GNAO Error Budget

GNAO-SYS-SIM-007

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Contents

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1 Introduction

The Gemini North Adaptive Optics (GNAO) instrument is a next generation multi-conjugate adaptive optics (MCAO) system designed for a wide range of science cases, producing near diffraction-limited image quality for J-, H- and K-bands. A useful tool to understand and optimize the performance delivered by the MCAO system is an error budget. A wavefront error budget was developed for the GNAO system presented at the Conceptual Design Review.[1]

Since then, there have been major changes to the baseline design and field of view.

- The number of laser guide stars (LGSs) has increased from four to five.
- The number of deformable mirrors (DMs) has increased from two to three.
- The science field of view where the performance requirements must be met has changed from a 2' diameter circle to an 85"x85" square field of view.

Also, our understanding of the circular buffers from Altair has changed. Previously, we were led to believe that the data corresponded to pseudo open-loop tip-tilt values, but now we know that the values correspond to residual tip-tilt. We also believe that a significant fraction of the uncorrected vibrations are introduced by Altair itself, and we plan to measure the vibrations using Alopeke.

The LGS constellation is shown in Figure 1.

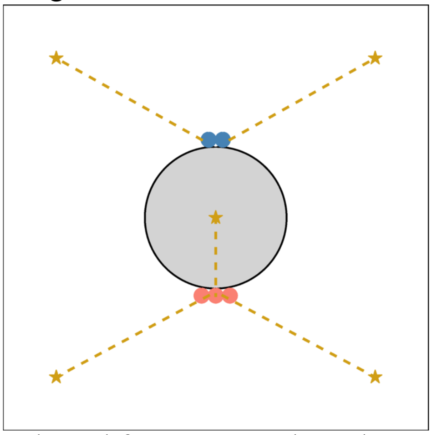

Figure 1: Launch configuration selected for GNAO. The colors of the launch telescope (blue and salmon) represent which of the two lasers is producing the laser light launched by the corresponding launch telescope.

The DM parameters are extracted from GNAO-SYS-SIM-005 and reproduced in Table 1.[2]

DM	Name	Pitch	Actuators	DM altitude	Pupil size
1	DM241	2.5 mm	17x17	0 m	37.5 mm
2	§DM468	2.5 mm	24x24	5700 m	60 mm
3	§DM241	5 mm	17x17	14500 m	75 mm

Table 1: Options for ALPAO DMs based on a 2.5 mm pitch for the ground-layer DM. The symbol § indicates a DM with a different pitch from what is available in the catalog.

[1]Marcos van Dam, Gaetano Sivo and Eduardo Marin, "Simulated Performance of GNAO," GNAO-SYS-SIM-001 v4.0 13 April 2020

[2]Marcos van Dam, Emmanuel Chirre and Gaetano Sivo, "Physical Parameters of Deformable Mirror for GNAO," GNAO-SYS-SIM-005, v1.0 16 December 2019.

All other parameters used in these calculations are reproduced from GNAO-SYS-SIM-001.

2 Wavefront error budget

A wavefront error budget is a collection of wavefront errors from different error sources.
For a single-conjugate AO system imaging on-axis, the terms in the error budget are summed in quadrature to calculate the total error. The Marechal approximation gives an estimate of the Strehl ratio, S, as a function of the phase, ϕ:

$$S = \exp[-\phi^2] \tag{1}$$

Where the relationship between the phase and the wavefront is

$$\phi = \frac{2\pi}{\lambda} wf \tag{2}$$

For MCAO systems, the error terms are not fully independent, so the sum of the error terms in quadrature is higher than the total wavefront error and the Strehl ratio is higher than the error budget predicts.

In this section, we present two error budgets for the simulated image quality (Section 5) and the on-sky performance (Section 6).

2.1 Simulated GNAO case

The purpose of building an error budget for the simulated GNAO case is two-fold: first, to get an idea about how the double-counting of error terms leads to an underestimate in the simulated Strehl ratio, and second, to understand how the performance of GNAO on-sky will differ from the output of simulations.

A wavefront error budget is developed for the case of an observation at zenith with noiseless NGS measurements using three NGSs at locations [0,35], [40,-30] and [-40,-20]. The error budget is tabulated in Table 2.

Error term	Factors relating to error term	Value
Atmospheric bandwidth	Frame rate	50 nm
Measurement noise	Photon return and noise	59 nm
Tomographic reconstruction	LGS number, location and altitude	125 nm
Generalized fitting	Number of DMs and actuator density	121 nm
Tip-tilt atmospheric bandwidth		25 nm
Tip-tilt noise		0 nm
Tip-tilt tomography		120 nm
TOTAL	Sum in quadrature	**226 nm**

Table 2: Wavefront error budget for the simulated case. The blue and gray shading denotes the high-order terms and tip-tilt related terms respectively.

The K-band Strehl ratio corresponding to the total error is 0.659, whereas the average Strehl ratio over the 85”x85” field is 0.730.

The generalized fitting error and the tomographic error as a function of position in the field is shown in Figure 2.

