12 IMAGE AND WAVEFRONT BUDGETS

12.1 Introduction

Error budgets are essential tools for controlling the various factors in the telescope and enclosure that degrade imaging performance. The elements that enter into the budgets include fabrication errors in the optics, misalignments and distortion due to the mounting of the optics in the telescope, tracking errors and vibration of the structure (e.g. wind shake), and thermal effects that contribute to image blur (e.g. "mirror seeing" and "dome seeing"). Image blur caused by the atmosphere ("atmospheric seeing") is not part of the error budget but is a key factor in setting the cap on the total contributions from all other sources. Separate budgets are developed for narrow field operation with natural seeing, and wide-field operation with the corrector and atmospheric dispersion compensator (ADC) with natural seeing. Error budgets for the different modes of AO operation are developed in Section 9.2. The results are summarized in this chapter, section 12.4. Science instruments will have their own internal error budgets.

The GMT error budgets serve three purposes:

1. Errors are allocated between various sources in order that the total contribution satisfies the imaging performance specifications set forth in the Science Requirements (Section 4.9). As the GMT design matures, error budget line items can be reallocated to provide relief in some areas at the expense of others in order to maintain specified performance. This reduces the total system cost and risk. The error budgets are dynamic tools that will be periodically updated throughout the life of the project.

2. The error budget is the top-level descriptor of imaging performance and is the input for the design of science instruments.

3. The error budget establishes top-level requirements for the GMT systems. Sub-system requirements are derived ("flow down") from these. Sub-systems are divided into component levels, which each have their own associated error.

The "top-down" error budgets reported in this section start with an overall specified system level of performance and apportion error allowances between subsystems. A "bottom up" approach starts with the predicted performance of subsystem components derived from engineering studies and combines these to estimate overall system performance. Although this is a top-down budget, the allocations are informed by studies conducted during the conceptual design phase and by the experience gained with similar systems on existing telescopes. Both top-down and bottom-up budgets will be developed during the preliminary design phase of the project and reconciled at the end of that phase, ensuring that the final GMT design can achieve the imaging requirements of the project.

GMT imaging will be limited by atmospheric ("natural") seeing for near-UV and visible wavelengths from the atmospheric cut-off to around 1 μm. The error budgets in this wavelength range are specified in terms of image size at a standard wavelength of 0.5 μm. A number of different metrics are commonly used for this purpose (e.g. FWHM, RMS spot sizes, and enclosed energy diameter). The conversion between different metrics is given in Section

12.3.4.2. GMT uses the diameter that encloses 80% of the energy, θ_{80}, as the metric for seeing-limited operation. Uncorrelated errors from different sources are combined in quadrature, i.e. as the square root of the sum of the squares or RSS. Section 12.3.2 contains the error budget for narrow-field, on-axis operation without the wide-field corrector or ADC. Section 12.3.3 covers wide-field, natural seeing operation with the corrector and ADC.

The error budgets are based on the seeing at the zenith, that being the most conservative criterion for determining optical tolerances and support system requirements. Atmospheric turbulence increases the seeing-limited image size with zenith distance as $(\sec z)^{0.6}$ in the Kolmogorov model. Monochromatic image sizes for off-zenith operation are allowed to grow as $(\sec z)^{0.6}$. Atmospheric dispersion also increases with zenith angle and is a function of wavelength and bandpass. It is not included in the budgets.

12.2 Requirements

The total error budget is specified from the imaging performance established by the GMT science requirements. Two levels of errors are reported: *specifications* which are sufficient to meet the science requirements and *goals* which are thought to be achievable, improving the overall performance.

The top level requirements for the GMT image error budget are given in Chapter 4, Section 4.9.4. The specifications and goals are reported in the error budget tables below.

12.3 Natural Seeing Error Budgets

12.3.1 Error Sources

The natural seeing error budgets include allocations for all contributors to image size delivered to the instruments. They are grouped in the tables by the following categories.

