

# Performance of MEGARA Spectrograph optical elements

E. Carrasco<sup>\*a</sup>, G. Páez<sup>b</sup>, R. Izazaga<sup>a</sup>, J. de la Luz Hurtado<sup>b</sup>, C. Pérez<sup>b</sup>, F. Granados<sup>a</sup>, D. Aguirre<sup>c</sup>, E. Percino<sup>a</sup>, J. Reyes<sup>a</sup>, A. Gil de Paz<sup>d</sup>, J. Gallego<sup>d</sup> & J. Iglesias<sup>e</sup>

<sup>a</sup>Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE, Mexico); <sup>b</sup>Centro de Investigaciones en Óptica (CIO, Mexico); <sup>c</sup>Universidad Autónoma de México, (UNAM, México);

<sup>d</sup>Universidad Complutense de Madrid (UCM, Spain); <sup>e</sup>Instituto de Astrofísica de Andalucía-CSIC (IAA, Spain)

## ABSTRACT

MEGARA is the new IFU and multiobject spectrograph for Gran Telescopio Canarias. The spectrograph will offer spectral resolution  $R_{\text{fwhm}} \sim 6,000, 12,000$  and  $18,700$ . Except for the optical fibers and microlenses, the complete MEGARA optical system has been manufactured in Mexico. 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. All these elements are very large and complex, with very efficient antireflection coatings. Here the optical performance of MEGARA collimator and camera lenses and the field lens is presented.

**Keywords:** Spectrographs, high precision optics, optical testing, coatings

## 1. INTRODUCTION

An overview of the science and the instrument status is described by Gil de Paz, A. et al. [1]; The detector cryogenic system by Ferrusca, D., et al. [2]; The fiber MOS positioning tool by Iglesias-Páramo, J., et al. [3]; MEGARA fiber MOS assignment tool (FMAT) by Gómez-Alvarez, P., et al. [4]; MEGARA exposure time calculator by Castillo-Morale, A., et al. [5]; MEGARA control system by Lefort, B., et al. [6]; MEGARA spectrograph mechanics and opto-mechanics in the AIV phase by Maldonado, M., et al. [7]; The large MEGARA pupil elements: assembly, tests, and performance by Martínez-Delgado, I., et al. [8]; MEGARA: high-precision alignment system for gluing fibers and microlenses by Pérez-Calpena, A., et al. [9]. In this paper we focus in the spectrograph main optics. The spectrograph optics is formed by 5-lenses, one of them aspheric and 7-lenses camera. The polishing techniques for MEGARA optics are presented by Izazaga-Pérez, R., et al. [10]. Except for the aspheric all of them were manufactured at INAOE and CIO. The coatings evaporations were carried out at CIO, the results are presented by Ortiz, R., et al. [11]. Here we described the optical performance of MEGARA main optics and field lens.

### 1.1 Collimator and camera optics

The  $f/3$  collimator has a focal length of 484.4mm for a singlet and two doublets. The  $f/1.5$  camera has a focal length of 245.9 mm for two doublets and three singlets. The last lens (CAM-S7) is also the cryostat window. In Table 1 a summary of MEGARA lenses specifications is presented. Given the diameters and specifications it is considered high precision optics. Except for the OLL-S1, manufactured by HOYA, all the lenses were manufactured at INAOE and CIO.

\*bec@inaoep.mx; phone 52 222 2663100; inaoep.mx

Table 1. MEGARA lenses specifications summary.

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

## 1.2 Results

The following tables we present the as-built parameters of the individual elements manufactured at INAOE and CIO. When a given specification was not achieved, the system optical performance was analysed by the optical designer and when accepted a Non Conformity (N/C) was recorded.

Table 2. Collimator lens COLL-D2 as-built parameters.

<b>AIV-TEC-MEG-084-3.3</b>		<b>Manufacturer</b>	<b>INAOE</b>		
<b>COLL-D2</b>					
<b>Ohara PBM2Y</b>					
<b>Parameter</b>	<b>Requirement</b>	<b>Measurement</b>	<b>Measurement</b>	<b>Measurement</b>	<b>Instrument or method</b>
<b>Surface 1</b>		Test plate	Surface 1		
RoC (mm)	Flat				Interferometer+reference flat
Used aperture $\Phi$ (mm)	250 x 100	—	$\Phi=250$	—	
Irr in used aperture	2 fr	—	0.8134	—	ZYGO Interferometer
Irr in $\Phi=90$	0.5 fr	—	0.0614	—	ZYGO Interferometer
MIL 13830 SD	20/10	—	20/10	—	Visual inspection vs. calibrated reference
Protective chamfer	1.0 x 45°	—	1.0 x 45°	—	Graduated reticle
AR Coating 370-980 nm					
R>1.3%	Tav > 98.7%		Tav=99.1%		CARY spectrometer
<b>Surface 2</b>			Surface 2	Surface2	
RoC (mm)	-728.1 +/-1	-728.1			Nodal slide optical bench
Used aperture $\Phi$ (mm)	250 x120				
Irr in used aperture	3 fr	0.3385 in $\Phi=140\text{mm}$		0.3113	Newton interf. / subapertures stitching
Irr in $\Phi=105$	1 fr	0.1887		0.1221	Newton interf./subapertures stitching
MIL 13830 SD	40/20		40/20		Visual inspection vs. calibrated reference
Protective chamfer	1.0 x 45°	—	1.0 x 45°	—	Graduated reticle
AR coating 370-980 nm	no coating	—	-	—	
<b>Lens</b>					
Edge diameter (mm)	272 +0/-0.015		272.1(**) <sup>†</sup>		Mitutoyo cal. $\pm 0.010$
Central thickness* (mm)	35 +/-0.1		34.96		Mitutoyo cal. $\pm 0.010$
Wedge (arcmin)	2		0.02		Mitutoyo cal. $\pm 0.010$

