TSPM Optical performance and Error Budget

for f5 Nasmyth

Code: TEC/TSPM-PDR-OP/002

Issue: 1.A

Date: 1/10/2017

Pages: 39

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Distribution List

Name	**Affiliation**
TSPM Team	All partners

Document Change Record

Issue	Date	Section	Page	Change description
1.A	1/10/17	All	All	First issue

Applicable and Reference Documents

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1. SUMMARY

The Telescope San Pedro Mártir (TSPM) on its Cassegrain configuration will be assembled around a closed design (converted MMT/Magellan telescope) with most of its optical parts already manufactured. The circumstances are different for the Nasmyth configuration because it requires a new optical design and the develop of the secondary mirror and WFC lens. The common elements shared between the Cassegrain and Nasmyth are:

- Primary Mirror. University of Arizona. Manufacturing.
- Atmospheric dispersion corrector (ADC).

The goal of this document is to demonstrate the feasibility of a typical Nasmyth configuration and present the error budget regarding optics performance to be able to define the mechanical requirements and a full picture of the expected performance, and identify the critical points involved in the configuration.

2. INTRODUCTION

This document analyzes the optical performance and the error budget for two TSPM F5 Nasmyth configurations: a spectroscopic telecentric mode for 1° FOV and, in section "*Wide field imagining Nasmyth configuration summary*", an image mode for 1° FOV (which is not the principal interest of these document but it is also included).

3. WIDE FIELD SPECTROSCOPIC NASMYTH CONFIGURATION.

3.1 Optical characteristics

The TSPM design in the Nasmyth F5.36 configuration is a three mirror classical Nasmyth system. The principal optical elements are a 6.5m parabolic primary mirror "M1", a hyperboloid secondary "M2", a tertiary mirror "M3", a WFC and the ADC. See Figure 1.

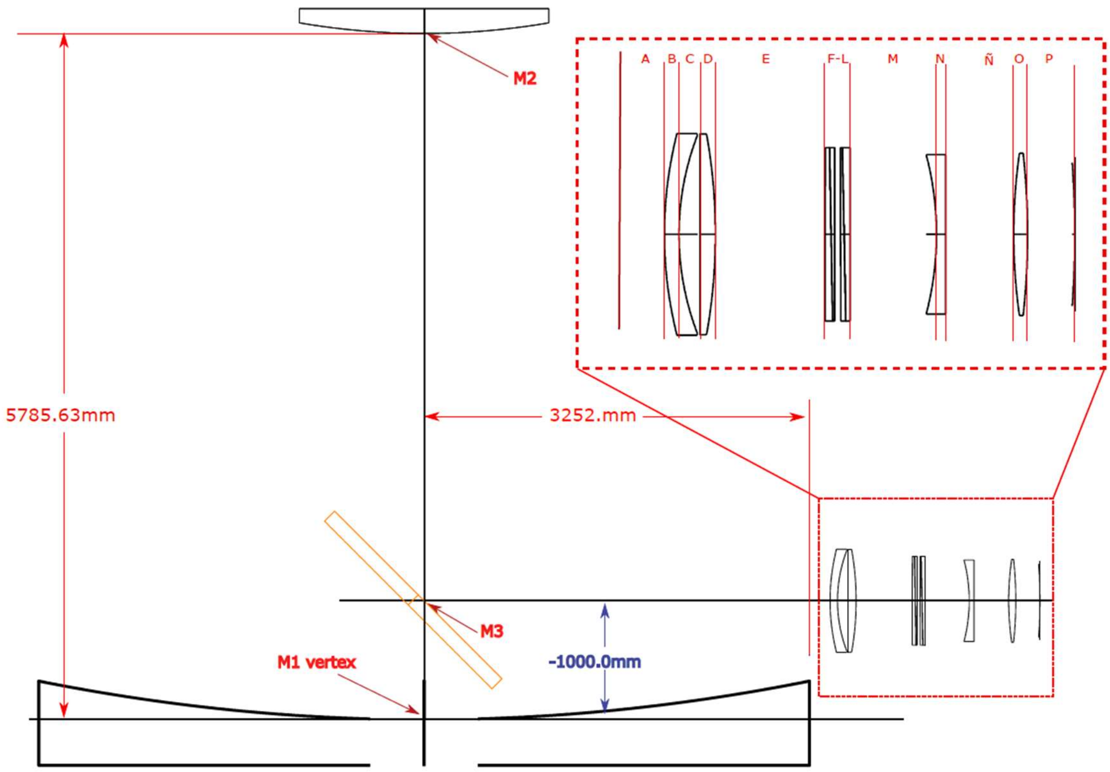

Figure 1. *Position of the optical elements in the Nasmyth configuration.*

A complete list of the elements, subsystems and its optical parameters is shown in Table 1, the notes shown on Figure 1, (A to P) are indicated for easier visualization of the dimensions and the element involved in Table 1.

Element		Curvature radius(mm)	Thickness(mm)	Material	Diameter(mm)	Conic
PRIMARY		-16255.300000	-5785.63	MIRROR	6502.4	-1.0000
SECONDARY		-6128.430731	5785.63	MIRROR	2106.0	-2.5834
			-1000.00		1250.2	
TERTIARY		Flat	-3252.00	MIRROR	1989.9	
	A		-176.48		921.8	
CORR1	B	-1774.100000	-63.00	SILICASCHOTT	870.0	
	C	-1188.900000	-90.00		850.0	
CORR2	D	Flat	-67.50	SILICASCHOTT	866.2	
	E	2445.400000	-473.98		865.5	
ADC_PRISM1	F		-25.40	S-FSL5Y	748.9	
	G		-0.13	CAF2SCHOTT	748.9	
ADC_PRISM2	H		-15.24	PBL6Y	748.9	
	I		-25.71		748.9	
ADC_PRISM3	J		-15.24	PBL6Y	748.9	
	K		-0.13	CAF2SCHOTT	748.9	
ADC_PRISM4	L		-25.40	S-FSL5Y	748.9	
	M		-373.58		750.5	
CORR3	N	1353.840854	-40.00	SILICASCHOTT	685.0	
	Ñ		-293.56		687.1	
CORR4	O	-2469.836412	-60.00	SILICASCHOTT	700.1	
	P	3201.538029	-204.00		698.8	
Image plane		4046.096679			617.9	-71.1352

Table 1. *Nasmyth spectroscopy mode system summary.*

The nominal telescope has strong field curvature as could be expected for this design, the optical design is compromised with the fact that the primary mirror is a parabola, this limits the family of possible solutions for the secondary mirror and thus requires to use a WFC. The wide field corrector is formed with four lenses (CORR 1, 2, 3 and 4), and provides a telecentric curve image plane well corrected on a circular 1.0º FOV. The WFC in the spectroscopic mode uses the ADC provided by the Cassegrain configuration, this element is compound by 4 prisms cemented in pairs, each pair of prisms rotate independently with a dependency of the air mass.

A list of the system elements for the configuration can be seen in Table 4. The Figure 2 (Top) shows the telescope layout with the half FOV ray trace. At the bottom figure the variation on the polychromatic RMS with the field can be seen. It is important to mention that the RMS is not the same for all the wavelengths, as can be seen in Figure 3.

FOV	Plate scale	Image Quality	Wavelength range	Focal curv.
1.0º	169 µm/"	0.138" average in wavelength and field	0.35 -1.00 µm	Curve R=4046mm K=-71.13

