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Authors	MANCINI, Dario; Marra, G.; CORTECCHIA, Fausto; Sedmak, G.; Ferragina, Luigi; et al.
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VST optomechanical technical specifications versus error budget

D.Mancini[1], G.Marra[1], F. Cortecchia[1] , G. Sedmak[2],
L. Ferragina[1], D. Fierro[1], O. Caputi[1], G. Mancini[1]

[1] INAF - Osservatorio Astronomico di Capodimonte, Via Moiariello 16 - 80131, Napoli, Italy
[2] Università di Trieste - Dipartimento di Fisica, Via Valerio, 2, 34127 Trieste, Italy

ABSTRACT

This paper concerns optomechanics tolerances specifications for VST telescope. It shows the strategy of tolerances definition for optomechanical systems. These prescriptions are the baseline for development and tests of VST telescope optomechanic components. The telescope is provided with an active optics control system, so some tolerances may be relaxed, respect to passive systems designs since they can be actively compensated. Gravitational and thermal deformations have been also considered. The design error budget strategy is described. This budget will be upgraded with the achieved budget including measured errors in order to compare them with the prescriptions. The Manufacturing, mounting and alignment tolerances have been evaluated within the whole telescope image quality error budget, in terms of rms spot radius. Since the telescope is seeing limited, effects of atmospheric seeing have also been considered in the error budget in terms of CIR. Do to its large field of view (1 degree square), the VST optical design (optomechanics tolerances included) is the first source of error if compared to a classical telescope design that has a small field of view. The overall optical quality depends also on telescope configuration (ADC and one-lens corrector or two-lens corrector configuration) and on observational zenith angle (0 ÷50°).

Keywords: Optomechanics tolerances, performance, error budget, CIR

1. INTRODUCTION

The VST image quality requirement was to have 80% EE in 2 pixel at z=0° zenith angle which corresponds to a rms spot diameter of 0.43”. This is the nominal budget, which has been translated in terms of technical prescriptions for all subsystems. VST telescope has been designed in order to have a large field of view. The budget allocated for optical design and optomechanical tolerances is greater respect to that reserved to the other subsystems, since they represent the main source of error if compared to a classical telescope design that has a small field of view. The design specifications and tolerances data, for the telescope mirrors with optical correctors’camera, and guiding and sensing camera have been taken into account.

2. IMAGE QUALITY BUDGET

The image quality budget includes the optical quality, active optic and guiding/sensing error budgets, but the errors that can be compensated (and therefore do not contribute to the degradation of the image quality) are not taken into account. The image quality budget covers error sources that cannot be analysed in an equally rigorous way. For example surface error quality can be accurately measured while local seeing can certainly be reduced by proper design but cannot be accurately predicted. In any case for some errors budget estimation is to be considered as a temporary measure. The image quality budget includes all error sources, which affect the phase of the Cassegrain focus after active optics correction. In fact in optical quality are included the effects of residual errors after that active corrections have been applied. The image quality budget for VST is expressed in terms of rms spot radius and also in terms of CIR. The image quality expressed in terms of Central Intensity Ratio (CIR) represents the decrease of the peak intensity of a long-exposure Point Spread Function with respect to its starting value, (peak intensity which would be with the theoretical telescope, same geometry of the aperture, no aberrations), with an atmospheric turbulence equal to 0.4 arcsec (best seeing at Paranal, where VST will be installed). The CIR is a function of the seeing, wavelength and telescope aberrations (the degradation due to the optical design must be taken into consideration). Budgets in terms of CIR and

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RMS spot radius have been computed following a breakdown structure. All subsystems errors expressed in terms of rms spot radius have been quadratic summed and the square root has been taken.
For the VST telescope the RMS spot radii as defined in ZEMAX have been taken into consideration. The final RMS spot radii have been obtained as the square root of the quadratic sum of all subsystems. The overall optical quality depends on telescope configuration (ADC and one-lens or two-lens configuration) and on zenith angle. The RMS spot radius budgets are polychromatic and computed as average on the overall field. Error sources are considered negligible if the associate optical quality is better than 0.00526 arcsec. Error sources, which affect the stability of the image, can be considered negligible if they do not introduce image motion larger than 0.00366 arcsec. These values are due to numerical roundness reasons. Unless otherwise notified it has been assumed that individual error sources described herein are not correlated. A seeing of 0.4 arcsec (which is the best seeing at Paranal) and a dome seeing of 0.033 arcsec have been considered. The overall error budget is reported for one wind condition corresponding to 50% time with the wind speed above 6 m/s.

