NGAO Performance Budget Summary
Keck Adaptive Optics Note 491

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1 Introduction

This document presents a summary of the performance budget studies conducted as part of the NGAO design study, and compares these predictions to the NGAO science and system requirements.

The eight performance budget studies and the personnel originally assigned to perform these studies are listed in Table 1. Five of these studies have produced KAONs, while studies on polarimetric performance and on transmission and background have produced power point slides presented at NGAO team meetings. The studies on observing efficiency and system uptime have been postponed, though KAON 463 contains material pertinent to both topics.

The science requirements presented in this report have been extracted from Table 4 of the NGAO Science Case Requirements Document (Revision 1), which has been released as KAON 455. This document will be referred to as the SciRD. The NGAO System Requirements Document is also utilized in this performance budget summary. This document has been released as KAON 456, and will be referred to as the SysRD. The SysRD lists performance requirements derived from the SciRD in Table 7 of the document. Both sets of requirements are included in this study for completeness.

Performance Budget	**KAON**	**Contributors**
Wavefront error and encircled energy	471	**Dekany**, Flicker, Gavel, Max, Wizinowich
Photometric precision	474	**Britton**, Dekany, Flicker, Olsen
Astrometric precision	480	**Cameron**, Britton, Dekany, Ghez, Lu
High contrast	497	**Flicker**, Dekany, Liu, Macintosh, Neyman
Polarimetric precision	-	**Ireland**, Dekany
Transmission and background	-	**Bouchez**, Dekany
Observing efficiency	463	**Le Mignant**
System uptime	-	**Johansson**, Chin

Table 1: Table of performance budgets, KAON reports generated by the performance budget teams, and team members. Team leads are in boldface.

Scenario	Exp. Time	TT GS	HO GS	LGS Ast. (asec)	TT Error	Sky Cvge	HO Error	1.65 μm Strehl
Io	10 sec	Sci. Target	Sci. Target	-	1.7 mas	n/a	96 nm	87%
Kuiper Belt	300 sec	Field Star	6xLGS	41	6.2 mas	10%	150 nm	61%
Exo Jupiter	300 sec	Sci. Target	6xLGS	12	3.3 mas	n/a	124 nm	76%
Ext. Groth	1800 sec	Field Star	6xLGS	90	18.5 mas	30%	159 nm	25%
Gal. Ctr.	30 sec	IRS 7	6xLGS	11	2.0 mas	n/a	170 nm	64%

Table 2: Summary of the error budgets for the five observing scenarios considered in this study. The second column shows the integration time assumed for the scenario. The third and fourth columns indicate the tilt and high order guide stars assumed for the scenario, respectively. For the Io and Exo Jupiter scenarios, the tilt guide star is the science object. For the Galactic Center, the tilt guide star is specified to be IRS 7. For the remaining two scenarios, a field star is used for tilt guiding. The fifth column indicates the optimal diameter of the LGS asterism for cases where lasers are employed for high order sensing. The sixth column indicates the tilt error budget. In scenarios where tilt guiding is performed using a field star, the tilt error budget depends on the proximity of the tilt star to the science target. For these cases, the seventh column indicates the fraction of sky over which the tilt error is less than or equal to the value in column five. The high order error budget is listed in the eighth column. The final column indicates the H band Strehl ratio attained in the observing scenario.

1.1 Wavefront Error and Encircled Energy

Error budgets for five observing scenarios have been generated as part of the wavefront error budget performance study. These error budgets are summarized in Table **??**. For the Extended Groth scenario, ensquared energy is the relevant scientific metric. Values of the K band ensquared energy as a function of spaxial size are listed in Table 3 for this case.

Requirements on wavefront error from the SciRD and the derived requirements from the SysRD are listed in Table 4. Also tabulated is an evaluation of whether these requirements are met are based on the performance estimates in Tables **??** and 3.

Spaxial Size (asec)	Ensq. Energy Fraction
.05	37%
.07	57%
.08	65%
.12	81%
.24	88%
.48	93%
1.00	95%

Table 3: Fractional 2.2 μm ensquared energy as a function of spaxial size for the Extended Groth observing scenario.

SciRD Sci. Case	Wavelength	Requirement
Asteroid shape	0.7-2.4 μm	20% Strehl at R band
Asteroid companions	0.7-2.4 μm	140 nm
Planets around low-mass stars	0.9-2.4 μm	140 nm
Gal. Ctr.	K band	170 nm at Gal. Ctr.
Nearby AGNs	JHK bands	As low as possible

SysRD Req. Number	Requirement
5	Wavefront error $\leq$ 140 nm rms for V $\leq$ 17 on-axis guide star
6	Wavefront error $\leq$ 140 nm rms for V $\leq$ 16 guide star $\leq$ 30 asec from science object
7	Wavefront error $\leq$ 170 nm rms for objects $\leq$ 5 asec from the Galactic Center
8	Encircled energy $\geq$ 50% within a 0.05 asec diameter circle at K band for sky coverage $\geq$ 5%
9	Encircled energy $\geq$ 50% within a 0.075 asec diameter circle at K band for sky coverage $\geq$ 30%

Table 4: Requirements from the NGAO SciRD (upper table) and SysRD (lower table) pertinent to the wavefront error and encircled energy performance budget.