Optical design:

The optical design of the GMT is aplanatic Gregorian for which all aberrations are zero at the center of the field in the geometrical optics approximation. The image size of the perfect, unperturbed system with no corrector/ADC is given by the diffraction-limited point spread function. The corrector/ADC introduces aberrations at the center of the field while correcting larger off-axis aberrations. The non-axisymmetric configuration of the atmospheric dispersion compensator also produces aberration. The contribution to the wide-field error budget is calculated as the RMS average of the 80% encircled energy diameters for field points approximately evenly distributed across the full field.

Optical surfaces:

The error budget takes into account figure and support errors not fully corrected by the active control of the primary and adaptive secondary mirrors. The residual errors are due to various factors: (a) an inability to distinguish between wavefront errors coming from the multiple surfaces in the system with the finite number of wavefront sensors in the focal plane, (b) fitting errors in the measured wavefront, (c) noise in the wavefront measurement, (d) imperfect knowledge of the mirror support influence functions, (e) cross-talk between the mirror modes, (f) force errors in the actuators, and (g) the inability to control higher order modes with the limitations of actuator force and spacing in the mirror supports.

The fast-steering secondary mirror segments, the fold mirror(s) on the instrument platform, and the corrector/ADC do not have active figure control. To some extent low spatial frequency wavefront errors from these surfaces will be corrected by the active systems on the primary mirror and by the adaptive secondary mirror when it is in use. The error budgets are conservative in the sense that they do not include this correction.

The error budget amounts for optical surfaces are derived from the error budgets from prior experience with similar large mirrors and support systems (MMT, Magellan, and LBT). For the GMT primary mirror, these are confirmed by FEA modeling of the proposed mirror support design, including actuator force errors representative of this type of support measured on existing systems. The primary mirror error budget for figure error is the specification for the prototype segment currently being fabricated.

Active alignment:

As described in Chapter 8, displacements and rotations of the primary mirror segments can be compensated to high accuracy by suitable motions of the secondary mirror segments. The GMT strategy for active alignment of the telescope requires that the primary mirror segments be moved close to their nominal positions with the hexapod segment supports and that final alignment and image stacking be done with the secondary mirror segments. The residual image errors from misalignment are due to (a) incomplete compensation of primary mirror misalignments using secondary mirror motion, (b) position and tilt errors of the secondary mirror segments, (c) small displacements of the focal plane, and (d) wavefront sensor error and servo lag. The update rate for the active alignment system is ≥30 seconds.

Wind disturbance:

Wind on the telescope structure will distort the surfaces of the primary mirror segments and perturb the alignment and pointing of the optics at frequencies higher than the active optics system and/or mount tracking with the main drives. In the AO modes of operation these errors will be compensated by the adaptive secondary mirror using tip-tilt and figure control. Non-AO modes rely on the stiffness of the primary mirror segments and telescope structure. Tip-tilt of the adaptive secondary mirror or the fast-steering secondary mirror controls image motion and de-stacking of the images in the seven subapertures.

The error budget values are derived from FE modeling of the primary mirror on its supports and dynamic response modeling of the GMT structure under wind load.

Thermal:

A non-uniform temperature distribution in the primary mirror segments will warp the borosilicate blanks, mostly in the low order bending modes. The effect is most pronounced early in the evening before the mirror ventilation systems have had a chance to equalize mirror temperatures with the ambient air. Most of the thermal bending is removed by the active figure control and the error budget term represents the residual uncorrected amount. The characteristic relaxation time for thermal distortion is 40-60 minutes depending on the design of the ventilation system.

Mirror seeing results from convection cells above the mirror surface driven by temperature differences between the front face surface and the ambient air. The short thermal relaxation time of the GMT mirrors and conditioning during the late afternoon/early evening allows this term to be relatively small.

Tracking:

Tracking errors include main drive servo errors not corrected by the fast steering or adaptive secondary mirrors, and flexure between the guide sensors and the focal plane. This error source also includes instrument rotator angle errors for wide-field observations.

