Inverse analysis method to optimize the optic tolerances of MEGARA: the future IFU and multi-object spectrograph for GTC

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ABSTRACT

Optical tolerances are specified to achieve the desired performance of any optical system. Traditionally the diverse sets of tolerances of a system are proposed by the designer of each of the subsystems. In this work we propose a method to corroborate the design tolerances and simultaneously to provide extra data of each parameter to the manufacturer. It consists of an inverse analysis in which we fix a modified merit function as a constant and evaluate distinct models of perturbed lenses via Monte Carlo simulations, determining the best possible tolerance for each parameter, and indirectly providing information of sensitivity of the parameters. The method was used to carry out an extensive tolerance analysis of MEGARA, a multi-object spectrograph in development for the GTC. The key parameters of the optics are discussed, the overall performance is tested and diverse recommendations and adjustments to the design tolerances are made towards fabrication at INAOE and CIO in Mexico.

Keywords: tolerancing, inverse tolerance analysis, spectrograph optics, optic manufacturing, Monte Carlo, performance test, MEGARA, GTC

1. INTRODUCTION

MEGARA[1, 2] (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 detailed design, construction and assembly phases are now funded and the instrument should be delivered to GTC before the end of 2016. The MEGARA Consortium is led by Universidad Complutense de Madrid and has as co-partners the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE; Puebla, Mexico), the Instituto de Astrofísica de Andalucía and the Universidad Politécnica de Madrid. At this time INAOE is developing the collimator and camera optic elements and the prisms of the project in collaboration with the Centro de Investigaciones en Óptica (CIO).

The instrument offers two 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 small compact bundle, of 8.5 arcsec x 6.7 arcsec with 70 µm fiber-core and 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 two IFUs. The fibers, organized in bundles, end in the pseudo-slit plate, which will be placed at the entrance focal plane of the MEGARA spectrograph.

In this work we propose a method to corroborate the design tolerances and simultaneously to provide extra data of each parameter to the manufacturer. It consists of an inverse analysis in which we fix a modified merit function as a constant and evaluate distinct models of perturbed lenses via Monte Carlo simulations, determining the best possible tolerance for each parameter, and indirectly providing information of sensitivity of the parameters. The method was used to carry out an extensive analysis of MEGARA optics fabrication and AIV tolerances, comparing it with the traditional approach of direct tolerancing. Also, the introduction of the refractive index melt values for the different collimator and camera elements is acknowledged. A comparison between the performances of the optics with refractive index melt and catalog values of the materials was made.

Optical design and engineering are changing continuously, as optical software develops and the computational power improves, more complex systems can be studied. A critical step is bring to reality a design is the determination of feasible tolerances, making a trade of in terms of cost and performance.

If there is sufficient money and time, any grade of precision can be adquired[3]. Thus, the specifications should be determined in a dual basis: 1) the requirements of performances and 2) the cost in time and funds that is determined by the application. In the fabrication of telescope instruments the process is not for commercial purposes, it is a handmade product . Therefore, the tolerances play an even bigger role in projects of this kind.

2. OPTICAL DESIGN AND TOLERANCES

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 element;
- 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 **detector**.

The shutter and the filters will be placed in the collimator barrel. Detailed information of the design requirements and further characteristics of the spectrograph are available in other publications[4, 5].

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

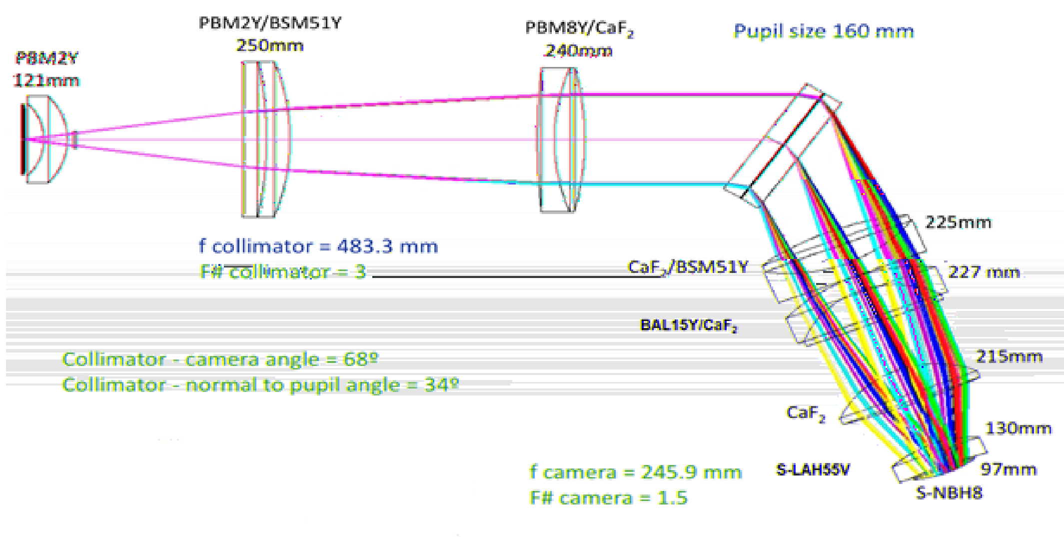

Figure 1. MEGARA optic system layout.

