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ANTIREFLECTIVE COATINGS FOR THE RED CAMERA OF WEAVE SPECTROGRAPH

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ABSTRACT

In this work we present the coatings of the spectrograph red camera of WEAVE -the new multi-object survey facility for the 4.2m William Herschel Telescope. The initial requirements of WEAVE red camera lenses, with reflectances as low as 0.4% through the wavelength interval from 590 nm to 959 nm at angles of incidence of 18° +/- 17° represented a challenge for both design and production. Based on initial requirements, several solutions to the same problem were achieved and tested. The customized designs have been continuously improved through theoretical and experimental approximations. From transmittance measurements at normal incidence we developed a method to determine the reflectance at different angles of incidence. We show the designs and coating transmittance obtained for the four glasses on test runs to guarantee that the designs were achievable experimentally. Additionally, we present the reflectance obtained on the lenses of the the first four lenses of WEAVE red camera.

Keywords: Antireflective coatings, spectrographs

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1. INTRODUCTION

WEAVE, acronyms of WHT Enhanced Area Velocity Explorer, is the new prime focus survey facility for the 4.2m WHT. In Dalton et al. [1] [2] an extensive description of the whole instrument is presented. A fibre positioning system will distribute along the 2°diameter field of view almost ~1000 objects simultaneously, 20 small integral field units (IFUs) of 11" x 12" (1.3" spaxels) each or a large IFU that covers a 1.3' x 1.5' (2.6" spaxels) field of view. WEAVE spectrograph will offer spectral resolutions R~5800 in the wavelength interval of 366 - 959 nm and high resolution R~21000 in the ranges 404 - 465 nm, 473 - 545 nm and 595 - 685 nm. The spectrograph is formed by a collimator mirror, a dichroic that directs the light to a blue and a red camera. The dispersive elements are volume phase holographic gratings. The 8 lenses of the cameras are identical except for the coatings optimized for the 366 to 606 nm and 579 - 959 nm wavelength intervals respectively. The first lens is an aspheric while the other seven are spheric, all of them of large aperture, with diameters between 195mm to 320 mm, and high optical accuracy. The spectrograph optical design was carried out at RALSpace. The spectrograph mechanical structure is in progress at NOVA. The 660 mm diameter mirror and the 14 spherical lenses of both cameras are being manufactured at INAOE in Mexico. In Izazaga et al. [3][4] detailed descriptions of the collimator and camera lenses manufacturing process are described. Here we discuss the design of the antireflective (AR) coatings to fulfill the requirements. The coating designs and deposition processes were carried out in a collaborative squeme between INAOE and CIO. INAOE provided the designs and discuss the expected performance with the CIO team as the depositions were carried out at their lab.

1.1 AR coating specifications

The antireflective coating specification was: Reflectance $R_{average} < 0.3\%$ (goal 0.2%), $R_{absolute} < 0.4\%$ (0.3) for an angle of incidence (AOI) between 0 and 35°, for a wavelength interval between 366 and 606 nm and 5790 to 9590 nm for the blue and red cameras respectively.

The optical quality requirements of the WEAVE spherical camera lenses are described in Izazaga et al. [2] and Hidalgo et al. [5]. In Table 1 the lenses main characteristics relevant to the coatings are presented. The largest diameter is 320 mm where the AR coatings must fulfill the requirements in Reflectance and adherence. For each camera, the coating designs where developed for four substrates: PBL1Y, S-FPL51, PBM2Y and SLAL-9.

Table 1. WEAVE camera lenses main characteristics.

Camera	Material	Units (mm)	Left Surf.		Right Surf.		Weight
Blue / Red	Ohara	Edge Ø	Coated Ø	C.A. Ø	Coated Ø	C. A. Ø	(kg)
Lens 2	PBL1Y	304	298	288.4	301.0	294.4	7.7
Lens 3	S-FPL51	320	316	306.3	313.0	302.5	10.2
Lens 4	PBL1Y	320	310	299.8	292.0	282.4	14.4
Lens 5	S-FPL51	298	296	288.4	296.0	288.2	8.8
Lens 6	PBM2Y	260	255	245.4	234.0	224.0	13.1
Lens 7	PBM2Y	238	222	212.3	182.0	172.4	13.0
Lens 8	S-LAL9	195	172	162.3	168.6	162.6	3.0

The main characteristics of these materials according to Ohara catalogue related to the coating design and deposition are shown in Table 2. The transmission properties of the coating depend mainly of the glass refractive index, the refractive index of the coating layers, the layers thickness and of the angle of incidence of the light into optical surface. The coatings are designed to produce that the relative phase change between the reflective beam in the border of the layer is 180°. When this condition is fulfilled destructive interference is produced between the two reflected beams before reaching the interface between the two mediums. There are single layer or multilayer AR coating that provide a very high efficiency in a reduced wavelength interval and AOI. The real challenge is to have high efficiency for a wide wavelength interval for a large range of AOI.