Table 3. Collimator lens COLL-D3 as-built parameters.

<b>AIV-TEC-MEG-084-3.4</b>		<b>Manufacturer</b>	<b>INAOE</b>		
<b>COLL-D3</b>					
<b>Ohara BSM51Y</b>					
<b>Parameter</b>	<b>Requirement</b>	<b>Measurement</b>	<b>Measurement</b>	<b>Measurement</b>	<b>Instrument or method</b>
<b>Surface 1</b>		Test plate	Surface 1		
RoC (mm)	-728.1 +/-1	-	-728.1	-	Nodal slide optical bench
Used aperture $\Phi$ (mm)	250 x120	-		-	
Irr in used aperture	3 fr	-	0.268	-	ZYGO interferometer
Irr in $\Phi=105$	1 fr	-	0.095	-	ZYGO interferometer
MIL 13830 SD	40/20	-	30/10	-	Visual inspection vs. graduated reference
Protective chamfer	1.0 x 45°	-	1.0 x 45°	-	Graduated reticle
AR coating 370-980 nm	no coating				
<b>Surface 2</b>			Surface 2		
RoC (mm)	-398.8+-0.4	-398.8		-398.8	Nodal slide optical bench
Used aperture $\Phi$ (mm)	250 x 120				
Irr in used aperture	2 fr	0.3253 in $\Phi=150$		0.6715	Newton interferometry/ subapertures stitching
Irr in $\Phi=105$	0.5 fr	0.1772		0.2057	Newton interferometry/ subapertures stitching
MIL 13830 SD	20/10		20/5		Visual inspection vs. graduated reference
Protective chamfer	1.0 x 45°		1.0 x 45°		Graduated reticle
AR Coating 370-980 nm Mean AOI = 8.5°; R < 1.3%	Tav > 98.7%		Tav= 99.4 %		CARY spectrometer
<b>Lens</b>					
Edge diameter (mm)	272 +/- 0.015		271.99		Mitutoyo calibrator $\pm 0.010$
Central thickness (mm)	35 +/-0.15		34.9		Mitutoyo calibrator $\pm 0.010$
Wedge (arcmin)	2 arcmin		1.16		Centering machine

Table 4. Collimator lens COLL-D4 as-built parameters.

<b>AIV-TEC-MEG-084-3.5</b>		<b>Manufacturer</b>	<b>CIO</b>	
<b>COLL-D4</b>				
<b>Ohara PBM8Y</b>				
<b>Parameter</b>	<b>Requirement</b>	<b>Measurement</b>	<b>Measurement</b>	<b>Instrument or method</b>
<b>Surface 1</b>		Test plate	Surface 1/Newton	
RoC	1259.9 +/- 2 mm	1260.8	1260.8	Interferometer
Used aperture $\Phi$	240 mm			
Irr in used aperture	2 fr	0.36 fr	1.14 fr	Interferometer
Irr in $\Phi=150$	0.5 fr	0.167 fr in $\Phi=138$	0.46 fr	Interferometer
MIL 13830 SD	20/10	—	20/10	Visual inspection
Rms surface roughness	20 Å	—		
Protective chamfer	1.0 x 45°	—	1 x 45°	Graduated reticule
AR Coating 370-980 nm Mean AOI = 4.5°; R < 1.3%	Tav > 98.7%	—	Tav = 99.05%	
<b>Surface 2</b>			Surface 2	
RoC	344.5 +/- 0.5 mm	—	344.53	Interferometer
Used aperture $\Phi$	240 mm	—		
Irr in used aperture	3 fr	—	1.6 fr	Interferometer
Irr in $\Phi=160$	1 fr	—	0.69 fr	Interferometer
MIL 13830 SD	40/20	—	40/20	Visual inspection
Rms surface roughness	30 Å	—		
Protective chamfer	1.0 x 45°	—	1.0 x 45°	Graduated reticule
Flat chamfer	5 mm	—	5.1 mm	Graduated reticule
AR coating 370-980 nm	No coating	—	—	
<b>Lens</b>				
Edge diameter	260 +0/-0.015	—	259.989	CMM
Central thickness	25 +/- 0.15	—	24.889	CMM
Wedge	2 arcmin	—	1 arcmin	Centering machine

Table 5. Collimator lens COLL-D5 as-built parameters.