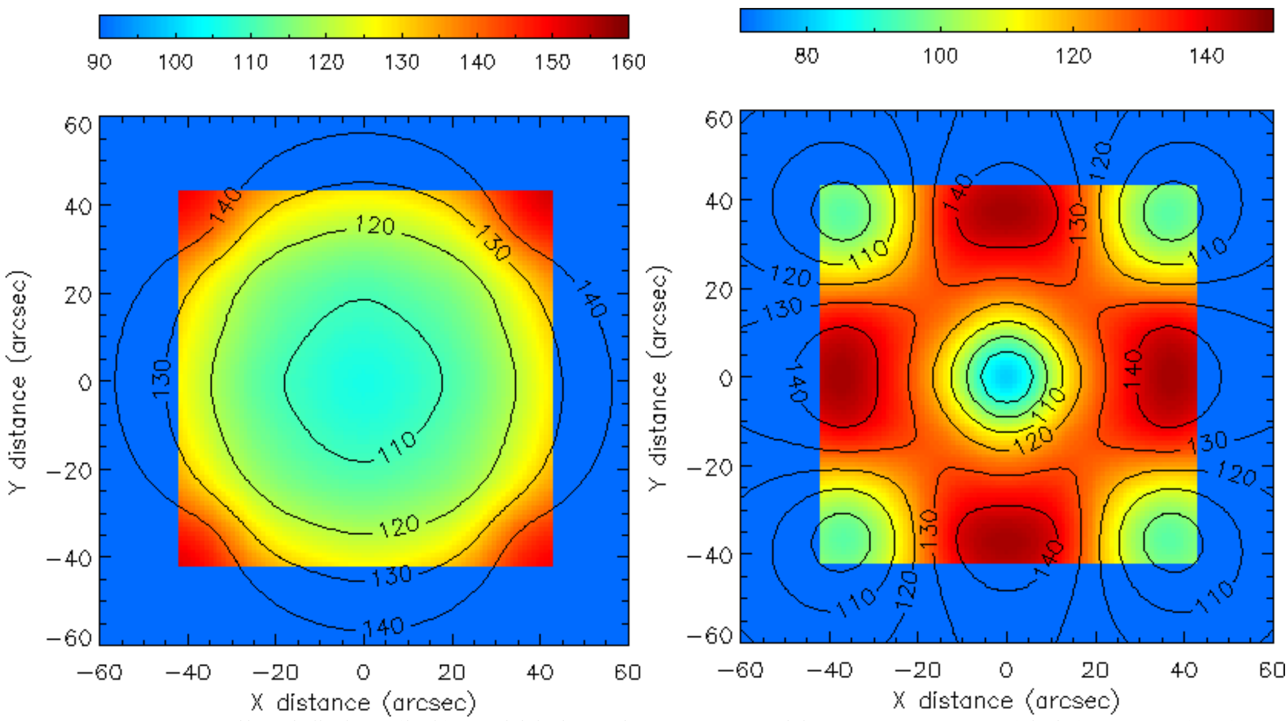

Figure 2: Generalized fitting (left) and high-order tomographic reconstructor (right) errors (nm) as a function of position in the field.

2.2 Real GNAO case

The error budget for the real GNAO case contains the same terms as the simulated case along with a number of additional terms (Table 3).

Error term	Factors relating to error term	Value
Atmospheric bandwidth	Frame rate	50 nm
Measurement noise	Photon return and noise	59 nm
Tomographic reconstruction	LGS number, location and altitude	125 nm
Generalized fitting	Number of DMs and actuator density	121 nm
Tip-tilt atmospheric bandwidth		25 nm
Tip-tilt noise		0 nm
Tip-tilt tomography		120 nm
Scintillation	High-altitude turbulence	18 nm
High-order telescope bandwidth	Frame rate	50 nm
Tip-tilt telescope bandwidth	Frame rate	90-234 nm
Dome seeing		39 nm
LGS focus	Sodium height variations	30 nm
LGS aberrations	LGS spot sampling	50 nm
M2 print-through	Secondary mirror	73-147 nm

Table 3: Wavefront error budget for the simulated case. The blue and gray shading denotes the high-order terms and tip-tilt related terms respectively. The red shading denotes the terms not included in the simulations.

There are two terms with high values which we must address: the tip-tilt telescope bandwidth error and the M2 print-through.

The tip-tilt error induced by the telescope and the instrument and the M2 print-through. The tip-tilt value of 234 nm is extracted directly from Altair telemetry and is expected to be much lower for GNAO provided that care is taken to reduce internal vibrations in the instrument. Vibration measurements will be made using ‘Alopeke that will provide a better indication of the tip-tilt disturbances. We are hopeful that with some work on reducing the vibration environment of the telescope, GNAO will deliver a corrected tip-tilt wavefront error of under 100 nm.

Work is in progress to address the M2 print-through, so we can be hopeful that this value will be much lower. In the error budget, we have the current value and a value with half the magnitude, in the expectation that the remediation work can deliver a secondary mirror with half as much print-through as the existing secondary mirror.

The measurement noise term is not included in the error budget because its value is wholly dependent on the brightness of the guide stars. The tip-tilt tomography error will also vary depending on the asterism, with the values for a number of cases tabulated in Table 4.

Number of NGSs	Best	Typical
1	217 nm	288 nm
2	150 nm	218 nm
3	99 nm	152 nm
4	69 nm	
6	38 nm	

Table 4: Tip-tilt tomographic error

For each number of stars in the field (1, 2 or 3), the best asterism was found by optimizing the radius of a symmetrical constellation.

NGS	Best (arcsec)	Typical (arcsec)
1	[0,0]	[40,0]
2	[-27,0] [27,0]	[-35,-2] [-20,38]
3	[0,31] [-26.8,-15.5] [26.8,-15.5]	[19,3] [48,15] [-32,-46]
4	[25,25],[-25,25],[25,-25],[-25,-25]	
6	[34,20],[34,-20],[0,-39], [-34,-20],[-34,19.5],[0,39]]	

Table 5: Asterisms used to calculate the tip-tilt tomography error

The typical asterism was obtained using a Monte-Carlo simulation assuming that the stars are evenly distributed in the field. The asterisms used are recorded in Table 5.

For fields with a lot of stars, the tip-tilt tomographic error can be reduced by adding more stars. A four star constellation can have a tomographic error as low as 69 nm, with a corresponding number of 38 nm for a six star constellation.