3. THE CENTRAL INTENSITY RATIO

It can be difficult to translate mechanical deformations and displacements into optical specifications expressed in terms of CIR (Central Intensity Ratio). Where it is possible, relations are given to translate the optical specifications into geometrical parameters, e.g. tilts and displacements. Whenever the exact shape of the wavefront error is known, an accurate calculation of CIR can be done computing the PSF of the system. Otherwise, if the r.m.s. slope error of the wavefront is known, the CIR can be estimated on the basis of the following approximated formulas:

for any wavefront error except random tilt

$$CIR = 1 - 2.89\left(\frac{\sigma}{\theta_0}\right)^2$$

for random tilt (image motion)

$$CIR = 1 - 5.98\left(\frac{\sigma}{\theta_0}\right)^2$$

where θ_0 is the full width at half maximum of the atmospheric seeing angle. Conversely, given a CIR value, the equations above can be used to get an estimation of the wavefront r.m.s. slope error σ.
For CIR calculation it has been assumed that individual errors are not correlated, so the CIR variation associated with the combination of N individual error sources is simply the linear sum of individual CIR variations

$$1 - CIR = \sum_{i=1}^{N} (1 - CIR_i)$$

where CIR_i is the CIR requirement for the error source i. The total CIR decreases if the sum of individual errors decreases.

4. IDENTIFICATION OF ERROR SOURCES

Wavefront errors include telescope aberrations that can be corrected by active optics and aberrations that cannot be corrected. An active correction may consist in a sag deformation of the primary mirror, or a displacement of the secondary mirror (for coma and focus correction), or in a combination of both. Auto-guiding errors may be considered at first order as active optics, but we prefer to consider them separately for their weight in the error budget computation.
Active optics can correct a wavefront error if the wavefront error itself satisfies the following conditions:

- ➢ its spatial frequency falls within the control range of active optics support of the primary mirror
- ➢ its time frequency falls within the control range of active support
- ➢ its variation within the field of view can be neglected
- ➢ its amplitude falls within the force range of active concept

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Aberrations that can be compensated by active optics must have low spatial frequencies that correspond to the first natural modes of the primary mirror.
With an active telescope as VST it is necessary to take into account the possible response of the control system. An error source may include a part that satisfies the four previous conditions and a part that does not. The first part is actively corrected, while the second part has to be taken into account in the budget.
In Figures 1-6 are reported the design overall budgets results respectively for the two –lens corrector configuration and for the ADC configuration (z=0° and z=50°) in terms of RMS spot radii and CIR.
In Table 6 there is a list of every label of the budget error and its meaning. The Image Quality Budget has been translated in terms of technical prescriptions for all subsystems.

5. TELESCOPE OPTICAL DESIGN AND OPTOMECHANICAL ERRORS

VST is designed in order to have a large field of view. The optical design with optomechanics tolerances is the main source of error if compared to a classical telescope design that has a small field of view. Under the label Telescope Optics Manufacturing are included only manufacturing high order aberration for M1, M2 and Correctors, while low order manufacturing errors and mechanical tolerances are included in Telescope design and Optomechanical tolerances. For the optomechanical tolerances a budget of 0.3” on rms spot diameter has been allocated and the leftover has been distributed among the other error sources. Optomechanics tolerances for mounting and manufacturing of the optics have been computed considering that telescope is actively controlled. So they have been relaxed, since compensation can be done with a high precision active control system of secondary mirror. Prescriptions data in terms of rms spot radius and CIR for optical design and optomecahnical tolerances are reported in Table 1.
The sensitivity tolerance analysis was done in terms of rms spot radius and 80% diffraction encircled energy radius. The study was performed looking at changes with respect to the nominal design values. As compensator the distance between M2 and M1 was used. The sensitivity analysis was done in order to compare it with the allocated budget error. An iterative procedure has been followed. The centered and decentered tolerances for both correctors configurations are reported in Tables 2-5.

Label	**RMS spot radius (arcsec)**	**CIR**	**Notes**
Tel. Design + Optomec. Tol.	0.13 0.15 0.18	0.69 0.59 0.419	2 lens ADC z=0 ADC z=50
Tel. Optics Manufacturing	0.0744	0.900	M1 M2 Correctors High orders aberrations

Table 1: Prescriptions errors for telescope design, optomechanical and high order manufacturing tolerances

Surface	**Component**	**Radius Toll**	**K toll**	**Fringes Pow/Irr**	**Thickness Toll**	**Glass**	**Index Toll**	**V-NO (%)**	**H**
1	M1	4	0,0001	4,0/ 0,25		REFL			
2	M2	2	0,001	4,0/ 0,25		REFL			
3					0.5				
4	L1	1		4,0/ 1,00	0,4	SILICA	0,001	0,2	5,00E-06
5	L1	3,5		4,0/ 1,00		AIR			
6					0,5	AIR			
7	L2	2		4,0/ 1,00	1	SILICA	0,001	0,2	5,00E-06
8	L2	15		4,0/ 1,00	0,5	AIR			
9	Filter			4	1	SILICA	0,001	0,4	5,00E-06
10	Filter			4	0,5				
11	Window	3,5		4,0/ 1,00	0,5	SILICA	0,001	0,4	5,00E-06
12	Window	3,7		4,0/ 1,00	0,3				