AIV-TEC-MEG-084-3.6	Manufacturer CIO				
COLL-D5					
Hellma CaF <sub>2</sub>					
Parameter	Requirement	Measurement	Measurement	Measurement	Instrument or method
Surface 1		Test plate	Surface 1	Surface 2	
RoC (mm)	344.5 +/- 0.5 mm	—	344.173	—	WYCO Interferometer
Used aperture $\Phi$ (mm)	236	—	236	—	
Irr in used aperture	3 fr	—	0.699	—	WYCO Interferometer subaperture stitching
Irr in $\Phi=160$	2 fr	—	0.462	—	WYCO Interferometer subaperture stitching
MIL 13830 SD	60/40	—	60/40	—	Visual inspection vs. calibrated reference
Protective chamfer	1.0 x 45°	—	1.0 x 45°	—	Graduate reticle
AR Coating 370-980 nm	no coating	—	—	—	
Surface 2		Test plate	Surface 1	Surface 2	
RoC (mm)	-542.5 ± 0.5	542.81	—	542.09	WYCO Interferometer
Used aperture $\Phi$ (mm)	236	236	—	236	
Irr in used aperture	2 fr	0.48	—	1.19	Newton interferometer / Image Analysis Software
Irr in $\Phi=160$	0.5 fr	0.24	—	0.35	Newton interferometer / Image Analysis Software
MIL 13830 SD	40/20	—	—	40/20	Visual inspection vs. calibrated reference
Protective chamfer	1.0 x 45°	—	—	1.0 x 45°	Graduate reticle
AR coating 370-980 nm R<1.3%	T <sub>av</sub> > 98.7%	—	—	98.9	CARY spectrometer
Lens					
Edge diameter (mm)	250 + 0.0/- 0.015	—	—	250.005	CMM
Central thickness* (mm)	45 ± 0.15	—	—	44.933	CMMM
Wedge (arcmin)	2	—	—	1.83	Centering LOH machine

Table 6. Camera lens CAM-D1 as-built parameters.

AIV-TEC-MEG-084-3.7		Manufacturer	CIO		
CAM-D1					
Hellma CaF2					
Parameter	Requirement	Measurement	Measurement	Measurement	Instrument or method
Surface 1		Test plate	Surface 1		
RoC (mm)	435.9 +/- 0.4 mm		436.160 mm		Wyko Interferometer
Used aperture $\Phi$ (mm)	216mm	—	$\Phi = 216$ mm	—	Wyko Interferometer and stitching ZEEKO software
Irr in used aperture	1 fr	—	0.31664 fr	—	Wyko Interferometer and stitching ZEEKO software
Irr in $\Phi = 160$	0.5 fr	—	0.21040 fr	—	Wyko Interferometer and stitching ZEEKO software
MIL 13830 SD	40/20	—	40/20	—	Mil. Std. Norm.
Protective chamfer	1.0 x 45°	—	1.0 x 45°	—	Graduated reticle
AR Coating 370-980 nm					
R>1.3%	Tav > 98.7%		Tav=98.7 %		CARY spectrometer
Surface 2				Surface2	
RoC (mm)	231.7 +/- 0.2 mm	231.796 mm	—	231.758 mm	Wyko Interferometer
Used aperture $\Phi$ (mm)	216 mm	130 mm	—	216 mm	Image Analysis Software
Irr in used aperture	2 fr	0.256 fr	—	1.03 fr	Image Analysis Software
Irr in $\Phi = 160$	1 fr	0.256 fr	—	1.03 fr <sup>1</sup>	Image Analysis Software
MIL 13830 SD	60/40	—	—	60/40	Mil. Std. Norm.
Protective chamfer	1.0 x 45°	—	—	1.0 x 45°	Graduated reticle
AR coating 370-980 nm	no coating	—	—	—	
Lens					
Edge diameter (mm)	236 +0.0/- 0.015 mm			235.998 mm	CMM
Central thickness* (mm)	60.0 +/- 0.1 mm			59.945 mm	CMM
Wedge (arcmin)	2			1.8	Centering machine

Table 7. Camera lens CAM-D2 as-built parameters.