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In the AR coating design there is always a trade-off between the number of layers, the AOI and the wavelength interval. Several possible solutions were studied.

Table 2. Main properties of the glasses of WEAVE camera lenses relevant to the coatings.

	S-FPL51	**S-LAL9**	**PBL1Y**	**PBM2Y**	**Properties**
Nd	1.497	1.691	1.548	1.620	Index of refraction
CTE (10^{-7}/ºC)					Linear coefficients of thermal expansion
-30~+70ºC	131	61	93	86	
100~+300ºC	155	74	106	97	

1.2 AR coating AOI specification

A detailed analysis was carried out regarding the AOI specification of the cameras coatings. Based in Zemax ray tracing, RAL Space provided histograms of the AOI of different rays at each interface air/glass for the spherical camera lenses. Based on these histograms an statistics analysis was carried out. The histograms are in Figure 1 and the statistics summary is shown in Table 3. Where: *Interval Max* is the highest bar on the histogram. Highest number of hits; *Average CV* is the average calculated by considering the central value of the bar rank. Hits have the central value; *Average Min* is the average calculated by considering the minimum value of the bar rank. Hits have the minimum value; *Average Max* is the average calculated by considering the maximum value of the bar rank. Hits have the maximum value; *Average* is the average of *Average CV*, *Average Min* and *Average Max*; and *SD* is the standard deviation of the average, not the sample.

Table 3. Histograms data of the number of rays that hit each surface of the camera lenses at different AOI intervals.

Element	Surface	# hits	Interval Max (°)	Average CV (°)	Average Min (°)	Average Max (°)	Average (°)	SD
Lens 2	**Right**	73660	21-24	18.0	16.5	19.5	18.0	1.5
	Left	72850	12-15	15.0	13.5	17.0	15.2	1.7
Lens 3	**Right**	72800	15-18	13.1	11.6	14.6	13.1	1.5
	Left	73900	12-15	14.7	13.2	16.2	14.7	1.5
Lens 4	**Right**	73600	12-15	17.0	15.5	20.9	17.8	2.8
	Left	73600	15-18	14.1	12.6	15.6	14.1	1.5
Lens 5	**Right**	72900	18-21	15.2	13.7	16.7	15.2	1.5
	Left	73050	12-15	14.6	13.1	16.4	14.7	1.6
Lens 6	**Left**	73100	6- 9	8.7	7.2	10.2	8.7	1.5
	Right	74250	15-18	16.2	14.7	17.7	16.2	1.5
Lens 7	**Right**	71950	12-15	11.7	10.2	13.2	11.7	1.5
	Left	72350	15-18	13.7	12.2	15.2	13.7	1.5
Lens 8	**Right**	72100	9-12	13.0	11.5	14.5	13.0	1.5
	Left	73650	12-15	15.6	14.1	17.2	15.7	1.5

Interval Max: highest bar on the histogram. Highest numer of hits.
Average CV: average calculated by considering the central value of the bar rank. Hits have the central value.
Average Min: average calculated by considering the minimum value of the bar rank. Hits have the minimum value.
Average Max: average calculated by considering the maximum value of the bar rank. Hits have the maximum value.
Average: average of Average CV, Average Min and Average Max
SD: Standard deviation of the average, not the sample.

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Figure 1. Histograms of number of rays hitting the indicated lens surface at different AOI bins.

From Table 3, it can be seen that there is a wide range of AOIs. The *Interval Max* values vary between 6° and 24°, the *Average CV* between 8.7° and 18°, *Average Min* between 7.2° and 16.5°, *Average Max* in 10.2° - 20.9°, *Average* values between 8.7 and 18°. However, looking at the histograms is clear that are less number of rays at angles larger that 21°. We decided to study the WEAVE case optimizing the coating between 0 and 20° and between 0° and 35°, but to analyze the coating performance at 0°, 10°, 20°, and 35° in both cases.

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2. DESIGNS

Several designs were developed and the advantages of each were evaluated. Here we report the designs chosen as the best option in terms of performance and manufacturing. The teams of INAOE and CIO collaborated very closely to achieve the best solutions. The designed presented here are based in five layers of three materials Ta2O5, SiO2 and MgF2.