Table 2. *Nasmyth configuration spectroscopy summary.*

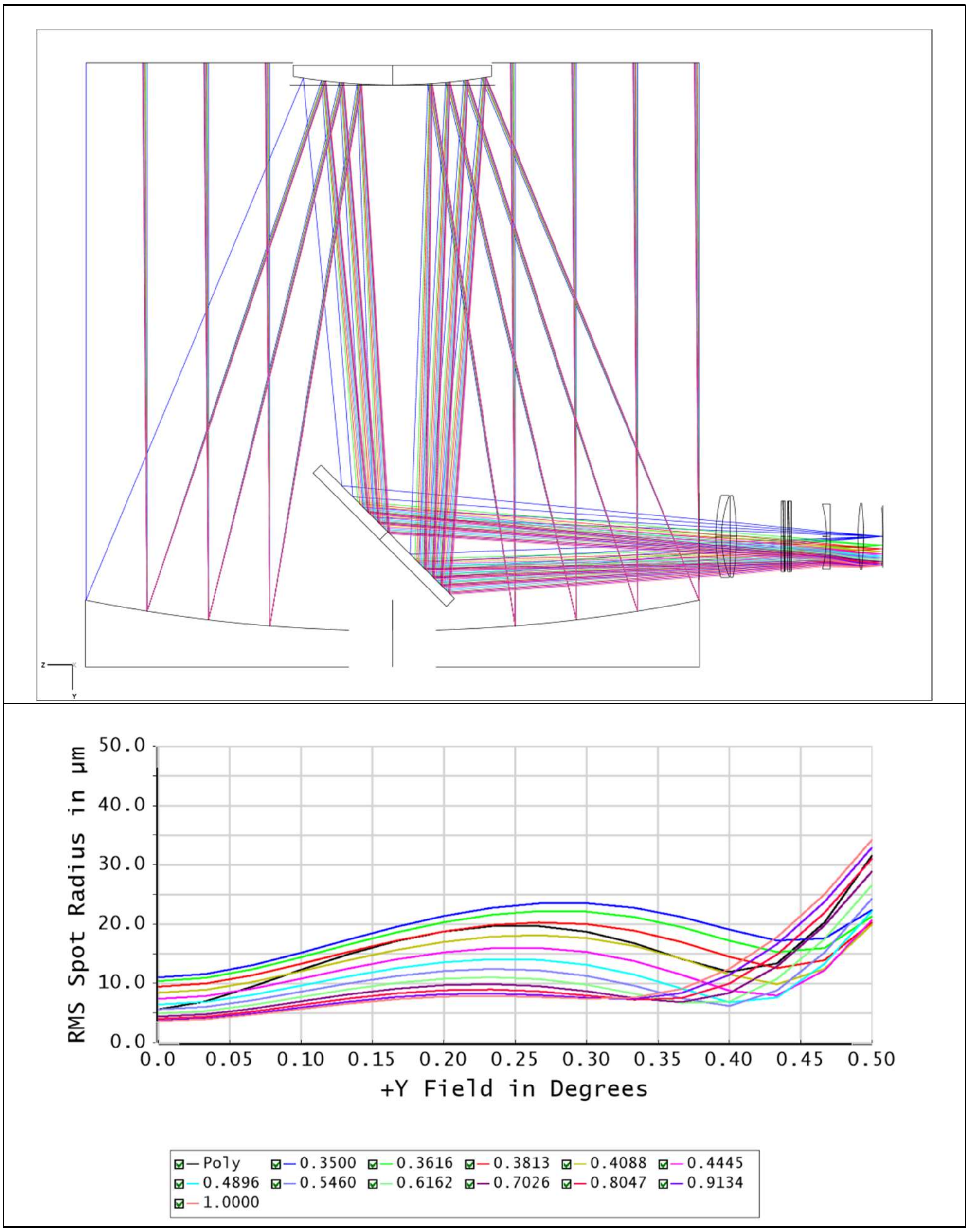

Figure 2. *Telescope layout (top). The spot RMS vs field (bottom). Notice the degradation in the edge of the field.*

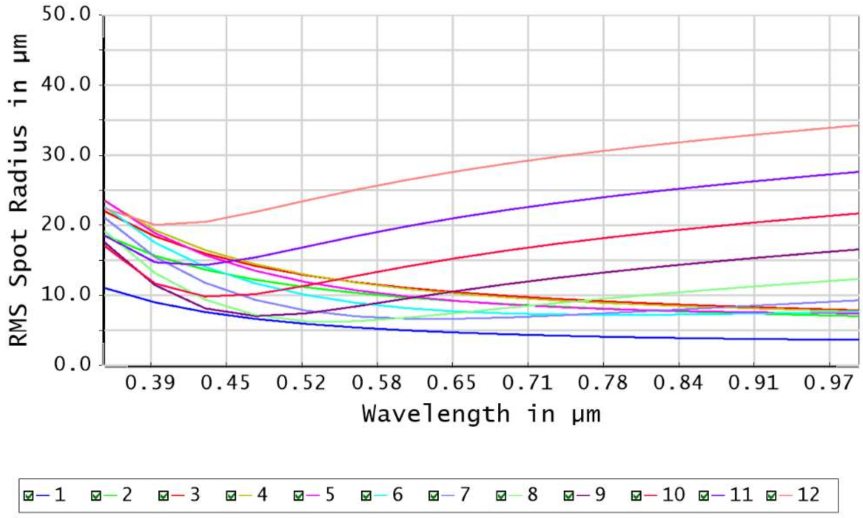

Figure 3. *RMS spot vs. wavelength, each line represents a different field.*

To give the reader an idea of the resulting image quality, in Figure 4 it is shown the spot diagram over the field, the circular region represent 1.0" or 169µm. It can be seen the degradation given by the change in the wavelength caused by the chromatic aberration, this can also be seen in Figure 3.

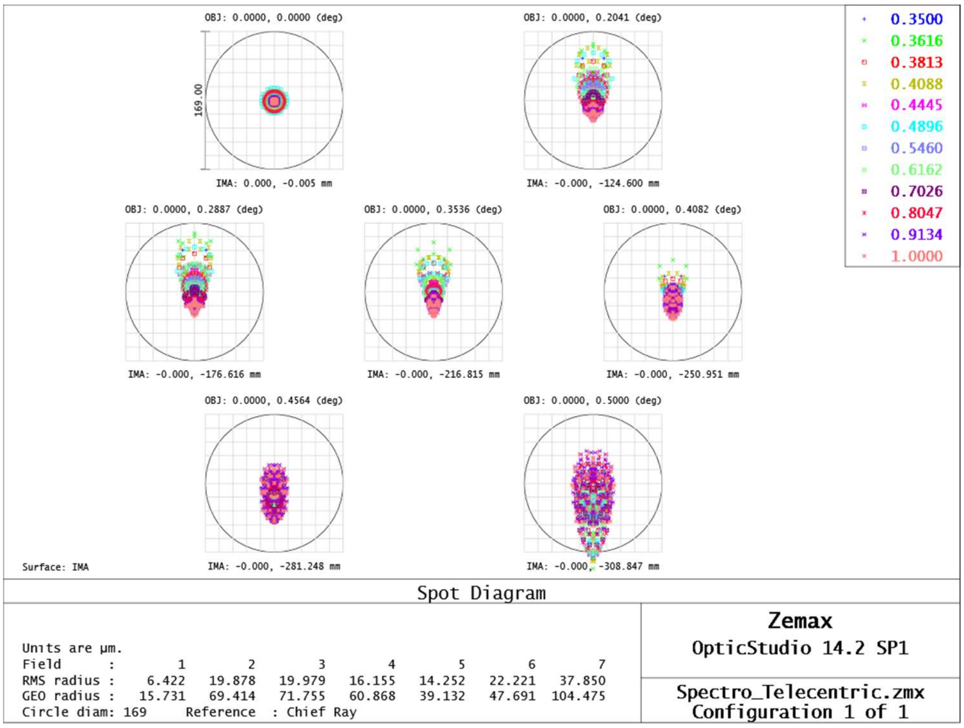

Figure 4. : *Spot diagrams over fields.*

The system vignetting is not caused by the corrector, then the only vignetting must be due to the obstruction that the secondary mirror generates. Table 4 shows the areas of M1 and M2, and the total collector area of the telescope.

Element	Semi - diameter (mm)	Area(m^2)
Primary	3251.20	33.21
Secondary	1053.00	3.48
	Total used area	29.72
	Percent non overshadowed M1	89.5%

Table 3. *Relation of M1 and M2 areas and vignetting.*

In Figure 5, it is shown vignetting diagram across the 1º FOV (provided unvignetted by the corrector).

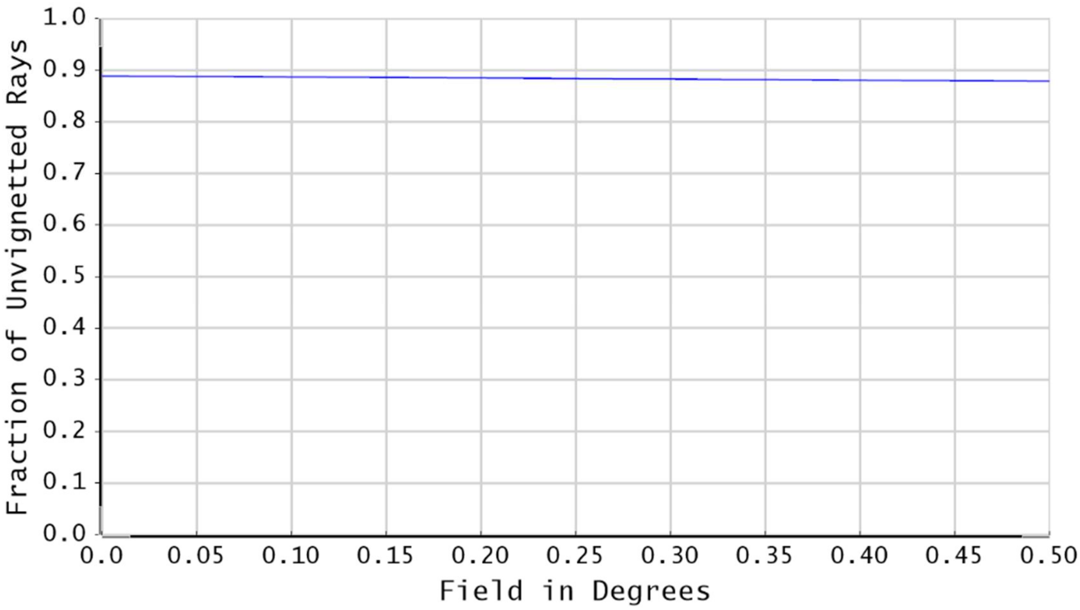

Figure 5. *Vignetting diagram.*

The diameters of the elements of the system could also generate vignetting. In the case of the tertiary mirror, Figure 6 shows the footprint on the mirror surface for the FOV sagittal and tangential, it can been see that the mayor and minor axis of the ellipse (a= 1440mm, b=2000mm) are sufficient to cover all the required field and a little more to avoid common polishing problems and on the other hand, avoid vignetting.

The wide field corrector for spectroscopy is telecentric and present field distortion and field curvature, see Figure 7, left. It should be noted that performing the evaluation on the curved image plane (Figure 7, center) makes evident the displacement of the image plane for different wavelengths.