Table 2: Centred tolerances for the two-lens corrector

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Element n°	Component	Element wedge		Element Tilt		El. Dec/Roll	
		Tir	Arcmin	Tir	Arcmin	Tir	mm
1	M1			0.0000	0.0	0.0055	0.02
2	M2			0.0000	0.0	0.0041	0.02
3	L1	0.0840	0.7	0.0630	0.5	0.0143	0.1
4	L2	0.1133	1.0	0.0566	0.5	0.0657	0.25
5	Filter	0.0729	0.7	0.0550	0.5	0.0000	1
6	Dewar window	0.1074	1.0	0.0541	0.5	0.1413	0.5

Table 3: Decentred tolerances for the two-lens corrector

Surface	Radius	Radius Toll	K toll	Fringes Pow/Irr	Thickness Toll	Glass	Index Toll	V-NO (%)	H
1	M1	4	0,0001	4,0/ 0,25		REFL			
2	M2	2	0,001	4,0/ 0,25		REFL			
3					0,5				
4	P1	3,8		4,0/ 1	0,5	N-PSK3	0,002	0,04	5,00E-06
5	P2			4,0/ 1	0,5	LLF1	0,002	0,04	
6	INF			4	0.4	AIR			
7	P3			4	0.5	N-PSK3		0,04	
8	P4			4	0.5	LLF1	0,002	0,04	
9		15		4,0/ 1	0.5	AIR			
10	L5	2,7		4,0/ 1	1	SILICA	0,002	0,04	5,00E-06
11		15		4,0/ 1	0.5	AIR			
12	Filter			4	1	SILICA		0,04	5,00E-06
13				4	0.5	AIR			
14	Window	3,5		4,0/ 1	0.5	SILICA		0,04	5,00E-06
15		3,7		4,0/ 1	0.3				

Table 4: Centred tolerances for ADC corrector

Element n°	Component	Element wedge		Element Tilt		El. Dec/Roll	
		Tir	Arcmin	Tir	Arcmin	Tir	mm
1	M1			0.0000	0.0	0.0055	0.0200
2	M2			0.0000	0.0	0.0041	0.0200
3	Prism1	0.0776	0.6	0.0443	0.3	0.0183	0.1000
4	Prism2	0.0704	0.6	0.0440	0.3	0.0000	0.400
5	Prism3	0.0870	0.7	0.0435	0.3	0.0000	0.4000
6	Prism4	0.0756	0.6	0.0432	0.3	0.0111	0.2500
7	L5	0.1135	1.0	0.0568	0.5	0.1408	0.5000
8	Filter	0.0729	0.7	0.0547	0.5	0.0000	1.0000
9	Window	0.1074	1.0	0.0537	0.5	0.1403	0.5000

Table 5: Decentred tolerances for ADC corrector

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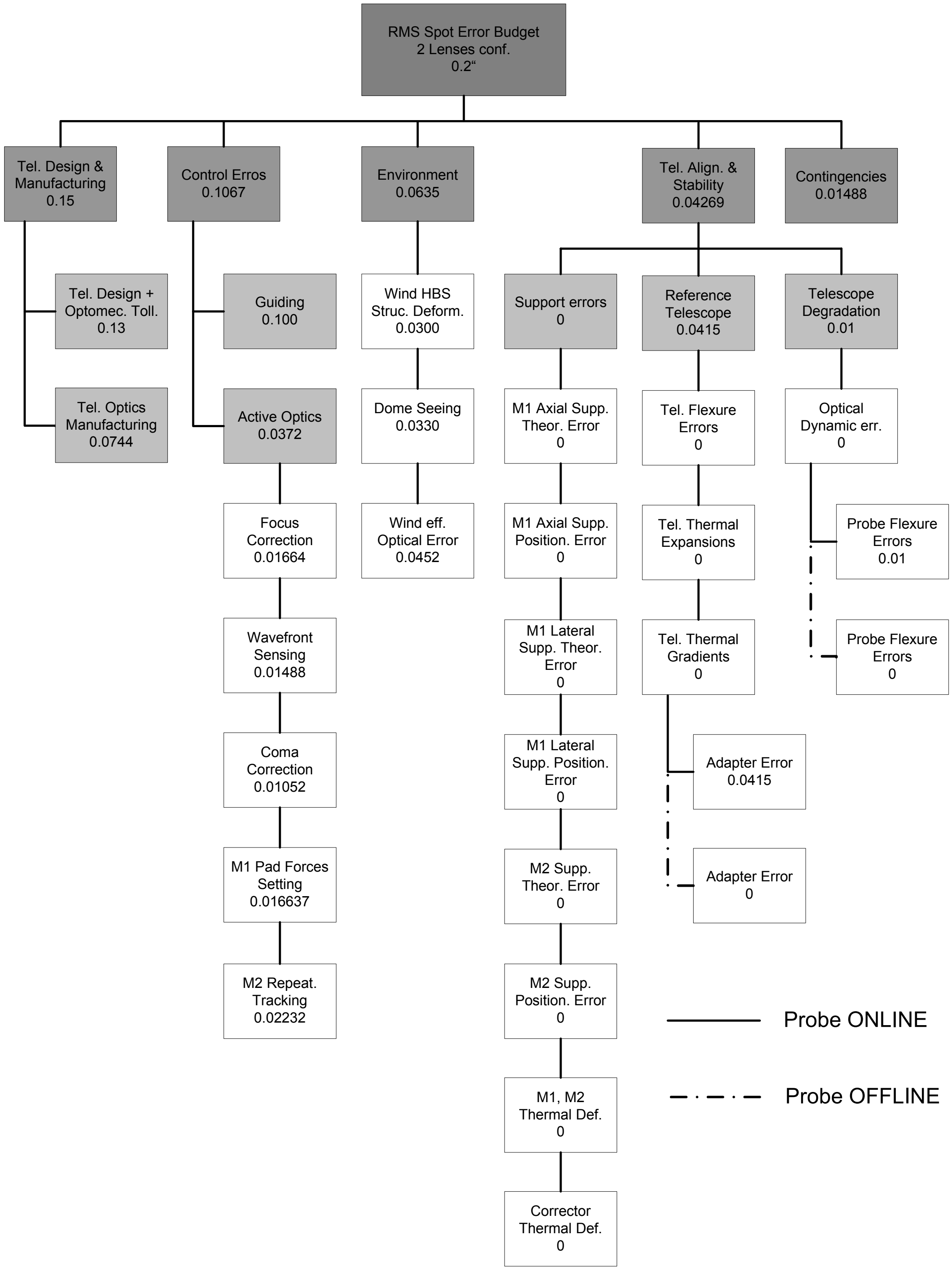