<b>AIV-TEC-MEG-084-3.8</b>		<b>Manufacturer</b>	<b>CIO</b>		
<b>CAM-D2</b>					
<b>Ohara BSM51Y</b>					
<b>Parameter</b>	<b>Requirement</b>	<b>Measure.</b>	<b>Measure.</b>	<b>Measure.</b>	<b>Instrument or method</b>
<b>Surface 1</b>		<b>Test Plate</b>	<b>Surface 1</b>	<b>—</b>	
RoC (mm)	231.7 ± 0.2	—	231.55	—	WYCO interferometer
Used aperture Φ (mm)	216	—			
Irr in used aperture	2 fr	—	1.77	—	WYCO interferometer
Irr in Φ= 160 (mm)	1 fr	—	0.52	—	WYCO interferometer
MIL 13830 SD	40 / 20	—	20/10	—	Visual inspection vs. graduated reference
Protective chamfer	1.0 x 45°	—	1.5 x 45°	—	Graduated reticule
AR Coating 370-980 nm	no coating	—	—	—	
<b>Surface 2</b>			<b>Surface 2</b>	<b>Surface2</b>	
RoC (mm)	Flat	Flat			Newton interferometer
Used aperture Φ (mm)	225				
Irr in used aperture	2 fr	0.2		0.95	Newton interferometer
Irr in Φ = 150 (mm)	0.5 fr	0.2		0.52	WYCO interferometer
MIL 13830 SD	20 / 10		20/10		Visual inspection vs. graduated reference
Protective chamfer	1.0 x 45°	—	1.5 x 45°		Graduated reticule
AR coating 370-980 nm Mean AOI=5.8°; R< 1.3%	Tav < 98.7 %	—	Tav=0.99%		
<b>Lens</b>					
Edge diameter (mm)	240 +0 /- 0.015		239.989		CMM
Central thickness (mm)	25 ± 0.1		24.119		CMM
Wedge (arcmin)	2		<1		Centering machine



Table 8. Camera lens CAM-D3 as-built parameters.

<b>AIV-TEC-MEG-084-3.9</b>		<b>Manufacturer</b>	<b>CIO</b>
<b>CAM-D3</b>			
<b>Ohara BAL15Y</b>			
<b>Parameter</b>	<b>Requirement</b>	<b>Measurement</b>	<b>Instrument or method</b>
<b>Surface 1 (CX)</b>		<b>Interferometry</b>	
RoC (mm)	269.2 ± 0.2	269.042	Wyko interferometer
Used aperture Φ	227 mm		
Irr in used aperture	1 fr	0.646	Wyko interferometer: & Zeeko 9 subapertures stitching & INAOE 9 subapertures stitching & Zeeko 4 subapertures stitching & INAOE 4 subapertures stitching
		0.696 (*)	
Irr in Φ= 150 mm	0.5 fr	0.262	
		0.3 (*)	
MIL 13830 SD	20/10	20/10	Visual inspection vs. graduated reference
Protective chamfer	1.0 x 45°	1.0 x 45°	Graduated reticule
AR Coating 370-980 nm Mean AOI = 13°; R < 1.3%	Tav > 98.7%	Tav=99.1	CARY spectrometer
<b>Surface 2 (CC)</b>		<b>Surface 2</b>	
RoC (mm)	145.1 ± 1	145.176	Wyko interferometer
Used aperture Φ	220 mm		
Irr in used aperture	2 fr	0.88	Wyko interferometer & Zeeko 4 subaperutes stitiching
Irr in Φ= 145	1 fr	0.2	Wyko interferometer
MIL 13830 SD	40/20	20/10	Visual inspection vs. graduated reference
Protective chamfer	1.0 x 45°	1.0 x 45°	Graduated reticule
Flat chamfer	10.2 mm	10.2 mm	Graduated reticule
AR coating 370-980 nm	No coating	—	
<b>Lens</b>			
Edge diameter	240 +0/-0.015	240.029	CMM
Central thickness (mm)	25 ± 0.15	25.094	CMM
Wedge	2 arcmin	< 1 arcmin	Centering machine

Table 9. Camera lens CAM-D4 as-built parameters.

AIV-TEC-MEG-084-3.10		Manufacturer	CIO		
CAM-D4					
Hellma CaF2					
Parameter	Requirement	Measurement	Measurement	Measurement	Instrument or method
Surface 1		Test plate	Surface 1	Surface 2	
RoC (mm)	145.1 +/- 0.1 mm	145.118	145.064	—	WYCO Interferometer
Used aperture $\Phi$ (mm)	215	100	215	—	Veeco Analysis Software
Irr in used aperture	2 fr	0.24	1.04	—	Veeco Analysis Software
Irr in $\Phi=145$	1 fr	—	0.70	—	Veeco Analysis Software
MIL 13830 SD	40/20	—	40/20	—	Mil. Std. Norm.
Protective chamfer	1.0 x 45°	—	1.0 x 45°	—	Graduate reticle
AR Coating 370-980 nm	no coating	—	—	—	
Surface 2		Test plate	Surface 1	Surface 2	
RoC (mm)	Flat	—	—	Flat	
Used aperture $\Phi$ (mm)	215	—	—	215	WYCO Interferometer and stitching ZEEKO software
Irr in used aperture	2 fr	—	—	1.15	Wyko Interferometer and stitching ZEEKO software
Irr in $\Phi=140$	0.5 fr	—	—	0.266	WYCO Interferometer
MIL 13830 SD	40/20	—	—	40/20	Mil. Std. Norm.
Protective chamfer	1.0 x 45°	—	—	1.0 x 45°	Graduate reticle
AR coating 370-980 nm R<1.3%	Tav > 98.7%	—	—	Tav = 99%	CARY spectrometer
Lens					
Edge diameter (mm)	220 + 0.0/-0.015	—	—	219.995	Coordinate Measuring Machine
Central thickness* (mm)	60 ± 0.1	—	—	60.046	Coordinate Measuring Machine
Wedge (arcmin)	2	—	—	1' 50"	Centering LOH machine

Table 10. Camera lens CAM-S5 as-built parameters.