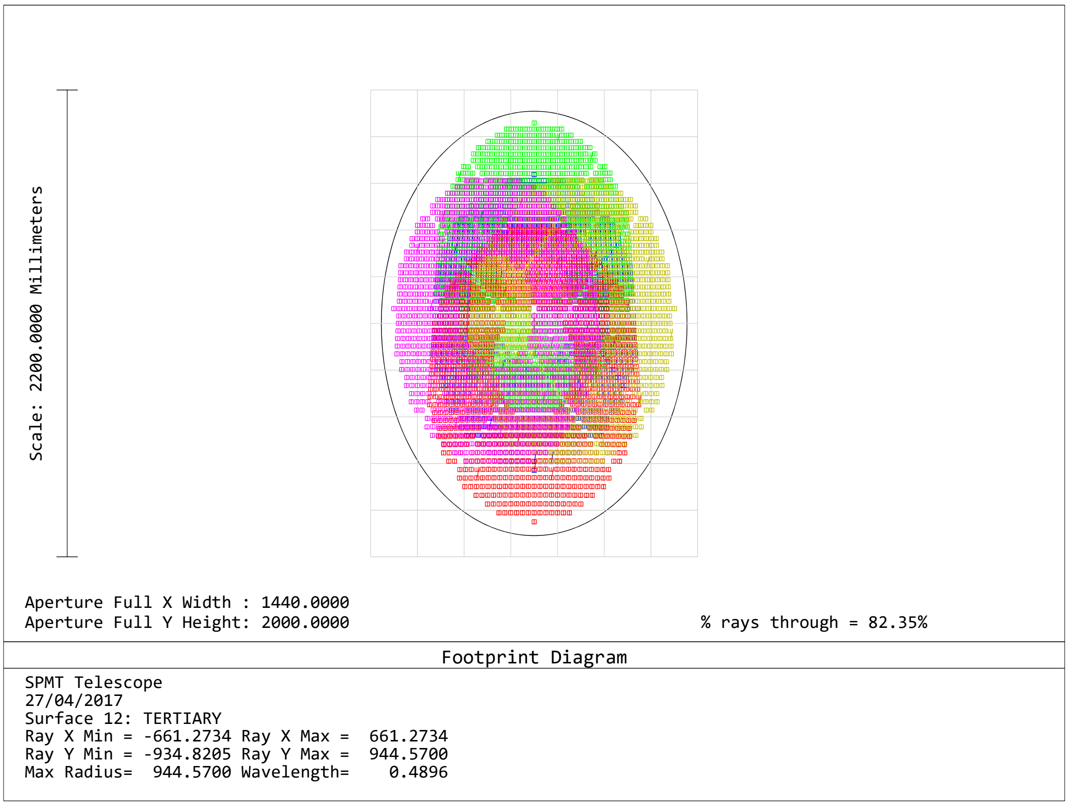

Figure 6. *Tertiary mirror (M3) footprint with different fields.*

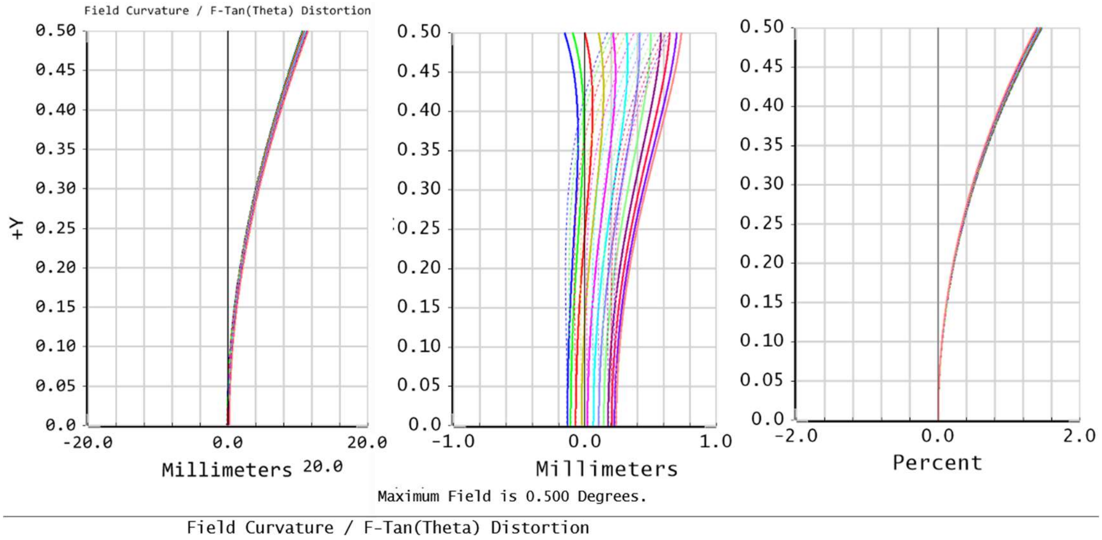

***Figure** 7. On the left, the field curvature after the corrector, (center) Image plane without the influence of the curve image plane. On the right, the distortion. Maximum field off axis is 0. 5º (1.0º diameter FOV). Maximum distortion in percentage is 1.42%.*

The distortion produces that the plate scale changes across the image plane. Table 4 shows the variation of the RMS polychromatic and the plate scale with the field position.

Field(Deg)	Effective focal lenght(mm)	Plate scale(µm/")	FWHM (")
0	34888.45	169.144	0.069
0.05	34903.18	169.215	0.075
0.1	34946.89	169.427	0.095
0.15	35020.29	169.783	0.120
0.2	35123.40	170.283	0.139
0.25	35258.05	170.936	0.146
0.3	35425.29	171.747	0.139
0.35	35627.09	172.725	0.119
0.4	35865.67	173.882	0.105
0.45	36143.78	175.230	0.127
0.5	36464.01	176.782	0.215

***Table 4.** Off axis plate scale changes (Polychromatic)**,** Effective focal length and image quality (FWHM) variation with field (Polychromatic).*

Considering the average plate scale of 171 µm /", the spot size in arc seconds is:

$$FWHM_{average} = 0.122''$$

$$FWHM_{max} = 0.215''$$

Another view of the field distortion shape is in Figure 8.

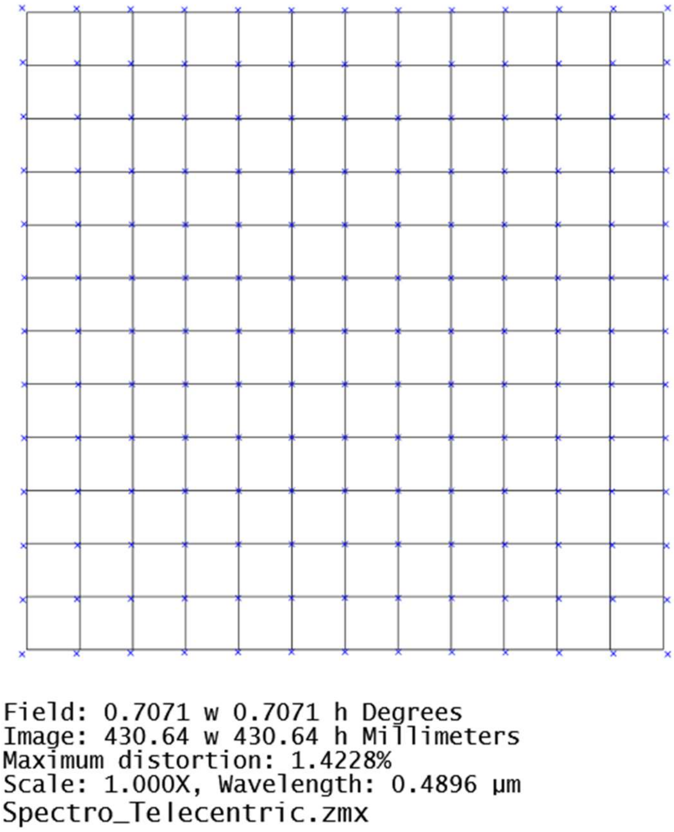

Figure 8. *Image distortion for a 1º full FOV.*

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

Exit pupil position	Exit pupil diameter
-534780.2 mm	99650.53 mm

Table 5: *Exit pupil parameters.*

3.2 Summary of optical requirements for image quality

The main requirements are:

- FOV 1.0º in diameter in wide field spectroscopy.
- Image quality can degrade 12% the FWHM at 0.5" (Wavelength 0.5μm).
- Wavelength range from 0.35μm to 1.0μm.

3.3 Error Budget summary

The error budget summary is given in Table 6. Although the grand total budget is given in terms of FWHM in arc seconds, different budget pieces are allocated through fried parameter r_0. For a comprehensive detail about these specifications and how to change between them see 5.2.

Item	FWHM(")	R0(m)
Nominal performance	0.1300	
M1 manufacturing, High order with AU contract	0.1840	>0.91m
M1 Manufacturing Errors. Low order.	0.0154	
M1 Manufacturing Errors. Uncertainties	0.0537	
M2 Manufacturing Errors. Low order	0.0124	
M2 Manufacturing Errors. Uncertainties	0.0411	
M2 manufacturing. High order	0.0399	>2.53m
M3 manufacturing. Surface irregularity and curvature	0.0217	
M3 high order. Structure function	0.0200	>5.06m
Corrector Fabrication	0.0400	
Corrector Aligment	0.0436	
Telescope Alignment	0.0504	
M2 Hexapod Residuals	0.0175	
Thermal. Compensation residual	0.0083	
Thermal-0.05 deg(C)	0.0372	
Guiding	0.0300	
M3 cell	0.0110	
M2 cell	0.0505	
Seeing	0.5000	
Total	0.5653	

Table 6: *Spectroscopic error budget summary table.*

This error budget contains the main error sources that can be modeled with a reasonable effort. Nevertheless, it could be expected 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. For completeness to the error budget, in the Table 7 are shown the compensators for all items involved in the tolerances performed for the error budget.

