

Design and testing of AR coatings for MEGARA optics

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ABSTRACT

We present the antireflection coatings of the optical elements of MEGARA, the new integral field and multi-object spectrograph for the Gran Telescopio Canarias. We describe the methodology for optimizing the solutions. We also present the results of the final deposited coatings. The main optics require broadband coatings in the range from 370 nm to 980 nm for different materials with a mean $R < 1.3\%$ at specific angles of incidence in each surface. For each material a specific arrangement of thicknesses of the same eight layers were produced and tested. For the spectrograph pupil elements four layer coatings were designed and produced $R < 0.3\%$. The design of main optics and pupil elements coatings have been shared between INAOE and CIO. The coating depositions have been performed at CIO in the Integrity 39 Denton Vacuum Deposition System. The main optics final coatings fulfill MEGARA requirements.

Keywords: antireflection coatings, optical design, thin films, optical testing, broadband coatings, MEGARA, GTC

1. INTRODUCTION

MEGARA^{1, 2, 3} (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 operation in La Palma (Spain). It has been developed under a contract with GRANTECAN. The MEGARA Consortium is led by Universidad Complutense de Madrid and has as co-partners the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE, Mexico), the Instituto de Astrofísica de Andalucía (IAA-CSIC, Spain) and the Universidad Politécnica de Madrid (UPM, Spain).

The instrument has an IFUs plus a MOS mode: a large compact bundle covering 12.5 arcsec x 11.3 arcsec on sky with 100 μm fiber-core; a fiber MOS positioner that allows to place up to 100 mini-bundles, 7 fibers each, with 100 μm fiber-core, within a 3.5 arcmin x 3.5 arcmin field of view, around the IFU. The fibers, organized in bundles, end in the pseudo-slit plate located at the entrance of MEGARA spectrograph. The collimator and camera optics and optomechanics are finished and delivered to UCM where the instrument integration is in progress.

In this work we present the results of the depositions of the AR coatings of the main optics elements. Throughput requirements are essential in any optical system, especially for astronomy. These are the considerations used for the throughput budget as we have divided the contributors to the GTC + MEGARA Throughput budget in the following parts:

- GTC optical mirror (reflectivity as in GTC documentation).
- MEGARA Folded-Cassegrain subsystems, which include all MEGARA subsystems from Field lens to the fiber exit at the spectrograph entrance.
- MEGARA spectrograph common optical path subsystems, which include the collimator plus camera optics spectrograph and the detector.
- MEGARA gratings, which provides the values for all Low-Resolution (LR), Medium-Resolution (MR) and High-Resolution (HR) gratings.

AR coatings are included in the MEGARA spectrograph common optical path subsystems and are the focus of this manuscript. At this time INAOE has finished the construction of the collimator and camera optics and the windows. The prisms manufacturing is in progress. The remaining coatings will be carried out at CIO.

2. OPTICAL DESIGN AND TRANSMISSION REQUIREMENTS

MEGARA optical system design consists of:

- a pseudo-slit, which has 119mm of length, and is composed by an arrangement of optical fibers. It is curved on a sphere surface of a radii of curvature (ROC) of 1075mm;
- the collimator, which is composed by one single and two double lenses, its focal length is 484.4 mm (at 632.8nm) and its f-number is 3.03. The optical elements of the collimator are presented in table 2. The only aspheric that is used is the COLL-S1;
- 18 high performance VPH gratings, which main characteristics are shown in table 1;
- the camera, composed by two doublets and three singlets with a total focal length of 245.9mm (average paraxial value) and f-number of 1.54. The last lens is the cryostat window and the image field is 61.4mm x 61.4mm;
- and the 4k x 4k pixel EV CCD detector.

The shutter and the cut-order filters are placed in the collimator barrel. Detailed information of the design requirements and as-built characteristics of the spectrograph are available in other publications^{4, 5, 6, 7}.

Figure 1 shows the component distribution of MEGARA along with the materials and diameters of each lens.