AIV-TEC-MEG-084-3.10		Manufacturer	CIO		
CAM-S5					
Hellma CaF2					
Parameter	Requirement	Measurement	Measurement	Measurement	Instrument or method
Surface 1		Test plate	Surface 1	Surface 2	
RoC (mm)	156 +/- 0.1 mm	156.036	156.084	—	WYCO Interferometer
Used aperture $\Phi$ (mm)	215	—	215	—	Veeco Analysis Software
Irr in used aperture	2 fr	—	0.92	—	Veeco Analysis Software
Irr in $\Phi=120$	0.5 fr	0.443	0.8097 <sup>1</sup>	—	Veeco Analysis Software
MIL 13830 SD	40/20	—	40/20	—	Mil. Std. Norm.
Protective chamfer	1.0 x 45°	—	1.0 x 45°	—	Graduate reticle
AR Coating 370-980 nm R<1.3%	Tav > 98.7%	—	Tav= 99.1%	—	
Surface 2		Test plate	Surface 1	Surface 2	
RoC (mm)	1143 +/- 0.8 mm	1143.19	—	1143.78	
Used aperture $\Phi$ (mm)	210	210	—	210	WYCO Interferometer and stitching ZEEKO software
Irr in used aperture	2 fr	0.364	—	1.28	Wyko Interferometer and stitching ZEEKO software
Irr in $\Phi=100$	0.5 fr	0.101	—	0.31	WYCO Interferometer
MIL 13830 SD	40/20	—	—	40/20	Mil. Std. Norm.
Protective chamfer	1.0 x 45°	—	—	1.0 x 45°	Graduate reticle
AR coating 370-980 nm R<1.3%	Tav > 98.7%	—	Tav= 98.7 %		CARY spectrometer
Lens					
Edge diameter (mm)	220 + 0.0/-0.015	—	—	219.990	Coordinate Measuring Machine
Central thickness* (mm)	62 ± 0.1	—	—	61.30 <sup>1</sup>	Coordinate Measuring Machine
Wedge (arcmin)	2	—	—	1' 50"	Centering LOH machine

Table 11. Camera lens CAM-S6 as-built parameters.

AIV-TEC-MEG-084-3.12		Manufacturer	CIO	
CAM-S6				
Ohara S-LAH55V				
Parameter	Requirement	Measurement	Measurement	Instrument or method
Surface 1		Test plate	Surface 1/Newton	
RoC	176.4 +/- 0.2	176.348	176.353	Slide optical bench/WYCO Interferometer
Used aperture $\Phi$	130			
Irr in used aperture	1 fr	0.346	0.49	Newton interferometer
Irr in $\Phi=60$	0.5 fr	0.056	0.18	Newton interferometer
MIL 13830 SD	20 / 10	—	20/10	Visual inspection vs. graduated reference
Protective chamfer	1.0 x 45°	—	1.0 x 45°	Graduate reticule
AR Coating 370-980 nm Mean AOI = 9.3°; R < 1.3%	Tav > 98.7 %	—	Tav = 98.76 %	CARY spectrometer
Surface 2			Surface 2	
RoC	365.8 +/- 0.3		366.023	Slide optical bench/ WYCO Interferometer
Used aperture $\Phi$	102			
Irr in used aperture	1 fr	—	0.139 fr	WYCO interferometer
Irr in $\Phi=50$	0.5	—	0.021 fr	WYCO interferometer
MIL 13830 SD	20 / 10	—	20/10	Visual inspection vs. graduated reference
Protective chamfer	1.0 x 45°	—	1.0 x 45°	Graduate reticule
Flat chamfer (mm)	15	—	15	Graduate reticule
AR coating 370-980 nm Mean AOI = 11.7°; R < 1.3%	Tav > 98.7 %	—	Tav = 98.71 %	CARY spectrometer
Lens				
Edge diameter	140 +0/-0.015	—	139.994	CMM
Central thickness	40.0 +/- 0.1	—	40.01	CMM
Wedge (arcmin)	2	—	1.5	Centering machine

Table 12. Camera lens CAM-S7 as-built parameters.