The spectral resolutions of MEGARA Baseline are R = 5,500 (in the whole range), R = 10,000 (in the whole optical range except the ranges covered by the high resolution gratings) and R = 17,000 in selected ranges defined by the Science Team. These values are referred to EED80. A maximum of 20% of different resolution is allowed due to the angle of 7.2º to see the whole camera. This margin depends on resolution and is well within the scientific requirement. The complete list of MEGARA gratings is given in table 1.

The design and the specifications and of each element of the collimator are shown in table 2, for the optic elements of the camera refer to the table 3. The parameters of design used for this analysis are expressed along with their tolerances.

VPH NAME	SETUP	R_{FWHM}	1- 2 Å	Å	Å	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.

COLLIMATOR OPTICAL ELEMENTS

ITEM	Material	R1 (mm)	R2 (mm)	Thickness	Wedge (arcmin)	Surf (fringes @ 0.632nm)	Index tolerance
COLL S-1	PBM2Y	-97.0 ± 0.1	-113.3 ± 0.1	35.00 ± 0.15	± 2	-	$\pm 2 \times 10^{-5}$
COLL D-2	PBM2Y	flat	-728.1 ± 1.0	35.00 ± 0.15	± 2	2	$\pm 2 \times 10^{-5}$
COLL D-3	BSM51Y	-728.1 ± 1	-398.8 ± 0.4	35.00 ± 0.15	± 2	2	$\pm 2 \times 10^{-5}$
COLL D-4	PBM8Y	1259.9 ± 2	344.5 ± 0.5	25.00 ± 0.15	± 2	2	$\pm 2 \times 10^{-5}$
COLL D-5	CaF_2	344.5± 0.5	-542.5 ± 0.5	45.00 ± 0.15	± 2	2	$\pm 1 \times 10^{-5}$

Table 2. Manufacturing parameters and their tolerances for the collimator (if the lens is a doublet is grouped with the same shadow).

CAMERA OPTICAL ELEMENTS

ITEM	Material	R1 (mm)	R2 (mm)	Thickness	Wedge (arcmin)	Surf (fringes @ 0.632nm)	Index tolerance
CAM D-1	CaF_2	435.9 ± 0.4	-231.7 ± 0.2	60.0 ± 0.1	± 2	2	$\pm 1 \times 10^{-5}$
CAM D-2	BSM51Y	-231.7 ± 0.2	Flat	25.0 ± 0.1	± 2	2	$\pm 2 \times 10^{-5}$
CAM D-3	BAL15Y	269.2 ± 0.2	145.1 ± 0.1	25.0 ± 0.1	± 2	2	$\pm 2 \times 10^{-5}$
CAM D-4	CaF_2	145.1 ± 0.1	Flat	60.0 ± 0.1	± 2	2	$\pm 1 \times 10^{-5}$
CAM S-5	CaF_2	156.0 ± 0.1	-1143.0 ± 0.8	62.0 ± 0.1	± 2	2	$\pm 1 \times 10^{-5}$
CAM S-6	S-LAH55V	176.4 ± 0.2	365.8 ± 0.3	40 ± 0.1	± 2	2	$\pm 2 \times 10^{-5}$
CAM S-7	S-NBH8	-162.5 ± 0.2	219.5 ± 0.2	30 ± 0.1	± 2	2	$\pm 2 \times 10^{-5}$

Table 3. Manufacturing parameters and their tolerances for the camera (if the lens is a doublet is grouped with the same shadow).

In the fabrication stages, the errors due to the singlet's manufacture are considered. The tolerance parameters are: radius of curvature, lens thickness, wedge as well as the aspheric parameters. Tables 2 and 3 provide manufacturing tolerances used to run the direct tolerance analysis.

The surface irregularity was calculated following the Zemax model that is giving in fringes the total irregularity at the maximum lens aperture and splits it between astigmatism and spherical at 50%. For all the cemented doublets only the external faces are considered, as the coupling materials makes the contribution to the wavefront error of these surfaces much smaller for the same quality.

In the present design the glue material, which is RTV141, of every doublet is acknowledged by considering a separation of 30 µm between each element.

Once the singlets are manufactured, the lenses are glued in doublets. The tilts or decentering in the glued cavities of the singlets were not considered as these have minimum effects on the performance with the used tolerances.

Notice that positioning errors in the barrel (along axis) are considered in the unknown errors.

The assembly, integration and verification (AIV) tolerances for these lenses and doublets within the barrel are shown in table 4 for the collimator and table 5 for the camera.

COLLIMATOR ASSEMBLY

BARREL	Tilt X (arcmin)	Tilt Y (arcmin)	Decenter X (mm)	Decenter Y (mm)
Singlet (aspheric), COLL-S1	± 2.1	± 2.1	± 0.3	± 0.3
Doublet 1, COLL-D2 /COLL-D3	± 2.1	± 2.1	± 0.3	± 0.3
Doublet 2, COLL-D4 /COLL-D5	± 2.1	± 2.1	± 0.3	± 0.3

Table 4. AIV tolerances for the collimator.

