TSPM Optical performance and Error Budget for f5 Cassegrain

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Applicable and Reference Documents

Nº	Document Name	Code

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1. SUMMARY

The Telescopio San Pedro Mártir will be assembled around a closed design (converted MMT/Magellan telescope) with most of its optical parts already manufactured. These are:

- Primary Mirror. University of Arizona. Closed design. To be manufactured.
- Secondary mirror from Magellan telescope. Manufactured. Already available.
- Imaging WFC from Magellan telescope. Manufactured. Already available.
- Spectroscopy WFC Magellan telescope. Manufactured. Already available.
- Mechanics are under design and to be manufactured under TSPM Project Office responsibility.

The goal of this document is to provide a comprehensive error budget regarding optics performance to be able to define the mechanical requirements and a full picture of the expected performance.

2. INTRODUCTION

This document analyzes the optical performance for the TSPM F5 Cassegrain imaging and spectroscopy configuration.

The analysis of other possible future optical configurations (mainly F5 Nasmyth and F11 Nasmyth) shall be included in a different document. Aside from the specifications of the new optical elements, common ones regarding mechanical tolerances are expected to be driven by the shortest F number configurations (TBC). The tolerances of the mechanical design will be driven by the tightest configuration, thus an analysis of all science configurations is required.

3. WIDE FIELD IMAGE ERROR BUDGET. CASSEGRAIN MODE

3.1 Optical characteristics

The San Pedro Mártir telescope design is a two mirror classical Cassegrain system. This is a 6.5m parabolic primary mirror and an hyperboloid secondary working together as F5.36.

The nominal telescope has strong field curvature as is expected for this design. A wide field corrector made with four lenses provides a flat focal surface well corrected on the central 0.5º FOV. See Table 1 and Figure 1.

FOV	Plate scale	Image Quality	Wavelength range	Focal curv.
0.5º	170 µm/"	0.13" average	0.33 -1.00 µm	flat

Table 1: *Wide field imaging summary.*

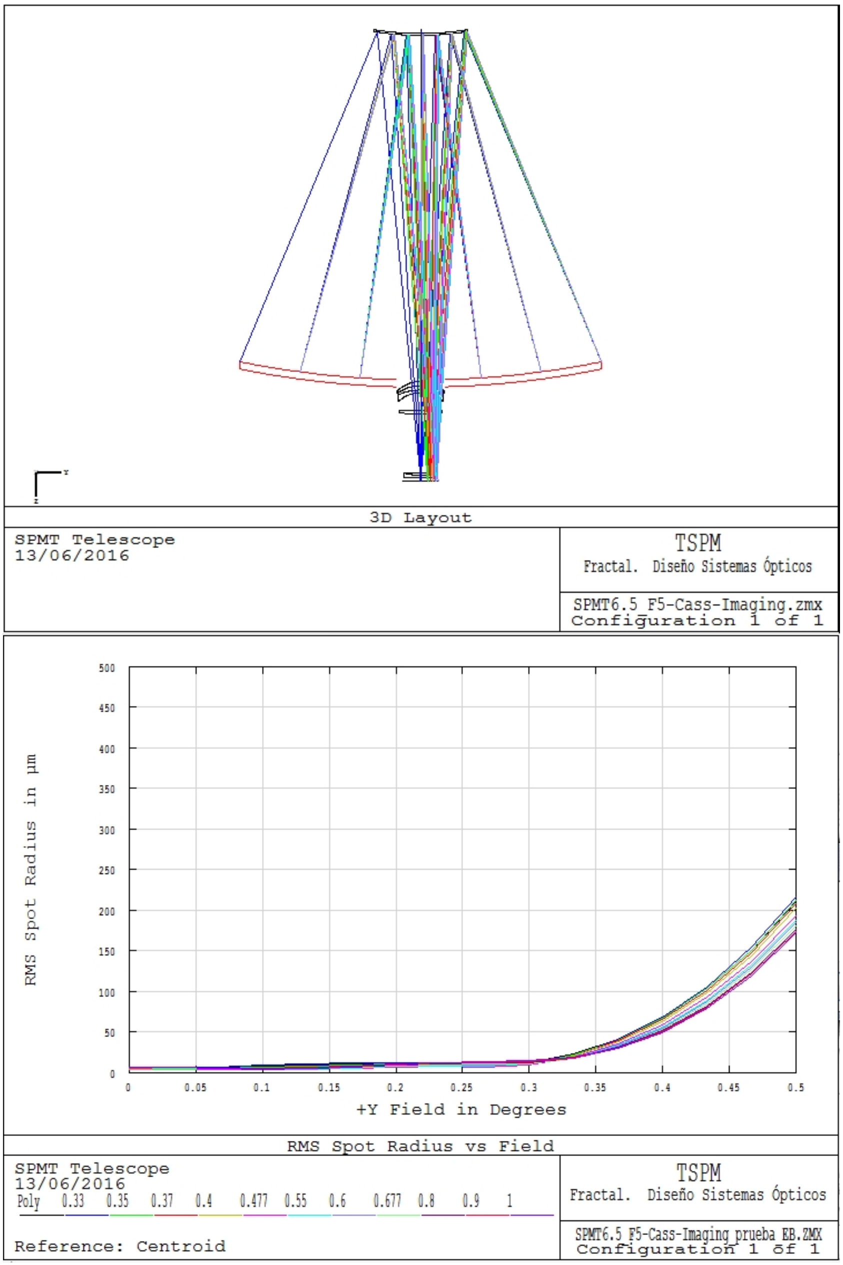


Figure 1: *Telescope layout (top). The spot RMS up to 0.5º out of axis (bottom). Notice severe degradation above 0.3º. As a reference 1" is 170 µm at the focal plane.*

In Figure 2 the 1º FOV is shown (provided unvignetted by the corrector). Rapid degradation above 0.6º is shown that arise a “comatic” PSF up to 400 µm RMS spot diagram in the 1º edge.

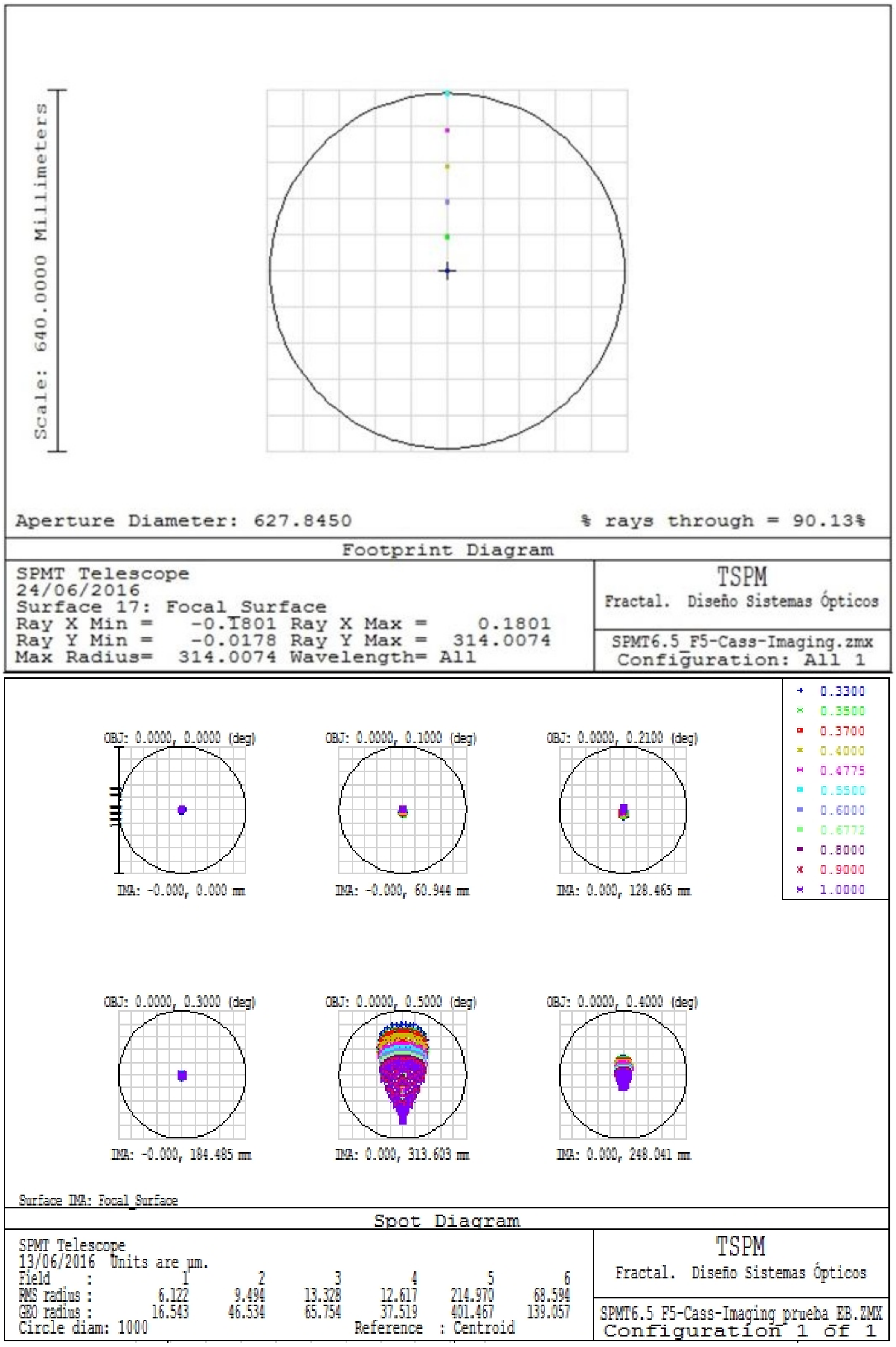


Figure 2: *Focal plane footprint with the different fields (top) and spot diagrams to these fields at the bottom.*

The corrected FOV in the central 0.5º FOV is shown in Figure 3. The average RMS is 9.1µm $FWHM_{average} = 2.4 \times 9.1 = 21.84$ µm and $FWHM_{max} = 2.4 \times 13.7 = 32.88$ µm.

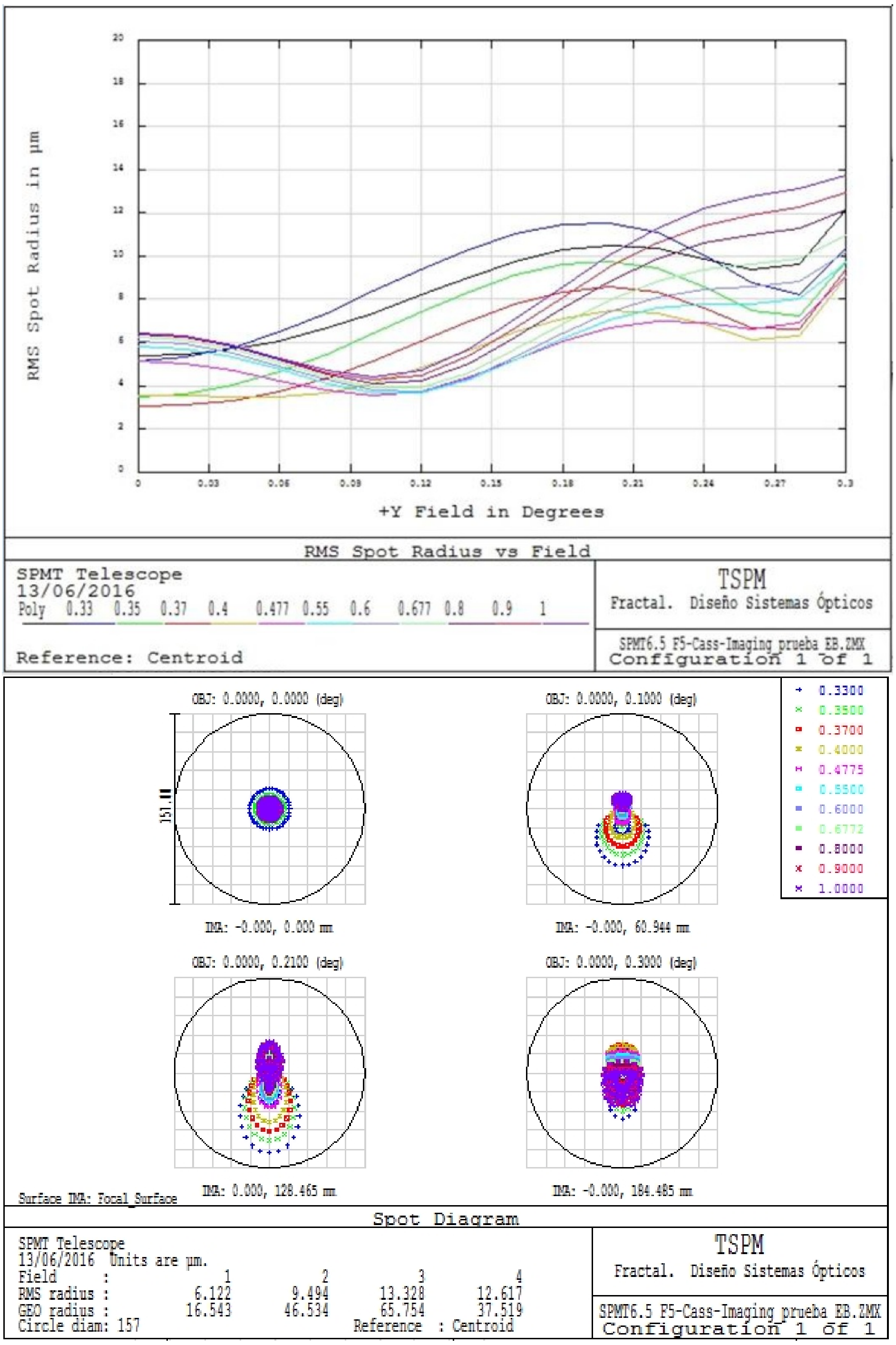


Figure 3: *Top figure, the RMS spot radius. Average for a cut line across the optical axis is 9.1 µm RMS. At the bottom a spot diagram.*

The wide field corrector minimizes field curvature at the cost of field distortion. See Figure 4.