2.1 FIVE LAYERS COATINGS Ta2O5, SiO2 and MgF2

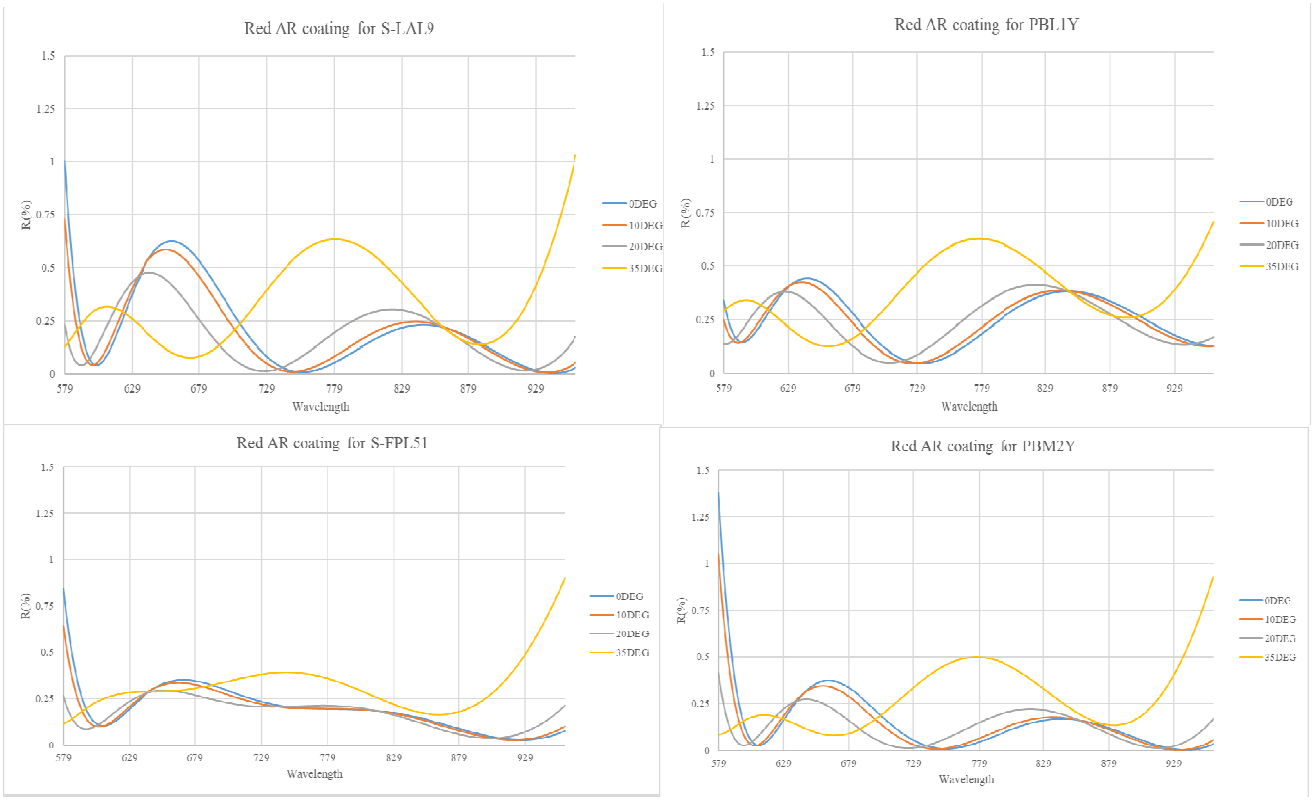


Figure 2. Reflectance for the four glasses of the red camera. Five-layers designs.

Table 4. Reflectance for different AOIs for the 5-layers coating designs.

AOI (°)	Reflectance (%) PBM2Y		S-LAL9		S-FPL51		PBL1Y	
	Ave	Max	Ave	Max	Ave	Max	Ave	Max
0	0.14	0.80	0.21	1.00	0.19	0.85	0.25	0.44
10	0.13	0.61	0.19	0.72	0.18	0.64	0.24	0.43
20	0.12	0.24	0.18	0.48	0.17	0.29	0.24	0.41
35	0.28	0.88	0.34	1.03	0.32	0.90	0.37	0.71

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2.2 SIX LAYERS COATINGS Ta2O5, SiO2 and MgF2

