	5.8°
CAM-D3	BAL15Y	13°	No coating
CAM-D4	CaF2	No coating	5.6°
CAM-S5	CaF2	18.5°	12°
CAM-S6	S-LAH55V	9.3°	11.7°
CAM-S7	S-NBH8	20.3°	14.8°

4.2 Pupil Elements coating specifications

The anitreflection coating wavelength interval $\Delta\lambda$ for the pupil elements is determined by the spectral configuration i.e. for each configuration the AR coating $\Delta\lambda$ is diferent. The angle of incidence for all the LR configurations is 34° and for MR is 10.5°, while for HR-R is 34° and for HR-I is 34.7°. The coating specification is R < 1.3%.

Table 11. Coating specifications for Low resolution windows.

Coatings @ LR configurations Windows (2 of each)	Substrate	AR coating Δλ (nm) @ AOI=34° R < 1.3%
(LR-U)	Fused Silica	360.0 - 445.0
(LR-B)	Fused Silica	390.0 - 570.0
(LR-V)	Fused Silica	470.0 - 620.0
(LR-R)	Fused Silica	550.0 - 780.0
(LR-I)	Fused Silica	670.0 - 920.0
(LR-Z)	Fused SIlica	750.0 - 990.0

Table 12. Coating specifications for Medium and High resolution prism.

Coatings for MR & HR configurations Prisms (2 of each)	Substrate	AR coating Δλ (nm) @ AOI 10.5° R < 1.3%
(MR-U)	PMB2Y	380 - 440
(MR-UB)	PMB2Y	410 - 480
(MR-B)	PMB2Y	440 - 520
(MR-G)	PMB2Y	480 - 560
(MR-V)	PMB2Y	520 - 610
(MR-VR)	PMB2Y	570 - 660
(MR-R)	PMB2Y	610 - 700
(MR-RI)	PMB2Y	660 - 760
(MR-I)	PMB2Y	720 - 830
(MR-Z)	PMB2Y	860 - 980
(HR-R)	PBM2Y	630 - 700 @ AOI 34°
(HR-I))	PMB2Y	837 - 888 @ AOI 34.7°

4.3 Coating design

The solution to the large number of coatings specified for the Field Lens and Main Optics at different AOI, has been developed at CIO. A very robust coating has been designed that fulfills the specifications for all the angles of the Main Optics. In fact, the design is better than the specs, see Figure 6, left panel. In addition to the Broad-Band coatings of the collimator and camera lenses, CIO has also designed specific Narrow-Band coatings for the VPHs windows and prisms. The AR coatings for Narrow-Band intervals are achieved by changing the thickness of the layer of the same 4 materials, as is ilustrated in Figure 6, right panel. The calibration of these coatings is in progress at CIO using a very modern and reliable Denton Vacuum System.

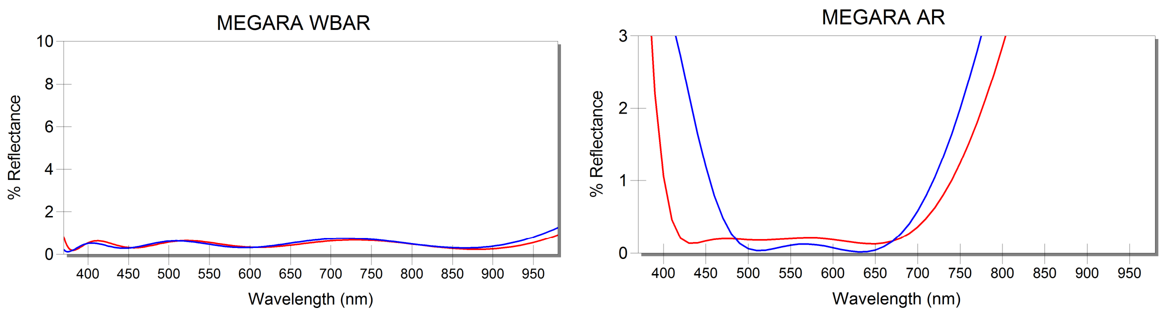

Figure 6. Left: Broad-Band AR coating design for the Field Lens and the Main Optics. Right: Narrow-Band AR coating design for the Pupil Elements; with this 4-layer design the different narrow intervals are achieved by modifying the thickness of the layers.

5. SUMMARY

The optics manufacturing process of MEGARA Main Optics is in progress at INAOE and CIO. We also have started the polishing of the first pairs of LR, MR and HR windows and the first MR and HR prisms. We have developed a plan to manufacture the spectrograph optics - that includes 12 lenses, 24 prisms, 36 windows- and one Field Lens within the MEGARA schedule. The Main Optics will be finished before the end of 2014.

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