Dome seeing:

An 80% encircled energy contribution of 0.025 arcsec is assumed for the effects of dome seeing, corresponding to approximately a +0.22°C temperature difference between the air in the enclosure and the outside air. Thermal modeling will show whether this is realistic.

12.3.2 Narrow-field Visible-band Error Budget (Case 1)

The narrow-field visible-band error budget, Table 12-1, applies to natural seeing operation without the use of adaptive optics. Active control of the primary mirror and secondary mirror positions maintain optical alignment in the telescope. The active supports on the primary mirror segments remove low-order aberrations due to support and thermal distortions of the optical surfaces. Both the segmented adaptive and segmented passive secondary mirrors will have fast steering capability to deal with pointing errors due to wind shake and tracking jitter in the telescope drives. The Case 1 error budget applies to the following conditions:

Telescope

Zenith distance	0°
Field diameter	0 arcmin
Wavelength	0.5 microns
Primary mirror	Segmented with active figure control, not phased.
Secondary mirror	Segmented, non-adaptive, fast steering mode.
Corrector/ADC	None.

Environmental (normal conditions)

Wind speed:	25th to 75th percentile useable nights (~4.0 m/s to 9.5 m/s).
Temperature:	+4° C to +17° C (5th to 95th percentile)
Temperature rate of change:	± 0.5 K/hr (~20th to ~90th percentile)
Time of night:	Between evening and morning astronomical twilight.

Table 12-1. Case 1, narrow-field natural seeing error budget.

GMT Error Budget Case 1: Visible band (500 nm), narrow field, active optics						
Sources		**Specification 80% ee (arcsec)**		**Goal 80% ee (arcsec)**		**Ref. §12.3.4**
Optical Design			0.017		0.017	5
Optical Surfaces:			0.190		0.101	
	Primary mirror segment figure	0.166		0.054		6
	Secondary mirror figure	0.081		0.075		7
	Primary mirror supports	0.036		0.036		8
	Secondary mirror supports	0.020		0.020		8
Active Alignment:			0.143		0.085	
	Primary segments	0.003		0.003		9
	Secondary segments	0.141		0.081		10
	Focal plane	0.010		0.005		11
	Sensor error	0.025		0.025		16
Wind disturbance			0.133		0.101	
	Primary mirror figure	0.075		0.075		12
	Optical alignment & pointing	0.109		0.065		13
	Focus	0.017		0.017		13
Thermal			0.106		0.060	
	Primary mirror figure	0.089		0.045		15
	Mirror seeing	0.057		0.039		3
Tracking			0.072		0.053	
	Drive errors	0.051		0.015		14
	Differential flexure	0.051		0.051		14
Dome seeing			0.025		0.025	4
Reserve			0.000		0.096	
Total error budget:			**0.302**		**0.210**	
Science Requirements			**0.300**		**0.210**	

12.3.3 Wide-field Visible-band Error Budget (Case 2)

The wide-field visible-band error budget, Table 12-2, applies to natural seeing operation over a 20′ field of view with the corrector and without the use of adaptive optics. Active control of the primary and secondary mirror positions maintains optical alignment in the telescope. The active supports on the primary mirror segments remove low-order aberrations due to support and thermal distortions of the optical surfaces. Both the segmented adaptive and segmented passive secondary mirrors will have fast steering capability to deal with pointing errors due to wind shake and tracking jitter in the telescope drives.

The Case 2 error budget applies to the following conditions:

Telescope

Zenith distance	0°
Field diameter	20 arcmin
Wavelength	0.37 - 1.0 microns
Primary mirror	Segmented with active figure control, not phased.
Secondary mirror	Segmented, non-adaptive, fast steering mode.
Corrector/ADC	Yes. ADC angle = 0° (no correction).