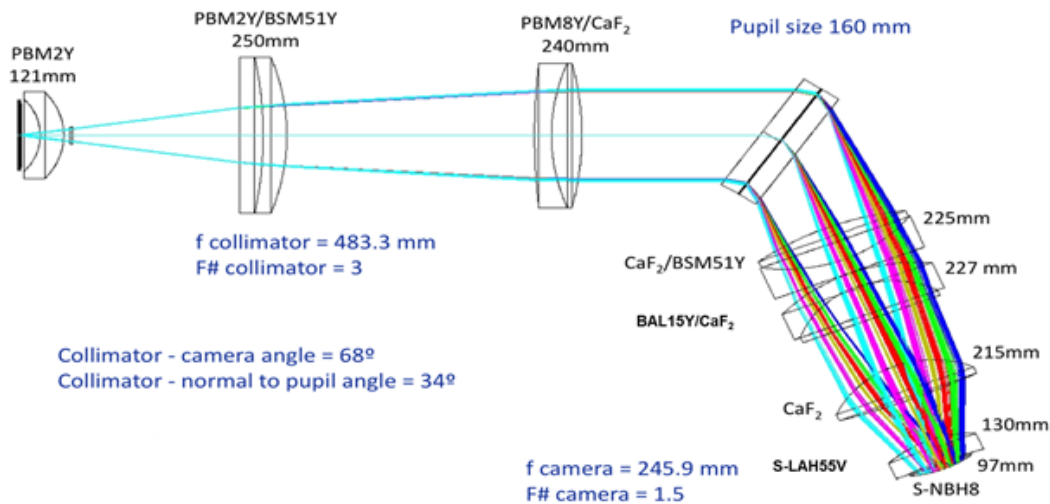


Figure 1. MEGARA optic system layout.

MEGARA offers resolutions of $R_{FWHM} \sim 6,000$, 12,000 and 18,700, respectively for the low-, mid- and high-resolution Volume Phase Holographic (VPH) gratings. The complete list of MEGARA gratings¹ is given in table 1.

As a high-level requirement, it has been defined that the total MEGARA throughput, considering fiber link and spectrograph, should be better than 30% at the central wavelength of the VPH675-LR i.e. low-resolution grating working in the red; $\sim 670\text{nm}$. This requirement is for the instrument only i.e. without including the GTC.

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

Table 1. MEGARA Baseline gratings. 18 configurations for several spectral ranges.

Table 2 summarizes the throughput expectations for the spectrograph common optical path only. This estimation includes the following contributors:

- Main Optics, which is composed by the collimator and the camera. We have assumed 1.5% Fresnel losses per glass/air interfaces and this implies that this is a worse case. INAOE and CIO provided coatings better than 1.3%.
- Detector includes the Quantum efficiency of the CCD231-E74 (Astro multi-2 AR coating) as provided by e2V.

The column Spectrograph main optical path summarizes the spectrograph transmission taken into account the previous two contributors.

MEGARA main optics require broadband AR coatings in the wavelength range from 370 to 980nm with $R < 1.3\%$. The AR coatings have been optimized for a different mean AOI for each surface. Table 3 gives an overview of the whole system and the requirements for each main optics element.

MEGARA pupil elements wavelength range transmission is defined by the different spectral configurations: six for LR, ten for MR and two for HR. The specification for these elements is $R < 0.3\%$ for the mean AOI that is different for each subgroup (LR, MR and HR). Table 4 provides a summary of all the pupil elements to be coated and their specific AOI and spectral ranges.

MEGARA spectrograph main optical path

λ (nm)	Main Optics	Detector	Main optical path
365	0.126	0.650	0.082
370	0.184	0.700	0.129
380	0.317	0.800	0.254
390	0.430	0.850	0.366
405	0.534	0.910	0.486
410	0.556	0.920	0.512
440	0.637	0.910	0.580
480	0.695	0.900	0.626
500	0.721	0.890	0.642
520	0.732	0.880	0.644
550	0.749	0.890	0.667
570	0.749	0.890	0.667
600	0.749	0.900	0.674
620	0.750	0.910	0.683
665	0.751	0.920	0.691
675	0.751	0.925	0.695
700	0.752	0.930	0.699
715	0.753	0.930	0.700
750	0.755	0.930	0.702
775	0.755	0.900	0.680
800	0.755	0.880	0.664
825	0.755	0.850	0.642
850	0.755	0.800	0.604
865	0.754	0.720	0.543
900	0.750	0.600	0.450
925	0.747	0.575	0.430
940	0.746	0.400	0.298
980	0.742	0.200	0.148

Table 2. MEGARA Spectrograph main optical path throughput budget. We include the contributions from main optics and detector.

Main Optics AR Coatings

Element	Substrate	Left surface (S1)	Mean AOI (deg)	R (%)	Right Surface (S2)	Mean AOI (deg)	R (%)	# of designs
Field Lens	Fused Silica	Wide AR coating 370-980 nm	2	R < 1.3 %	Wide AR coating 370-980 nm	2.8	R < 1.3 %	2
	(SK1300)							
	ne=1.46058							
COLL-S1	PBM2Y		21.2			17.1		2
	nd= 1.62004							
COLL-D2	PBM2Y	4.9	No coating			1		
	nd= 1.62004							
COLL-D3	BSM51Y	No coating			Wide AR coating 370-980 nm	8.5	R < 1.3 %	1
	nd=1.60311							
COLL-D4	PBM8Y	Wide AR coating 370-980 nm	4.5	R < 1.3 %	No coating			1
	nd=1.59551							
COLL-D5	CaF2	No coating			Wide AR coating 370-980 nm	7.3	R < 1.3 %	1
	nd=1.43384							
CAM-D1	CaF2	Wide AR coating 370-980 nm	10.8	R < 1.3 %	No coating			1
	nd=1.43384							
CAM-D2	BSM51Y	No coating			Wide AR coating 370-980 nm	5.8	R < 1.3 %	1
	nd=1.60311							
CAM-D3	BAL15Y	Wide AR coating 370-980 nm	13	R < 1.3 %	No coating			1
	nd=1.55671							
CAM-D4	CaF2	No coating			Wide AR coating 370-980 nm	5.6	R < 1.3 %	1
	nd=1.43384							
CAM-S5	CaF2	Wide AR coating 370-980 nm	18.5	R < 1.3 %		12		2
	nd=1.43384							
CAM-S6	S-LAH55V		9.3			11.7		2
	nd=1.83481							
CAM-S7	S-NBH8		20.3			14.8		2
	nd=1.72047							