Item	M2					Corrector	Image plane
Compensator	Axial Z(mm)	Lateral X(mm)	Lateral Y(mm)	Tilt X (Deg)	Tilt Y (Deg)	Z(mm)	Z(mm)
M1 Manufacturing Errors. Low order.	3.124					17.084	0.238
M1 Manufacturing Errors. Uncertainties	0.918						
M2 Manufacturing Errors. Low order	1.667					14.035	0.233
M2 Manufacturing Errors. Uncertainties	0.108						
M3 manufacturing. Surface irregularity and curvature	0.005						
Corrector Fabrication	0.132						1.403
Corrector Aligment	0.016	0.614	0.564	0.013	0.014		
Telescope Alignment	1.841	0.280	0.358	-0.009	0.007		
Thermal. Compensation residual	1.131						

Table 7. *Compensators for tolerance on different items on the error budget*

3.4 Nominal design

The optical quality of the nominal design will be measured in terms of FWHM. The FOV will sample with 12 fields and 12 wavelengths, the merit function is built to evaluate directly the radius to the 50% of the encircled energy in two dimensions and to process the average, in that way the tolerance analysis provide directly the FWHM in arc seconds ("). For completeness and in order to compare with the Cassegrain configuration the encircled energy plots are shown for both configuration in Figure 9 (Cassegrain) and Figure 10 (Nasmyth). The image quality summary in terms of the spot radius RMS (μm) over all the fields and wavelength is shown in Table 8.

Wavelenght		Poly	0.350	0.362	0.381	0.409	0.445	0.490	0.546	0.616	0.703	0.805	0.913	1.000	
Field (Deg)	0.00	5.62	11.03	10.40	9.47	8.43	7.40	6.45	5.63	4.95	4.41	4.01	3.76	3.65	Spot radius RMS (μm)
	0.03	7.01	11.60	10.96	10.01	8.94	7.88	6.91	6.06	5.36	4.79	4.37	4.09	3.95	
	0.07	9.54	13.12	12.43	11.42	10.29	9.16	8.11	7.19	6.41	5.77	5.28	4.93	4.74	
	0.10	12.32	15.18	14.43	13.32	12.06	10.81	9.65	8.61	7.72	6.98	6.39	5.95	5.70	
	0.13	14.94	17.41	16.57	15.33	13.93	12.52	11.21	10.03	9.01	8.16	7.46	6.93	6.61	
	0.17	17.15	19.55	18.61	17.22	15.64	14.06	12.57	11.24	10.09	9.11	8.32	7.72	7.34	
	0.20	18.77	21.38	20.33	18.77	17.01	15.24	13.58	12.09	10.81	9.73	8.86	8.19	7.79	
	0.23	19.66	22.75	21.58	19.85	17.89	15.93	14.10	12.46	11.06	9.90	8.98	8.31	7.90	
	0.27	19.68	23.50	22.21	20.30	18.15	15.99	13.99	12.22	10.74	9.56	8.66	8.05	7.71	
	0.30	18.72	23.54	22.12	20.02	17.66	15.31	13.15	11.29	9.79	8.69	7.97	7.57	7.43	
	0.33	16.78	22.77	21.21	18.91	16.33	13.79	11.50	9.63	8.28	7.51	7.26	7.37	7.60	
	0.37	14.12	21.21	19.49	16.97	14.17	11.46	9.13	7.48	6.72	6.84	7.53	8.39	9.09	
	0.40	11.96	19.09	17.22	14.50	11.52	8.78	6.83	6.21	6.95	8.39	9.99	11.45	12.48	
	0.43	13.38	17.24	15.31	12.60	9.88	7.97	7.63	8.82	10.76	12.87	14.88	16.61	17.81	
	0.47	20.30	17.61	15.96	13.93	12.46	12.24	13.32	15.25	17.51	19.80	21.93	23.78	25.05	
	0.50	31.61	22.41	21.35	20.31	20.00	20.70	22.26	24.34	26.64	28.94	31.09	32.96	34.27	
Average		15.72	18.71	17.51	15.81	14.02	12.45	11.27	10.53	10.17	10.09	10.19	10.38	10.57	
Maximum		31.61	23.54	22.21	20.31	20.00	20.70	22.26	24.34	26.64	28.94	31.09	32.96	34.27	
Minimum		5.62	11.03	10.40	9.47	8.43	7.40	6.45	5.63	4.95	4.41	4.01	3.76	3.65	

Table 8. *Spot radius RMS variation with field and wavelength.*

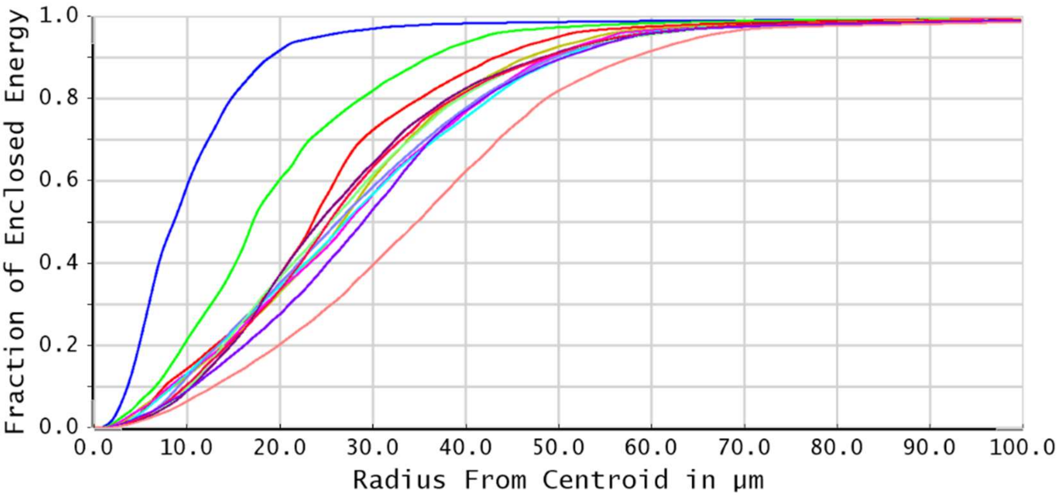

Figure 9. *Encircled energy plot for all the fields and wavelengths Cassegrain configuration, spectroscopic mode 1.0 FOV.*

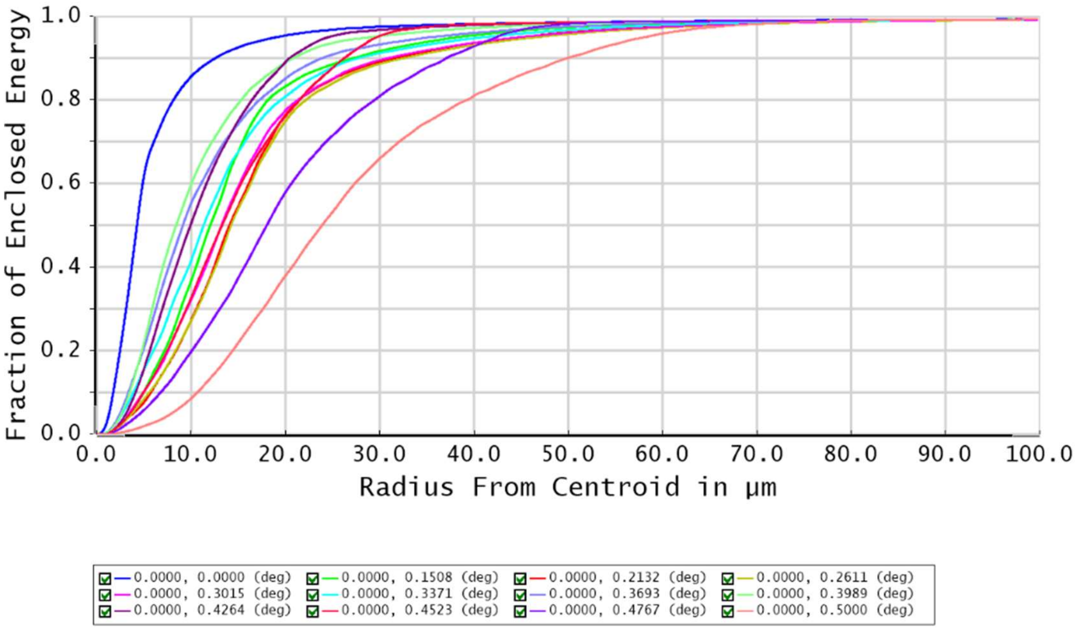

Figure 10. *Encircled energy plot for all the fields and wavelengths, Nasmyth configuration, spectroscopic mode 1.0 FOV.*

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 9.

ROC	CC
-16255.3 ± 3mm	-1 ± 0.0002

Table 9: *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.

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.

Degradation results are shown in Table 6.

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. The uncertainties in the measurement provided by UA have been used.

ROC	CC
-16255.3 ± 1mm	-1 ± 1x 10^{-4}

Table 10. *M1 error uncertainties.*

Degradation results are in Table 6.

3.7 M1. Manufacturing Errors. High order

The UA has specified 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 appendix 5.1.

The specifications for the structure function are summarized in Table 11. 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 11: *M1 summary surface quality specifications.*

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

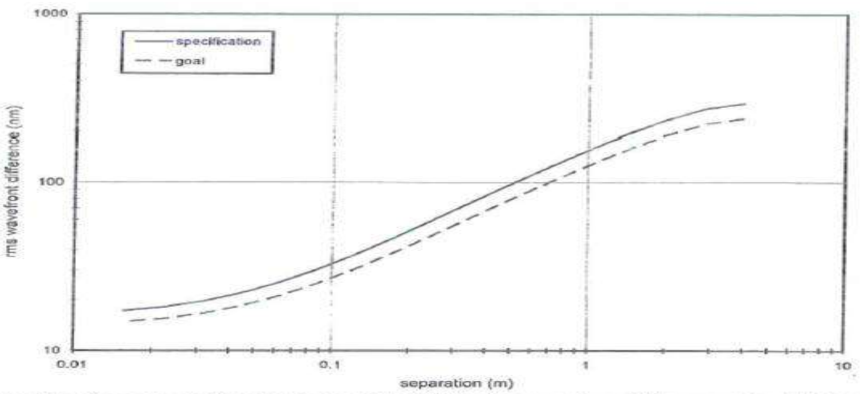

Figure 1. Specification and goal for the figure of the TAO primary mirror. The quantity plotted is the square root of the wavefront structure function, i. e. the rms wavefront difference between points in the aperture as a function of their separation.