Environmental (normal conditions)

Wind speed:	25th to 75th percentile useable nights (~4.0 m/s to 9.5 m/s)
Temperature:	+4° C to +17° C (5th to 95th percentile)
Temperature rate of change:	± 0.5 K/hr (~20th to ~90th percentile)
Time of night:	Between evening and morning astronomical twilight.

Table 12-2. Case 2 wide-field natural seeing error budget.

GMT Error Budget Case 2: Visible band (0.37-1 μm), wide field, active optics

Contributions		**Specification 80% ee (arcsec)**		**Goal 80% ee (arcsec)**		**Ref. §12.3.4**
Optical Design			0.055		0.055	5
Optical Surfaces:			0.204		0.108	
	Primary mirror segment figure	0.166		0.054		6
	Secondary mirror figure	0.081		0.075		7
	Primary mirror supports	0.036		0.036		8
	Secondary mirror supports	0.020		0.020		8
	Corrector elements	0.076		0.038		18
Active Alignment:			0.178		0.129	
	Primary segments	0.088		0.088		9
	Secondary segments	0.141		0.081		10
	Corrector elements	0.059		0.040		17
	Focal plane	0.010		0.005		11
	Sensor error	0.025		0.025		16
Wind disturbance			0.133		0.101	
	Primary mirror figure	0.075		0.075		12
	Optical alignment & pointing	0.109		0.065		13
	Focus	0.017		0.017		13
Thermal			0.106		0.060	
	Primary mirror figure	0.089		0.045		15
	Mirror seeing	0.057		0.039		3
Tracking			0.101		0.074	
	Drive errors	0.071		0.021		14
	Differential flexure	0.071		0.071		14
Dome seeing			0.025		0.025	4
Reserve			0.168		0.165	
Total error budget:			**0.380**		**0.280**	
Science Requirements			**0.380**		**0.280**	

12.3.4 Explanation

12.3.4.1 General notes

The entries in Table 12-1 and Table 12-2 are combined by root-sum-square, RSS. This is not strictly correct for non-Gaussian sources such as those characterized by an atmospheric PSF (e.g. structure functions). The differences are not great and, for simplicity, are currently ignored in the budgets.

Several of the GMT error budget terms are derived from structure functions. The method is explained in Section 10.2.3 and can be described as a method of specifying errors at all spatial scales that follow the functional form of the Kolmogorov model of seeing. Hill (1994) outlines the procedure for using these functions to establish optical tolerances for the series of 3.5 m, 6.5 m, and 8.4 m SOML telescopes.

The last column in the tables refers to the sections below.

12.3.4.2 Conversion factors

The factors used to convert between different forms of error specification follow.

Gaussian full-width half maximum (FWHM) to 80% encircled energy (θ_{80}):	1.52
Atmospheric FWHM to θ_{80}:	1.89
Gaussian RMS radius to 80% encircled energy (θ_{80}):	2.54

FWHM from Fried's parameter (r_0):

$$\theta_{fwhm} = 0.976 \frac{\lambda}{r_0(\lambda, z)} \text{ radians}$$

12.3.4.3 Mirror seeing

Zago (1998) gives the expression for mirror seeing as

$$\theta_{fwhm} = 0.18 F_r^{-0.3} \Delta T$$

where θ_{fwhm} is the mirror seeing in arcseconds, F_r is the Froude number,

$$F_r = \frac{Tv^2}{\Delta T g D}$$

T is the temperature (K), ΔT is the temperature difference between the mirror surface and the air, v is the wind speed across the mirror, g the acceleration of gravity, and D the mirror diameter. We use $D = 8.4$ m.

The error budget for mirror seeing, $\theta_{80} = 0.057''$, implies a maximum mirror to air temperature difference of $\Delta T = +\ 0.4$ K with a 1 m/s wind. The allowed temperature difference depends weakly on wind speed v, roughly as $v^{0.5}$. The goal of $\theta_{80} = 0.039''$ gives $\Delta T \leq 0.3$ K when $v = 1$ m/s. Thermal control of the front surface of the primary mirror segments is discussed in Section 10.9.