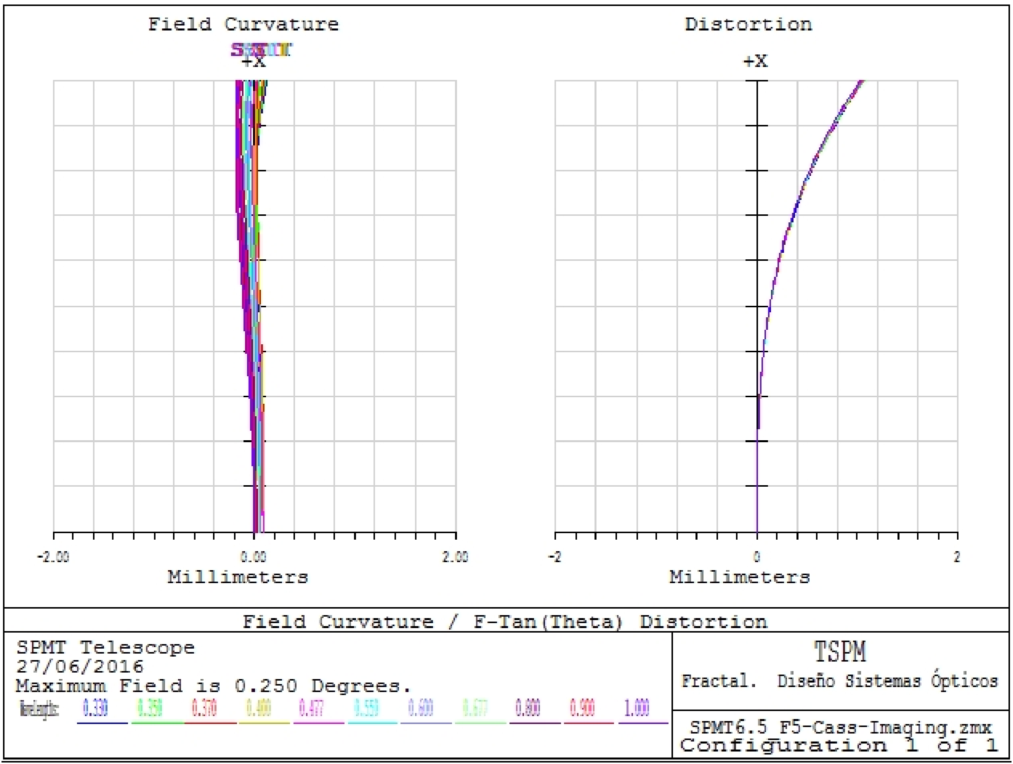


Figure 4: *On the left field curvature after the corrector. On the right distortion. Maximum field off axis is 0.25º (0.5º diameter FOV). Maximum distortion in percentage is 0.68%.*

Thus the plate scale changes as we move out of the optical axis.

Field	0 to 0.2º	0.2º to 0.4º	0.4º to 0.6º
Plate scale	169 µm/"	170 µm/"	172.7 µm/"

Table 2: *Off axis plate scale changes.*

Considering the average plate scale of 170 microns/", the spot size in arc seconds is:

$FWHM_{average} = 21.84 / 170 = 0.128''$

$FWHM_{max} = 32.88 / 170 = 0.193''$

Another view of the field distortion shape is in Figure 5.

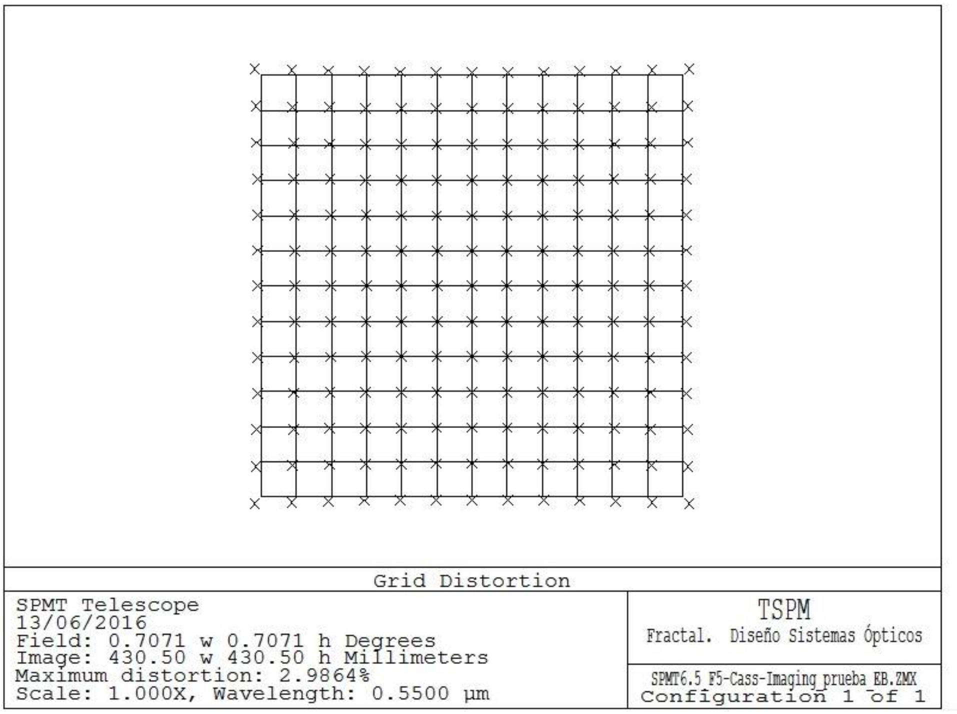


Figure 5: *Image distortion for a 1º full FOV.*

Finally it is to be noticed that the focal plane is non telecentric.

Exit pupil position	Exit pupil diameter
-2565mm	478mm

Table 3: *Exit pupil parameters.*

3.2 Summary of optical requirements for image quality

The main science requirements in this mode are

- FOV 0.5º in diameter in wide field imaging.
- Image quality can degrade 10% the FWHM at 0.5" arc sec. Degrade 0.5" FWHM to 0.55". That is 0.23".

3.3 Error Budget summary

The error budget summary is given in Table 4. Although the grand total budget is given in terms of FWHM in arc seconds, different budget pieces are allocated through another specifications, in particular RMS spot radius and fried parameter r_0. For a comprehensive detail about these specifications and how to change between them see 6.2.

ITEM	FWHM	Rms (µm)	R_0 (cm)	Comment
Nominal performance	**0.121**	8.6		Nominal design F5 Cassegrain Imaging mode 0.5º FOV
M1 manufacturing, surface irregularity with AO	**< 0.184**		> 91	Based on UA contract spec Kolmogorov structure function
M1 manufacturing, CC and ROC	**0.022**	1.54		Based on 100 MC and contract spec.
M1 manufacturing, CC and ROC uncertainties	**0.059**	4.22		Measurement uncertainties provided by UA. Based 100MC
M2 manufacturing, CC and ROC uncertainties	**0.020**	1.42		Magellan M2 as built. Mirror uncertainties measure.
M2 manufacturing, surface irregularity, curvature	**0.040**		253	Specs for the MMT telescope. Apply to Magellan (TBC)
Corrector fabrication	**0.065**			MMT document
Telescope alignment (active optics)	**0.045**	3.2		200 Monte Carlo runs in normal distribution
M2 hexapod residuals	**0.025**	1.8		100 Monte Carlo runs in normal distribution
Thermal	**0.047**	3.4		Operation temperature ranges shall be introduced
Guiding	**0.030**			Based on TSPM requirement
TOTAL (rms squared)	**0.254**			Full budget

Table 4: *Error budget summary table.*

This error budget contains the main error sources that can be modeled with a reasonable effort. Nevertheless we could expect some further degradation due to unpredictable sources, such as windshake of the telescope structure or WFS close loop sensitivity that will set the ultimate correction level during AO operation.

3.4 Nominal design

The optical quality of the nominal design will be measured in terms of RMS spot radius.

The FOV will sample the focal plane with 7 fields that are sensitive to any non-symmetric aberration, see Figure 6. There are three fields placed at the 0.5º circle, three at 0.35º circle (50% of the FOV area) and one at the optical axis that is weighted x3, so all positions have the same mean weight.

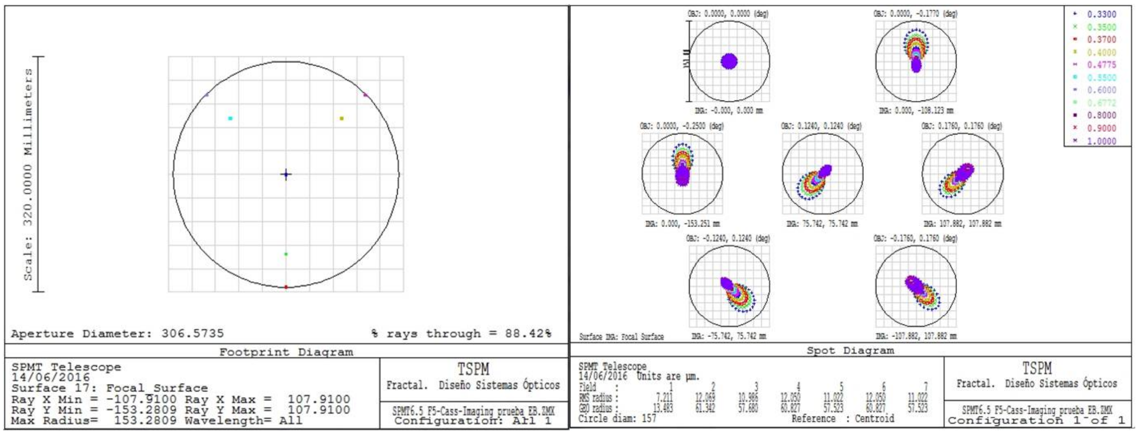


Figure 6: *On the left the positions of the seven fields with their corresponding spot diagrams on the right.*

For completeness and in order to compare with the original MMT conversion optical Spec (Fabricant, Mc Leod and West 1999) we show the encircled energy plot in Figure 7.

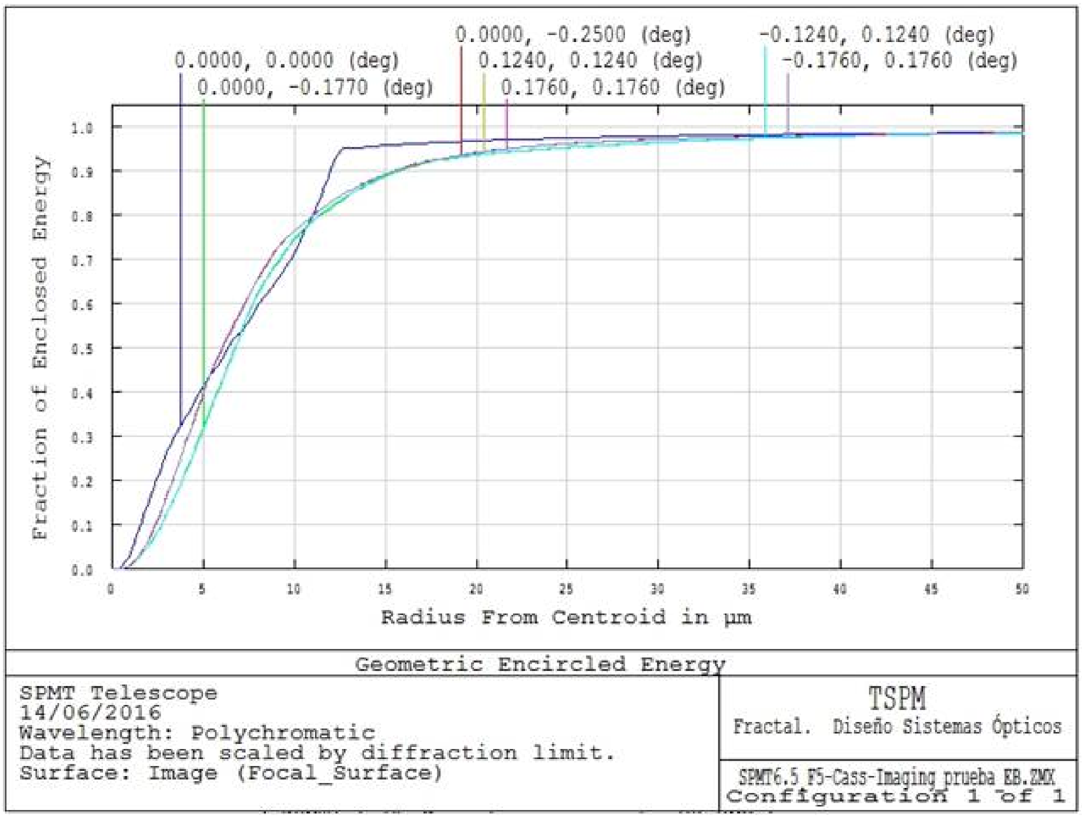


Figure 7: *Encircled energy plot for all the fields and wavelengths.*

The image quality summary, as computed with Zemax is shown in Table 5

FOV 0.5º	Spot RMS	50% Encircled Energy diameter	80% Encircled Energy diameter	90% Encircled Energy diameter
Average of 7 fields	**8.6 µm (0.12")**	12.8 µm (0.08")	22 µm (0.13")	28 µm (0.16")

Table 5: *Nominal image quality. To change from spot RMS to FWHM, RMS is multiplied by 2.4 and divide by plate scale 170 µm/". We use 0.12" in the EB.*

3.5 M1. Manufacturing Errors. Low order.

The low order manufacturing errors are related to the radius of curvature and the conic constant of M1. Manufacturing tolerances provided by UA are given in Table 6.

ROC	CC
-16255.3 ± 3mm	-1 ± 0.0002

Table 6: *M1 Low order tolerances*

The effects of these errors are computed using a Monte Carlo statistical analysis. The tolerances are taken in a uniform statistic (same probability) within the tolerance range.