Table 3. Summary of the main optics AR coatings designed for MEGARA.

Windows and Prisms AR Coatings

Element	Substrate	Surface AR Width	Mean AOI (deg)	R (%)
(LR-U) windows (2)	Fused Silica (SK1300) ne=1.46058	360 nm - 445 nm	34	R < 0.3 %
(LR-B) windows (2)		390 nm - 570 nm		
(LR-V) windows (2)		470 nm - 620 nm		
(LR-R) windows (2)		550 nm - 780 nm		
(LR-I) windows (2)		670 nm - 920 nm		
(LR-Z) windows (2)		750 nm - 990 nm		
(MR-U) prisms (2)	PMB2Y nd= 1.62004	380 nm - 440 nm	10.5	
(MR-UB) prisms (2)		410 nm - 480 nm		
(MR-B) prisms (2)		440 nm - 520 nm		
(MR-G) prisms (2)		480 nm - 560 nm		
(MR-V) prisms (2)		520 nm - 610 nm		
(MR-VR) prisms (2)		570 nm - 660 nm		
(MR-R) prisms (2)		610 nm - 700 nm		
(MR-RI) prisms (2)		660 nm - 760 nm		
(MR-I) prisms (2)		720 nm - 830 nm		
(MR-Z) prism (2)		860 nm - 980 nm		
(HR-R) prisms (2)		630 nm - 700 nm	34	
(HR-I) prisms (2)		820 nm - 900 nm		

Table 4. Summary of the pupil elements AR coatings designed for MEGARA.

3. ANTIREFLECTIVE COATINGS DESIGN

Antireflection coatings can range from a simple single layer having virtually zero reflectance at just one wavelength, to a multilayer system of more than a dozen layers, having virtually zero reflectance over a range of several octaves.

In the case of the main optics a wide spectral region needs to be covered, thus the apparent dispersion of the equivalent periods may cause trouble. This dispersion can be reduced by using equivalent periods of one-eighth-wave thickness instead of quarter-wave. Each quarter wave in the original design is then replaced by two periods in series. This adds considerably the number of layers.⁸

The MEGARA main optics AR designed coatings consist in eight layers of three different materials to fulfill the requirements of transmission in the wavelength range at the AOI presented in table 3.

The range of the AR for the pupil elements is considerably narrower compared to that of the main optics, thus the requirements are more demanding, to fulfill these, several four layer designs were produced and optimized for each spectral band presented in table 4.

Theoretical designs were achieved through different methods^{9, 10} based on the materials available for the deposition. Then an optimization of the design is implemented defining the targets of reflection and the mean AOI of each optical element.

A Damped Least-Square algorithm was used for optimization with iterations varying from 100 to 200. Specialized software was used and due to the wide range of wavelengths in the main optics, dispersion of the materials to be deposited in the substrate was acknowledged.

A total of 18 designs were developed for the main optics and another 18 for the pupil elements including LR windows and MR – HR prisms.

4. ANTIREFLECTIVE COATINGS TESTING RESULTS

After the fabrication of each of the optical elements, the deposition of the coating materials was made in the Integrity 39 Denton Vacuum Deposition System located at CIO, León, Guanajuato and the transmission of the coating on a witness was measured in an Agilent Cary-5000-UV-Vis-NIR® spectrophotometer.

Several witness samples of each substrate were polished and coated to make the transmission measurements prior and during the final deposition. Three transmission measurements were carried for each one and the average was computed. To extract the transmission of the coated surface of the witness from the measurement, the procedure was the following:

1. A simulation of the substrates was made, in Zemax, emulating a witness with an ideally perfect AR where the transmission is 99.99%.
2. Theoretical values of the total transmission are obtained.
3. Fresnel losses on the uncoated surface of the sample and absorption losses of the substrate from the measurement were eliminated dividing by the theoretical transmission of the witness sample.