12.3.4.4 Dome seeing

The empirical relation between seeing and the difference in air temperature between inside and outside the enclosure was derived from measurements at the Canada-France-Hawaii-Telescope by Racine et. al. (1991):

$$\theta_{fwhm} = 0.1'' \Delta T^{1.2}$$

A value of $\theta_{80} = 0.025''$ is assumed for the contribution of dome seeing which implies a maximum temperature difference of 0.22 K. Thermal control of the GMT enclosure is discussed in Section 14.9.3.

12.3.4.5 Optical design

The on-axis (Case 1) image size for the aplanatic Gregorian optical design is diffraction-limited with $\theta_{80} = 0.017''$ at 500 nm for the segmented mirror configuration with no corrector. The encircled energy performance for the wide-field configuration (Case 2) is set by the design of the corrector/ADC. The RSS average of the 80% encircled energy over the 20′ diameter field is $\theta_{80} = 0.055''$.

The GMT optical design is discussed in Chapter 6.

12.3.4.6 Primary mirror figure

The polishing contract for the GMT1 primary mirror segment specifies the surface figure accuracy in terms of its structure function after removal of the lowest order modes (Chapter 10). The specified structure function with $r_0 = 91.9$ cm corresponds to an image size $\theta_{fwhm} = 0.110''$ at λ=0.5 μm ($\theta_{80} = 0.17''$). Neglecting tilt and piston errors, which are included in the alignment budget, the error budget for the ensemble of seven mirrors is the same as for one mirror in the seeing-limited regime. The accuracy achieved on the LBT 8.4 m mirrors was $\theta_{80} = 0.054''$ (GMT goal) but did not include radius errors that are important for GMT.

12.3.4.7 Secondary mirror figure

The structure function specification for the secondary mirror figure is $r_0 = 49.9$ cm or, scaled to the entrance pupil of the telescope, r'_0=393 cm. This corresponds to an image size of $\theta_{fwhm} = 0.026''$ at λ=0.5 μm (θ_{80}=0.039″). The goal for secondary mirror figure is the accuracy achieved with the Magellan f/11 mirror, $\theta_{80} = 0.026''$.

The structure function requirement does not include a tolerance on radius of curvature. The optical sensitivity is 550 μm RMS image radius per mm for radius variation between segments after active correction with the primary and secondary mirror motions. The tolerance on the radius non-uniformity is 0.05 mm which gives a contribution to the error budget of 0.056″ RMS diameter ($\theta_{80} = 0.071''$). The absolute tolerance on radius will be larger. The residual wavefront error after active correction is approximately three waves p-v ($\lambda = 0.5$ μm). Active figure control on either the primary or secondary mirrors will further reduce this source of error.

The total error budget for secondary mirror figure is the root-sum-square of the structure function and radius contributions, $\theta_{80} = 0.081''$ (goal 0.075″).

12.3.4.8 Mirror supports

The error budget for the primary mirror support after closed loop figure correction with the active optics system is $\theta_{80} = 0.036''$. The design of the mirror support system that meets this specification is described in Section 10.8. The RMS error for the ensemble of seven mirrors after removing the alignment terms is the same as for a single segment since the errors combine in RMS.

The secondary mirror support has a structure function allocation of $r_0 = 120$ cm or, scaled to the entrance pupil of the telescope, $r'_0 = 953$ cm after removal of alignment terms. This corresponds to an encircled energy specification of $\theta_{80} = 0.020''$.

12.3.4.9 Primary mirror segment static alignment

Quasi-static misalignments of the primary mirror segments will be corrected by motions of the secondary mirror segments that essentially recover the full narrow-field diffraction-limited performance of the optics. The residual image size and wavefront error, assuming optimal correction with the active optics, is given in Chapter 8, Table 8-2. The narrow-field RSS 80% encircled energy specification for six degrees of primary segment motion is $\theta_{80} = 0.003''$, assuming RMS primary mirror displacement errors of 100 microns in x, y, and z and 3-axis tilt errors of 3.6″. Corrected over a 20′ field, $\theta_{80} = 0.088''$.