Figure 11. *TSPM M1 structure function specification.*

For details about this function see appendix (Kolmogorov structure function).

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 5.2.2 for details.

Error Source	Image FWHM at zenith (arcsec)	r_0 at zenith (cm)	Image FWHM at 30° elevation (arcsec)	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 12: *M1 grand total budget updated to r_0 = 91cm specification. Notice that the total error is not obtained with the quadratic 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 12), 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.
- The process needs to be repeated 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. The manufacturing tolerances to be used (TBC) are in Table 13.

The as-built results will be compensated with the following variations in positions

- Compensate with M2-M1 distance.

- Compensate with corrector/focal plane position.
- Compensate back focal distance.

ROC (mm)	CC (mm)
6128.431 ± 2 mm	-2.5834± 0.001 mm

Table 13: *M2 Low order tolerances. Tolerance corresponds to measurement uncertainties.*

Degradation results are in Table 6.

3.9 M2 Manufacturing Errors. Low order. Uncertainties

CC and ROC uncertainties cannot be compensated. Just M2 focus position can be used. A Monte Carlo analysis was performed (uniform probability within tolerances),

ROC (mm)	CC (mm)
6128.431 ± 0.202 mm	-2.5834± 0.0004 mm

Table 14: *M2 Low order tolerances. Tolerance correspond to measurement uncertainties.*

Degradation results are in Table 6.

3.10 M2 Manufacturing Errors. High order

The mirror specification is given following the Magellan M2 methodology. It is allocating the same specification room for high order errors (low order errors are not considered as will be compensated with M1 active system and CC /ROC tolerance compensation procedure).

The original specification is shown in Table 15.

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

Table 15: *M2 original specification*

The M2 mirror acceptance test shall be obtained computing the structure function from the interferogram. Computing the RMS wavefront (structure function from the interferogram), the results shall be done in a similar way as reported by Magellan in Figure 12. It can be seen that at mid frequencies the error is larger than specified while at low frequencies is much lower.

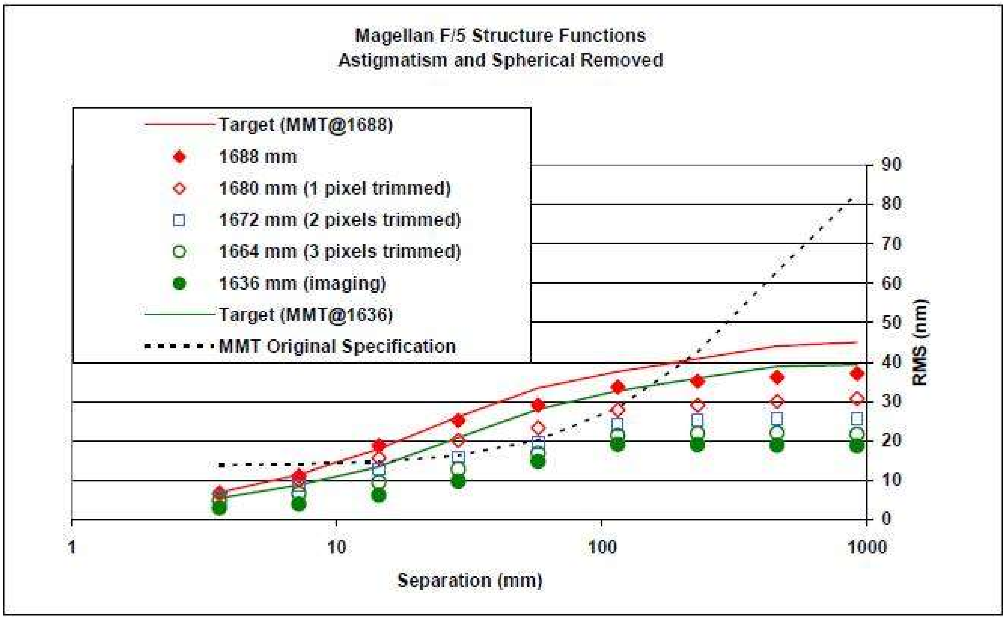

Figure 12. *Structure function measured results and original specification.*

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 16.

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 16: *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".

See in Table 6.

The model we obtain for the original specification is given in Figure 13: **RMS wavefront function for M2 with r0=2.53mts.**

Model. FWHM = 0.04”, $r_0 = 2.53$ m

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

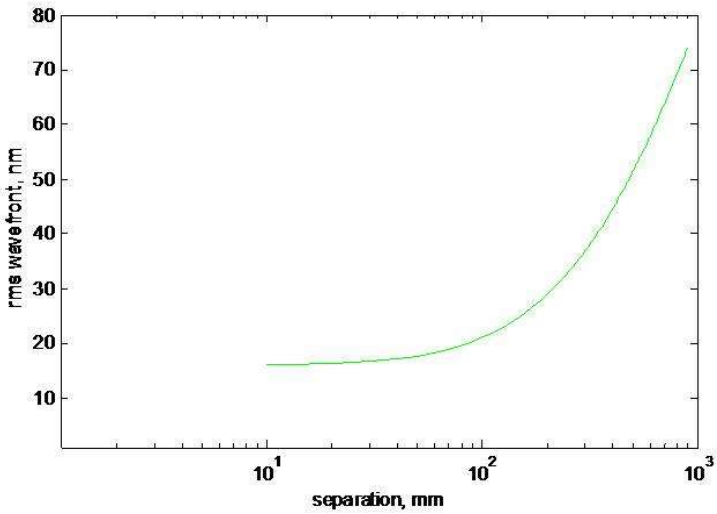

Figure 13: *RMS wavefront function for M2 with r0=2.53mts.*

3.11 M2 mechanism 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 position shall be adjusted by a vane-end mechanism, which shall provide the resolution shown in Table 17.

	Dx (mm)	Dy (mm)	Dz (mm)	Rx (“)	Ry (“)
M2 accuracy	± 0.003	± 0.003	± 0.001	± < 0.5	± < 0.5

Table 17: *M2 mechanism resolution mechanism*

As the system cannot provide better adjustment than the mechanism resolution, the error associated to this system has been evaluated. A 200 Monte Carlo analysis (uniform statistics within the tolerance range) was done with the previous tolerances and no compensation of any type. Degradation results are in Table 6.

It is important to mention that the precisions included in this section are those that have been requested throughout the range of the mechanism to guarantee the optical performance, however, it has been demanded better incremental precisions that shall apply to smaller range and a better measurement resolution. See: SP/TSPM-TL-SM/001.

3.12 M3 low order. Curvature. Irregularity

M3 curvature tolerance given by the irregularity of the surface (departure from flatness in fringes) as well as a combination of spherical + astigmatism is considered. For a 200MC (uniform tolerance distribution) Degradation results are in Table 6.

ROC fringe	Irreg (1/2spher+1/2 astigmat)
± 1	± 1

Table 18: *M3 Low order tolerances. Tolerance correspond to measurement uncertainties in interference fringes.*

3.13 M3 high order. Structure function

The same polishing specification as for M2 has been used. As the M3 used footprint is half M2 footprint the equivalent r0 scales to twice at the grand total budget.

For the error budget M2 r0=253 cm is equivalent **M3 r0=506 cm** at the pupil budget. In any case the polishing spec scales a factor 6.5 to the surface so the polishing spec will have an error of r0=78cm. See contribution to the image quality in Table 6.

3.14 M2 and M3 supports

The design of the M2 and M3 are honeycomb to minimize the weight and flexion on the optical surfaces, the structural design is considering the strategy to hold the mirror in the better form possible to minimize the effect of the supports in touch with the mirrors. Unfortunately, in both cases the static support is not enough and each mirror need an active cell.

To calculate the contribution or the effects of the cells to the final image quality it was performed a FEA analysis. For more information, see documents (TSPM Subsystem M3 and M2). The easier way to modeling in Zemax the contributions given by the deformation of the optical surface is with grid sag element.

The contribution of the M3 active cell is 0.011” in terms of FWHM, in the case of M2 the mechanical design is not complete and don’t include active system, the contribution is 0.107” in terms of FWHM which is unacceptable. The error budget for the Nasmyth spectroscopic configuration (0.565” FWHM) do not fulfill the requirement of 12% in degradation from the seeing (0.5” FWHM), however is better than the 0.71” given by the Cassegrain spectroscopic configuration. The error budget presents a value of 0.0505” FWHM, which is the maximum allowable to fit the error budget at least for an image configuration. The design of the active optics for M2 is in development and will be done in the future. Degradation results are in Table 6.

3.15 Corrector fabrication

The tolerances for the fabrication of the elements in the corrector are shown in Table 19, a compensator for the axial position of M2 and the position of the image plane has been used, see Table 7. Degradation results are in Table 6.