In cases when the $\text{AOI} \geq 10^\circ$ the measurement could not be taken directly at the angle specified. To sort out this limitation, the measurements of transmission of the witnesses were taken at normal incidence and then extrapolated to the designated AOI of each element using the method described below:

- i. Theoretical transmission functions of the coating at normal incidence and at the mean AOI were produced aided by optical software.
- ii. A coefficient function was achieved by dividing the transmission function at the mean AOI by that at normal incidence.
- iii. The transmission of the witness sample was measured at normal incidence using the Cary-5000 spectrophotometer at CIO.
- iv. The witness sample transmission at the mean AOI was inferred from the experimental data measured at normal incidence, applying the coefficients obtained in (ii).
- v. The effects of absorption and the reflections in the uncoated side of the sample were eliminated using the method described above, steps 1- 3.

In the following figures we present the performance results of the current coated elements of the main optics.

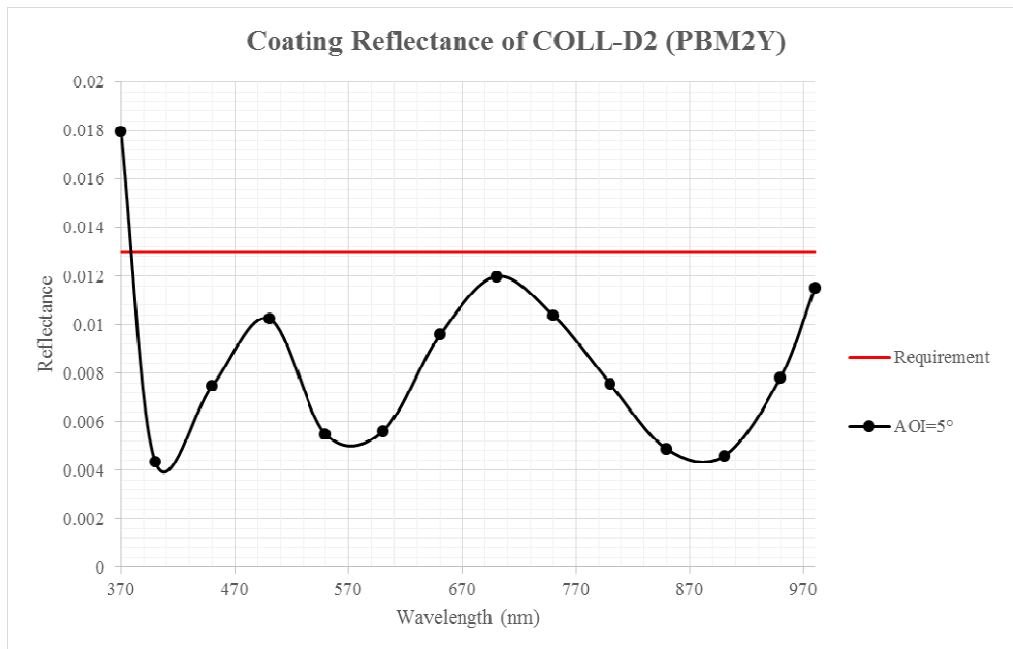


Figure 2. Performance of the AR coating in PBM2Y substrate at incidence of 5°.

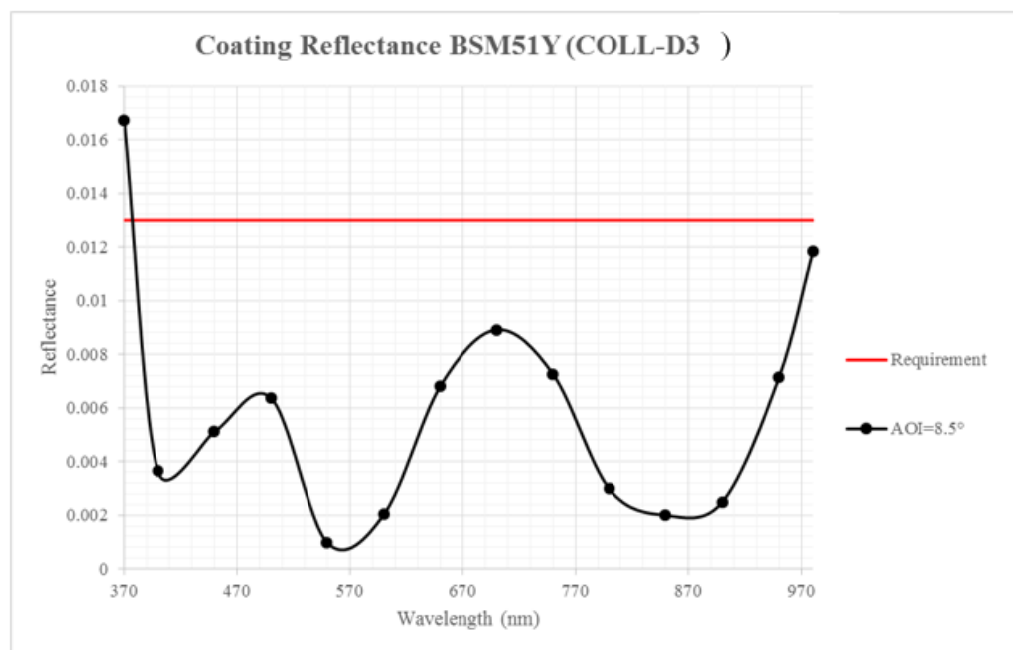


Figure 3. Performance of the AR coating in BSM51Y substrate at incidence of 9°.