12.3.4.10 Secondary mirror segment static alignment

Fine alignment of the primary-secondary mirror segments is done by translating and tilting the secondary mirrors segments as described in Chapter 8 which also gives the image error sensitivity to secondary misalignment (See Table 8-5). The RSS 80% encircled energy specification for six degrees of secondary segment motion is $\theta_{80} = 0.141''$ assuming RMS secondary mirror displacement errors of 2.0 microns parallel to the mirror surface (2 DOFs), 4.0 microns in piston, 0.10″ in tilt about the segment vertex, and 0.36″ rotation about the segment axis. The goal is $\theta_{80} = 0.081''$ which implies RMS position errors of 1.0 micron for displacements, 0.07″ tilt about the vertex, and 0.18″ rotation about the segment axis.

12.3.4.11 Focal plane static alignment

The GMT instruments mount on the Instrument Platform (IP) and are referenced to it. Displacement of the IP and rotator assembly causes a misalignment of the focal plane. Lateral displacements will create a pointing error that will be compensated by the telescope drives.

Residual field aberrations (mostly astigmatism) will be introduced to the center field but for reasonable displacements (<10 mm) can be ignored.

Piston errors will be compensated by refocusing the telescope. Spherical aberration will be produced when the IP is not at the optimal back focus. This error amounts to $\theta_{80} = 0.010''$ for a 2 mm displacement (specification) or $\theta_{80} = 0.005''$ for 1 mm (goal). The gravity deflection of the Instrument Platform is discussed in Section 7.6.1.

12.3.4.12 Primary mirror figure wind disturbance

The distortion of the primary mirror segment surface from a 9 m/s wind blowing on the surface is presented in Section 10.8.10. The error budget specification of $\theta_{80} = 0.075''$ is easily met. In practice wind speeds on the primary mirror will be much less due to attenuation by the enclosure.

Rigid body motion of the segments will cause pointing and alignment errors. These are included in a separate budget item.

12.3.4.13 Wind disturbance of optical alignment, pointing, and focus

Dynamic effects of wind blowing on the telescope structure and optics will cause pointing errors, misalignment of the optics, and focus errors. These have been modeled for the telescope pointing into a 13 m/s wind (~90-95 percentile) and the results are summarized in Section 7.6.3.2. This is more conservative than the normal wind conditions that apply to the error budget.

The principal wavefront error comes from tilt of the whole upper structure followed by uncorrelated tilt of the individual subapertures and higher order aberrations (focus, coma). The error budget specification of $\theta_{80} = 0.110''$ (0.067″goal) is derived for the case of closed vents, no wind screen, and 2% structure damping. The specification assumes a 50% reduction (70% goal) in image motion at 8 Hz by fast tip-tilt of the secondary mirror segments.

12.3.4.14 Tracking errors

Closed loop tracking errors are a combination of servo performance and guide sensor error. The error budget specification is $\theta_{80} = 0.072''$ (goal 0.053″). This compares to 0.051″ achieved on the Magellan 6.5 m telescopes in winds up to 9 m/s with no wind screen. The goal assumes additional correction to the tracking by fast tip-tilt secondary motion.

12.3.4.15 Primary mirror thermal distortion

The specification for primary mirror thermal distortion is derived from the UA 95-02 structure function allocation of 214 cm. The proposed design has successfully been used in ventilation systems on the MMT, Magellan telescopes and LBT mirrors as described in Section 10.9. The specification corresponds to $\theta_{80}=0.089''$. The goal of 0.045″ will require strict attention to details of the thermal control and active figure control.

12.3.4.16 Active wavefront sensor

An encircled energy budget of $\theta_{80} = 0.025''$ is allocated for the active wavefront sensors and is consistent with the RMS errors in the Magellan sensors.