Figure 1: VST Image Quality budget in terms of RMS spot radius, for two-lens corrector configuration

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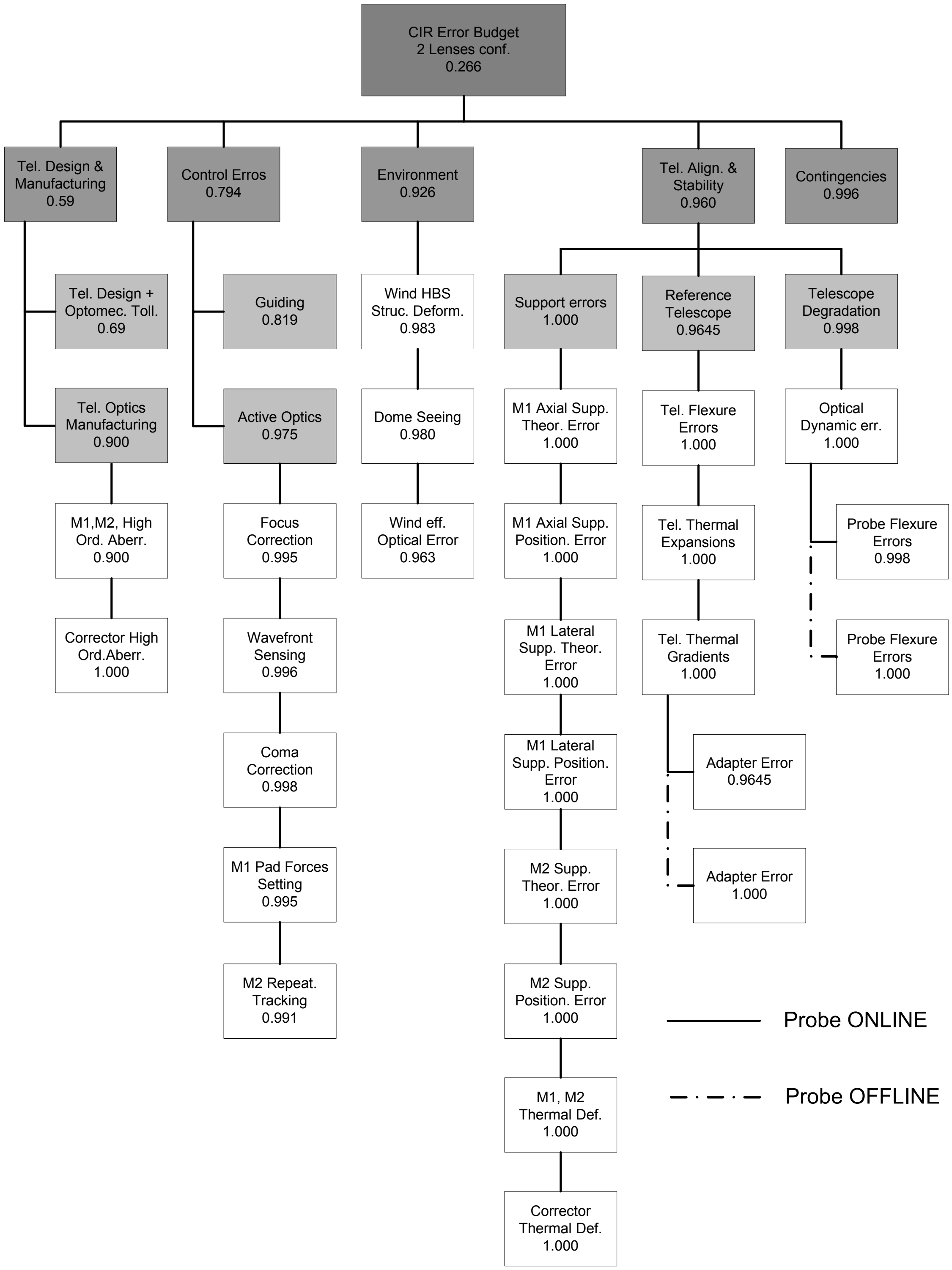