CAMERA ASSEMBLY

BARREL	Tilt X (arcmin)	Tilt Y (arcmin)	Decenter X (mm)	Decenter Y (mm)
Doublet 1, CAM-D1/CAM-D2	± 2.1	± 2.1	± 0.15	± 0.15
Doublet 2, CAM-D3/CAM-D4	± 2.1	± 2.1	± 0.15	± 0.15
Singlet 1, CAM-S5	± 2.1	± 2.1	Compensator	Compensator
Singlet 2, CAM-S6	± 2.1	± 2.1	± 0.15	± 0.15
Singlet 3, CAM-S7	± 2.1	± 2.1	± 0.15	± 0.15

Table 5. AIV tolerances for the camera.

The "unknown errors" are given by the measurement precision errors of the manufactured surfaces or values whose measurement is not foreseen at all. These errors cannot be compensated except with the final instrument focus. Tolerances are given in table 6. ROC and thickness measurement errors will be provided by CIO and INAOE when the optical elements are finished.

UNCOMPENSATED ERRORS

ITEM	MEGARA unknown tolerances (mm)
ROC measurement	± 0.02
Thickness measurement	± 0.01
Compensator decenter precision	± 0.005
Lens position in barrel	± 0.1

Table 6. Tolerances due to uncompensated errors.

3. IMAGE QUALITY

MEGARA performance has to be guaranteed after fabrication and assembly considering all the possible error sources. We analyze the error budget regarding image quality in at least the most demanding instrument modes in terms of image quality.

The image quality requirement is to have the resolution element in four pixels[6] (60 µm). The value that contains the 80% of the encircled energy coming from a fiber whose projection is 50µm is a diameter of 34.32 µm.

$$EE_{80} = 602 \quad 34.322 = 49.22$$

For this reason the total value of the EE_{80} through the optical system has to be lower or equal to 49.2 µm in diameter, or 24.6 µm (half of 49.2 µm) in radius. From the previous calculations the value of the requirement when analyzing the image performance will have a value of EER_{80} µm.

Figure 2 shows an example of a spot diagram in configuration LR-U it can be seen that the requirements of design are met, due to the fact that 80% of energy is within the circle of 50µm of diameter in the spectrum coverage.

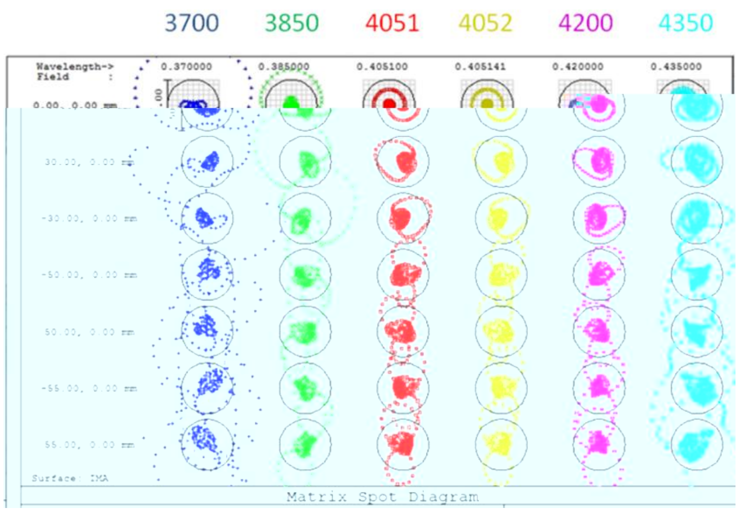

Figure 2. Spot diagram of the spectra from fibers at different positions of the pseudo-slit in the configuration of the grating VPH405-LR (LR-U). Different colors correspond to different wavelengths.

All possible errors in image quality shall amount a maximum degradation value of EED_{80} < 49.2µm. For optical analysis the evaluation of the total error will not be made in terms of EED_{80}, but in terms of RMS spot radius, and considering a 1D Gaussian profile in the spectral direction. Thus, in order to compute the total amount of degradation, we will translate the EED_{80}

Thus EED_{80} = 49.2 µm, will become EER_{80}=24.6 µm or

$$_{80} / 1.28 = 19.22 \ \mu m,$$

The total error is built by a number of contributors:

$$\sigma_{total}^2 = \sigma_{design}^2 + \sigma_{fabrication}^2 + \sigma_{alignment}^2 + \sigma_{thermal}^2 + \ldots$$

The error analysis has to include all these degradation contributors to image quality and the quadratic sum of all of them has to fulfill the requirement. In the following sections we will provide the analysis of tolerances of the fabrication and alignment and provide a table of results with all the possible contributors.

4. FITTING OF THE REFRACTIVE INDEX MELT VALUES

The refractive index melt values used to fit the dispersion curve of the materials were in these four lines: nC, nd, nF and ng. These index values were issued by the provider of the blanks to the MEGARA team and the precision of the measures goes as far as 1 x 10^{-5}. The optical software ZEMAX was used to do a polynomial fit with the real refractive indexes.

The problem with fitting melt data is the generally low number of points available; typically 3-5 (in this particular case we have 4). Most fitting routines need at least 8 points for good accuracy. So, the problem is to extrapolate from a few points the variation in index over a large enough number of points to fit the resulting dispersion accurately. The accuracy of the resulting melt fit at the defined data points depends largely upon the extent of the wavelength range.