12.3.4.17 Corrector element alignments

The leading lens of the wide-field corrector and ADC elements is mounted in the central primary mirror segment cell, a very stiff location in the GMT structure. The telecentrator lens is fixed to the Instrument Platform. The alignment sensitivity matrix and tolerances are contained in GMT document 1373 (2005). The encircled energy budget of $\theta_{80} = 0.059''$ is derived from the position tolerances in Table 12-3 combined in RSS without active correction. The goal of $\theta_{80} = 0.040''$ assumes low-order modes are corrected with the active supports on the primary segments.

Table 12-3. Corrector/ADC position tolerances.

Element/misalignment	Δx (mm)	Δy (mm)	Δz (mm)	θx (deg)	θy (deg)
Corrector lens 1	0.5	1.0	1.0	0.01	0.01
ADC	0.5	1.0	1.0	0.01	0.01
Telecentrator	2.0	3.0	2.0	0.02	0.02

12.3.4.18 Corrector fabrication errors

Fabrication tolerances were checked with the Zemax optical design software. The RSS method of combining errors produced the 80% encircled energy diameter specification of 0.076″. The Monte Carlo method gives the goal value of 0.038″.

12.4 AO Wavefront Error Budgets (summary)

GMT will be diffraction-limited at wavelengths greater than 1 micron using adaptive optics. Several modes of AO operation are planned with different requirements for the optical system. For AO operations, wavefront error or Strehl ratio are appropriate and the standard metrics for performance. GMT uses RMS wavefront error specified in nanometers for the AO error budgets below.

Table 12-4 shows the maximum wavefront error allowed by the GMT top-level AO performance specifications from Chapter 4, Section 4.9.4.3.

Table 12-4. Derived GMT AO wavefront error budget from Chapter 4.

GMT AO Wavefront Requirements				
	Requirements		**Goals**	
λ(μm)	**Strehl ratio**	**RMS wavefront (nm)**	**Strehl ratio**	**RMS wavefront (nm)**
1.2	0.20	243	0.25	225
1.6	0.40	244	0.60	182
2.2	0.70	209	0.90	113
3.5	0.90	180	0.95	126
4.8	0.95	173	0.99	77

The wavefront error budgets for adaptive optics operation are developed in Section 9.2. Table 12-5 summarizes the error budget from Table 9.8 in Section 9.2.10. The three AO modes are natural guide star (NGS), laser tomography AO (LTAO), and extreme contrast AO (ExAO). The notes in the right column refer to explanatory notes in Section 9.2.10.

Table 12-5. Residual uncompensated wavefront error budget for a bright natural star on axis under average atmospheric conditions at zenith (r_0 = 14.3 cm, τ_0 = 2.1 ms, θ_0 = 2.1″ at 500 nm and L_0 = 25 m).

Wavefront error source	**RMS wavefront error (nm)**			**Note** (Section 9.2.10)
	NGS	**LTAO**	**ExAO**	
Subapertures	50 cm	50 cm	32 cm	
Read rate	1 kHz	1 kHz	1 kHz	
Primary mirrors figure	20	20	15	1
Secondary mirror figure	20	20	15	1
Piston anisoplanatism (1 min calibration)	25	25	0	2
Piston errors from primary edge sensors	25	25	25	3
AO optical train (non-common path)	18	21	0	4
Science instrument	20	20	7	5
Fitting error	121	121	80	6
Atmospheric temporal lag	93	93	61	7
WFS measurement noise propagation	83	28	50	8
Reconstruction error	52	95	0	9
High order total	**189**	**190**	**117**	
Anisoplanatism error	260 @13″	148 @ 1′	0	10
Residual windshake	50	50	30	11
TOTAL:				
On-axis	**196**	**196**	**121**	
Off-axis	**325 @ 13″**	**246 @ 1′**		

12.5 References

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