Figure 2: VST Image Quality budget in terms of CIR, for two-lens corrector configuration

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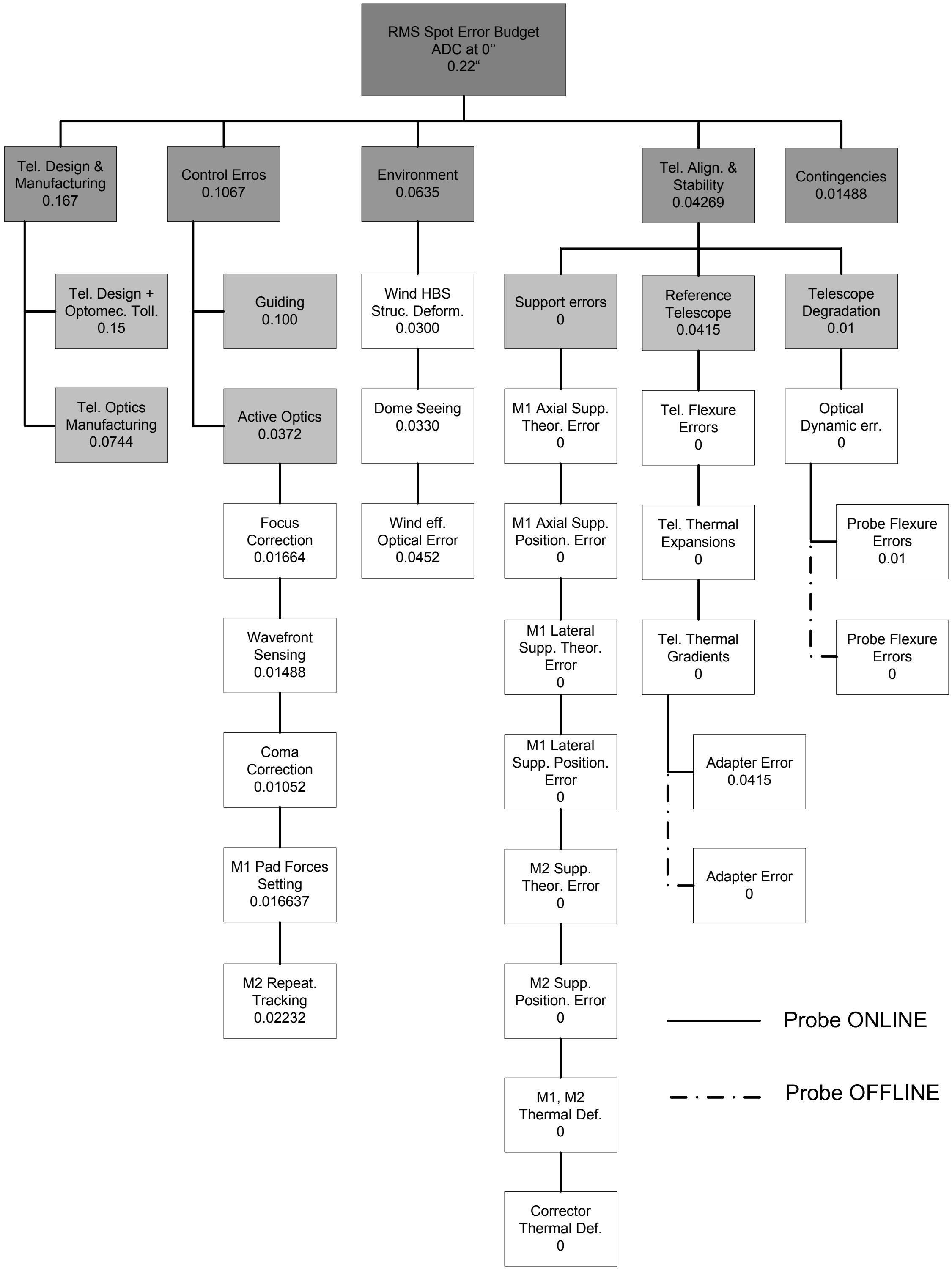

Figure 3: VST Image Quality budget in terms of RMS spot radius, for ADC corrector configuration