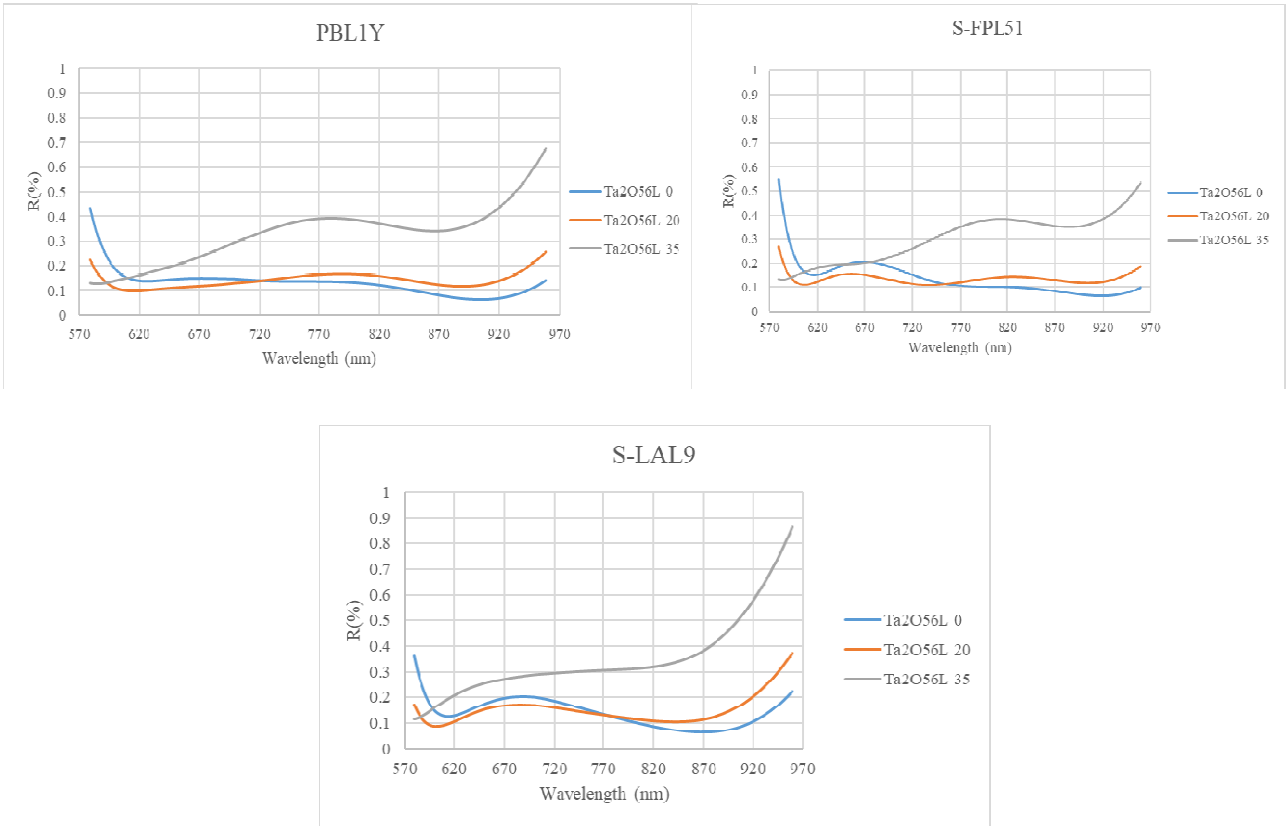


Figure 3. Reflectance of three glasses of the red camera. Six-layers designs.

Table 4. Reflectance for different AOIs for the 6-layers coating designs.

AOI (°)	Reflectance (%)					
	PBL1Y		S-FPL51		S-LAL9	
	Ave	Max	Ave	Max	Ave	Max
0	0.13	0.43	0.14	0.55	0.21	0.49
20	0.14	0.26	0.13	0.27	0.20	0.29
35	0.33	0.68	0.30	0.53	0.36	0.47

3. TEST RUNS DATA

The coating evaporations were performed at CIO in the Integrity 39 Denton Vacuum Deposition System. In all the depositions at least a witness samples is included to evaluate the coating quality by measuring afterwards the transmittance of the sample(s). The instrument used for this measurement is a spectrophotometer UV-VIS Perkin-Elmer® Lambda 12, calibrated against patterns of the Mexican metrology entity CENAM. The spectrophotometer is at CIO metrology laboratory. Here we present the Reflectance derived from the transmittance measurement for witness samples of the same camera glasses shown in Table 1 and 2. For each sample three transmittance measurements are performed and the average is used for the rest of the calculations.

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From the transmittance witness sample data, it is required to remove the Fresnel losses due to the interface glass/air of the uncoated surface and the absorption losses due to the thickness of the witness sample. The principle is the following: the actual thickness of a given sample is modelled in Zemax considering an ideal coating of 99.9% transmittance at an AOI of 0° on one surface and the other surface uncoated. Zemax provides values at specific wavelengths. The transmittance of the ideal coating is divided by the data measurements obtained at normal incidence. Once the mentioned effects are removed, the reflectance of the witness sample can be calculated as R = 1-T where T is the transmittance.

These calculations are straightforward if the measured transmittance is very close to the design one. In practice there are variations related to several parameters during the evaporation process resulting in difference between the thickness of the actual coating layers and the design.

To be able to calculate the reflectance at other AOI it is indispensable to find the design corresponding to the actual reflectance measured experimentally. A re-optimization through damped least squares of the design is done, using the experimental data as boundary to fit a theoretical model. In this way we can predict the actual coating behaviour at greater AOIs. This type of analysis aids also in estimating the error in the thickness of each layer, providing insight of the process of deposition itself.