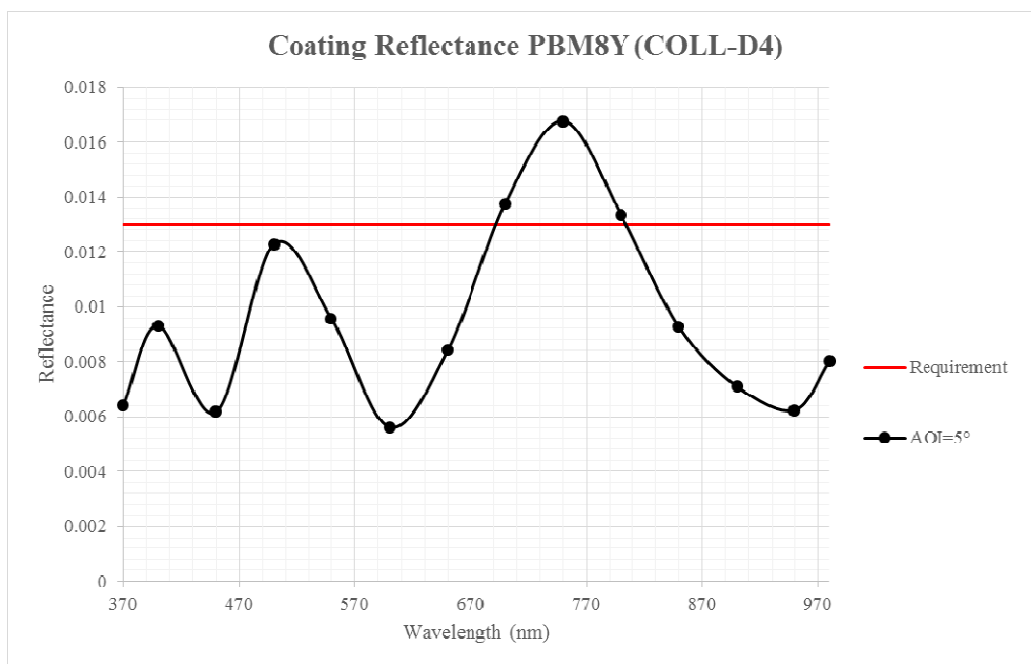


Figure 4. Performance of the AR coating in PBM8Y substrate at incidence of 5° .

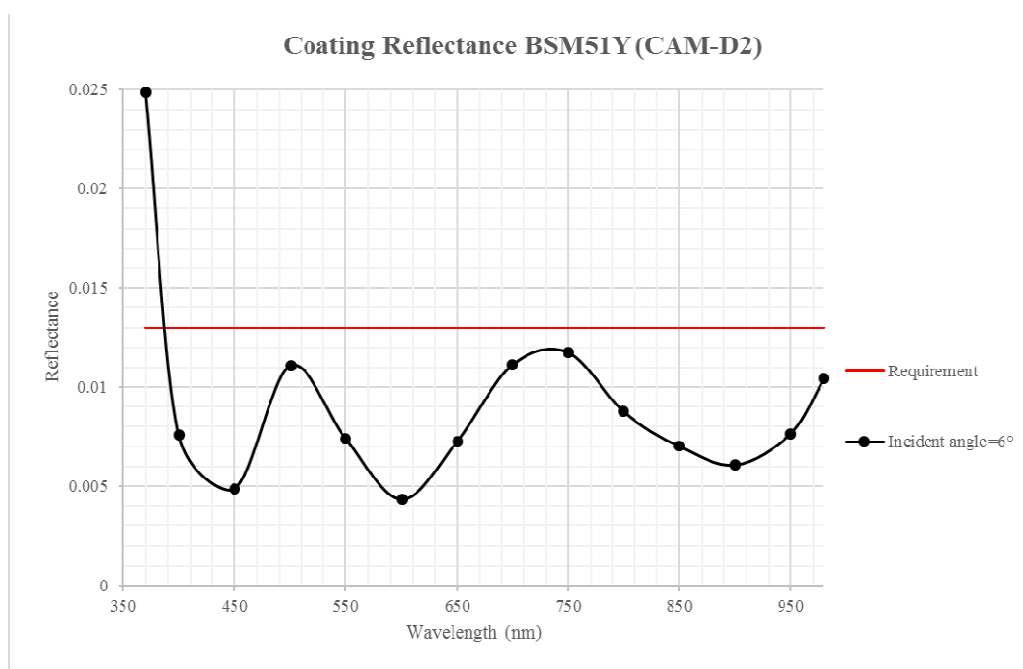


Figure 5. Performance of the AR coating in BSM51Y substrate at incidence of 6° .