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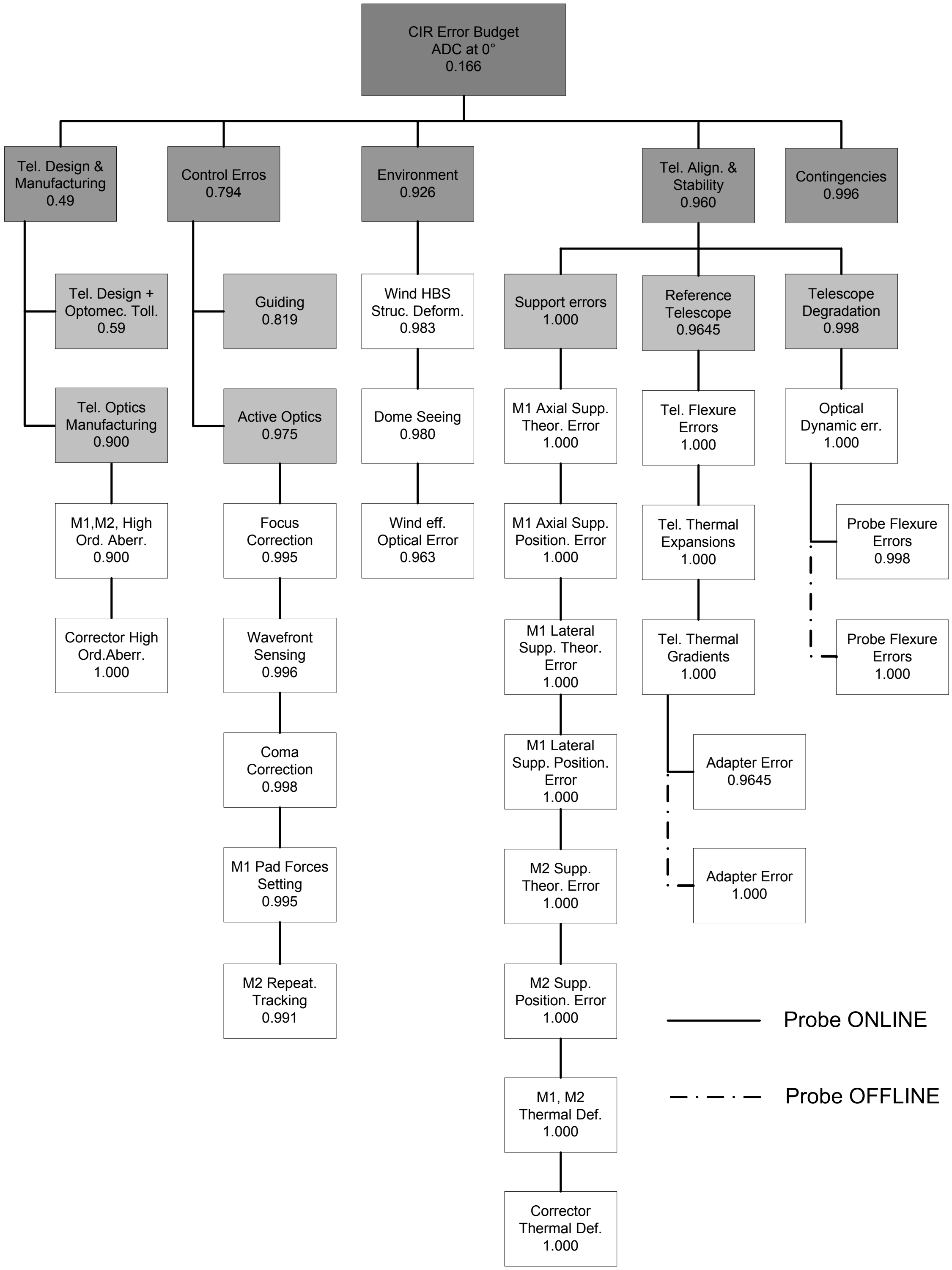

Figure 4: VST Image Quality budget in terms of CIR, for ADC corrector configuration at 0° zenith angle