Corrector fabrication							
		Nominal R(mm)	R(mm)	Fringes (curvature)	Thickness(mm)	Wedge(Deg)	Irregularity (Ast+Sph) Fringes
	Sup 1	-1774.1	±1	-	±3		±1
Corr 1	Sup 2	-1188.9	±1	-	±3	±0.0141	±1
	Sup 1	flat	-	±1	±3		±1
Corr 2	Sup 2	2445.4	±1	-	±3	±0.0141	±1
	Sup 1	1353.841	±1	-	±3		±1
Corr 3	Sup 2	Flat	-	±1	±3	±0.0141	±1
	Sup 1	-2469.836	±1	-	±3		±1
Corr4	Sup 2	3201.538	±1	-	±3	±0.0141	±1

Table 19. *Corrector fabrication tolerances.*

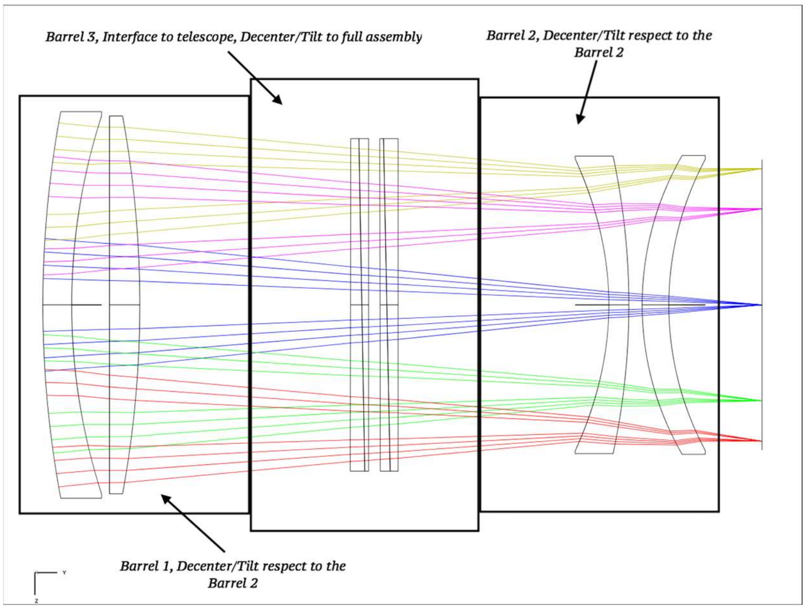

Figure 14. *WFC and ADC. The barrels 1 and 3 are hold by barrel 2 in the geometrical center of the corrector system.*

3.16 Corrector alignment.

The corrector barrel is made of three subassemblies, B1, B2 and B3, B2 is the interface to the elevation ring. Thus, only tolerances of B1 and B3 barrels will be considered here. B2 alignment (full assembly) is shown in Figure 14. Table 20 shows the tolerances in the elements, the degradation in the image quality associated with these tolerances is shown in Table 6. Is important to mention than the tolerances in this section and in the section "Telescope alignment Errors" are governed by the differential distortion budget

Corrector aligment	Barrel 1 Corrector 1 Corrector 2 Barrel 3 Corrector 3 Corrector 4
thickness(mm)	**0.1**
Desp X(mm)	**0.14**
Desp Y(mm)	**0.14**
Tilt X(Deg)	**0.013**
Tilt Y(Deg)	**0.013**

Table 20: *Elements alignment tolerances within each barrel.*

3.17 Telescope alignment Errors

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

Telescope alignment	M1	M3	B2	Nasmyth rotator
thickness(mm)	±1	±0.2	±1	±1
Desp X(mm)	±1		±0.1	±0.13
Desp Y(mm)	±1		±0.1	±0.13
Tilt X(Deg)	±0.0083	±0.006	±0.0055	±0.0083
Tilt Y(Deg)	±0.0083	±0.006	±0.0055	±0.0083

Table 21. *Telescope alignment tolerances*

The greatest strain is M2 lateral displacement at low elevations. But this is not an issue, as M2 will be mounted on a mechanism that will move to its optimal position with a WFS feedback.

There are four opto-mechanical blocks in the f5 Nasmyth configuration; M1, M2, M3 and corrector Barrel "B2". Specific interface was defined from the mechanical design for each block.

To obtain the alignment tolerances, we must define a reference system for all the interfaces. The mechanical design coordinate system was placed in the virtual opto-mechanical axis where is not an accessible point, so it is necessary to define a procedure to align the elements M1 and M2 to the Cassegrain optical axis and determine the Nasmyth optical axis to align M3, WFC, ADC and instrument.

The optical model has been adapted to allow the four optical blocks to move about their interfaces, see Figure 15.

- M1 optical axis moves in its cell with the tolerances reported by UA of ±1mm.
- M3 moves in its cell with the tolerances obtained iteratively with the Monte Carlo analysis.
- M2 is a compensator that can be moved anywhere with the mechanism. A record of the required ranges to be adjusted is obtained.
- The Barrel 2 can be moved about its interface inside telescope structure.
- The field flattener and focal plane is moved about the rotator interface.

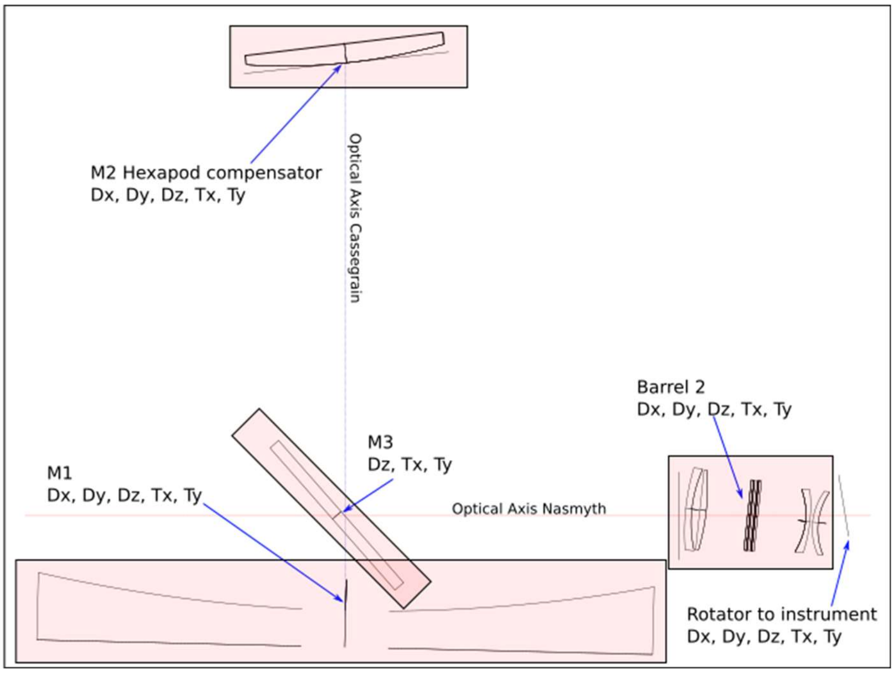

Figure 15: *Optical layout showing examples of different movements of the optical blocks about their interfaces. DX, DY and DZ is for decenters while Tx and Ty is for tilts.*

The final set of values considered is shown in Table 21. M2 is the only compensator, mounted in its mechanism, it is free to move to the optimum position to minimize the spot rms, M1 and M3 absolute position and tilts are the worst offenders. See contribution to the image quality in Table 6.

3.18 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.

3.18.1 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 ULE.
- M3 mirror will almost be fixed because is made of ULE.

- Change in the optical axis position of the four interfaces considering a steel structure, CTE = 12 x 10^{-6} (TBC).
- Change within the four 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.

The error budget includes two different contributions due to the temperature:

The "***Thermal compensation residual"*** is the residual contribution originated from moving the secondary mirror to practically recover the optical performance. Image degradation over the analyzed temperature (-5°C to 20°C) range is 0.0083".

The ***"Thermal -0.05 deg(c)"*** is maximum degradation on the image quality (0.037") over all the temperature range compensating with M2 and including an error of 0.05°C on the thermometers resolution. The calculations are similar to those made for "***Thermal compensation residual***", then a change is made in the system temperature by 0.05°C where M2 is not used to compensate.

Thermal T(-5° to 20° C)	
Nominal	0.001
Best	0.037
Worst	0.039
Mean	0.038
Std Dev	0.0004
Compensator Statistics:	
M2 Z(mm)	
Nominal	-0.005
Minimum	-0.902
Maximum	0.159
Mean	-0.338
Std. Dev.	0.258
90% >	0.0384
80% >	0.0380
50% >	0.0376
20% >	0.0375
10% >	0.0375

Table 22: *Thermal effects within the operation range, tolerances are running compensating with secondary position within an error of 0.05C.*

1.000	0.500	0.250	0.125	0.063	0.050	ºC
0.63	0.28	0.11	0.016	0.039	0.037	FWHM(")

Table 23. *Image degradation with a temperature variation from 0.05 ℃ to 1.0 ℃ without correction.*

Major offender is coming from the distance between M1 and M2 (6 m of steel). An active correction at the level of 0.05ºC or better, using temperature sensors in the truss structure connecting M1 and M2, will be included. A change of 0.05ºC would give degradation 0.037". 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.

3.19 Differential distortion

In this section is presented the result of the differential distortion budget applied to Nasmyth in spectroscopic configuration. For a complete explanation of the problem see document (*TEC/TSPM-PDR-OP/003-Distortion Error Budget for f5 Cassegrain*). This section uses the same procedure to obtain the contributions in Table 24.

The alignment tolerances used to determine the differential distortion are the same from the error budget in Table 21 and Table 20. The requirements for the alignment given by the distortion budget are very rigid, much more than requirements imposed by the image quality error budget.

Distortion budget		
ITEM	Movement (")	
Nominal	0.000	
Telescope Alignment	0.118	200 MC

Corrector Alignment	0.199	200 MC
ADC bore sight	0.110	No data. Allocated budget
Total	0.257	

Table 24. *Distortion budget summary.*

We have allocated 0.25" of differential shift for this budget piece (total budget from Cassegrain 0.3"). We have used Zemax and the differential shift has been computed for two objects separated 0.5º. At this position we obtain the maximum shift within the 1º FOV, so this is the worst case scenario.