3.1 Example of the data analysis

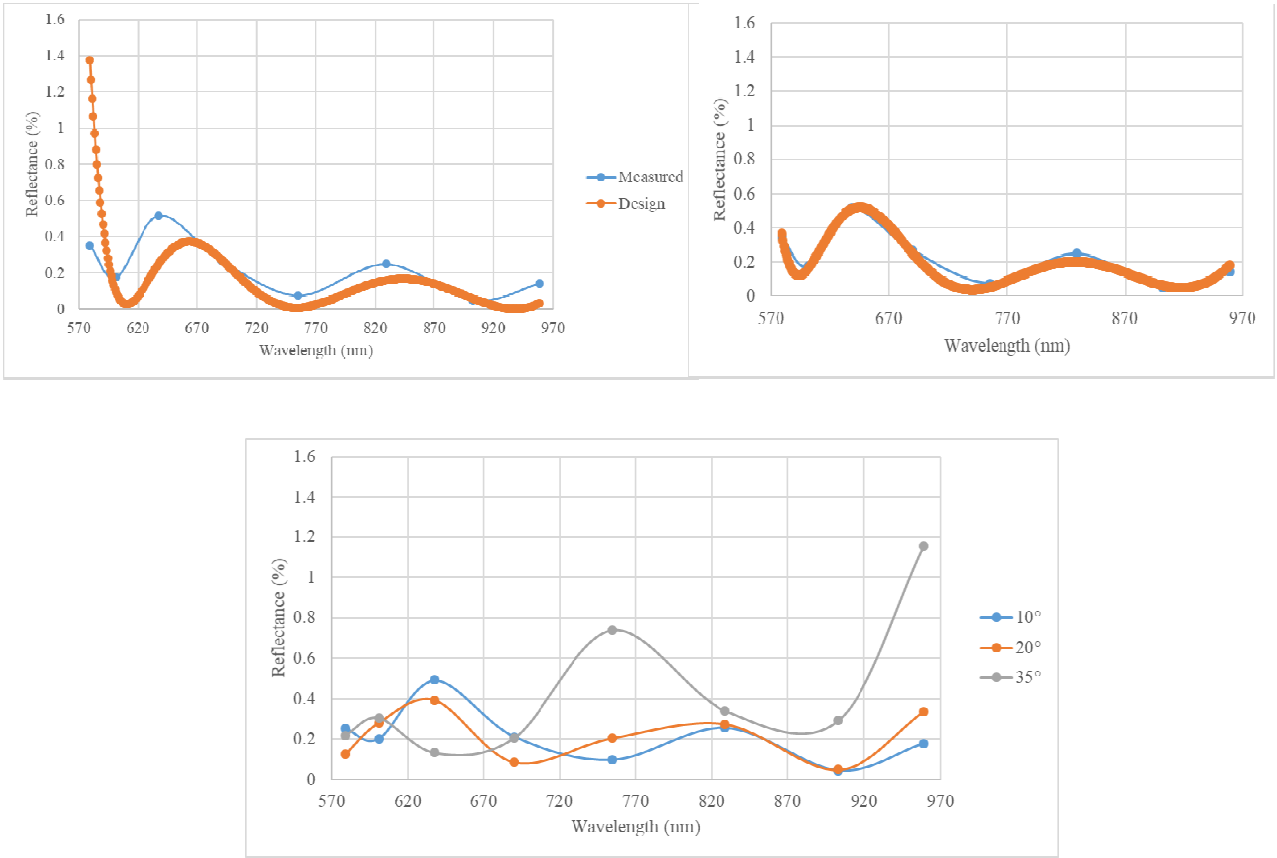


Figure 4. Top left: experimental data and theoretical reflectance, after removing Fresnel reflections from the second surface. Top right: Re-optimized design that fits the experimental data. Bottom: data extrapolation to non-normal AOI.

Figure 4 shows the data analysis process, the measurements of transmission are obtained experimentally, Fresnel effects are removed, the resulting curve is compared to the theoretical reflectance based on the AR design. The initial design is

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modified to match the experimental data by a re-optimization. Finally, the experimental data can be extrapolated to alternative AOIs based on the theoretical model.

3.2 REPEATIBILITY

CIO has worked intensively to characterize the Integrity 39 Denton Vacuum Deposition System. There are several factors. In Figure 5 we show the reflectance results for two PBM2Y witness samples in two different depositions for the same coating prescription. Samples L62 y L64 were coated in the first run and L63 y L65 in the second one. In Table 5 the average reflectance for different angles of incidence is reported. These results include all the experimental and measurements errors.