In case we just use the back focal distance, the Merit function degrades from RMS spot 8.4 µm (nominal image quality) to 11.2 µm. This is a very large degradation, so we follow the same strategy as advised for the MMT.

Once M1 is manufactured, the as built ROC and CC values are feedback in the design. We allow moving the M2 position and the corrector + focal distance from the nominal position.

After running a new 200 MC statistical analysis, see 6.3 the results are summarized in Table 7.

Nominal	200MC	Degradation
8.4 microns rms	90% MC < 8.55 µm	**1.54 µm**
Compensator	M2 position	3.6mm range in 200MC
Compensator	WFC + focal plane position	14.8mm range in 200MC

Table 7: *Results for M1 MC Analysis and M2 compensator range.*

3.6 M1. Manufacturing error uncertainties

The uncertainty in the final measurement of the ROC and CC cannot be compensated except with the M2 position adjustment for focusing. We have used the uncertainties in the measurement provided by UA, ROC = ±1mm and k = ± $1x\ 10^{-4}$. Results are in Table 8.

Nominal	100MC	Degradation
8.4 microns RMS	90% MC < 9.4 µm	**4.22 µm**
Compensator	M2 position	± 0.45mm range in 100MC

Table 8: *MC output for the uncertainty error.*

The 4.22 µm are 0.059”, which will be used in the EB. The MC details are shown in 6.4.1.

3.7 M1. Manufacturing Errors. High order

The UA has specify M1 surface error using a structure function with two objectives:

- Specify error at different spatial frequencies (from mm to meter level).
- Using the Kolmogorov turbulence model to obtain the structure function. So degradation is compared to the natural seeing baseline structure function. See 6.1.

The specifications for the structure function are summarized in Table 9. This error is due to the polishing effects.

r_0 (Frieds , cm)	λ (nm)	Max TIS	Roughness	D
> 91 (goal 118)	500	2% (goal 1.5%)	< 20 Å	6.5 m

Table 9: *M1 summary surface quality specifications.*

The structure function profile from UA technical specification for TSPM is given bellow.

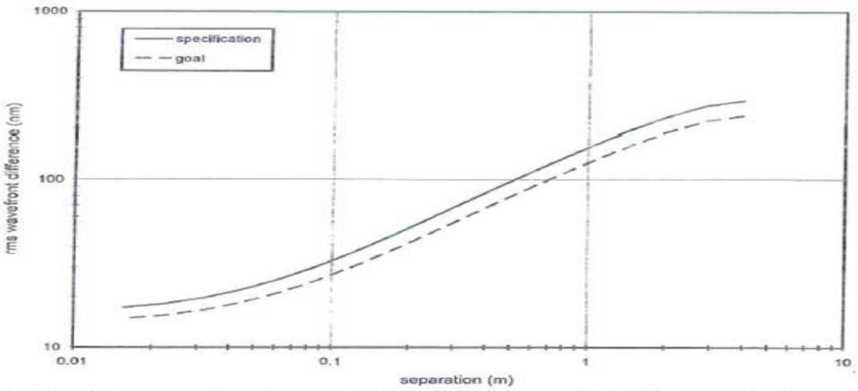


Figure 1. Specification and goal for the figure of the TAO primary mirror. The quantity plotted is the square root of the wavefront structure function, i. e. the rms wavefront difference between points in the aperture as a function of their separation.

Figure 8: *TSPM M1 structure function specification.*

For details about the function see 6.1.

It is to be noticed that to allocate a full budget we need to consider more items on M1 and that the active optics system is providing the required compensation for gravity and thermal effects.

We will use the M1 budget of the former converted MMT telescope with the updated specification on polishing errors. The FWHM is obtained from r_0 as 0.98 x 0.0005 /910 (in rad), or **FWHM = 0.11**". See 6.2.2 for details.

Error Source	Image FWHM at zenith (arcsec)	$\mathbf{r}_0$ at zenith (cm)	Image FWHM at 30° elevation (arcsec)	$\mathbf{r}_0$ at 30° elevation (cm)
Polishing/Testing	~~0.093~~ 0.11	~~109~~ 91	0.093	109
Primary Support[1]	0.072	141	0.130	78
Wind Forces	0.050	214	0.083	122
Ventilation Errors	0.050	214	0.050	214
Material Homogeneity	0.050	214	0.050	214
Reflective Coating	0.025	400	0.025	400
Total Primary	~~0.150~~[2] 0.184	~~60~~ 55	0.220[2]	45

[1] Includes design and operation
[2] r_0 error propagation

we must propagate errors as $\Sigma r_0^{-1.67}$

Table 10: *M1 grand total budget updated to r_0 = 91cm specification. Notice that the total error is not obtained with the cuadratic sum of FWHM, but with the propagation of the Frieds parameter r_0. These has to be computed as $\sum r_0^{-5/3}$*

The polishing/testing specification for TSPM is updated to r_0 = 91 cm (as shown in Table 10), while the error estimated for other sources are kept as considered at the MMT error budget (confirmed with UA).

The real structure function to verify specification will be obtained from the mirror interferogram with the following procedure.

- Take two random points in the M1 interferogram. Get the separation between them in meters.
- Get the wavefront difference in phase (in nm). Square the difference (to avoid negative values) and store the value associated to that separation.
- Sort values by separation range. Average values within each range. This provides the rms^2 of the surface or the structure function. The square root is the specification.
- Repeat process many times (until a stable solution is found).

For details see article, Robert E Parks ("Specifications: Figure and Finish are not enough")

3.8 M2 Manufacturing Errors. Low order

The low order manufacturing errors are related to the radius of curvature and the conic constant of M2. We have the manufactured values provided by Magellan report are given in Table 11.

The optical file can be updated regarding as- built ROC.

- Compensate with M2-M1 distance, currently is 6184.11 (new is 6183.82).
- Compensate with corrector/focal plane position, currently is 29.38 (new is 30.61)

The nominal Merit function is fully recovered (no error).

ROC (mm)	CC (mm)
5151.64 ± 0.202 mm	2.6950 ± 0.0004 mm

Table 11: *M2 Low order tolerances. Tolerance correspond to measurement uncertainties.*

Nevertheless **K and ROC uncertainties** cannot be compensated. Just M2 focus position can be used. A Monte Carlo analysis was used (uniform probability within tolerances), see Table 12 and 6.4.

Nominal	200MC	Degradation
8.4 microns rms	90% MC < 8.52 µm	**1.42 µm**
Compensator	M2 focus	0.1 mm range in 100MC

Table 12: *M2 unknown tolerances.*

3.9 M2 Manufacturing Errors. High order

The Magellan M2 mirror is already available to be used at TSPM.

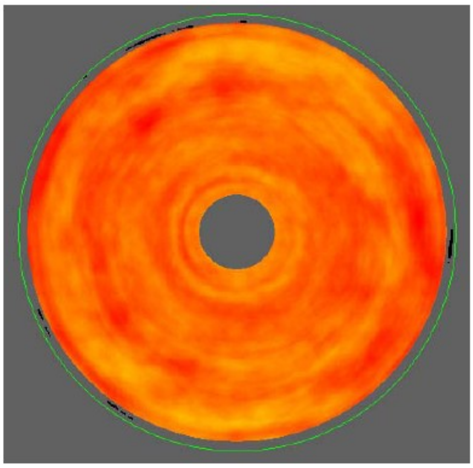
The goal is to incorporate as-built parameters in the design if possible.

The original specification is shown in Table 13.

r_0 (Frieds , cm)	λ (nm)	Roughness	D
> 253 (0.04" FWHM)	500	11.2nm RMS	0.61 m

Table 13: *M2 original specification*

The M2 mirror surface interferogram is shown in Figure 9.



Final polishing cell surface map over the 1636 mm imaging aperture. RMS = 16 nm, P/V astigmatism = 47 nm at 75 degrees. Data range is ± 150 nm.

Figure 9: *M2 interferogram.*

Computing the RMS wavefront (structure function from the interferogram), the results are given in Figure 10 as reported by Magellan. It can be seen that at mid frequencies the error is larger than specified while at low frequencies is much lower.

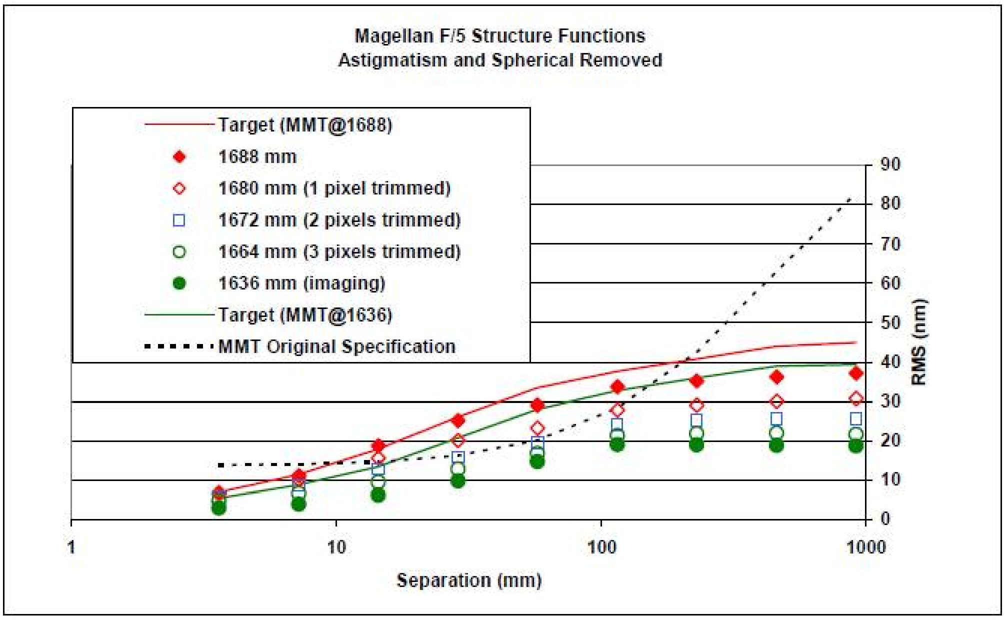


Figure 10: *Structure function measured results and original specification.*

Astigmatism and spherical is being removed in the reports. These low order aberrations will be partially compensated by adjusting M2 distance and the M1 active system for the astigmatism.

The as measured values are shown in Table 14.

Zernike Term	1636 mm CA	1688 mm CA
Z4 (astigmatism)	$-25.3(\rho^2\cos(2\theta))$ nm	$-26.8(\rho^2\cos(2\theta))$ nm
Z5 (astigmatism)	$18.1(\rho^2\sin(2\theta))$ nm	$16.1(\rho^2\sin(2\theta))$ nm
Z8 (spherical)	$-29.7(6\rho^4-6\rho^2+1)$ nm	$-61.3(6\rho^4-6\rho^2+1)$ nm

Table 14: *Astigmatism and spherical for two different M2 apertures.*

Thus basically we will maintain residuals fitting the average the **nominal specification**.

R0 = 253mm or FWHM = 0.04".

The model we obtain for the original specification is given in Figure 11

Model. FWHM = 0.04", $r_0 = 2.53$ m

Pupil magnification size = 2530 / 4.1 = 610mm; σ = 11.2 nm, λ = 500 nm

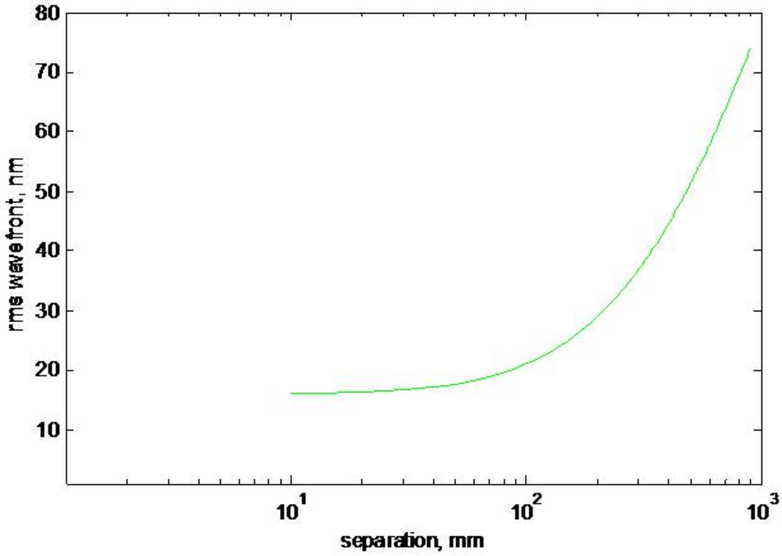


Figure 11: *RMS wavefront function for M2 with r0=2.53mts.*

3.10 M2 hexapod accuracy

The active optics system will be using M2 during the observation to compensate misalignment in the optical axis of the telescope due gravitational structure strain and thermal changes.

M2 is mounted on a hexapod whose mechanism shall have to provide the resolution shown in Table 15.

	Dx (mm)	Dy (mm)	Dz (mm)	Rx (")	Ry (")
M2 accuracy	± 0.003	± 0.003	± 0.001	± < 1	± < 1

Table 15: *Hexapod resolution mechanism*

As the system cannot provide better adjustment than the mechanism resolution, we have evaluated the error associated to this system.

A sensitivity analysis point out the worst offenders, see Table 16. These are tilt and focus resolution that are almost one order of magnitude more sensitive than decenters (these could be relaxed if needed).

Worst offenders:

Type	Value	Criterion	Change
TPAR 10 3	0.00026000	0.00852520	0.00011040
TTHI 10 10	-0.00100000	0.00851592	0.00010111
TPAR 10 4	-0.00026000	0.00850759	9.2788E-005
TPAR 10 4	0.00026000	0.00850759	9.2788E-005
TTHI 10 10	0.00100000	0.00849347	7.8667E-005
TPAR 10 3	-0.00026000	0.00849055	7.5745E-005
TPAR 10 2	0.00300000	0.00842677	1.1969E-005
TPAR 10 1	0.00300000	0.00842385	9.0486E-006
TPAR 10 1	-0.00300000	0.00842385	9.0486E-006
TPAR 10 2	-0.00300000	0.00842097	6.1619E-006

Table 16: *Worst offenders. TPAR10 3and TPAR10 4 are for tilts.*

A 100 Monte Carlo analysis (uniform statistics within the tolerance range) was done with the previous tolerances and no compensation of any type.