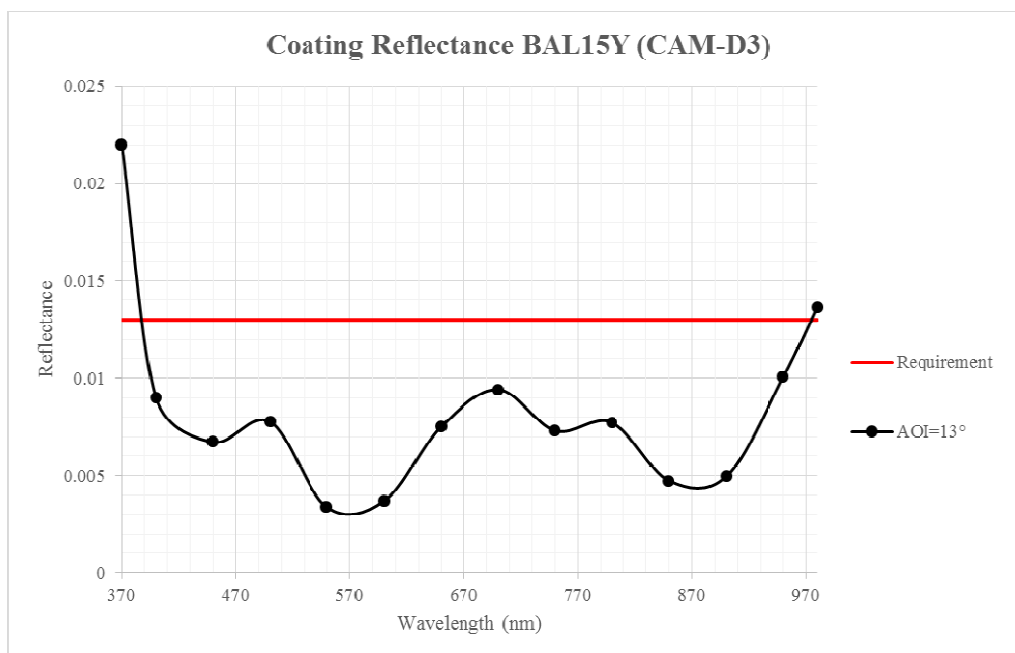


Figure 6. Performance of the AR coating in BAL15Y substrate at incidence of 13°.

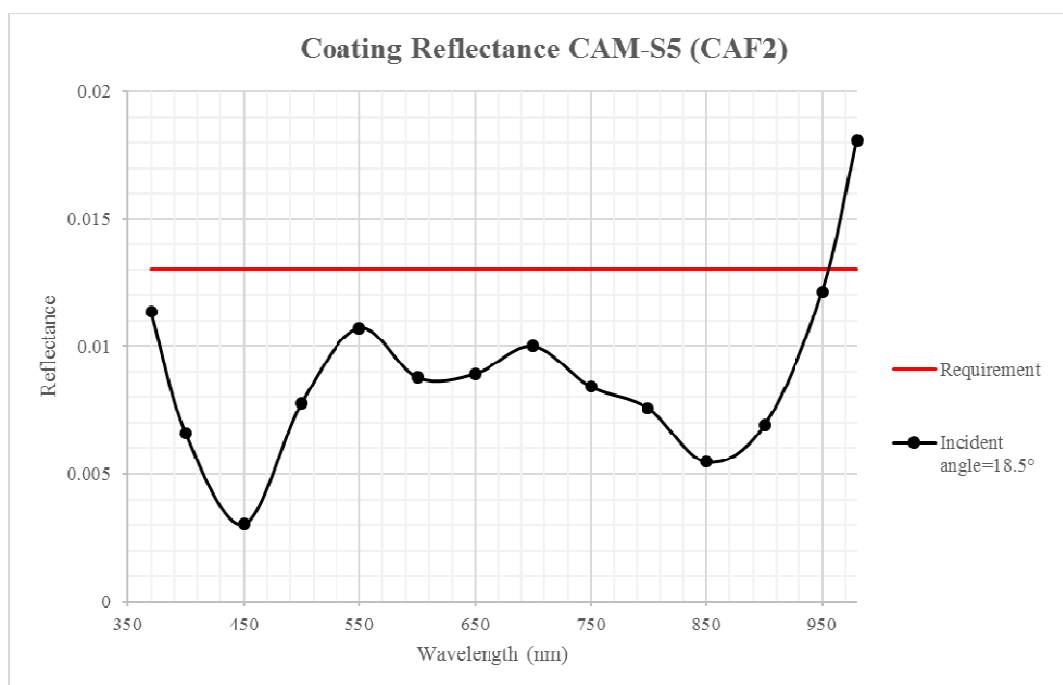


Figure 7. Performance of the AR coating in CAF2 substrate at incidence of 18.5°.