<b>AIV-TEC-MEG-084-3.13</b>		<b>Manufacturer</b>	<b>INAOE</b>
<b>CAM-S7</b>			
<b>Ohara S-NBH8</b>			
<b>Parameter</b>	<b>Requirement</b>	<b>Measurement</b>	<b>Instrument or method</b>
<b>Surface 1</b>		Surface 1	
RoC (mm)	-162.5+/-0.2	<b>-162.750<sup>1</sup></b>	Nodal slide optical bench
Used aperture $\Phi$ (mm)	97		
Irr (P-V) in used aperture	2 fr	0.3882	ZYGO Interferometer
Irr (P-V) in $\Phi=20$ mm	0.25 fr	0.0533	ZYGO Interferometer
MIL 13830 SD	20/10	<b>40/10<sup>1</sup></b>	Visual inspection vs. calibrated reference
Protective chamfer	1.0 x 45° max	1.0 x 45° max	Graduated reticle
AR Coating 370-980 nm AOI= 20.3°; R>1.3%	T <sub>av</sub> > 98.7%	T = 99.5 %	CARY spectrometer
<b>Surface 2</b>		Surface 2	
RoC (mm)	219.5 +/- 0.2	<b>219.85<sup>1</sup></b>	Nodal slide optical bench
Used aperture $\Phi$ (mm)	86		
Irr (P-V) in used aperture	2 fr	0.1153	ZYGO Interferometer
Irr (P-V) in $\Phi=10$ mm	0.25 fr	0.1172	ZYGO Interferometer
MIL 13830 SD	20/10	20/10	Visual inspection vs. calibrated reference
Protective chamfer	1.0 x 45° max	1.0 x 45° max	Graduated reticle
AR coating 370-980 nm AOI=14.8°; R>1.3%	T <sub>av</sub> > 98.7%	T = 99.3 %	CARY spectrometer
<b>Lens</b>			
Edge diameter (mm)	110 -0.02/-0.08	109.95	Mitutoyo Calibrator $\pm 0.010$
Central thickness* (mm)	30+/-0.1	30.05	Mitutoyo Calibrator $\pm 0.010$
Wedge	2 arcmin	0.06	Mitutoyo Calibrator $\pm 0.010$

Table 13. Field lens as-built parameters.

AIV-TEC-MEG-084-3.1		Manufacturer	INAOE		
Field lens					
Fused silica					
Parameter	Requirement	Measurement	Measurement	Measurement	Instrument or method
Surface 1		Test plate	Surface 1	Surface 2	
RoC (mm)	-2147.6 ±2	—	-2146.7	—	Oriel optics slide bench ±1
Used aperture $\Phi$ (mm)	260	—	—	—	
Irr in used aperture	4 fr	—	1.043 fr	—	ZYGO Interferometer
Irr in $\Phi=10$	0.25 fr	—	0.0232 fr	—	ZYGO Interferometer
MIL 13830 SD	20/10	—	10/5	—	Visual inspection vs. calibrated reference (Bryson optical corp. 7641866)
Protective chamfer	1.0 x 45°	—	1.3 x 45°	—	Mitutoyo cal. ±0.010
AR Coating 370-980 nm					
R<1.3%	Tav > 98.7%		Tav = 99.21%		CARY spectrometer
Surface 2		Test plate	Surface 1	Surface 2	
RoC (mm)	-1731.8 ±2	-1731.89	—		Oriel optics slide bench ±1
Used aperture $\Phi$ (mm)	260	288	—		
Irr in used aperture	4 fr	0.4844 fr	—	1.312 fr	Newton interferometer
Irr in $\Phi=10$	0.25 fr	0.0508 fr	—	0.0993 fr	Newton interferometer
MIL 13830 SD	20/10	20/10	—	10/5	Visual inspection vs. calibrated reference (Bryson optical corp. 7641866)
Protective chamfer	1.0 x 45°	—	—	1.3 x 45°	Mitutoyo cal. ±0.010
AR coating 370-980 nm R<1.3%	Tav > 98.7%	—	—	Tav = 99.19%	CARY spectrometer
Lens					
Edge diameter (mm)	274 +0/-0.015		273.93 <sup>1</sup>		Mitutoyo cal. ±0.010
Central thickness* (mm)	30 ±0.1		30.17 <sup>1</sup>		Mitutoyo cal. ±0.010
Wedge (arcmin)	2		0.03		Mitutoyo cal. ±0.010