ZEMAX does melt fitting using the following algorithm[7]:

First, a fit of the actual dispersion data is computed using the Conrady formula. The Conrady formula is used because it is stable and reasonable when as few as three points are defined.

$$n = n_0 + \frac{A}{\lambda} + \frac{B}{\lambda^{3.5}}$$

Then a Conrady fit of the nominal data is computed using only the defined wavelength points.

A large number of index points covering either the entire usable wavelength range of the nominal glass is generated. To each nominal index value, an offset is added which is the difference between the two Conrady fits that were generated using only the melt data wavelengths.

Finally, the resulting data is fit using the Schott formula.

$$n^2 = a_0 + a_1\lambda^2 + a_2\lambda^{-2} + a_3\lambda^{-4} + a_4\lambda^{-6} + a_5\lambda^{-8}$$

The real values of refractive index were within the tolerances of catalog (between ±3 x 10-4 and ±6 x 10-4) and proved to be quite good in terms that no lens had to be modified. The adjustment to the catalogue values of each material is stated in table 2.3. The index of the S-LAH55V glass stayed as in catalog due to its melt error being comparable to the polynomial fit error of the ZEMAX software.

Glass	Catalog Value (Nd)	Melt Value (Nd)	Difference
S-NBH8	1.72047	1.72064	1.7 x 10^{-4}
S-LAH55V	1.83481	No change	-
BAL15Y	1.55671	1.55674	3 x 10^{-5}
PBM8Y	1.59551	1.59567	1.6 x 10^{-4}
BSM51Y	1.60311	1.60334	2.3 x 10^{-4}
PBM2Y	1.62004	1.61997	-7 x 10^{-5}

Table 7. Comparison between the values of the refractive index of the different glasses of MEGARA.

It can be noticed that the worst departure from the nominal index is that of the BSM51Y, this type of glass is used in both the collimator and the camera, COLL-D3 and CAM-D2 respectively. The best melt is that of the glass S-LAH55V, this material is used in only one element of the camera, the CAM-S6, one of the most sensible elements of the whole system, we are assuring with this refractive index melt values that one of the worst behaving elements is under control.

The design had feedback from the data and a little change was made to optimize the performance: the distance from the last lens to the detector increased to 9.036mm. This corrected the reduced performance of the system due to melt errors

5. DIRECT TOLERANCE ANALYSIS

The errors associated to different tolerances were computed analytically or with MC models. In the case of these work we focus on the latter ones, Monte Carlo (MC) models a normal probabilistic distribution between the lower and upper limits was used and the associated error was considered at the 90% level of occurrences, thus the current analysis expect that 90% of the systems will be within the current expectations.

The first approach to the tolerancing of optical elements was to define feasible manufacturing and AIV tolerances as those in tables 2 to 5 and then MC analyses for each subsystem are computed, where a merit function (MF) is defined, in this case we take the RMS spot radius. The uncompensated errors are limitations that the design encounters when measurements of the parameters are made, so those of table 6 are fixed.

The nominal performance is obtained in two of the more sensible configurations of the instrument[8]. We have taken the VPH890-LR (LR-Z) with the following wavelengths and fields.

- Wavelengths (nm): 804, 850, 890, 930, 963.
- Fields (mm along the slit): -55, -30, 0, +30, +55 (90% of the useful pseudo-slit length)

And the VPH405-LR (LR-U) with the following wavelengths and same fields.

- Wavelengths (nm): 365, 385, 405, 420, 428.

A sensibility analysis of the design was made for the collimator and camera in order to identify the critical parameters. The model evaluates the image quality up to the focal plane position. From the sensitivity analysis the compensators for each unit were obtained and will be assembled independently. Here are some characteristics of the optical subsystems for the analysis:

- The pupil elements (spectral dispersers) will be accepted as individual units fulfilling their allocated image quality requirement.
- During the AIV process no compensators in the collimator will be used except the nominal focusing range after the assembly.
- CAM S5 decenter is defined as compensator and will be mounted in an individual sub-cell to allow positioning and centering of the barrel. In the camera AIV, S5 centering will be adjusted interferometrically.

5.1 Collimator fabrication tolerance analysis

The compensator for the collimator is the nominal focusing system at the pseudo-slit position.

The aspheric surface is tolerated for the aspheric coefficients in order to allow a maximum sag error at the lens edge of Note that this lens is very close to the focal plane, thus very small footprint is on the lens and relaxed specifications are possible. No interferometric testing is required for this surface (the aspherical departure is too large) and mechanical profilometry is enough for the considered error. Post-polishing will be applied in case CNC is used for the surface generation.

With LR-Z, 1000 MC simulations were run starting with a MF of 0.01023 mm rms. The 90% of the systems were below 0.01043 mm RMS, being the degradation 0.00203 mm RMS.

With LR-U, 1000 MC simulations were run starting with a MF of 0.00851 mm rms. The 90% of the systems were below 0.00871 mm RMS, being the degradation 0.00186 mm RMS.

Regarding collimator focusing compensator, the position range is lower than ± 1.2mm. In addition, we should add 0.5mm to compensate for order sorting focusing differences.