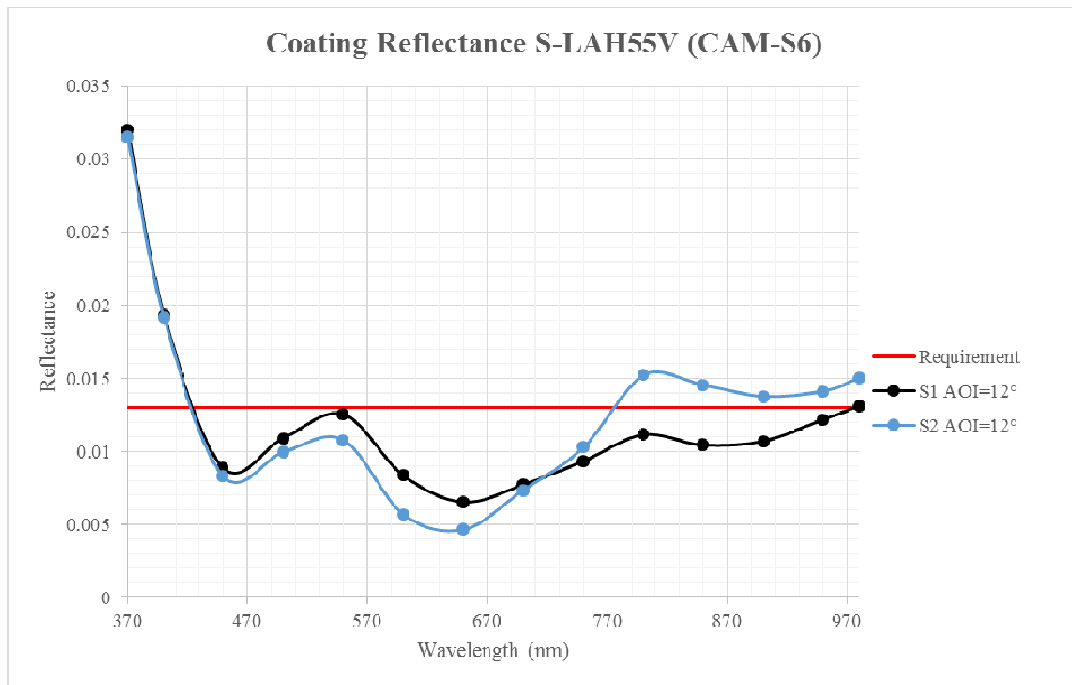


Figure 8. Performance of the AR coating in S-LAH55V substrate at incidence of 12°. Both surfaces of CAM-S6 are presented.

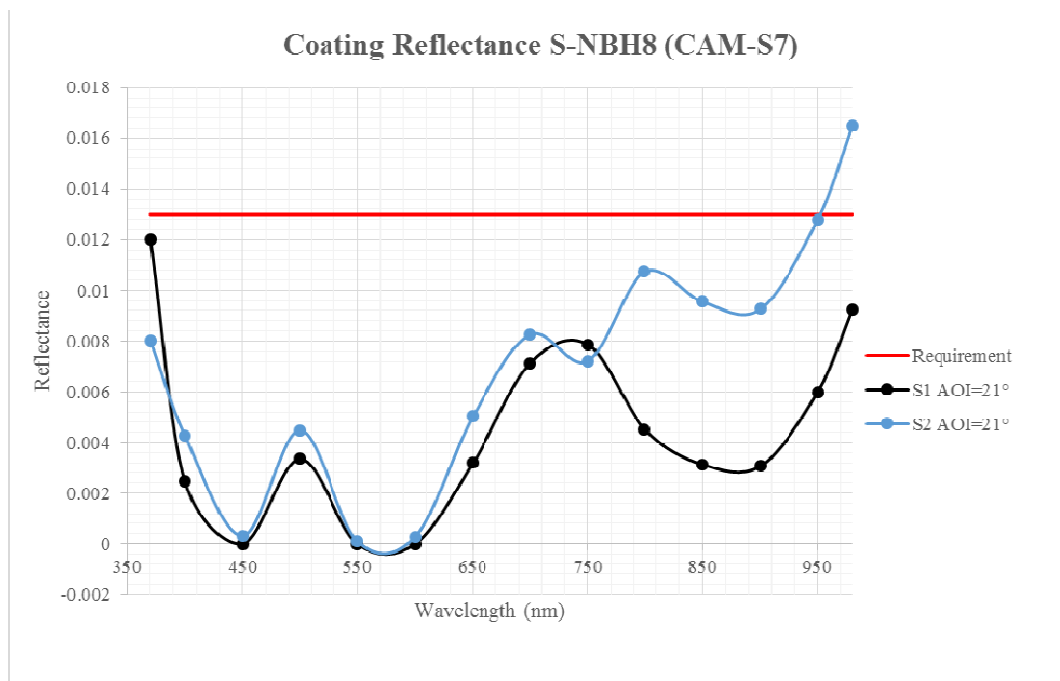


Figure 9. Performance of the AR coating in S-NBH8 substrate at incidence of 21°. Both surfaces of CAM-S7 are presented.