The parameters that introduce a decenter in the optical axis are tilts, decenters and lens wedges. Axial movements do not affect the results. As the field corrector is not already manufactured, making the analysis of this piece has sense in difference with Cassegrain configuration. We allocated some of the budget to the boresight of the corrector and will focus our work on the alignment of the different pieces: M1, M2, M3, WFC and Rotator interface.

4. WIDE FIELD IMAGINING NASMYTH CONFIGURATION SUMMARY

4.1 Optical characteristics

The image mode in the Nasmyth configuration is not the first priority in this stage of the project; nevertheless it has been also analyzed. This mode doesn't use the ADC but uses the first two lens of the corrector re located in a different place. It needs a new set of lenses for the last barrel. All the system tolerances used for the error budget are the same as the used in the spectroscopic mode. Table 25 shows the system summary with the main characteristics of the optical elements which can be seen in the configuration layout Figure 16.

Comment	Curvature radius(mm)	Thickness(mm)	Material	Diameter(mm)	Conic
PRIMARY	-16255.30	-5784.22	MIRROR	6502	-1.00
SECONDARY	-6128.43	5784.22	MIRROR	2106	-2.58
		-1000.00		1254	
TERTIARY	Flat	0.00	MIRROR	1994	
		-3526.73		926	
		-274.73		926	
CORR1	-1774.10	-63.00	SILICASCHOTT	870	
	-1188.90	-219.16		850	
CORR2		-67.50	SILICASCHOTT	853	
	2445.40	-1036.00		852	
CORR3	806.20	-55.00	N-BK7	655	-2.02
	2205.30	-22.86		666	
CORR4	-660.50	-55.00	SILICASCHOTT	670	
	-691.10	-169.78		655	
Image plane				656	

Table 25. *Nasmyth imagining mode system summary.*

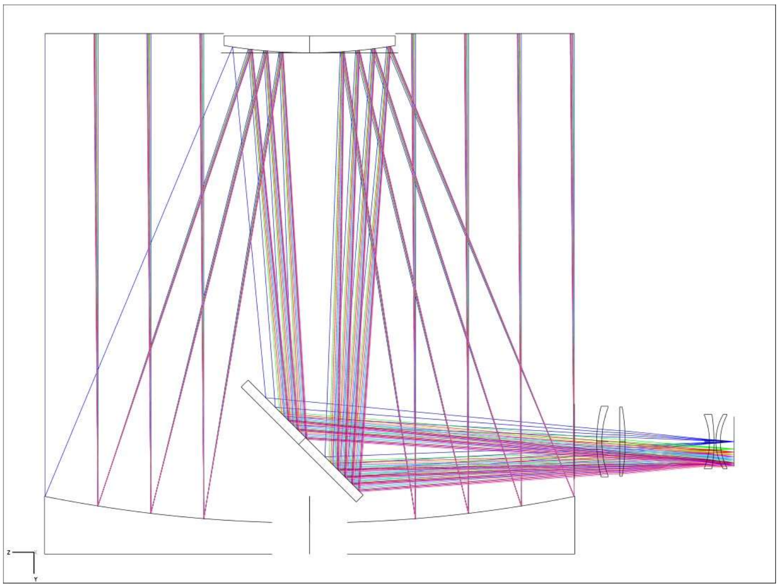

Figure 16. *Nasmyth imagining layout.*

Figure 17 shows the spot diagram over the field; the circular region represents 1.0”. or 169µm., The variation of the spot RMS across the field can also be seen in more detail in Figure 18.

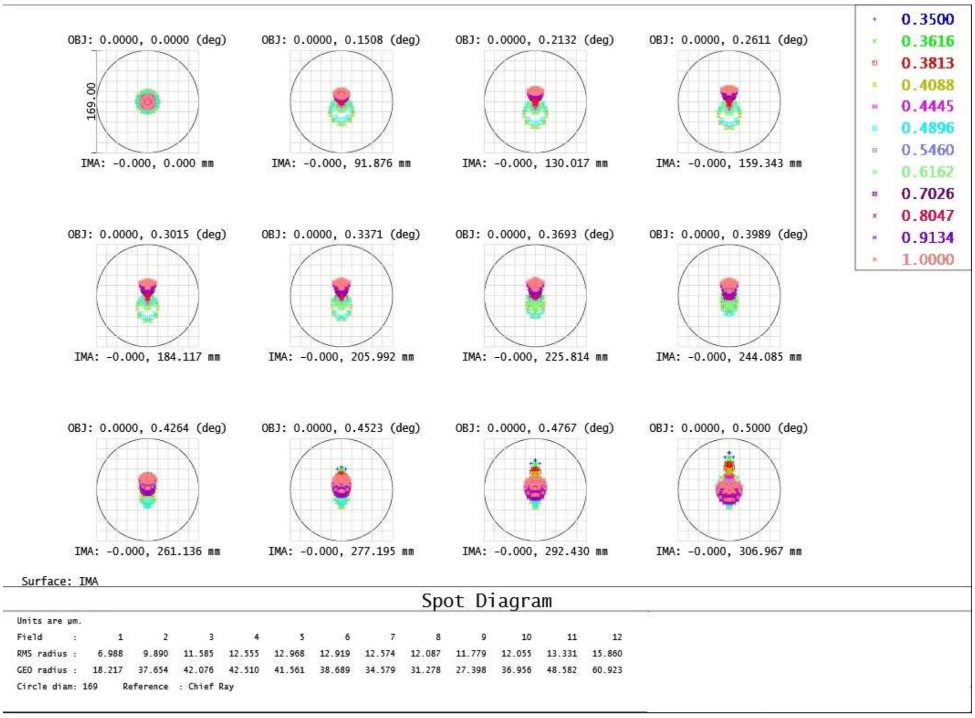

Figure 17. *Imagining mode spot diagram, the circle corresponds to 1".*

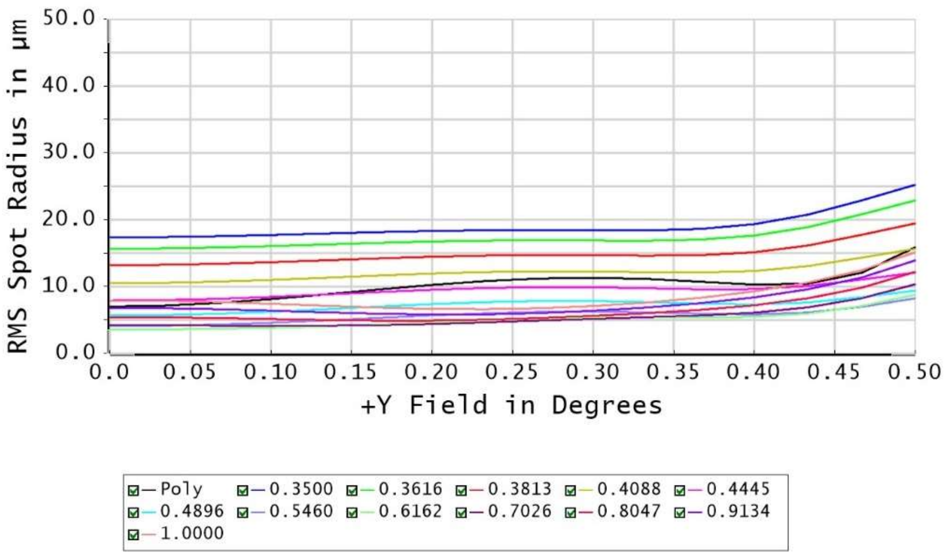

Figure 18. *RMS spot radius across the field.*

As can be expected for an imagining mode, the image plane is flat, Figure 19 shows the image plane deviation for each different wavelength, the image planes are symmetrical around the flat image plane. Also, as can be expected in this case there is distortion on the image as can be seen in Figure 19 and Figure 20, the maximum distortion is 0.8%, much less than in the spectroscopic mode.

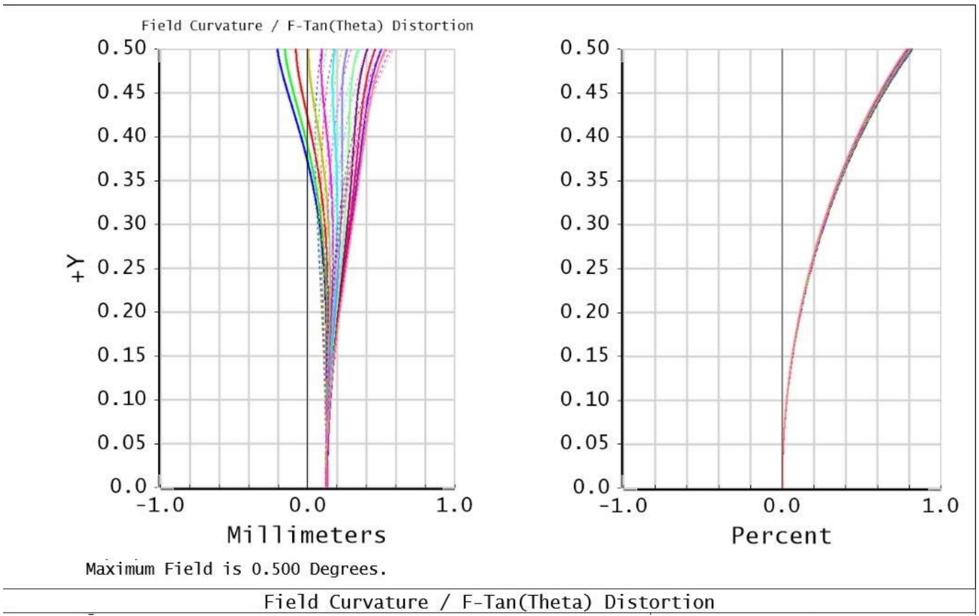

Figure 19. *Field curvature and distortion.*

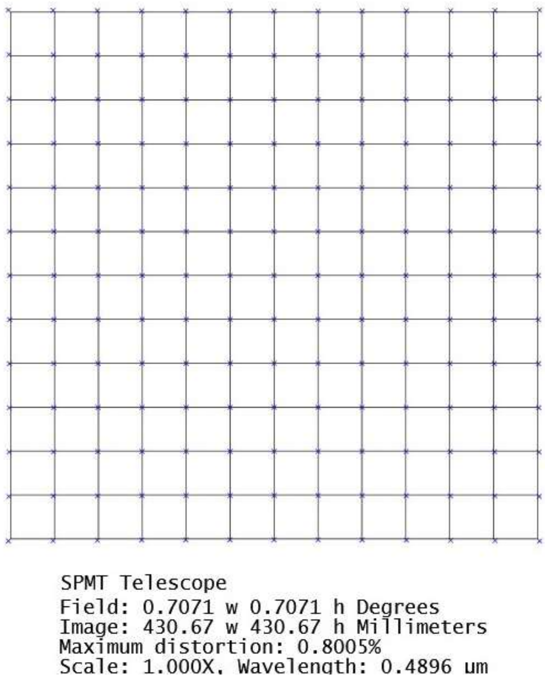

Figure 20. *Distortion grid.*

The image quality error budget is shown in Table 26.