5.2 Camera fabrication tolerance analysis

The as-built data will be reported with the uncertainty of the measured values in order to compute the optimum position of CAM S-5 and focal position.

With LR-Z 1000 MC simulations were run starting with a MF of 0.00871 mm rms. The 90% of the systems were below 0.00994 mm RMS, being the degradation 0.00479 mm RMS.

With LR-U 100 MC simulations were run starting with a MF of 0.00714 mm rms. The 90% of the systems were below 0.00857 mm RMS, being the degradation 0.00474 mm RMS.

Regarding the CAM-S5 compensators we obtain these variations,

- decenter ranges < 0.25mm

- position range < ± 1.6mm
- And the focal position range < ± 0.11mm

5.3 Collimator AIV tolerance analysis

Tilts along X or Y axis are 2.1 arcmin, thus making, in the worst case, the total tilt to be 3 arcmin.

The collimators elements are not worst offenders in the system and some relaxation can be introduced without degradation, thus no problems are foreseen.

With LR-Z 1000 MC simulations were run starting with a MF of 0.01023 mm rms. The 90% of the systems were below 0.01044 mm RMS, being the degradation 0.00208 mm RMS.

With LR-U 1000 MC simulations were run starting with a MF of 0.00851 mm rms. The 90% of the systems were below 0.00874 mm RMS, being the degradation 0.00199 mm RMS.

Regarding the focus compensator the position range used is below ± 0.02mm.

5.4 Camera AIV tolerance analysis

The compensators for the camera are located in CAM-S5. Positioning of this element will be adjusted after manufacturing. The centering of CAM-S5 will be done with fine adjustment lateral screws with the camera under interferometric inspection to remove non-symmetrical aberrations on axis. In this case the total tilt of the elements is 3 arc minutes (decomposed in X and Y tilts).

With LR-Z 1000 MC simulations were run starting with a MF of 0.00963 mm rms. The 90% of the systems were below 0.01042 mm RMS, being the degradation 0.00398 mm RMS.

With LR-U 1000 MC simulations were run starting with a MF of 0.00834 mm rms. The 90% of the systems were below 0.00890 mm RMS, being the degradation 0.00311 mm RMS.

Regarding the CAM-S5 compensators, decentering ranges below 0.31mm in any axis (x-y).

The focusing range (at the collimator) is below ± 0.012mm.

5.5 Uncompensated errors

The compensator decentering tolerance is given by the positioning resolution that will be used to adjust CAM-S5. We are considering that this is the minimum centering precision that can be achieved.

With LR-Z 1000 MC simulations were run starting with a MF of 0.01023 mm rms. The 90% of the systems were below 0.01046 mm RMS, being the degradation 0.00218 mm RMS.

With LR-U 1000 MC simulations were run starting with a MF of 0.00851 mm rms. The 90% of the systems were below 0.00903 mm RMS, being the degradation 0.00302 mm RMS.

Regarding collimator focusing compensator, position range < ± 0.5mm.

6. INVERSE TOLERANCE ANALYSIS

Simulations of inverse tolerance adjustment were performed, defining a permissible increment in degradation, typically one order of magnitude less than the original value in the merit function (RMS Spot radius)[8, 9]. This analysis was done with the same configurations from the previous section, LR-Z and LR-U. To be able to guarantee the performance in any of these two configurations will suffice to make the other configurations meet the established requirements.

Since the direct tolerance analysis proved that the global performance of the system is almost the same considering the refractive index melt values, the inverse analysis of tolerances presented in this work is only of the system corrected by these melts.

This process consists in a fixation of the MF maximum increment, i.e. the permissible degradation per parameter to be toleranced, the computations are done in an iterative way where the variable are the tolerances *per se*. For the iterations to converge in the desired increment of MF, the criteria must change monotonically and softly with each variation of the tolerance parameter. For RMS spot radius, which is the criteria used in this work, this is commonly the case.

The results are presented in tables 9 through 16 in the next section where the direct analysis value of each tolerance is compared to the values obtained through the inverse analysis. In some cases the range of tolerance is not symmetric so the two extremes of the range are shown. The objective is to have more information about the behavior of the merit function in each parameter and the advantages of having refractive index melt values to feedback the optical system. The results of the inverse analysis are shaded in gray.

7. DISCUSSION OF RESULTS

7.1 Direct tolerance analysis

In table 8 a summary of the values of the global performance with catalog glasses and the addition of refractive melt values is presented to compare both performances of the spectrograph.

The performance in the two situations is almost the same, we have a variation of 0.3 µm maximum so we can conclude with these results that the correction of the distance to the detector from the last lens was able to mitigate the degradation introduced by the refractive index melt values and that any other modification to the design is unnecessary.

The real values of the indexes were close enough to their nominal values and they already were within the tolerances expressed in the R.3. Having the real values of one parameter allows us to have feedback on the design thus, we reduce the parameters to be toleranced and have more room for error in other parameters.