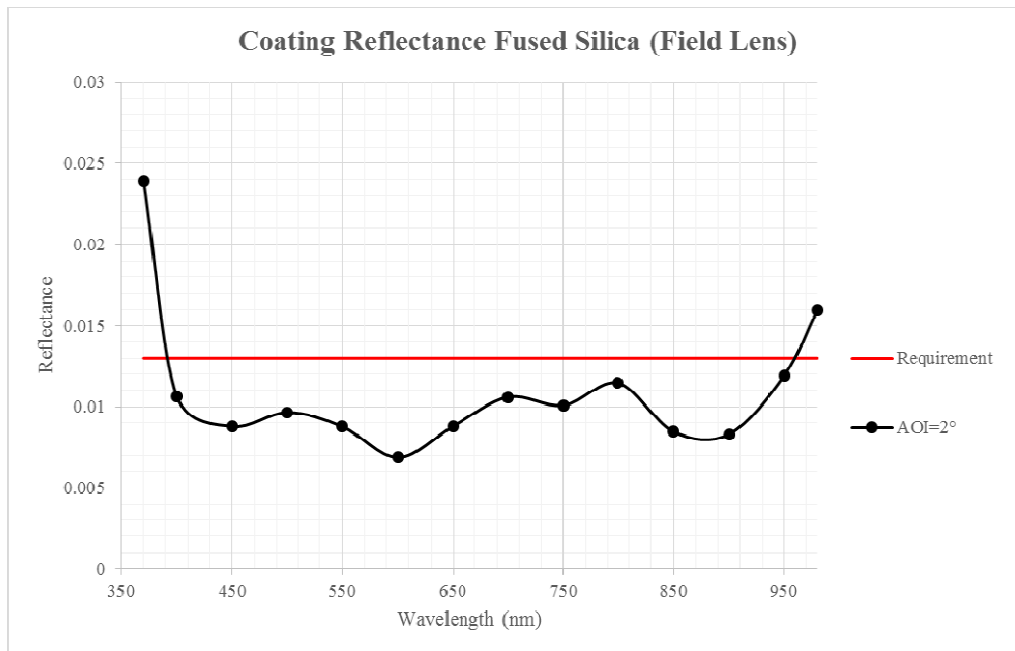


Figure 10. Performance of the AR coating in Fused Silica substrate at incidence of 2°.

Coated Element	Average Reflectance
Field Lens	0.011
COLL-S1 S1*	0.013
COLL-S1 S2*	0.013
COLL-D2	0.009
COLL-D3	0.006
COLL-D4	0.009
CAM-D2	0.009
CAM-D3	0.008
CAM-S5 S1	0.009
CAM-S5 S2	0.009
CAM-S6 S1	0.012
CAM-S6 S2	0.013
CAM-S7 S1	0.004
CAM S7 S2	0.007
AVERAGE TOTAL LOSS	0.124

Table 5. Average reflectance of main optics coated elements including the total loss due to the main optics. *Estimated values.

All AR coatings of the main optics fulfill the requirement of average reflectance ≤ 0.013 maintaining stability throughout the spectral range as can be seen in table 5 and figures 2 to 10. The total average loss of the main optics is estimated in 0.124 this gives a total average throughput of 0.876. Compared to the average values in table 2 where the average total throughput is 0.659 there is an improvement of 33%.

Currently the pupil elements are being coated, the windows for LR configurations are already finished and their average reflectance is shown in table 5. It can be noticed that the requirement of average reflectance ≤ 0.003 is not completely fulfilled. Such small values of reflectance are more complicated to measure and several times they are within the error of the measurement instrument. Thus, the decision was made to go on with these depositions as they do not affect substantially the overall performance of the spectrograph.

Coated Element	Average Reflectance
LR-U	0.005
LR-B	0.009
LR-V	0.004
LR-R	0.004
LR-Z	0.003

Table 6. Average reflectance of LR coated windows.

5. CONCLUSIONS AND FURTHER WORK

Currently all the main optic elements from the collimator and the camera have been built, coated and delivered to UCM., The LR windows are already coated and delivered. The HR windows have been delivered. Thirty out thirty six MR windows have been finished and delivered. The MR prisms manufacturing is in progress, AR coating designs have been developed and are now being tested.

The broad band AR designs of the main optics have been effectively tested using a method of analysis to remove Fresnel effects. Transmission data obtained at normal incidence were extrapolated to other AOIs. In most of the spectral bands the AR coatings exceed the performance requirements.

We present the global average transmission of the spectrograph and compared with the expected one. The spectrograph global transmission is better by 33% than the requirement. Therefore, MEGARA spectrograph throughput will be the best in a 10m telescope.

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