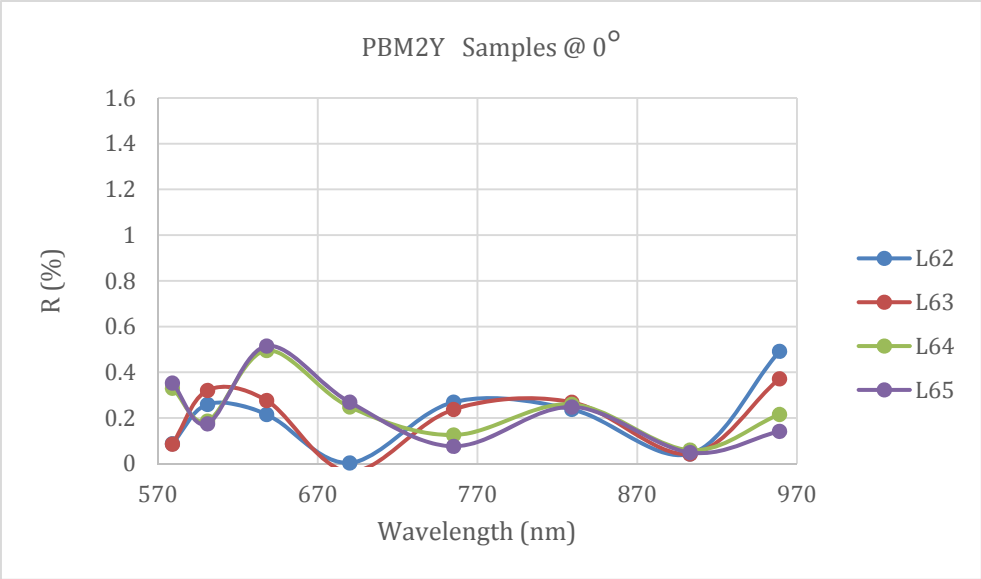


Figure 5. Reflectance obtained in different coating runs.

Table 5. Average reflectance obtained in two different runs for the same coating design.

Sample	Average R (%)			
	0°	10°	20°	35°
L62	0.20	0.21	0.26	0.56
L63	0.20	0.21	0.26	0.55
L64	0.24	0.23	0.24	0.47
L65	0.23	0.22	0.22	0.42

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4. FINAL COATINGS

4.1 LENS 6 AND LENS 7 (PBM2Y)

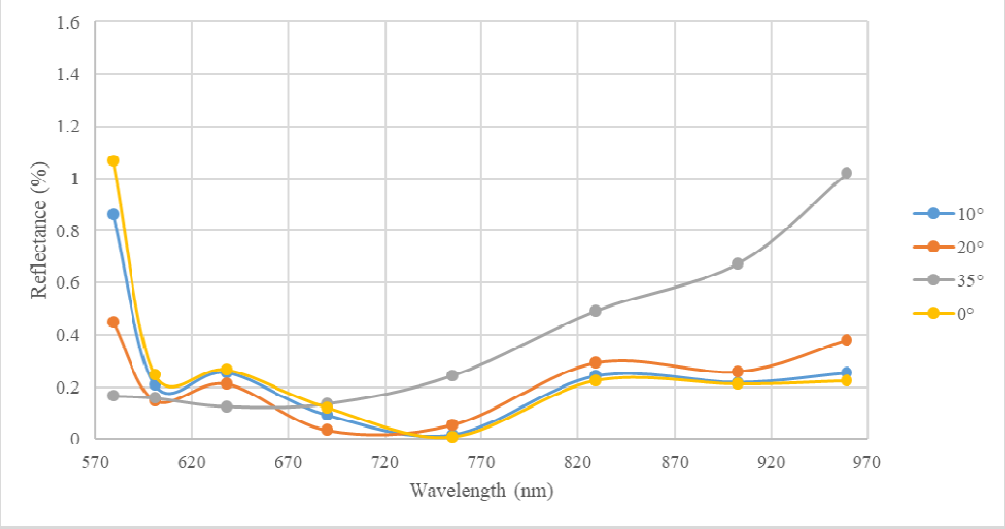


Figure 6. Reflectance obtained for PBM2Y Lens 6 and Lens 7. Surface 1.

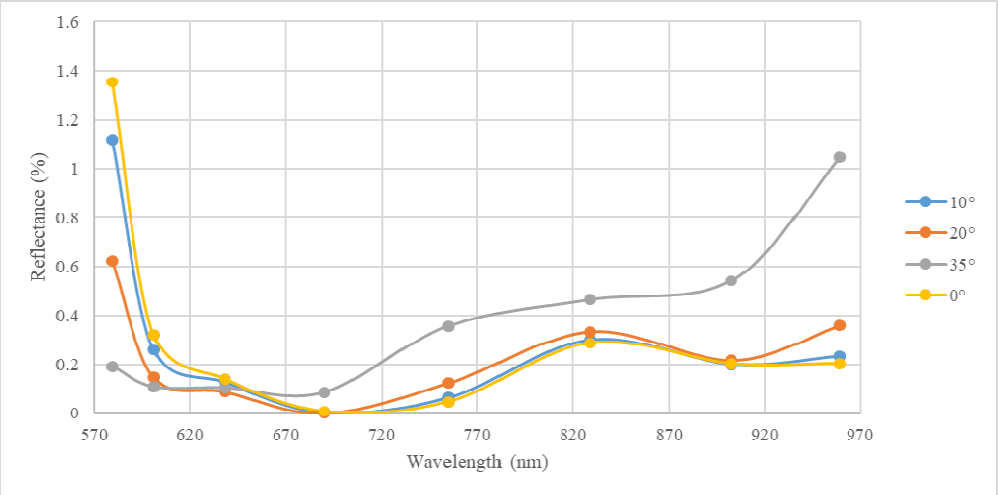


Figure 7. Reflectance obtained for PBM2Y Lens 6 and Lens 7. Surface 2.