Results are given in 6.6. The merit function was degraded from 8.4 µm to 8.59 µm.

Thus the allocated budget is $8.6^2 - 8.4^2 = \mathbf{1.8}^2$

3.11 Alignment Errors

Alignment errors account not only for the pure misalignment of optics, but also for the strain deformations due to gravity.

The greatest strain is M2 lateral displacement at low elevations. But this is not an issue, as M2 will be mounted on a hexapod that will move to its optimal position with a WFS feedback. The preliminary FEM output was analyzed in term of image quality and the details are given in 6.9.

There are four opto-mechanical blocks in the wide field imaging mode; M1, M2, WFC and a field flattener. Specific interface was defined from the mechanical design for each block, see Figure 12.

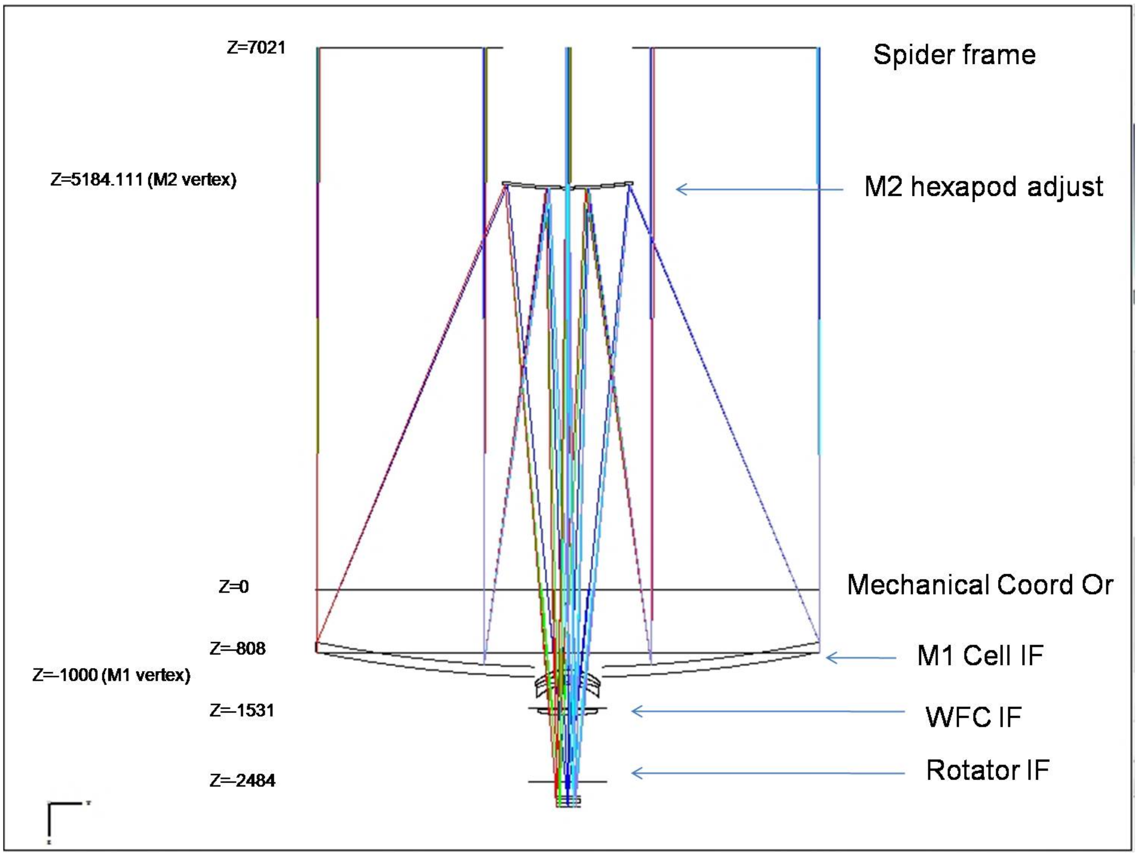


Figure 12: *Optical layout with the main opto-mechanical interfaces.*

In order to obtain the alignment tolerances we have to define a reference system for all the interfaces. The mechanical design coordinate system was placed in the virtual opto-mechanical axis of the elevation axis. This is not an accessible point, so we suggest to place the coordinate system for this analysis in the M1 cell (could be also used the WFC interface). A real mechanical interface plate exists at these positions.

The optical model has been adapted to allow the four optical blocks to move about their interfaces, see Figure 13.

- M1 optical axis moves in its cell with the tolerances reported by UA of ±1mm.
- M2 is a compensator that can be moved anywhere with the hexapod. A record of the required ranges to be adjusted is obtained.
- The WFC barrel can be moved about its interface inside the M1 cell.

- The field flattener and focal plane is moved about the rotator interface.

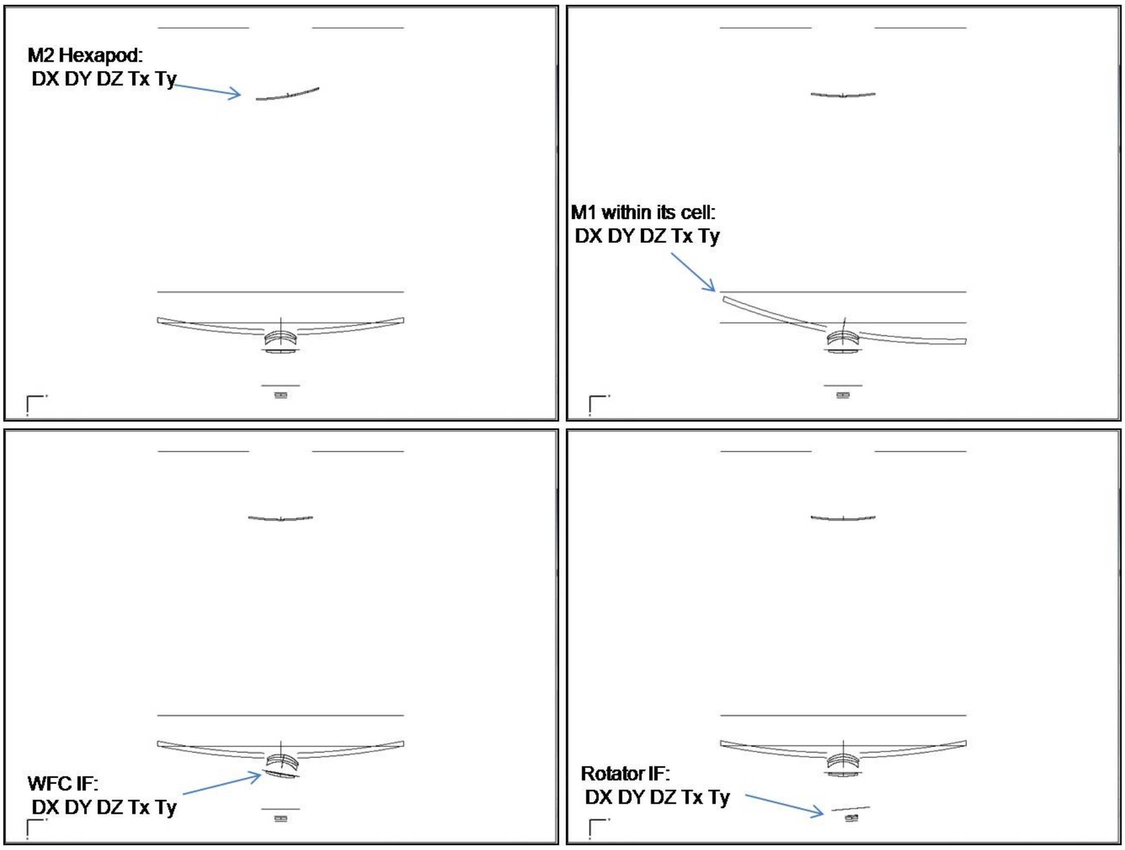


Figure 13: *Optical layout showing examples of different movements of the optical blocks about their interfaces. DX, DY and DZ is for decenters while Tx and Ty is for tilts.*

The initial set of values that we have considered are shown in Table 17. M2 is mounted in the hexapod and is free to move on the optimum position to minimize the spot rms.

	Dx (mm)	Dy (mm)	Dz (mm)	Rx (º)	Ry (º)
M1 in cell	± 1	± 1	± 1	± 0.032	± 0.032
WFC to cell	± 0.2	± 0.2	± 1	± 0.032	± 0.032
Rotator to cell	± 1	± 1	± 0.5	± 0.024	± 0.024
M2	Comp	Comp	Comp	Comp	Comp

Table 17: *Tolerance set used in the analysis.*

The sensitivity analysis for a close tolerance set indicates (see Table 18) that the WFC and rotator absolute position in z are the worst offenders.

Worst offenders: 15(WFC), 27(Rotator),6 (M1)

Type	Value	Criterion	Change
TTHI 15 15	0.80000000	0.00861785	0.00021689
TPAR 27 3	0.02400000	0.00858382	0.00018286
TTHI 27 27	-0.50000000	0.00856244	0.00016149
TPAR 27 3	-0.02400000	0.00855904	0.00015808
TPAR 6 3	0.03200000	0.00854217	0.00014122
TPAR 27 4	0.02400000	0.00851469	0.00011373
TPAR 27 4	-0.02400000	0.00851469	0.00011373
TPAR 6 2	-1.00000000	0.00851326	0.00011230
TPAR 27 2	1.00000000	0.00851115	0.00011019
TPAR 6 3	-0.03200000	0.00851088	0.00010993

Table 18: *Sensitivity analysis for the surfaces M1(6), WCF (15) and rotator (27).*

The Monte Carlo results for 200 trials, see 6.7, with uniform statistics show a degradation of 3.2 microns RMS:

$$\mathbf{9.0^2 - 8.4^2 = 3.2^2}$$

We keep track of these 200 MC M2 compensation movements; as these will be used to define the hexapod mechanism ranges, see Table 19.

Decenter x (mm)	Decenter y (mm)	Decenter z (mm)	Tilt x (º)	Tilt y (º)
-4 / +4.34	-3.86 / +4.74	-0.94 / +0.95	-0.031 / +0.031	-0.035 / +0.031

Table 19: *M2 required range for alignment compensation.*

3.12 Thermal errors

Thermal errors are those that arise due to a change in temperature within the telescope operation range. The M2 mirror active system will be used to compensate for these effects.

3.12.1 Homogeneous temperature change

The model includes the following effects and the temperature is considered to change homogenously through the optical system.

- M1 change in ROC due to the borosilicate E6 glass CTE = 2.9 x 10^{-6} m/º.
- M2 mirror will almost be fixed because is made of Zerodur.
- Change in the optical axis position of the four interfaces considering a steel structure, CTE = 12 x 10^{-6} (TBC).
- Change within the first three WFC lens positions (aluminum barrel, TBC).
- Change in shape for the four lenses considering their corresponding CTEs, silica.
- Change in refractive index for the four lenses and corresponding Dn/dt.

In the model we have adjusted M2 position to recover the image quality.

Nominal	-5 ºC	+6.5 ºC	+18 ºC
8.41 μm RMS	8.46	8.406	8.41
Compensator	M2 z position	M2 z position	M2 z position
Compensator, mm	-0.535	0.08	0.696

Table 20: *Thermal effects within the operation range. Negative number in the compensator shortens the distance between M1 and M2 at the given temperature.*

The maximum difference is between 8.41 µm and 8.46 µm, this 0.9 µm RMS. All the error is basically negligible as far as M2 is exactly adjusted.

Just for comparison we give the image quality between two states with 1ºC difference where M2 was not compensated. Image degradation is unacceptable.

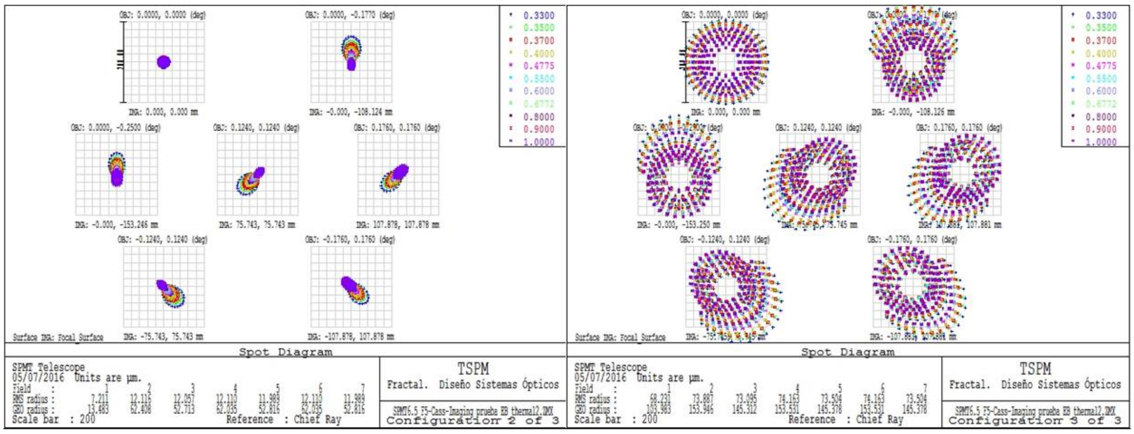


Figure 14: *PSF change due to a 1ºC uniform change in the telescope without any M2 adjustment.*

Going to even lower levels, as 0.1ºC with no adjustment imply a degradation from 8.41 µm to 10.73 µm. Thus the telescope should be adjusted to levels better than 0.1ºC.

Major offender is coming from the distance between M1 and M2 (6 m of steel). We suggest providing an active correction at the level of 0.05ºC or better, using temperature sensors in the truss structure connecting M1 and M2. A change of 0.05ºC would give degradation from 8.41 to 9.06 or 3.4 µm. We will use this value in the EB.