Item			**)**		**Comment**
	100µm fiber core **LR-Z catalog materials**	**100µm fiber core** **LR-Z with melt values**	**100µm fiber core** **LR-U catalog materials**	**100µm fiber core** **LR-U with melt values**	
Nominal performance	9.62	9.81	8.02	8.20	Nominal design in one representative mode
Collimator fabrication [a]	1.79	2.03	1.82	1.86	1000 Monte Carlo runs in normal distribution.
Camera fabrication [a]	5.01	4.79	4.53	4.74	1000 Monte Carlo runs in normal distribution.
Collimator AIV [b]	1.83	2.08	2.13	1.99	1000 Monte Carlo runs in normal distribution.
Camera AIV [b]	3.60	3.98	3.10	3.11	1000 Monte Carlo runs in normal distribution.
Uncompensated	2.29	2.18	2.44	3.02	1000 Monte Carlo runs in normal distribution.
Thermal	2.10	2.10	2.10	2.10	Worst case. Analytical model
Glass homogeneity	3.60	3.60	3.60	3.60	Analytical model
Pupil elements	5.00	5.00	5.00	5.00	Allocated Estimation
Detector Flatness	1.32	1.32	1.32	1.32	
Pseudo-slit curvature	3.20	3.20	3.20	3.20	
Atmospheric Effect	0.14	0.14	0.14	0.14	Performance Difference between 0.77 and 1atm
TOTAL (RMS squared)	14.03	14.23	12.76	13.05	**Target value: 19.22**

Table 8. Estimated values for the different Image Quality Error Budget contributors with melt and nominal refractive indexes of glass. [a] lens thickness, wedge, surface irregularity, curvature. [b] axial and lateral decenter, tilts.

7.2 Inverse tolerance analysis for LR-Z

For the manufacturing tolerances in the collimator it can be seen from table 9 that the tolerances could be loosened by several factors, which means that the current tolerances are trustworthy. They are feasible and relatively easy to achieve, this analysis proves that the collimator is not a critical factor on the performance of the spectrograph.

Reviewing the element COLL-D3 (BSM51Y) for which the difference between the refractive index melt and catalog values is larger we can see that there is not a substantial change in the resulting tolerances, this implies that the MF behaves in similar way, i.e. the greater the its value is, the tighter the values of tolerances are, as the error margins in both are equal we can imply an equal merit function behavior and thus good performance in this element.

MANUFACTURING ERRORS OF COLLIMATOR OPTICS								
ITEM	R1 (mm)		R2 (mm)		Thickness (mm)		Wedge (arcmin)	
	Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A.	Inverse A.
COLL S-1	-97.0 ± 0.1	-0.2 +0.12	-113.3 ± 0.1	-0.1 +0.2	35.00 ± 0.15	-0.11 +0.3	±2	-4 +2
COLL D-2	flat	-	-728.1 ± 1.0	±2	35.00 ± 0.15	±0.3	±2	±2.6
COLL D-3	-728.1 ± 1	±2	-398.8 ± 0.4	±0.8	35.00 ± 0.15	±0.3	±2	±4
COLL D-4	1259.9 ± 2	±4	344.5 ± 0.5	±0.8	25.00 ± 0.15	±0.3	±2	-2.9 +4
COLL D-5	344.5 ± 0.5	±0.8	-542.5 ± 0.5	±1.2	45.00 ± 0.15	±0.3	±2	-2.6 +3

Table 9. Comparison between direct and inverse analysis tolerances for the collimator using refractive index melt values.

In the camera manufacturing tolerances a misbehavior of the MF can be acknowledged a , as can be noticed in table 10. This due the fact that non-symmetric tolerance limits are set
of the camera are biased towards the positive range of the tolerance, meaning that the room for a permissible error in the negative range is diminished. An explanation of this phenomenon is proposed in the conclusions. Direct analysis tolerances appear not to be tight enough, but if we go over the other side of the tolerance range we can certainly see an increment in the positive range. So in the end, with direct analysis tolerances, as they are symmetric, these errors can compensate statistically.

If attention to CAM-D2 (PMB2Y) is given it can be seen that there is a difference of about 30% between the wedges. The reason for that is that the real refractive index being higher than the catalog one, then smaller perturbations in the angle of incidence create more degradation, yet the results are within the design tolerances, thus there is no concern in having problems with this lens.

It can be also noticed in table 10 that the two elements more sensible to the wedge parameter are CAM-S5 (CaF2) and CAM-S6 (S-LAH55V), i.e. this two elements are susceptible to change in the tolerance range due to a change of angle on the surface. The latter, despite having the real refractive index value closer to the catalog one, intrinsically generates more degradation towards the negative angles of wedge in its first surface in this configuration. A similar situation affect CAM-S5 but in its second surface. So we can deduce that between CAM-S5 and CAM-S6 the AIV must be crucial and that is the proven reason that CAM-S5 decenter is set as compensator to enhance image quality at each different configuration.