Item	FWHM(")	R0(m)
Nominal performance	0.0914	
M1 manufacturing, High order with AU contract	0.1840	>0.91m
M1 Manufacturing Errors. Low order.	0.0143	
M1 Manufacturing Errors. Uncertainties	0.0370	
M2 Manufacturing Errors. Low order	0.0114	
M2 Manufacturing Errors. Uncertainties	0.0189	
M2 manufacturing. High order	0.0399	>2.53m
M3 manufacturing. Surface irregularity and curvature	0.0199	
M3 high order. Structure function	0.0200	>5.06m
Corrector Fabrication	0.0332	
Corrector Aligment	0.0124	
Telescope Alignment	0.0192	
M2 Hexapod Residuals	0.0207	
Thermal. Compensation residual	0.0084	
Thermal-0.05 deg(C)	0.0175	
Guiding	0.0300	
M3 cell	0.0110	
M2 cell	0.0505	
Seeing	0.5000	
Total	0.5503	

Table 26. *Imagining error budget summary.*

Item	M2					Corrector	Image plane
Compensator	Axial Z(mm)	Lateral X(mm)	Lateral Y(mm)	Tilt X (Deg)	Tilt Y (Deg)	Z(mm)	Z(mm)
M1 Manufacturing Errors. Low order.	3.387					17.424	15.996
M1 Manufacturing Errors. Uncertainties	0.881						
M2 Manufacturing Errors. Low order	1.687					14.957	15.040
M2 Manufacturing Errors. Uncertainties	0.105						
M3 manufacturing. Surface irregularity and curvature	0.005						
Corrector Fabrication	0.245						3.242
Corrector Aligment	0.007	0.902	0.409	0.009	0.019		
Telescope Alignment	1.829	2.464	3.010	0.018	0.014		
Thermal. Compensation residual	1.352						

Table 27. *Compensators ranges for imagining mode.*

In the same way than in the spectroscopic mode, the optical quality of the nominal design has be measured in terms of FWHM. The FOV will be sampled with 12 fields and 12 wavelengths, the merit function is built to evaluate directly the radius to the 50% of the encircled energy in two dimensions and to process the average, in that way the tolerance analysis provides directly the FWHM in arc seconds.

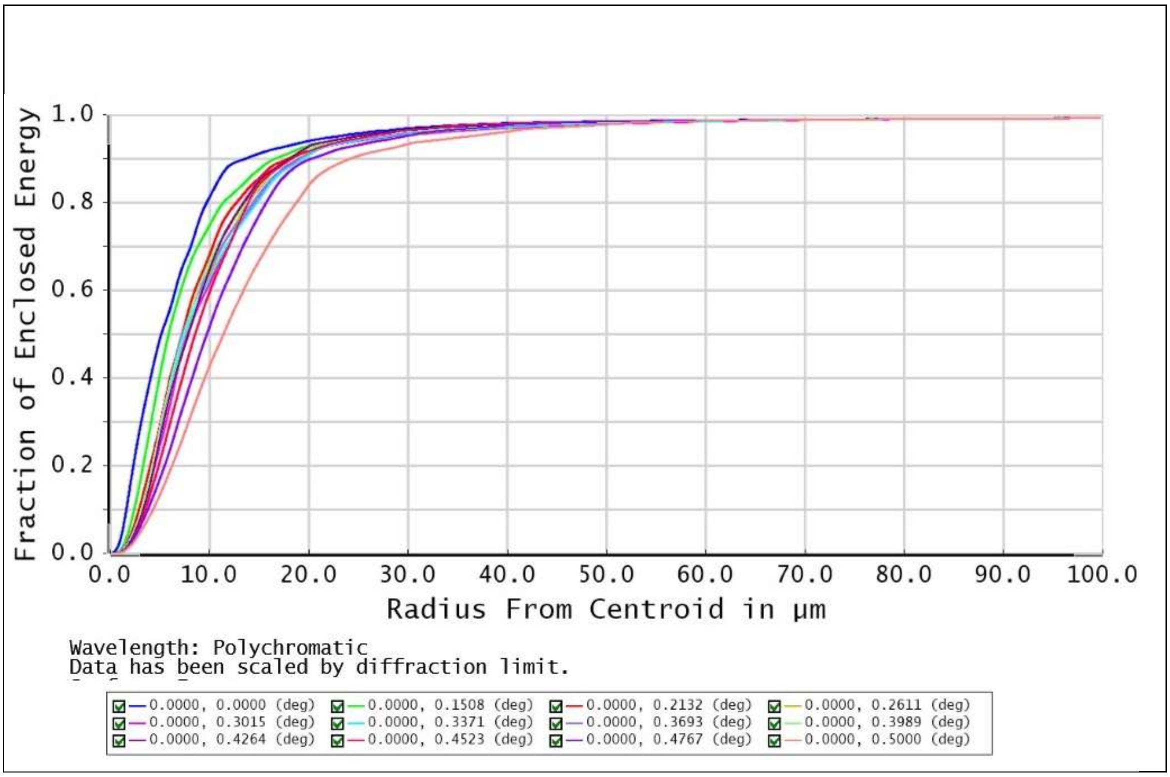

Figure 21. *Geometric encircled energy Nasmyth configuration imagining mode.*

5. APPENDIX

5.1 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.

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

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.*

The M1 specification is reproduced (see Figure 22) with the following parameters

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

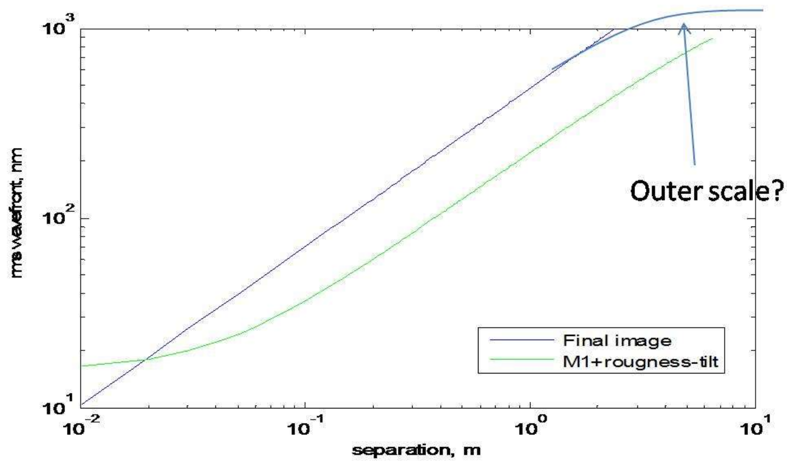

Figure 22. *Structure function for M1 in green, and pure Kolmogorov (no corrections for r_0=0.34").*

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 12 for example.

5.2 Useful expressions to measure image quality

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

The Gaussian model is used as a first approximation for a PSF, the following relations allow 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

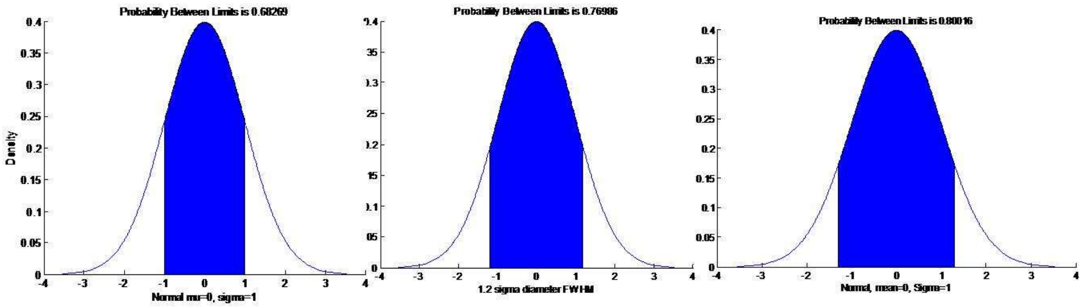

Figure 23: *Area within each considered edge for a Gaussian model*

Example, from spot RMS to FWHM

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

5.2.2 From r0 to FWHM

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

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

This model will be used (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.

5.3 M2 original error budget

A copy of the budget to specify the M2 optics in the MMT conversion as a reference is shown in Table 28.

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 28: *M2 original error budget.*

6. BIBLIOGRAPHY

1. *TEC/TSPM-PDR-OP/003 Distortion Error Budget for f5 Cassegrain*
2. *TEC/TSPM-PDR-OP/001 TSPM Optical performance and Error Budget for f5 Cassegrain*