In order to minimize the thermal sensitivity of the telescope, the bars between M1 and M2 could be made of carbon fiber, CTE = - 0.5 x 10^{-6}. This change would improve the performance in a change of 0.1ºC (from 8.41 µm to 8.88 µm).

Full athermalization (no degradation with temperature) would be possible if a combination of materials giving an equivalent CTE of 3.25 x 10^{-6} in the 6.184 m can be provided.

3.12.2 Temperature change with gradients

This scenario is out of the current EB analysis. It has been partially analyzed in the "Optical Specifications for the MMT conversion", chapter 8.2.

The high order (non-homogeneous blank CTE or dn/dt) variations are not considered for the lenses. For M1 and M2 blank manufacturers (Ohara and Schott) are specified with maximum

PV CTE variations. The errors are allocated within the specific budget of each mirror already provided in the high order budgets Table 10 for M1 and Table 37 for M2. We will maintain the original budget allocation.

The mirror seeing, which does not correspond to this budget is also analyzed. Specifications over the temperature control system are derived.

4. WIDE FIELD SPECTROSCOPY ERROR BUDGET. CASSEGRAIN MODE

4.1 Optical characteristics

The San Pedro Mártir telescope Spectroscopic mode requires the modification of the imaging corrector (4 lenses) by suppressing the field flattener (forth lens) and changing the third lens.

The nominal telescope has strong field curvature as is expected for this design. The wide field corrector made with three lenses provides curved focal surface with 1º FOV. See Table 21 and Figure 15. An ADC after this corrector is used for the atmospheric dispersion.

FOV	Plate scale	Image Quality	Wavelength range	Focal curv.
1º	170 µm/" average	0.35" average	0.33-1.00 µm	3404 mm

Table 21: *Wide field spectroscopic FOV summary. Image quality as obtained from RMS average from all considered fields.*

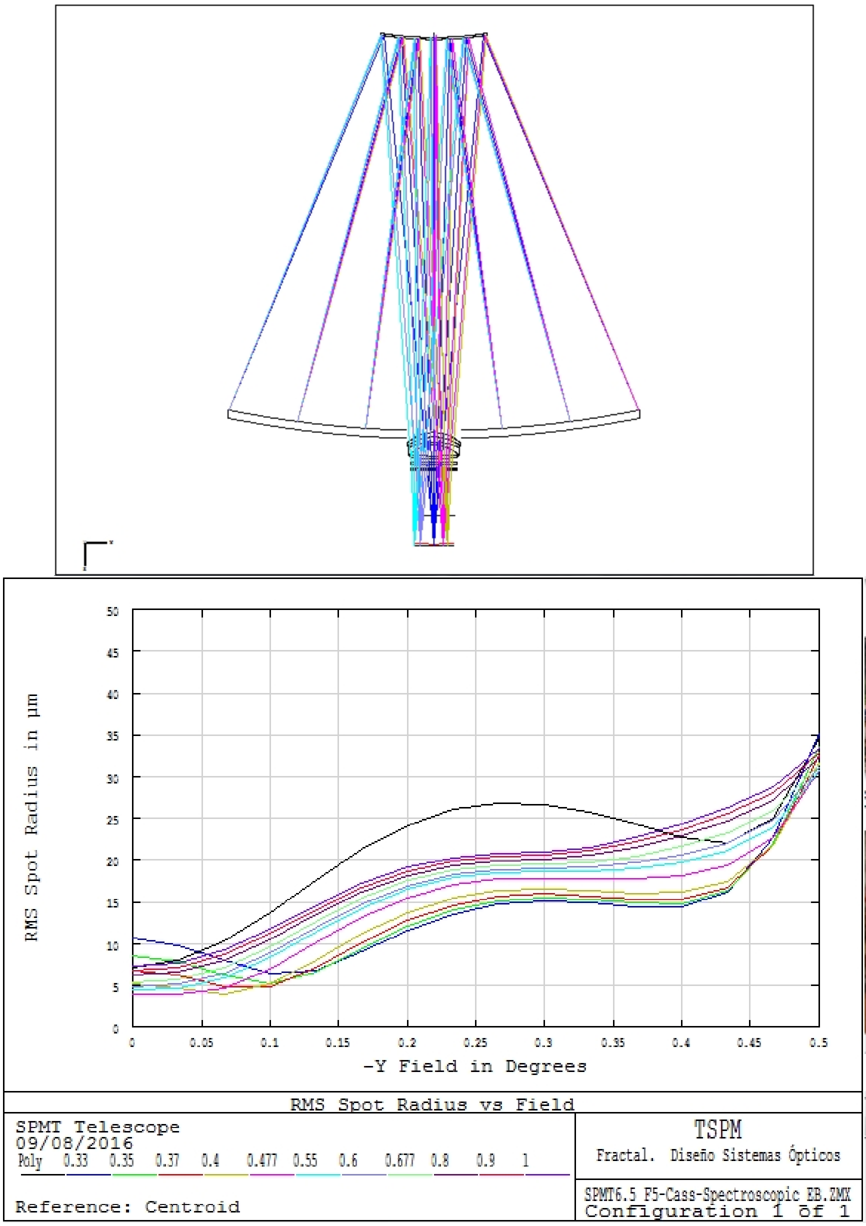


Figure 15: *Telescope layout (top). The spot RMS up to 0.5º out of axis (bottom). Notice polychromatic average (black curve) is above monochromatic size due to lateral color. As a reference 1" is 170microns at the focal plane.*

In Figure 16 the 1º FOV is shown (provided unvignetted by the corrector). Notice lateral color in the intermediate fields (between 0.2 and 0.45º).

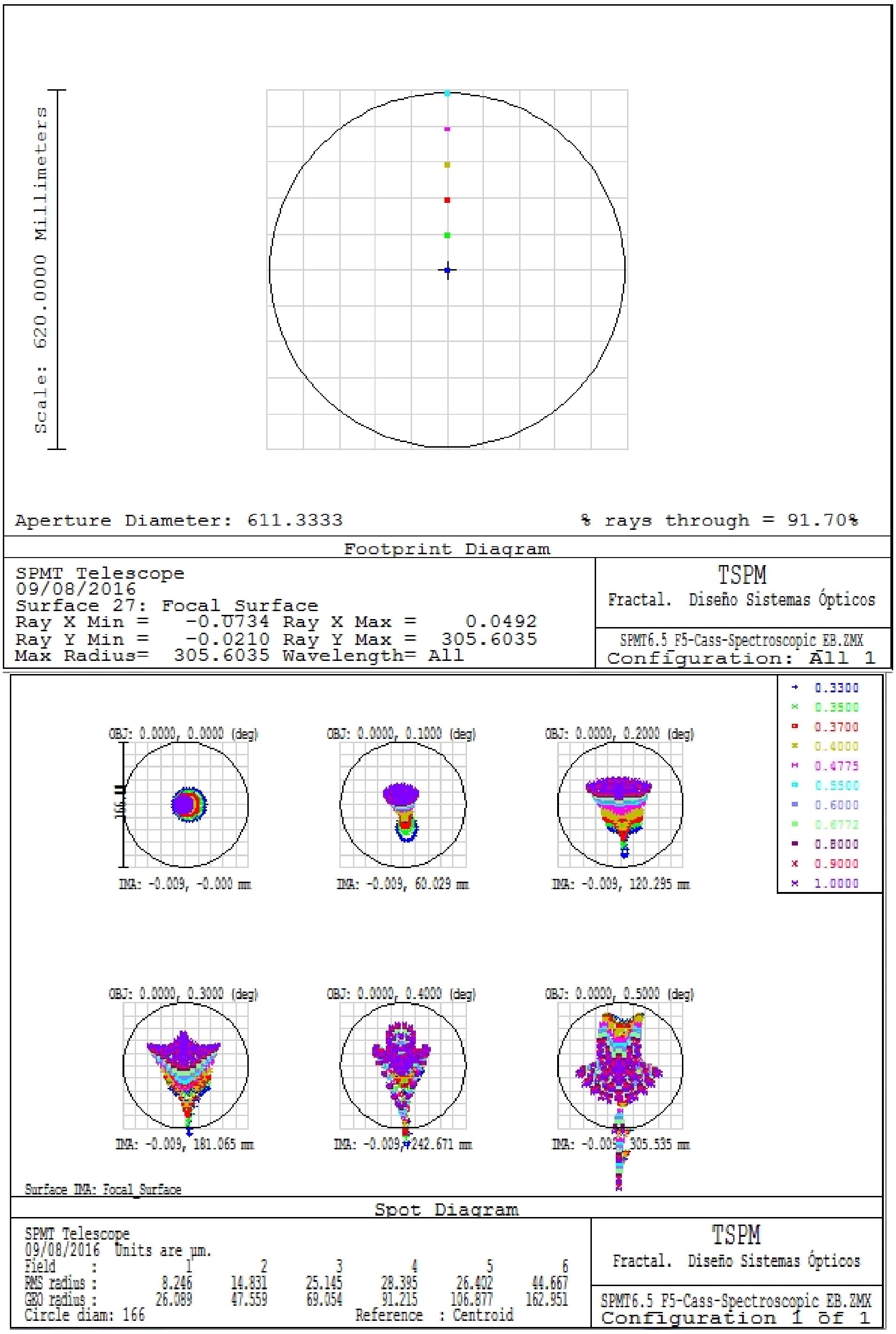


Figure 16: *Focal plane footprint with the different fields (top) and spot diagrams to these fields at the bottom. The circle diameter corresponds to 1" in the center of the FOV.*

The wide field corrector minimizes spherical and coma of the bare design although high field curvature remains in the FOV. See Figure 17.

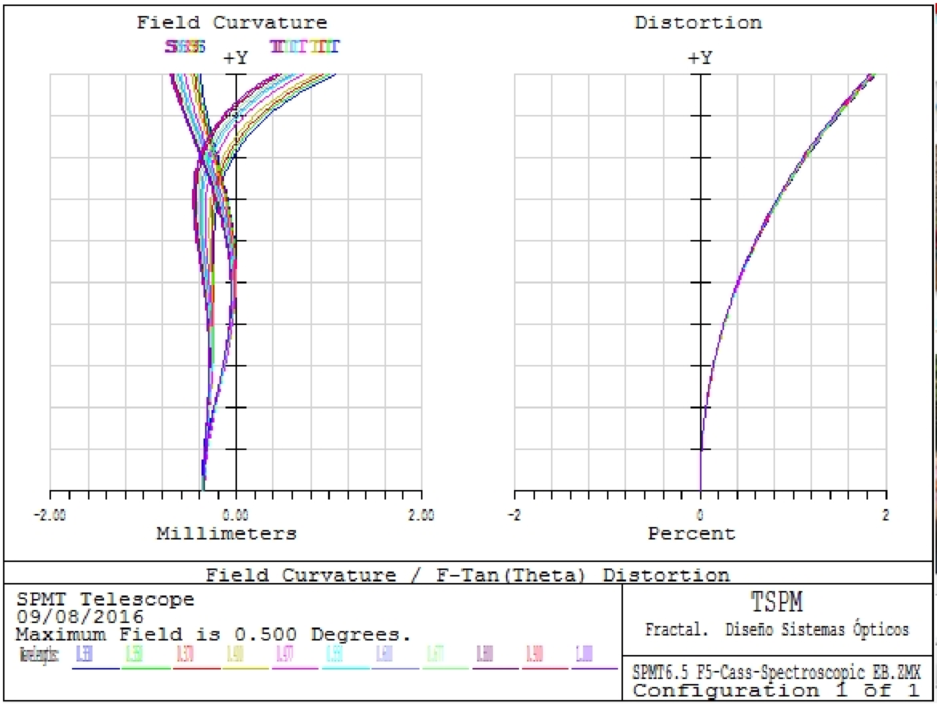


Figure 17: *On the left field curvature after the corrector. On the right distortion. Maximum field off axis is 0.5º (1º diameter FOV). Maximum distortion in percentage is 1.8%.*

The plate scale changes as we move out of the optical axis as given in Table 22.

Off axis position (º)	0	0.1	0.2	0.3	0.4	0.5
Plate Scale (µm/")	166.5	167.0	168.0	169.8	172.7	176.8

Table 22: *Off axis plate scale changes.*

Image quality changes almost a factor 5 between center and field edge, the spot size in arc seconds is:

$FWHM_{\text{on axis}} = 9.1 \times 2.4 / 166 = 0.13$”

$FWHM_{0.25^{\circ}} = 27.1 \times 2.4 / 169 = 0.38$”

$FWHM_{1^{\circ}} = 45 \times 2.4 / 177 = 0.61$”

Another view of the field distortion shape is in Figure 18.

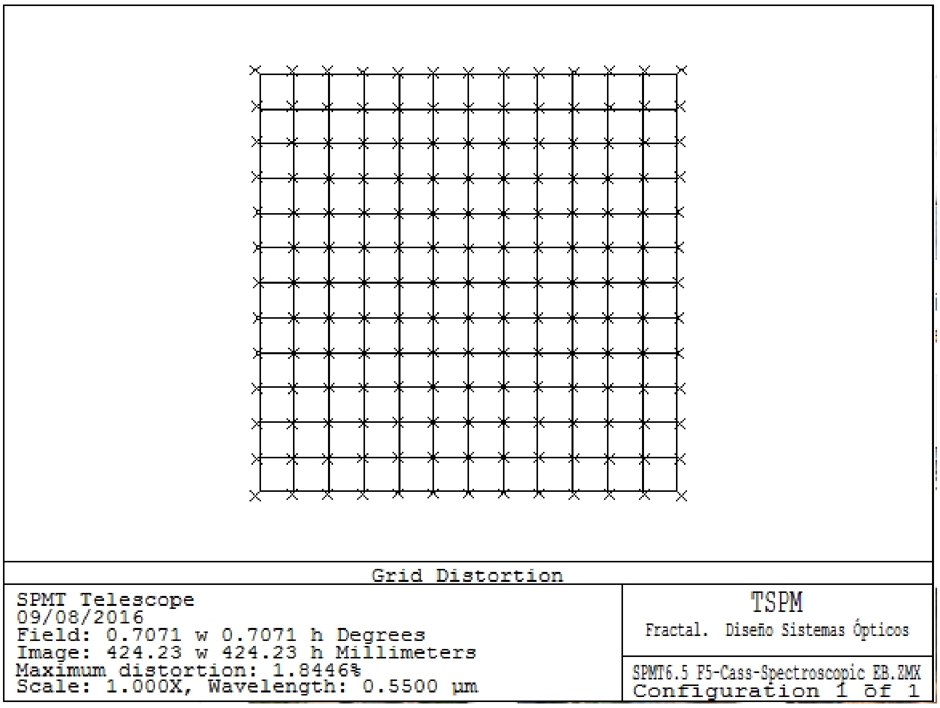


Figure 18: *Image distortion for a 1º full FOV.*

Finally it is to be noticed that the focal plane isn't flat nor telecentric. This is an issue regarding some of the instrumentation to be placed at the focal plane (for example with fiber optics), that would need to be placed following the curvature and with a tilt unless a telecentric lens is added.