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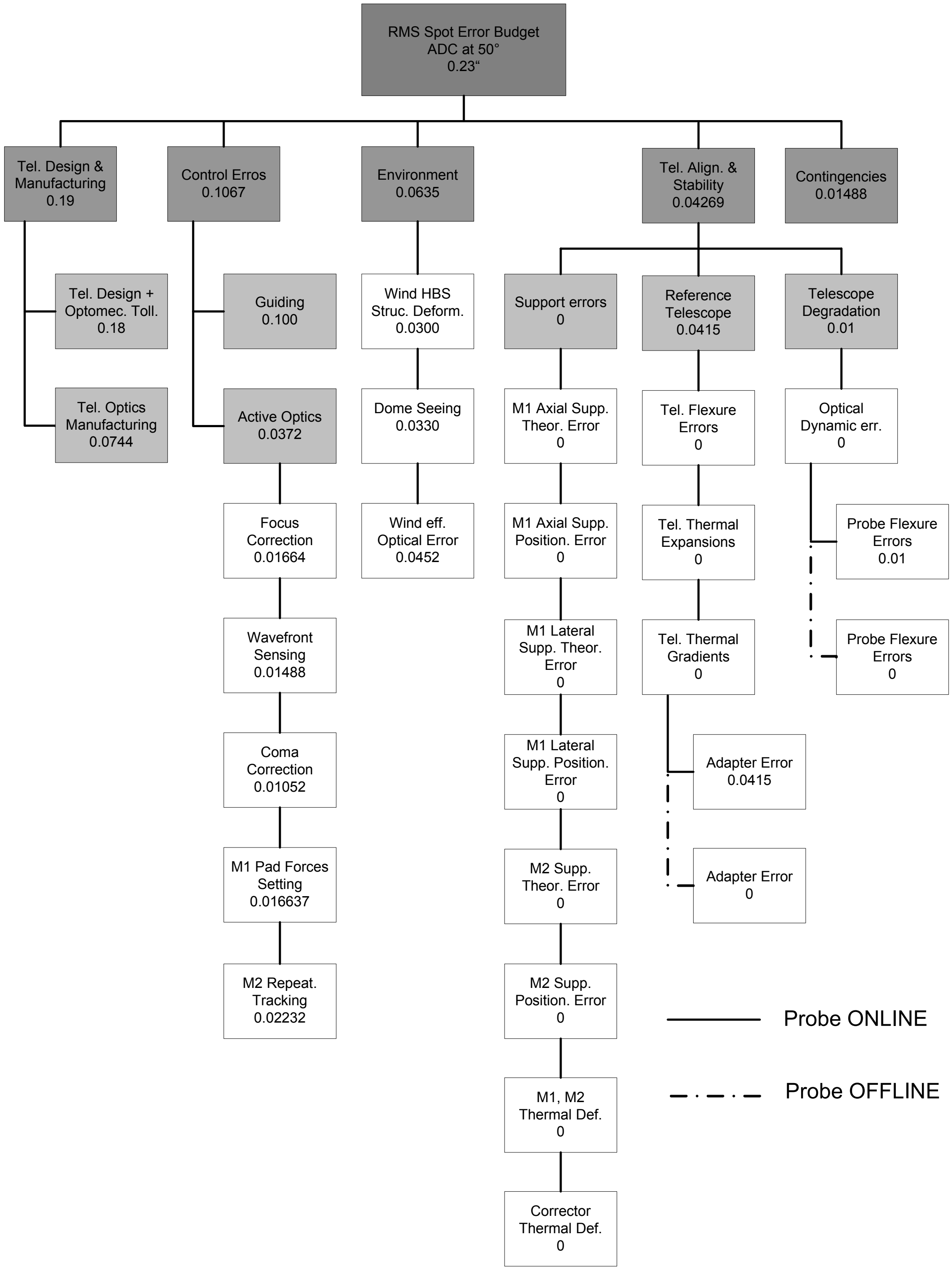

Figure 5: VST Image Quality budget in terms of RMS spot radius, for ADC corrector configuration at 50° zenith angle

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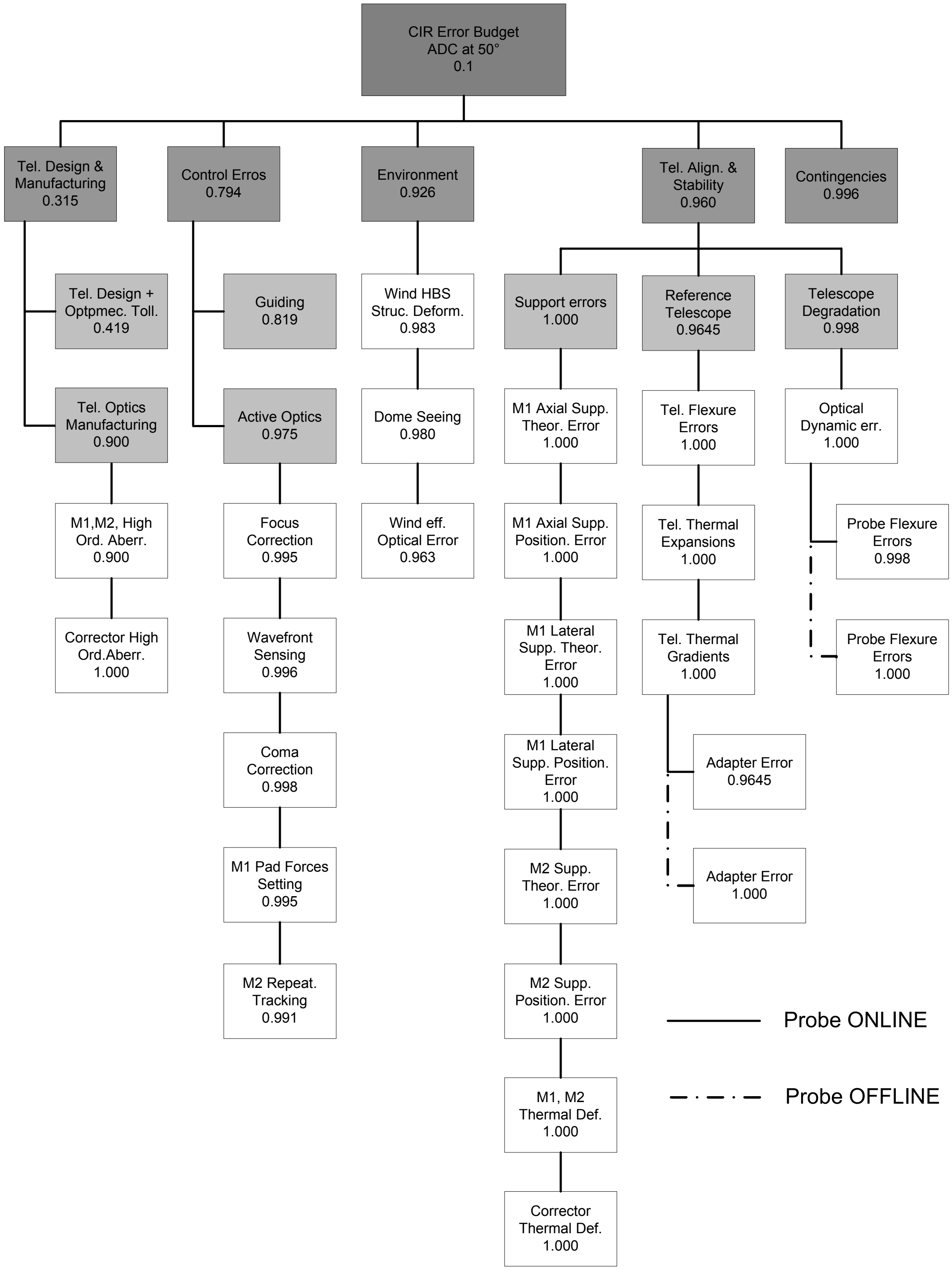