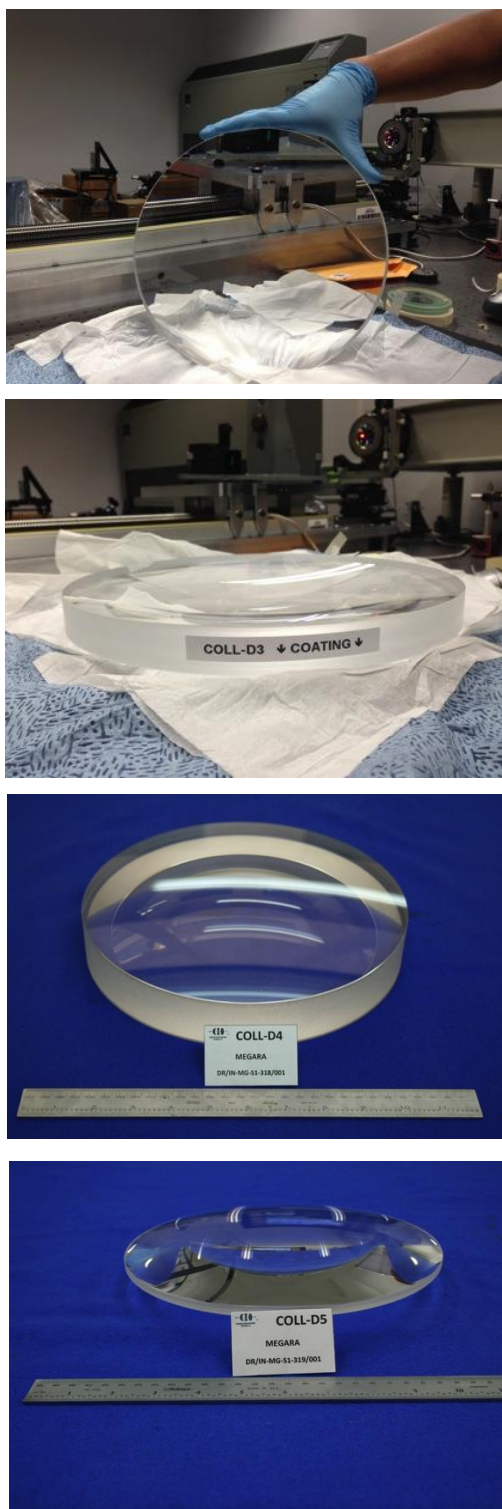


Figure 1. Collimator lenses. From top to bottom: COLL-D2 (PMB2Y), COLL-D3 (BSM51Y), COLL-D4 (PBM8Y) and COLL-D5 (CaF<sub>2</sub>).

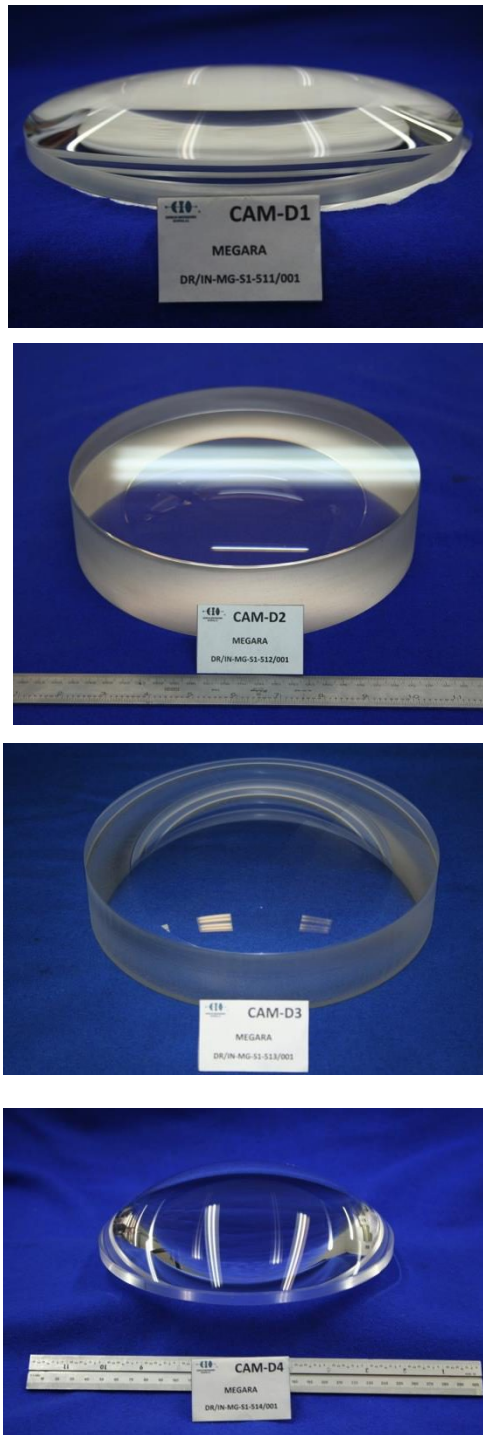


Figure 2. Camera lenses. From top to bottom: CAM-D1 (CaF<sub>2</sub>), CAM-D2 (BSM51Y), CAM-D3 (BAL15Y) and CAM-D4 (CaF<sub>2</sub>).



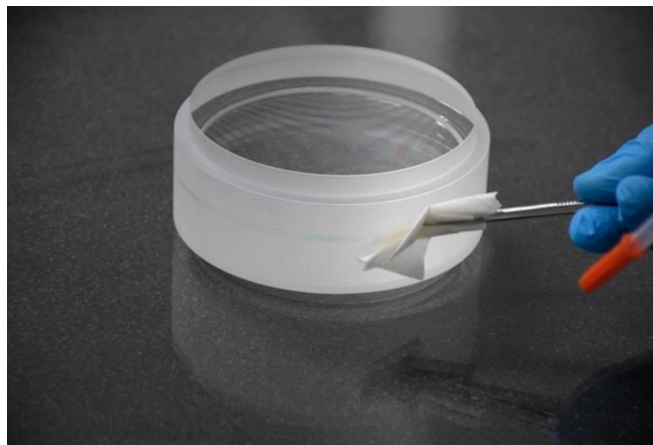


Figure 3. Camera lenses. From top to bottom: CAM-S5 (CaF<sub>2</sub>), CAM-S6 (S-LAH55) and CAM-S7 (S-NBH8).