Exit pupil position	Exit pupil diameter
-7047mm	1333mm

Table 23: *Exit pupil parameters*

4.2 Summary of optical requirements for image quality

The main science requirements in this mode are

- FOV 1º in diameter in wide spectroscopic mode.

- Image quality can degrade 10% the FWHM at 0.5" arc sec. Degrade 0.5" FWHM to 0.55". That is 0.23". This degradation that also apply to the imaging mode will allow to degrade the nominal image quality from 0.36" to 0.43" in the average.

4.3 Error Budget summary

The error budget summary is given in Table 24. Some of the budgeted items didn't change from the imaging mode. These are not repeated here again. As in the imaging mode, the total budget is given in terms of FWHM in arc seconds, different budget pieces are allocated through another specifications, in particular RMS spot radius and Fried parameter $r_{0.}$ For a comprehensive detail about these specifications and how to change between them see 6.2.

ITEM	FWHM	RMS (µm)	r_0 (cm)	Comment
Nominal performance	**0.36**	25.8		Average
M1 manufacturing, surface irregularity with AO	**<0.184**		> 91	Same as imaging. See 3.5
M1 manufacturing, CC and ROC	**0.060**	4.3		200 Monte Carlo runs in normal distribution
M1 manufacturing, CC and ROC uncertainties	**0.079**	5.6		Measurement uncertainties provided by UA. Based 100MC
M2 manufacturing, CC and ROC uncertainties	**0.028**	2.0		200 Monte Carlo runs in normal distribution
M2 manufacturing, surface irregularity, curvature	**0.040**		253	Same as imaging. See 3.9
Corrector fabrication	**0.220**			MMT document
Telescope alignment (active optics)	**0.17**	12.3		200 Monte Carlo runs in normal distribution
M2 hexapod residuals	**0.036**	2.6		200 Monte Carlo runs in normal distribution
Thermal	**0.069**	4.9		Operation temperature ranges shall be introduced
Guiding	**0.03**			Based on TSPM requirement
TOTAL (rms squared)	**0.512**			Full budget

***Table 24:** Error budget summary table.*

This error budget contain the main error sources that can be modeled with a reasonable effort. Nevertheless we could expect some further degradation due to unpredictable sources, such as windshake of the telescope structure or WFS close loop sensitivity that will set the ultimate correction level during AO operation.

As a general concept, we have been using the same tolerance values as in the imaging mode and have evaluated in the spectral performance the image degradation. It can be seen that due to the larger FOV, the same tolerances produce a degradation average between two and three times the degradation obtained in the imaging mode.

In order to put this into perspective, we have to consider that the average nominal image quality RMS size is three times the image quality RMS size. So we are "nominal spectral image quality" limited in the sense that this portion is taking most of the quality budget. Lowering current tolerance values will provide minimum improvement in the image quality.

4.4 Nominal design

The optical quality of the nominal design will be measured in terms of rms spot radius.

The FOV will sample the focal plane with 7 fields that are sensitive to any non-symmetric aberration, see Figure 19. There are three fields placed at the 1º circle, three at 0.7º circle (50% of the FOV area) and one at the optical axis that is weighted x3, so all positions have the same mean weight.

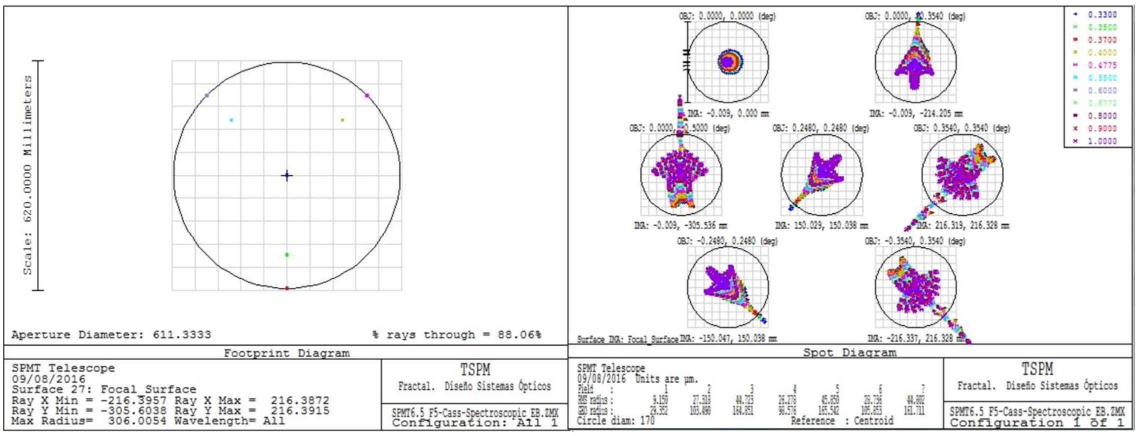


Figure 19: On the left the positions of the 7 fields whose corresponding spot diagrams are on the right.

For completeness and in order to compare with the original MMT conversion optical Spec (Frabricant, Mc Leod and West 1999) we show the encircled energy plot in Figure 20.

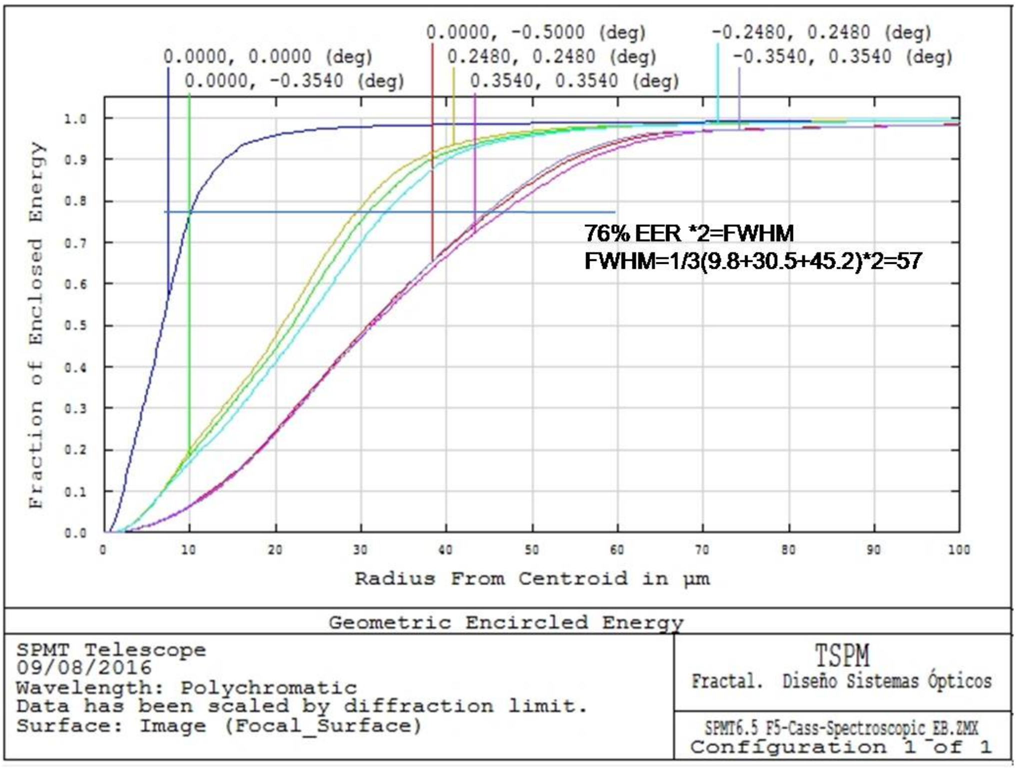


Figure 20: *Encircled energy plot for all the fields and wavelengths. Notice the degradation for the different field diameters.*

The image quality summary, as computed with Zemax is shown in Table 25

FOV 0.5º	Spot rms*	50% Encircled Energy diameter	80% Encircled Energy diameter	90% Encircled Energy diameter
Average of 7 fields	**25 µm (0.15")**	39.8 µm (0.23")	60 µm (0.35")	70.5 µm (0.41")

Table 25: *Nominal image quality. To change from spot RMS to FWHM, RMS is multiplied by 2.4 and divide by plate scale 170 µm/". We use 0.35" in the EB.*

4.5 M1. Manufacturing Errors. Low order

We use the same tolerances that were provided for the imaging mode. For clarity repeated in Table 26.

ROC (mm)	CC
-16255.3 ± 3mm	-1 ± 0.0002

Table 26: *M1 Low order tolerances*

As in the previous mode, once M1 is manufactured, the as built ROC and CC values are feedback in the design. We allow moving the M2 position and the corrector + focal distance from the nominal position.

After running a new 200 MC statistical analysis (uniform tolerance sample), see 6.3 the results are summarized in Table 27.

Nominal	200MC	Degradation
25.8 microns rms	90% MC < 26.17 µm	**4.3 µm**
Compensator	M2 position	3.6mm range in 200MC
Compensator	WFC + focal plane position	14.1mm range in 200MC

Table 27: *Results for M1 MC Analysis and M2 compensator range.*

4.6 M1. Manufacturing Errors. High order

The error budget contribution for this piece (at the pupil position) is the same as for the imaging mode, see 3.7.

4.7 M1. Manufacturing error uncertainties.

The uncertainty in the final measurement of the ROC and CC can't be compensated except with the M2 adjustment. We have used the tolerances in the measurement provided by UA,

ROC = ± 1 mm and k= ± 1 x 10^{-4}.

Nominal	100MC	Degradation
25.8 μm rms	90% MC < 26.4 μm	**5.6 μm**
Compensator	M2 position	± 0.46mm range in 100MC

Table 28: *Results for uncertainties in M1 parameters.*

The 5.6 microns are 0.079” that will be used in the EB. The details of the MC are shown in 6.4.2.

4.8 M2 Manufacturing Errors. Low order

A in the imaging analysis, we have the manufactured values provided by Magellan report are given in Table 29.

The optical file can be updated regarding as- built ROC.

- Compensate with M2-M1 distance, current 6184.11 (new 6183.82).
- Compensate with corrector/focal plane position current 29.38 (new 30.61)

The nominal Merit function is fully recovered (no error).

ROC	CC
5151.64 ± 0.202mm	2.6950 ± 0.0004

Table 29: *M2 Low order tolerances. Tolerance correspond to measurement uncertainties.*

Nevertheless **K and ROC uncertainties** cannot be compensated, we repeat the analysis for the spectroscopic mode. Just M2 focus position can be used. A Monte Carlo analysis was used (uniform probability within tolerances), see Table 30 and 6.5.

Nominal	200MC	Degradation
25.8 µm RMS	90% MC < 25.89 µm	**2.0 µm**
Compensator	M2 focus	0.11mm range in 200 MC

Table 30: *M2 unknown tolerances.*

4.9 M2 Manufacturing Errors. High order

The error budget contribution for this piece (at the pupil position) is the same as for the imaging mode, see 3.9.

4.10 M2 hexapod accuracy

We repeat the same analysis as the imaging mode.

M2 is mounted on a hexapod that will provide the following resolution in the mechanism, Table 31Table 31.

	Dx (mm)	**Dy (mm)**	**Dz (mm)**	**Rx (“)**	**Ry (“)**
M2 accuracy	± 0.003	± 0.003	± 0.001	± < 1	± < 1

Table 31: *Hexapod resolution mechanism*

As the system cannot provide better adjustment than the mechanism resolution, we have evaluated the error associated to this system.

A sensitivity analysis point out the worst offenders, see Table 32. The sensitivity results are slightly different that the ones found in the imaging mode. These are tilt and focus resolution that are almost one order of magnitude more sensitive than decenters (these could be relaxed if needed).

Worst offenders:

Type	Value	Criterion	Change
TTHI 10 10	-0.00100000	0.02580102	0.00014160
TPAR 10 3	0.00026000	0.02571256	5.3146E-005
TPAR 10 4	0.00026000	0.02569461	3.5195E-005
TPAR 10 4	-0.00026000	0.02568724	2.7821E-005
TPAR 10 3	-0.00026000	0.02567051	1.1092E-005
TPAR 10 2	0.00300000	0.02566816	8.7415E-006
TPAR 10 1	-0.00300000	0.02566329	3.8771E-006
TPAR 10 1	0.00300000	0.02566144	2.0207E-006
TPAR 10 2	-0.00300000	0.02565662	-2.7982E-006
TTHI 10 10	0.00100000	0.02557629	-8.3126E-005

Table 32: *Worst offenders. TPAR10 3and TPAR10 4 are for tilts.*

A 200 Monte Carlo analysis (uniform statistics within the tolerance range) was done with the previous tolerances and no compensation of any type.

Results are given in 6.6. The merit function was degraded from 25.65 µm to 25.78 µm

Thus the allocated budget is $25.78^2 - 25.65^2 = \mathbf{2.6}^2$

4.11 Alignment Errors

We repeat the same analysis as the one done in 3.11.