MANUFACTURING ERRORS OF CAMERA OPTICS								
ITEM	R1 (mm)		R2 (mm)		Thickness (mm)		Wedge (arcmin)	
	Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A.	Inverse A.
CAM D-1	435.9 ± 0.4	-0.22 +0.8	-231.7 ± 0.2	-0.06 +0.4	60.0 ± 0.1	±0.2	±2	±4
CAM D-2	-231.7 ± 0.2	-0.06 +0.4	Flat	-	25.0 ± 0.1	±0.2	±2	-1.8 +4
CAM D-3	269.2 ± 0.2	-0.03 +0.4	145.1 ± 0.1	-0.06 +0.2	25.0 ± 0.1	-0.2 +0.08	±2	±4
CAM D-4	145.1 ± 0.1	-0.06 +0.2	Flat	-	60.0 ± 0.1	±0.2	±2	-1.2 +4
CAM S-5	156.0 ± 0.1	-0.01 +0.2	-1143.0 ± 0.8	-2 +0.56	62.0 ± 0.1	-0.02 +0.2	±2	±4
CAM S-6	176.4 ± 0.2	-0.31 +0.4	365.8 ± 0.3	±0.6	40 ± 0.1	-0.02 +0.2	±2	-2.5 +0.7
CAM S-7	-162.5 ± 0.2	-0.07 +0.4	219.5 ± 0.2	±0.4	30 ± 0.1	-0.2 +0.02	±2	±4

Table 10. Comparison between direct and inverse analysis tolerances for the camera using refractive index melt values.

Looking at the table 11 it is noticed that regarding the collimator AIV there is no significant change between the results obtained in inverse tolerancing the most affected tolerance is in the second doublet, it appears that towards negative angle the tolerance range tightens. The problem seems to be COLL-D4 (PBM8Y) as COLL-D5 is made of CaF2 and the index in this crystal is always stable, yet if a comparison between these values and the direct tolerance is made, then the change is no more than 28% tighter in both cases. Eventually, the error is compensated with the positive side of the tolerance range when MC analyses are applied.

COLLIMATOR ASSEMBLY								
BARREL	Tilt X (arcmin)		Tilt Y (arcmin)		Decenter X (mm)		Decenter Y (mm)	
	Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A.	Inverse A.
COLL-S1 (Aspheric)	±2.1	±4.2	±2.1	±4.2	±0.3	±0.39	±0.3	-0.6 +0.3
COLL-D2/ COLL-D3	±2.1	±4.2	±2.1	±3.3	±0.3	±0.37	±0.3	±0.6
COLL-D4/ COLL-D5	±2.1	-1.5 +4.2	±2.1	±2.2	±0.3	±0.54	±0.3	-0.26 +0.6

Table 11. Comparison between direct and inverse analysis AIV tolerances for the collimator using refractive index melt values.

Some of the crucial parameters are in table 11 which contain the tolerances of AIV for the camera. As it can be seen the tilt on X and the decenter on Y. The element CAM-S5 maintains its sensitivity throughout the simulations, therefore a possible improvement should be to minimize the error in this parameter when the assembly is being done. In the Y axis appears to be more room for error in tilt, but not in decenter as in the system the positive range of tolerance drops to half in doublet CAM-D1 (CaF_2) / CAM-D2 (BSM51Y). We can associate this increase of sensitivity to the change in the refractive index and dispersion of the material in CAM-D2 as CAM-D1 is made of CaF_2 which is a crystal.

In CAM-S6 (S-LAH55V) the tolerance range of the decenter in Y also decreases but in the negative side. These is the effect of all the other refractive index melt values combined, as the melt value of this particular element is almost the same that the catalog one, and is comparable to the effect in the doublet CAM-D1 / CAM-D2.

CAMERA ASSEMBLY										
BARREL	Tilt X (arcmin)			Tilt Y (arcmin)		Decenter X (mm)		Decenter Y (mm)		
	Direct A.	Inverse A.		Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A:	Inverse A.	
CAM-D1 / CAM-D2	±2.1	±4.2		±2.1	±4.2	±0.15	±0.13	±0.15	-0.16	+0.06
CAM-D3 / CAM-D4	±2.1	-1	+2.7	±2.1	±2.6	±0.15	±0.3	±0.15	-0.3	+0.17
CAM-S5	±2.1	±0.8		±2.1	±2	Comp.	-	Comp.	-	
CAM-S6	±2.1	-4.2	+2.1	±2.1	±4.2	±0.15	±0.14	±0.15	-0.05	+0.18
CAM-S7	±2.1	-2.5	+4.2	±2.1	±4.2	±0.15	±0.16	±0.15	-0.15	+0.2

Table 12. Comparison between direct and inverse analysis AIV tolerances for the camera using refractive index catalog values.

7.3 Inverse tolerance analysis for LR-U

In table 13 it is shown that for the collimator the behavior of the fabrication tolerances and hence the MF in this configuration is very similar to that on the LR-Z and that the tolerances obtained with refractive index melt and catalog values are the same in almost all of the parameters. When not equal, the value is looser than the design tolerance (values in green).

For COLL-D2 (PBM2Y) we can see some bias in the wedge parameter towards positive angles, being the negative one tighter than the design tolerance. Despite that, these are feasible tolerances and are not to be worried.