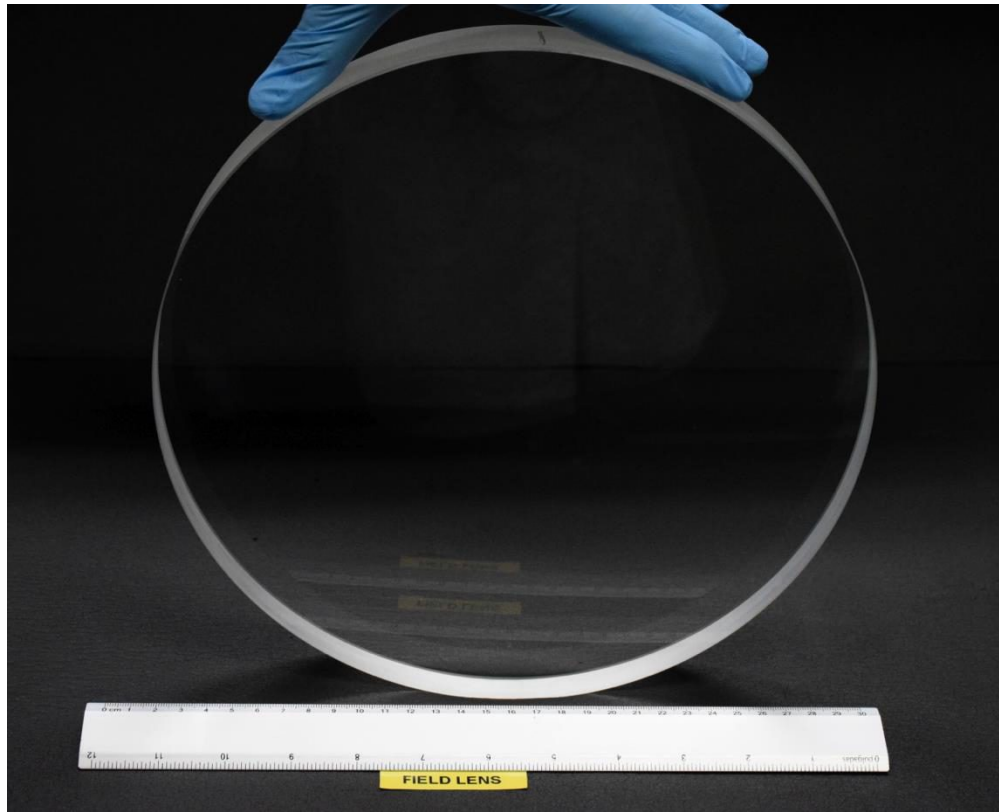


Figure 4. Field lens. Ohara SK1300 (fused Silica). 274 mm diameter.

## 2. CONCLUSIONS

MEGARA collimator and camera lenses and the field lens - manufactured at INAOE and CIO -except for the aspheric- comply the specifications. There are 9 different materials with individual complexity regarding polishing and testing. From Ohara, SK1300, PBM2Y, BSM51Y, PBM8Y, BSM51Y, BALY15Y, S-LAH55V, S-NBH8 and Hellma CaF<sub>2</sub>. The largest diameter is 270 mm while the smallest is 110 mm. The doublets were cemented at INAOE. The individual elements- doublets and singlets- were mounted in their corresponding cells and integrated in the barrels. The collimator and camera were tested at a subsystem level. Both fulfil the requirements. MEGARA is in the acceptance, integration and verification process at Universidad Complutense de Madrid. The laboratory acceptance is scheduled for September 2016 and the delivery to the observatory for December 2016.

## REFERENCES

- [1] Gil de Paz, A., et al. "MEGARA, the new intermediate-resolution optical IFU and MOS for GTC: getting ready for the telescope". Proc. SPIE, this volume. (2016).
- [2] Ferrusca, D., et al., "Integration and characterization of the cryogenic system of MEGARA", Proc. of SPIE, this volume (2016).

- [3] Iglesias-Páramo, J., et al., "The MEGARA fiber MOS positioning tool", Proc. of SPIE, this volume (2016).
- [4] Gómez-Álvarez, P., et al., "MEGARA fiber MOS assignment tool (FMAT)", Proc. of SPIE, this volume (2016).
- [5] Castillo-Morales, A., et al., "MEGARA exposure time calculator", Proc. of SPIE, this volume (2016).
- [6] Lefort, B., et al., "MEGARA control system", Proc. of SPIE, this volume (2016).
- [7] Maldonado, M., et al., "MEGARA spectrograph mechanics and opto-mechanics in the AIV phase", Proc. of SPIE, this volume (2016).
- [8] Izazaga-Pérez, R., et al., "Polishing techniques for MEGARA optics", Proc. of SPIE, volume 9912 (2016)
- [9] Martínez-Delgado, I., et al., "The large MEGARA pupil elements: assembly, tests, and performance", Proc. of SPIE, this volume (2016)
- [10] Pérez-Calpena, A., et al., "MEGARA: high-precision alignment system for gluing fibers and microlenses", Proc. of SPIE, this volume (2016).
- [11] Ortiz, R., et al., "Design and testing of AR coatings for MEGARA optics", Proc. of SPIE, this volume (2016).