The four opto-mechanical blocks in the wide field spectral mode are M1, M2, WFC and rotator interface. The same specific interfaces were defined from the mechanical design, see 3.11 for details.

The initial set of values that we have considered are shown in Table 33. M2 is mounted in the hexapod and is free to move on the optimum position to minimize the spot rms.

	Dx (mm)	Dy (mm)	Dz (mm)	Rx (º)	Ry (º)
M1 in cell	± 1	± 1	± 1	± 0.032	± 0.032
WFC to cell	± 0.2	± 0.2	± 1	± 0.032	± 0.032
Rotator to cell	± 1	± 1	± 0.5	± 0.024	± 0.024
M2	Comp	Comp	Comp	Comp	Comp

Table 33: *Tolerance set used in the analysis.*

The sensitivity analysis for a close tolerance set indicates (see Table 34) that the main error contribution is dominated by M1 tilt. Notice that rotator tolerances are very relaxed as no optics are placed after this interface.

Worst offenders: Surf 6 (M1), surf 15(WFC), surf 38 (rot)

Type	Value	Criterion	Change
TPAR 6 3	0.03200000	0.02842279	0.00287398
TPAR 6 4	-0.03200000	0.02655296	0.00100415
TPAR 6 4	0.03200000	0.02654752	0.00099871
TPAR 6 3	-0.03200000	0.02620358	0.00065477
TTHI 15 15	-1.00000000	0.02583745	0.00028864
TPAR 15 3	-0.03200000	0.02576307	0.00021426
TPAR 6 2	1.00000000	0.02574900	0.00020019
TTHI 38 38	0.50000000	0.02567511	0.00012630
TPAR 15 4	-0.03200000	0.02565170	0.00010289
TPAR 6 1	1.00000000	0.02564777	9.8961E-005

Table 34: *Sensitivity analysis for the surfaces M1(6), WCF(15) and rotator (38).*

The Monte Carlo results for 200 trials, see 6.7, with uniform statistics show a degradation of 12.3 µm RMS:

$$\mathbf{28.3^2 - 25.5^2 = 12.3^2}$$

We keep track of these 200 MC M2 compensation movements; as these will be used to define the hexapod mechanism ranges, see Table 35. These are slightly lower than the values in the imaging mode.

Decenter x (mm)	Decenter y (mm)	Decenter z (mm)	Tilt x (º)	Tilt y (º)
-3.6 / +3.6	-3.6 / +3.6	-0.94 / +0.95	-0.029 / +0.029	-0.028 / +0.028

Table 35: *M2 required range for alignment compensation.*

4.12 Thermal errors

We repeat the analysis of the imaging mode to confirm allocated budget. The M2 mirror active system will be used to compensate for these effects.

4.12.1 Homogeneous temperature change

The model includes the following effects and the temperature is considered to change homogenously through the optical system.

- M1 change in ROC due to the borosilicate E6 glass CTE=2.9 x 10^{-6} m/º.
- M2 mirror will almost be fixed because is made of Zerodur.
- Change in the optical axis position of the four interfaces considering a steel structure, CTE=12 x 10^{-6} (TBC).
- Change within the first three WFC lens positions (aluminum barrel, TBC).
- Change in shape for the lenses considering their corresponding CTEs, silica.
- Change in refractive index for the lenses and ADC corresponding Dn/dt.

In the model we have adjusted M2 position to recover the image quality.

Nominal	-5ºC	+6.5ºC	+18ºC
25.88 µm RMS	25.78 µm	25.8 µm	25.84 µm
Compensator	M2 z position	M2 z position	M2 z position
Compensator, mm	- 0.532	0.08	0.695

Table 36: *Thermal effects within the operation range. Negative number in the compensator shortens the distance between M1 and M2 at the given temperature.*

The maximum difference is between 25.78 µm and 25.84 µm, this 1.7 µm RMS. All the error is basically negligible as far as M2 is exactly adjusted. The compensator position is basically the same as the obtained in the imaging mode.

A in the imaging mode discussion, major offender is coming from the distance between M1 and M2 (6 m of steel). We suggest providing an active correction at the level of 0.05 º or better, using temperature sensors in the truss structure connecting M1 and M2. A change of 0.05ºC would give degradation from 25.88 to 26.35 or 4.9 µm. We will use this value in the EB.

As in the imaging mode, full athermalization (no degradation with temperature) would be possible if a combination of materials giving an equivalent CTE of 3.25 x 10^{-6} in the 6.184 m can be provided.

5. CONCLUSIONS

The EB for the two main science modes: imaging and spectroscopy has been done. Expected image quality values are 0.25" and 0.50" for each mode. Tolerances are those provided for the imaging mode. The spectral mode image quality is limited by the nominal design, thus using tighter tolerances do not improve much performance.

A specific requirement on the spectral mode image quality should be provided considering the nominal performance given in Table 25.

Temperature change of the telescope as a whole is a quite sensitive parameter. Adjustment is levels better than 0.1º should be provided with M2. A passive compensation of the main steel structure could be considered to relax sensitivity to temperature changes.

6. APENDIX

6.1 Kolmogorov structure function

The atmospheric turbulence induces a change in refractive index and phase as a wavefront propagates through the atmosphere. In the Kolmogorv model (r0 is used to define statistical changes in the wave structure function). The phase variance between two points is given by Eq1 for long exposure images.

$$\left(\frac{\lambda}{2\pi}\right)^2 6.88\left(\frac{x}{r0}\right)^{5/3} \qquad \textit{Eq 1}$$

As the original Kolmogorov model turbulence cell structure at different scales does not reproduce some of the mirror characteristics, this structure function has to be corrected by adding roughness at high spatial frequencies and removing tilt from the phase variance.

$$\delta^2(x) = 2\sigma^2 + \left(\frac{\lambda}{2\pi}\right)^2 6.88\left(\frac{x}{r_0}\right)^{5/3}$$

$$\delta^2(x) = \left(\frac{\lambda}{2\pi}\right)^2 6.88\left(\frac{x}{r_0}\right)^{5/3}\left[1 - 0.975\left(\frac{x}{D}\right)^{1/3}\right]$$

Eq 2: *On top, phase variance with the roughness contribution, and down with the tilt term removed.*

We can reproduce M1 specification (see Figure 21) with the given parameters

r_0 = 91 cm, λ = 500nm, scattering = 2%, D = 6.5 m (x maximum value); σ = 11.2nm

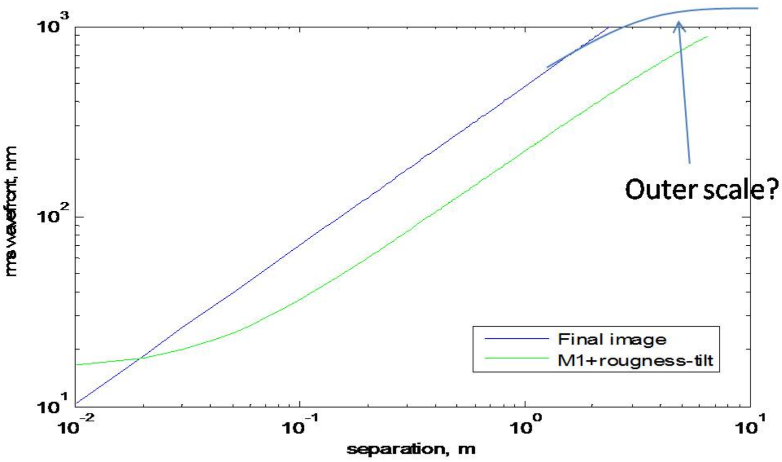


Figure 21: *Structure function for M1 in green, and pure Kolmogorov (no corrections for r_0=0.34").*

In our error budget M1 and M2 were defined using this specification.

The final allocated budget for each mirror is composed of many other pieces that contribute with different r_0 to give the final value. See Table 10 for example.

6.2 Useful expressions to measure image quality

6.2.1 From RMS spot radius to encircled energy using a gaussian distribution

As we use a Gaussian model as a first approximation for a PSF, the following relations allow us to change between encircled area within the PSF, FWHM and RMS.

80% energy in 2.56 x RMS

76% energy in 2.4 RMS (FWHM)

68% energy in 2 radius RMS

RMS in x axis distance from centroid

2 x RMS collect 68% of the energy

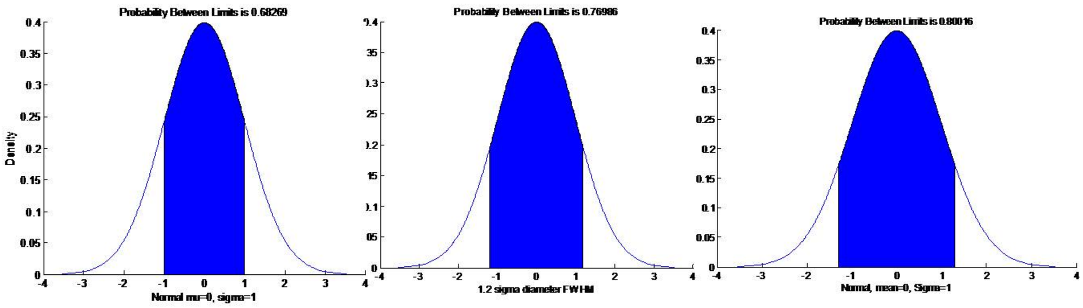


Figure 22: *Area within each considered edge for a Gaussian model*

Example, from spot RMS to FWHM

FOV 0.5º RMS = 8.6 µm (2.4 x 8.6 / 170 = 12.1" FWHM)

6.2.2 From r0 to FWHM

$$FWHM = 0.98\left(\frac{\lambda}{R_0(\lambda)}\right)$$

The Kolmogorov FWHM of long exposure atmospheric seeing is given by (in rads):

We will use this model (converted MMT assumption). It is valid under the assumption that the telescope aperture is >>than r_0. Some better fit could be to consider 1.2 λ/r_0. Some other values are available considering corrections on the Kolmogorov outer scale.

6.3 M1. Low order. Monte Carlo summary

6.3.1 Imaging mode

Number of traceable Monte Carlo files generated: 200

Nominal	0.00841417		
Best	0.00838013	Trial	65
Worst	0.00859733	Trial	28
Mean	0.00843678		
Std Dev	6.5223E-005		

Compensator Statistics:
Thickness Surf 4:

Nominal	:	-6184.107413
Minimum	:	-6185.895671
Maximum	:	-6182.308365

Mean : -6184.074716
Standard Deviation: 0.822752
Thickness Surf 6:
Nominal : 29.437817
Minimum : 21.992038
Maximum : 36.805133
Mean : 29.763463
Standard Deviation: 4.317152
90% > 0.00855038
80% > 0.00850595
50% > 0.00840587
20% > 0.00838383
10% > 0.00838174

6.3.2 Spectroscopy mode

Number of traceable Monte Carlo files generated: 200

Nominal	0.02581251		
Best	0.02554422	Trial	174
Worst	0.02628666	Trial	130
Mean	0.02584392		
Std Dev	0.00021873		

Compensator Statistics:
Thickness Surf 4:
Nominal : -6184.680790
Minimum : -6186.483531
Maximum : -6182.877317
Mean : -6184.593436
Standard Deviation: 0.871574

Thickness Surf 6:
Nominal : 28.843657
Minimum : 21.784281
Maximum : 35.937028
Mean : 28.959997
Standard Deviation: 4.242135

90% > 0.02617817
80% > 0.02607217
50% > 0.02581967
20% > 0.02561725
10% > 0.02557345

6.4 M1 Low order uncertainties Monte Carlo Summary

6.4.1 Imaging mode

Number of traceable Monte Carlo files generated: 100

Nominal	0.00841445		
Best	0.00841129	Trial	54

Worst	0.00967930	Trial	29
Mean	0.00881629		
Std Dev	0.00037620		

Compensator Statistics:
Thickness Surf 5:

Nominal	:	0.000063
Minimum	:	-0.445236
Maximum	:	0.441423
Mean	:	0.031139
Standard Deviation:		0.265809

90% >	0.00939934
80% >	0.00918405
50% >	0.00867025
20% >	0.00847818
10% >	0.00844150

End of Run.

6.4.2 Spectroscopy mode

Number of traceable Monte Carlo files generated: 100

Nominal	0.02581928		
Best	0.02575083	Trial	74
Worst	0.02656869	Trial	52
Mean	0.02599498		
Std Dev	0.00024782		

Compensator Statistics:
Thickness Surf 5:

Nominal	:	0.001714
Minimum	:	-0.462893
Maximum	:	0.464454
Mean	:	0.010307
Standard Deviation:		0.275080

90% >	0.02642590
80% >	0.02626695
50% >	0.02588026
20% >	0.02579387
10% >	0.02577755

End of Run.

6.5 M2. Low order Monte Carlo Summary

6.5.1 Imaging mode

Nominal	0.00840679		
Best	0.00840586	Trial	5
Worst	0.00861923	Trial	56

Mean 0.00844621
Std Dev 4.7736E-005

Compensator Statistics:
Thickness Surf 5:
Nominal : 0.000002
Minimum : -0.046671
Maximum : 0.050743
Mean : 0.002834
Standard Deviation: 0.023570

90% > 0.00851315
80% > 0.00847602
50% > 0.00843135
20% > 0.00840879
10% > 0.00840710

End of Run.

6.5.2 Spectroscopy mode

Number of traceable Monte Carlo files generated: 200

Nominal 0.02581928
Best 0.02581214 Trial 52
Worst 0.02597005 Trial 75
Mean 0.02584251
Std Dev 3.3702E-005

Compensator Statistics:
Thickness Surf 5:
Nominal : 0.001714
Minimum : -0.053115
Maximum : 0.058030
Mean : -0.000463
Standard Deviation : 0.031284

90% > 0.02589144
80% > 0.02586038
50% > 0.02583030
20% > 0.02581525
10% > 0.02581408

6.6 M2 Accuracy. Monte Carlo summary

6.6.1 Imaging mode

Number of traceable Monte Carlo files generated: 100
Nominal 0.00841480
Best 0.00842868 Trial 49
Worst 0.00868507 Trial 39
Mean 0.00851872
Std Dev 5.3431E-005
90% > 0.00859886

80% > 0.00856615
50% > 0.00851373
20% > 0.00846455
10% > 0.00845346
End of Run.