Figure 6: VST Image Quality budget in terms of CIR, for ADC corrector configuration at 50° zenith angle

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	Label	Meaning	Notes
1	Tel. Design and Manufacturing	-	Sum of 2 and 3
2	Tel. Design + Optomec. Tol.	Telescope optics design + Optics tolerances (no high order aberration) + Mechanics tolerances	
3	Tel. Optics Manufacturing	-	Sum of 4 and 5
4	M1, M2, High Ord. Aberr.	M1, M2 high order aberrations	
5	Corrector High Ord. Aberr.	Corrector high order aberrations	
6	Control Errors	-	Sum of 7 and 8
7	Guiding	Guiding error (50% time with the wind speed above 6 m/s)	
8	Active Optics	-	Sum of 9, 10, 11, 12 and 13
9	Focus Correction	Hexapod 1 optical axis sensitivity	
10	Wavefront Sensing	Pupil rotation within the exposure time, reaction time of the control system, wavefront sensor assembly	
11	Coma Correction	Hexapod 1 decentering and tilt sensitivity	
12	M1 Pad Forces	M1 axial pad sensitivity	
13	M2 Repeat. Tracking	Hexapod 2 decentering and tilt sensitivity (image stability during active secondary mirror re-alignment)	
14	Environment	-	Sum of 15, 16 and 17
15	Wind HBS Struc. Deform.	Telescope tilt e deformation on HBS due to wind	
16	Dome Seeing	Dome seeing close to telescope (no free atmospheric turbulence)	
17	Wind eff. Optical Error	Image movement due to M1, M2 misalignment due to wind	
18	Tel. Align. & Stability	-	Sum of 19, 28 and 33
19	Supports Errors	-	Sum of 20, 21, 22, 23, 24, 25, 26 and 27
20	M1 Axial Supp. Theor. Error	Error due to geometry of M1 axial support system and numbers of pads	
21	M1 Axial Supp. Position. Error	Error due to bad positioning of M1 axial pads	
22	M1 Lateral Supp. Theor. Error	Error due to geometry of M1 lateral system (VLT like, Beta=0.75)	
23	M1 Lateral Supp. Position. Error	Error due to bad positioning of the M1 lateral pads	
24	M2 Supp. Theor. Error	Error due to geometry of M2 supports system	
25	M2 Supp. Position. Error	Error due to bad positioning of the M2 supports system	
26	M1, M2 Thermal Def.	M1 and M2 thermal deformations (optics and supports)	
27	Corrector Thermal Def.	Correctors thermal deformations (optics and supports)	
28	Reference Telescope	-	Sum of 29,30,31,32
29	Tel. Flexure Errors	Telescope flexure errors	
30	Tel. Thermal Expansions	Telescope thermal errors	
31	Tel. Thermal Gradients	Telescope thermal gradient error	
32	Adapter Errors	Adapter and probe rotation error (deviation from a pre-calibrated field aberration map due to probe misalignments).	Probe On Line and Off Line
33	Telescope Degradation	-	Sum of 34 and 35
34	Optical Dynamic errs.	Optics misalignment errors during 30’ observation	
35	Probe Flexure Errors	Guiding and sensing arm tilt (flexure) during 30’ observation	Probe ONLINE and OFFLINE
36	Contingencies	Contingencies	

Table 6: Meaning of labels in the Error Budget Diagrams

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