MANUFACTURING ERRORS OF COLLIMATOR OPTICS											
ITEM	R1 (mm)			R2 (mm)		Thickness (mm)			Wedge (arcmin)		
	Direct A.	Inverse A.		Direct A.	Inverse A.	Direct A.	Inverse A.		Direct A.	Inverse A.	
COLL S-1	-97.0 ± 0.1	±0.2		-113.3 ± 0.1	±0.2	35.00 ± 0.15	-0.17	+0.3	±2	±4	
COLL D-2	flat	-		-728.1 ± 1.0	±2	35.00 ± 0.15	±0.3		±2	-1.3	+2.3
COLL D-3	-728.1 ± 1	±2		-398.8 ± 0.4	±0.8	35.00 ± 0.15	±0.3		±2	-4	+2.3
COLL D-4	1259.9 ± 2	-4	+2.9	344.5 ± 0.5	±0.8	25.00 ± 0.15	±0.3		±2	-1.9	+4
COLL D-5	344.5± 0.5	±0.8		-542.5 ± 0.5	±1.2	45.00 ± 0.15	±0.3		±2	-2.6	+3.4

Table 13. Comparison between direct and inverse analysis tolerances for the collimator using refractive index melt values

The camera manufacturing tolerances in this configuration, shown in table 14 are similar to those obtained in LR-Z, but

tightened and the negative side of the threshold is loosened. We conclude that this phenomenon is physically explained if we acknowledge that the configurations cover opposite sides of the spectrum. LR-
LR-
due to the dispersion of the light, rays hit in different spots of the system surfaces. In a global performance Monte Carlo, the degradations in the system due to ROC tolerances will compensate, so it is best to keep the symmetrical tolerance ranges as in design.

MANUFACTURING ERRORS OF CAMERA OPTICS												
ITEM	R1 (mm)			R2 (mm)			Thickness (mm)			Wedge (arcmin)		
	Direct	Inverse A.		Direct A.	Inverse A.		Direct A.	Inverse A.		Direct A.	Inverse A.	
CAM D-1	435.9 ± 0.4	-0.8	+0.17	-231.7 ± 0.2	-0.4	+0.04	60.0 ± 0.1	±0.2		±2	-4	+2.8
CAM D-2	-231.7 ± 0.2	-0.4	+0.04	Flat	-		25.0 ± 0.1	±0.2		±2	-4	+3.4
CAM D-3	269.2 ± 0.2	-0.4	+0.02	145.1 ± 0.1	-0.2	+0.03	25.0 ± 0.1	-0.06	+0.2	±2	-4	+2.2
CAM D-4	145.1 ± 0.1	-0.2	+0.03	Flat	-		60.0 ± 0.1	±0.2		±2	-4	+2.1
CAM S-5	156.0 ± 0.1	-0.2	+0.1	-1143.0 ± 0.8	-0.5	+2	62.0 ± 0.1	-0.2	+0.02	±2	±4	
CAM S-6	176.4 ± 0.2	-0.4	+0.07	365.8 ± 0.3	- 0.35	+0.6	40 ± 0.1	-0.2	+0.01	±2	-0.7	+2.3
CAM S-7	-162.5 ± 0.2	-0.4	+0.1	219.5 ± 0.2	±0.4		30 ± 0.1	-0.01	+0.2	±2	±4	

Table 14. Comparison between direct and inverse analysis tolerances for the camera using refractive index melt values.

The collimator AIV tolerances remain to be acceptable and not critical to the system (table 15).

COLLIMATOR ASSEMBLY										
BARREL	Tilt X (arcmin)			Tilt Y (arcmin)		Decenter X (mm)		Decenter Y (mm)		
	Direct A.	Inverse A.		Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A.	Inverse A.	
COLL-S1 (Aspheric)	±2.1	±4.2		±2.1	±4.2	±0.3	±0.37	±0.3	-0.57	+0.6
COLL-D2/ COLL-D3	±2.1	-1.9	+4.2	±2.1	±3.3	±0.3	±0.32	±0.3	-0.6	+0.19
COLL-D4/ COLL-D5	±2.1	-1.9	+4.2	±2.1	±2.3	±0.3	±0.54	±0.3	-0.39	+0.6

Table 15. Comparison between direct and inverse analysis AIV tolerances for the collimator using refractive index melt values.

Looking at table 16 the performance of the mayor part of the system is improved using the refractive index melt values as feedback for the design. In this particular case (LR-U) some of the camera elements perform slightly better than in LR-Z (10% difference), but especially in element CAM-S5 the parameter of tilt in X is greatly improved by a possible relaxation of the tolerance up to three times the inverse value of the latter configuration. Due to the fact that we need to assure that the performance is good in all configurations, the results for this case are acknowledged, but the same recommendation in this matter is kept, i.e. to minimize errors in the decenter on Y.

CAMERA ASSEMBLY								
BARREL	Tilt X (arcmin)		Tilt Y (arcmin)		Decenter X (mm)		Decenter Y (mm)	
	Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A.	Inverse A.	Direct A.	Inverse A.
CAM-D1/ CAM-D2	±2.] TJ.02							

The amount of data that comes from this kind of analyses is large, thus there are several extensive studies and insights that remain to be done if specifically required or needed. The results presented here are intended to be a guideline for the fabrication process and it can be extended depending of the advances in the polishing, measuring and AIV of the optical system.

Using these custom calculated tolerances in the system would give the performance expected as MC simulations were run with this set of tolerances, but the objective of this study is not to change the ones given by design and that are feasible in fabrication. The purpose is to give insight of each parameter in detail and determine possibilities in unexpected events.

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