Table 6. Average reflectance obtained for Lens 6 and Lens7.

	Reflectance (%)			
	Surface 1		Surface 2	
AOI	Ave	Max	Ave	Max
0	0.29	1.07	0.32	1.35
10	0.27	0.86	0.29	1.12
20	0.23	0.45	0.23	0.62
35	0.38	1.02	0.36	1.04

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4.2 LENS 4 (PBL1Y)

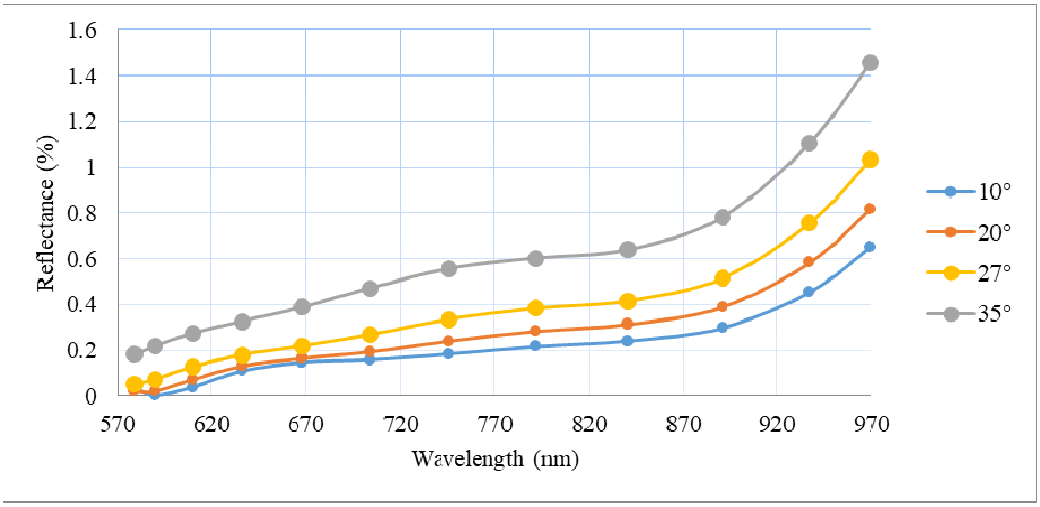


Figure 8. Reflectance obtained for PBL1Y Lens 4. Surface 1

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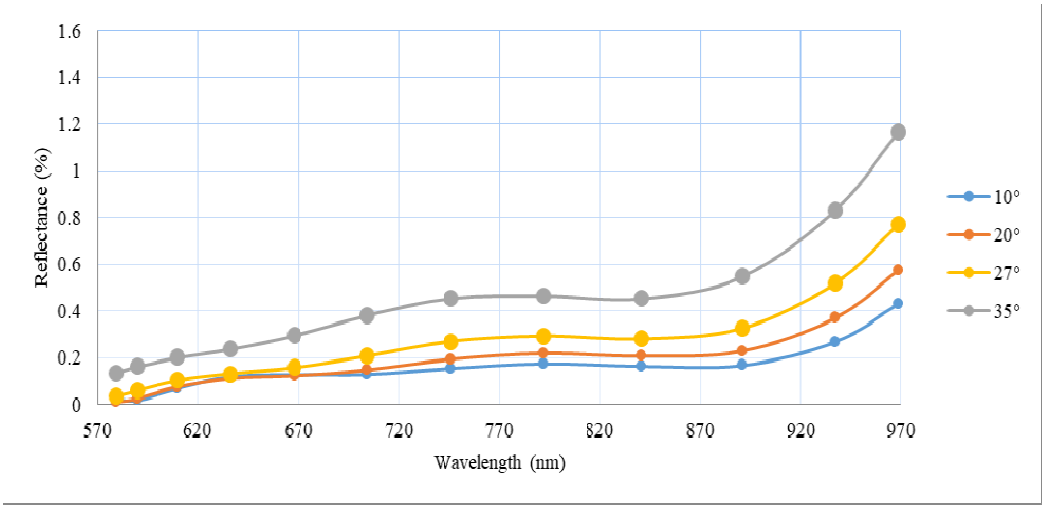


Figure 8. Reflectance obtained for PBL1Y Lens 4. Surface 2.

Table 7. Average reflectance obtained for Lens 4.