6.6.2 Spectroscopy mode

Number of traceable Monte Carlo files generated: 200

Nominal	0.02565942		
Best	0.02558115	Trial	117
Worst	0.02583668	Trial	190
Mean	0.02568952		
Std Dev	6.4151E-005		

90% > 0.02578794
80% > 0.02574903
50% > 0.02567970
20% > 0.02562679
10% > 0.02560581

6.7 Alignment. Monte Carlo summary

6.7.1 Imaging mode

Number of traceable Monte Carlo files generated: 200

Nominal	0.00840095		
Best	0.00819599	Trial	162
Worst	0.00990600	Trial	141
Mean	0.00873682		
Std Dev	0.00024063		

Compensator Statistics on M2:

M2 Dz:
Nominal : 0.000026
Minimum : -0.938358
Maximum : 0.950249
Mean : -0.004230
Standard Deviation: 0.543343

M2 Dx:
Nominal : 0.000216
Minimum : -3.996057
Maximum : 4.344521
Mean : -0.025355
Standard Deviation : 2.145640

M2Dy:
Nominal : 0.030757
Minimum : -3.858384
Maximum : 4.745530
Mean : -0.034684
Standard Deviation : 2.184720

M2Rx:
Nominal : -0.000848
Minimum : -0.030826
Maximum : 0.031529

Mean : -0.001418
Standard Deviation : 0.016434
M2Ry:
Nominal : 0.000006
Minimum : -0.035721
Maximum : 0.031069
Mean : 0.000408
Standard Deviation : 0.014804
90% > 0.00904056
80% > 0.00893223
50% > 0.00871372
20% > 0.00855430
10% > 0.00846187

6.7.2 Spectroscopy mode

Number of traceable Monte Carlo files generated: 200

Nominal	0.02554881		
Best	0.02535479	Trial	191
Worst	0.02969765	Trial	8
Mean	0.02673152		
Std Dev	0.00098442		

Compensator Statistics:
Thickness Surf 10:
Nominal : 0.001907
Minimum : -0.924768
Maximum : 0.957040
Mean : 0.001232
Standard Deviation: 0.529425

Parameter 1 Surf 10:
Nominal : -0.002146
Minimum : -4.145890
Maximum : 4.416102
Mean : 0.097553
Standard Deviation: 2.152034

Parameter 2 Surf 10:
Nominal : -0.002930
Minimum : -4.426897
Maximum : 4.354981
Mean : 0.049143
Standard Deviation: 2.245005

Parameter 3 Surf 10:
Nominal : -0.000002
Minimum : -0.038767
Maximum : 0.037042
Mean : 0.000247
Standard Deviation: 0.018016

Parameter 4 Surf 10:
Nominal : -0.000071
Minimum : -0.032565

Maximum : 0.034052
Mean : -0.000007
Standard Deviation: 0.016148

90% > 0.02835479
80% > 0.02750291
50% > 0.02641057
20% > 0.02588723
10% > 0.02572695

End of Run.

6.8 M2 original error budget

We copy as a reference the budget to specify the M2 optics in the MMT conversion in Table 37.

Notice that the r_0 corresponding to 60cm in the secondary, scales a factor 4.13 at the primary to 253cm. because the ratio of pupil magnification between both mirrors.

Secondary Error Budget

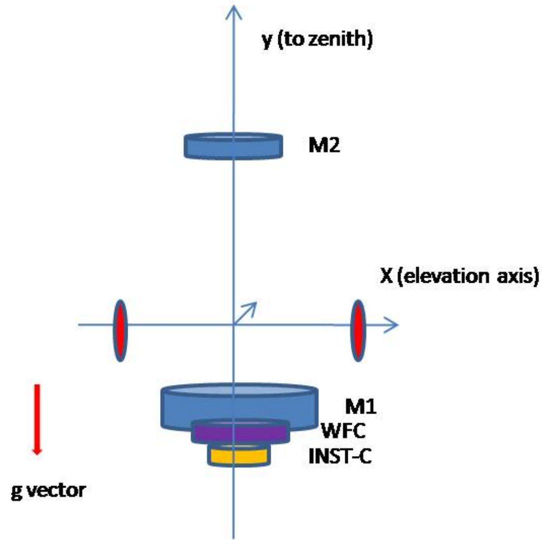
Error Source	Image FWHM (arcsec)	$\mathbf{r}_0$ f/5 (cm)	$\mathbf{r}_0$ f/9 (cm)
Polishing/Testing	0.022	109	69
Secondary Support[1]	0.017	141	89
Wind Forces	0.011	214	135
Ventilation Errors	0.011	214	135
Material Homogeneity	0.011	214	135
Reflective Coating	0.006	400	253
Total Secondary	0.040[2]	60	38

[1] Includes design and operation
[2] r_0 error propagation

Table 37: *M2 original error budget.*

6.9 FEM mechanical output

We have introduced in the optical model the interface deformations obtained by CIDESI in the FEM



of the telescope (provided in April 2016), see

Figure 23 and Table 38.

In order to focus on the relevant behavior, we only translate rotations and displacements above 1” (2.77 x 10^{-4o}) and 10 µm.

We use SPMT6.5_MecEB.zmx Optical model for the evaluation

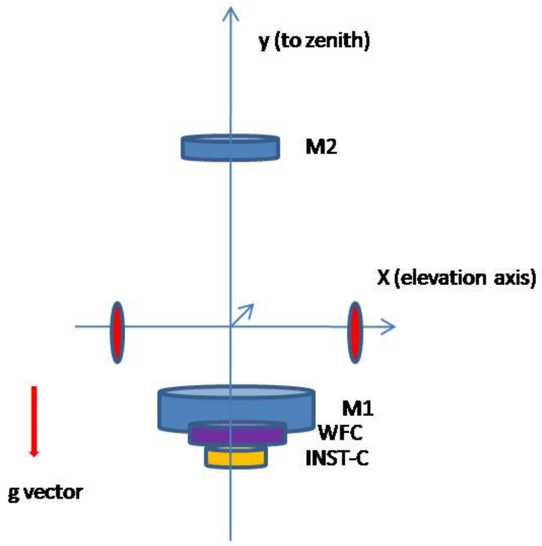


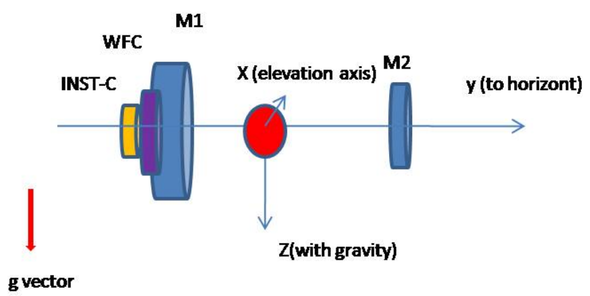
Figure 23: *Mechanical concept for the gravity strain pointing to zenith.*

Cassegrain at zenith (Z)									
	Nominal Coordinates (mm)			Displacement (µm)			Rotations º (“)		
RN	**X**	**Y**	**Z**	**Ux**	**Uy**	**Uz**	**Rx**	**Ry**	**Rz**
M1 cell									
	-	-808	-	-	-26	-	-	-	-
M2 cell									
	-	7021	-	-	-546	-	-0.5”	-	-
WFC									
	-	-1531	-	-	-188	-	-0.5”	-	-
INST-C									
	-	-2484	-	-	-167	-	-0.5”	-	-

Table 38: *Output FEM displacements for each interface.*

Notice that tilts are lower than 1” and strains between M1 and WFC and INST-C (rotator around 150µm).

The same analysis is reported by CIDESI pointing at horizon. See Figure 24 and Table 39.



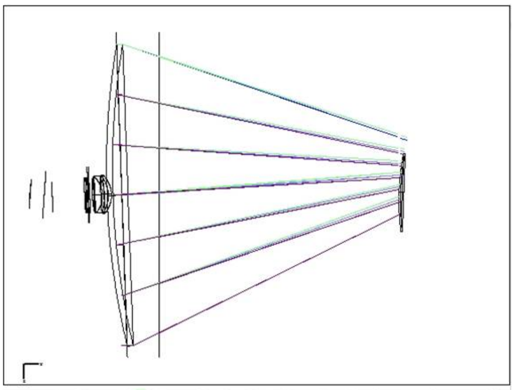


Figure 24: *Optical layout on the right with the telescope model with the FEM displacements.*

As in the previous case M2 has the largest deformation (that will be adjusted by the hexapod).

Cassegrain at horizont (H)									
	Nominal Coordinates (mm)			Displacement (µm)			Rotations º (")		
RN	**X**	**Y**	**Z**	**Ux**	**Uy**	**Uz**	**Rx**	**Ry**	**Rz**
M1 cell									
		-808			97.9	48.2	-1" (2.8e-4)		
M2									
		7021			62.3	78.9	30" (0.008)		
WFC									
		-1531			155	84	-1.5"(-4.2e-4)		
INST-C									
		-2484			162	89	-2" (-5.7e-4)		

Table 39: *FEM output*

The differences between M1 and WFC and the instrument rotator flange are around 60 µm in Y axis and 40 µm in Z axis, and maximum rotations are 2" except for M2.

When these values (at the horizon pointing that is the worst case) are introduced in the optical design the image quality degrades, see Figure 25.

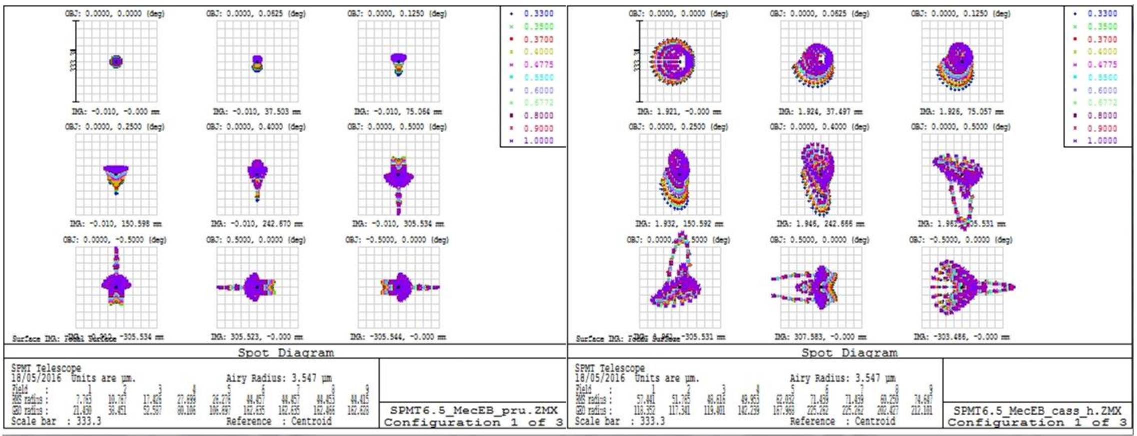


Figure 25: *On the left nominal, on the right degraded (horizon pointing).*

On the left, the nominal performance 21.71 µm RMS spot radius (we are using here a different field specification). On the right, the image is degraded to 53 µm RMS after values given in Table 39.

If we setup M2 hexapod compensation, the image quality is recovered by moving M2:

Uy =100µm in Y (optical axis), Uz= 9.5 µm and -1.6” in Rx tilt. These numbers have to be compared with the FEM values, see Table 40.

	Uy	Uz	Rx
FEM	62.3	78.9	30”
M2 after correction	100	9.5	-1.6”

Table 40: *Top row, FEM values for M2. Bottom row show new values in M2 to recover image quality.*

After M2 compensation, the spot RMS is back to the nominal image quality of 21.68 µm.

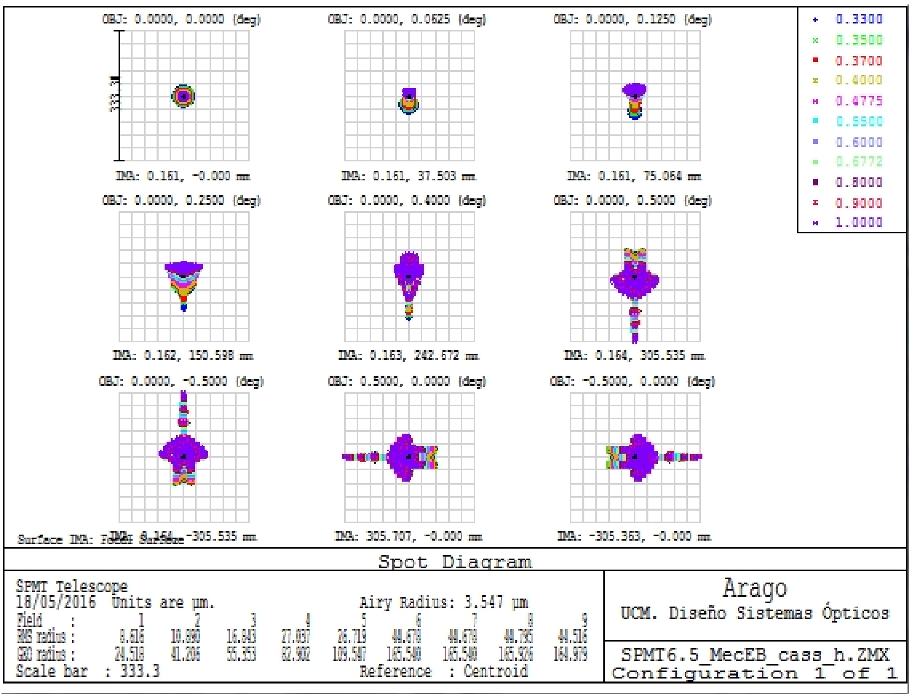


Figure 26: *Spots after compensation*

Thus basically we confirm that the image quality degradation due to gravitational strain can be included within the general alignment error and will be compensated by the M2 active system.