	Reflectance (%)			
	Surface 1		Surface 2	
AOI	Ave	Max	Ave	Max
10	0.21	0.65	0.15	0.43
20	0.27	0.82	0.19	0.57
27	0.36	1.03	0.26	0.77
35	0.58	1.45	0.44	1.17

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4.3 LENS 8 (SLAL-9)

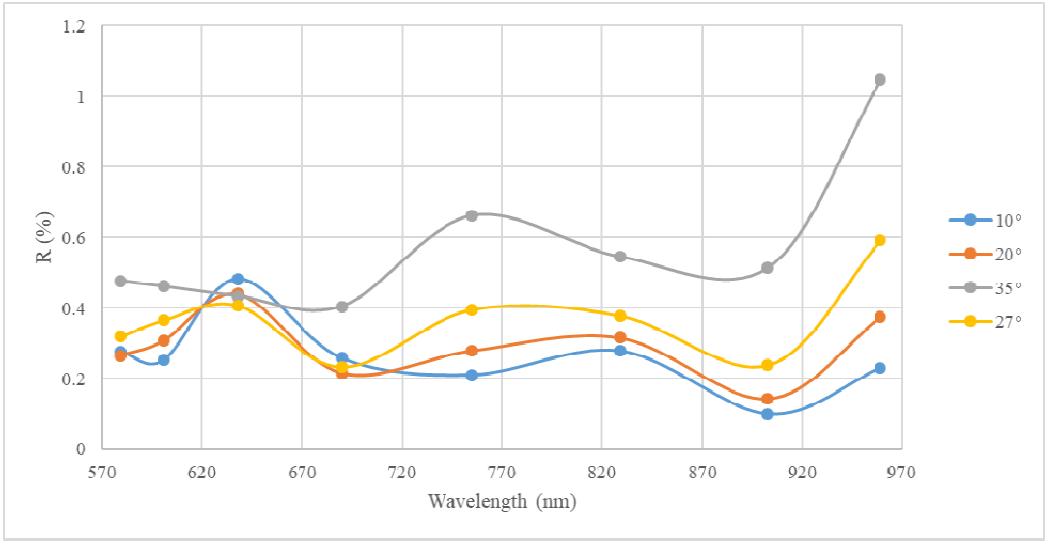


Figure 9. Reflectance obtained for SLAL-9 Lens 8. Surface 1.

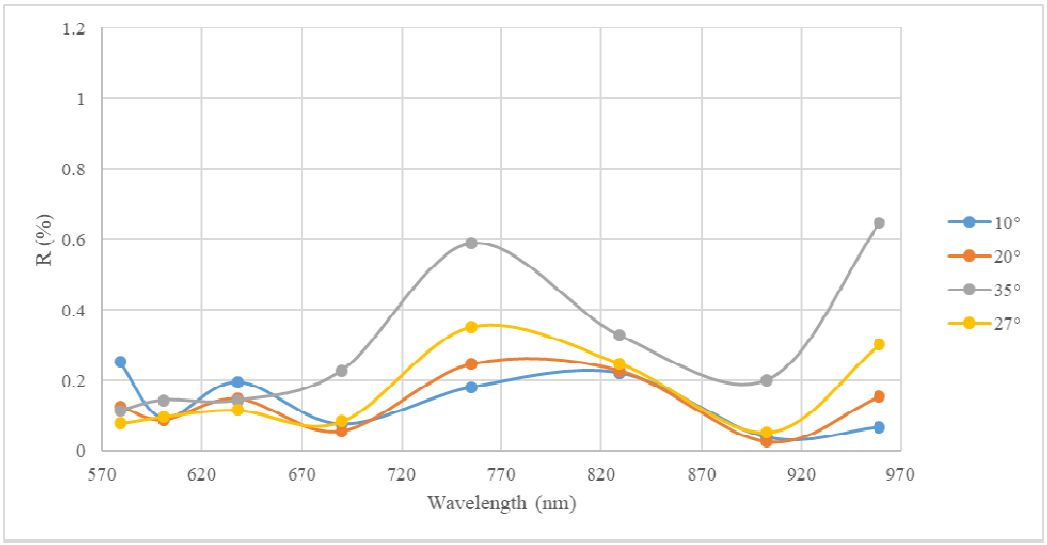


Figure 10. Reflectance obtained for SLAL-9 Lens 8. Surface 2.

Figure 5. Histograms of number of rays hitting the indicated lens surface at different AOI bins

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Table 8. Average reflectance obtained for Lens 8.

	Reflectance (%)			
	Surface 1		Surface 2	
AOI	Ave	Max	Ave	Max
10	0.26	0.50	0.15	0.32
20	0.26	0.48	0.14	0.25
27	0.29	0.44	0.13	0.25
35	0.57	1.05	0.30	0.65

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5. CONCLUSIONS AND FURTHER WORK

Great amount of R&D has been done in the determination of the most suitable material combination and optimal optical properties of AR coatings for the specific case of WEAVE. The requirements are large AOI and a medium size spectral range. Red Camera coatings are soon to be finished and the Blue Camera along with its AR coatings are under development.

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