1.2 Photometric Precision

SciRD Sci. Case	Observing Wavelength	Requirement
Asteroid companions	0.7 - 2.4 μm	5% at 0.6 asec with Δm=3
Planets around low-mass stars	0.9 - 2.4 μm (L band?)	0.05 mag relative to primary star

SysRD Req. Number	Requirement
13	H-band photometric accuracy of $\leq$ 0.05 mag at 0.6 asec for ΔH = 3 for a V $\leq$ 17 on-axis guide star
14	H-band photometric accuracy of $\leq$ 0.05 mag relative to primary star at 1.0 asec separation for ΔH = 13 for a V $\leq$ 16 guide star $\leq$ 30 asec from science object
20	Strehl or PSF stability requirement?

Table 5: Requirements from the NGAO SciRD (upper table) and SysRD (lower table) pertinent to the photometric performance budget.

Towards improving the photometric stability delivered by NGAO, this study included the following recommendations:

- Require turbulence monitoring capabilities that deliver C_n^2 measurement on minute timescales. Measurements from a turbulence monitor will establising a baseline of C_n^2 profiles that may be used to understand both mean turbulence conditions and the degree of variability about the mean. This will help to establish expectations for photometric stability. An understanding of the turbulence conditions under which NGAO is operating will significantly aid both operators and observers in making decisions on target selection and observing strategy. Use of turbulence profiles in postprocessing algorithms also shows promise in improving photometric precision.

- Consider providing an auxiliary camera for contemporaneous measurements of the PSF. The purpose of this camera would be to perform observations of a reference point source for use in deconvolution of data from the science camera. The exact requirements on this camera would depend upon the adaptive optics architecture selected for NGAO and the photometric requirements ultimately placed on the system.

But to be useful this camera should be Nyquist sampled and should be deployable independently of the science detector. This camera should also be deployable over a field large enough to find a point source reference for PSF calibration.

- As a step towards understanding the requirements for this auxiliary PSF camera, consider conducting NIRC2 and/or OSIRIS imaging camera experiments with the existing single conjugate AO system and the T6 DIMM/MASS turbulence profile equipment. These experiments will indicate the utility of contemporaneous PSF measurements, and may provide near term benefits for Keck Observatory.
- Consider providing facility deconvolution pipelines for Keck NGAO data. This is a more efficient alternative than having each observing team reimplement these techniques as part of their research effort, and could improve the quality and quantity of scientific output from Keck Observatory.

1.3 Astrometric Precision

SciRD Sci. Case	Observing Wavelength	Requirement
Asteroid companions	0.7 - 2.4 μm	Uncalibrated detector distortion $\leq$ 1.5 mas
Planets around low-mass stars	0.9 - 2.4 μm (L band?)	$\approx$ 1/10 of the PSF FWHM
Galactic Center	K band (L band?)	0.1 mas

SysRD Req. Number	Requirement
15	Uncalibrated detector distortion < 1.5 mas
16	1/10 of the PSF FWHM
17	Astrometric accuracy $\leq$ 100 μas at K band for objects $\leq$ 5 asec from the Galactic Center

Table 6: Requirements from the NGAO SciRD (upper table) and SysRD (lower table) pertinent to the astrometric performance budget.

Towards improving the astrometric stability delivered by NGAO, this study included the following recommendations:

- Require turbulence monitoring capabilities that deliver C_n^2 measurement on minute timescales. Measurements from a turbulence monitor will establish a baseline of C_n^2 profiles that may be used to understand both mean turbulence conditions and its degree of variability. This will help to establish expectations for astrometric stability. An understanding of the turbulence conditions under which NGAO is operating will significantly aid both operators and observers in making decisions on target selection and observing strategy. Use of turbulence profiles in post-processing algorithms also shows promise in improving astrometric precision.

- Consider providing an auxiliary camera for contemporaneous measurements of the PSF. The purpose of this camera would be to perform observations of a reference point source to provide the optical transfer function for use in post-processing algorithms which are currently under development. The exact requirements on this camera would depend upon the adaptive optics architecture selected for NGAO and the photometric requirements ultimately placed on the system. But to be useful this camera should be Nyquist sampled and should be deployable independently of the science detector. This camera should also be deployable over a field large enough to find a point source reference for PSF calibration.

- Require the ability to solve for and monitor optical distortion in the AO system and science instrument. Examples would be a well-machined pin hole slit mask placed as far upstream in the optical path as possible, or possibly a grid of fibers. It must be possible to rotate and translate either of these elements to solve simultaneously for their positions and the optical distortions. It is may also be possible to achieve this goal with on-sky tests, but work in this area is on-going.

- Consider providing an atmospheric dispersion corrector (ADC). This element must be driven as the telescope tracks (in contrast to the ADC at VLT which is preset at a given zenith distance). However, little work has been done to quantify the accuracy of the correction provided by these devices for astrometry, so we can not be certain as to whether such a device would make identifying and correcting residual atmospheric refraction more difficult.

- The current generation AO system provides a stable plate scale (changes by $\leq 1 \times 10^{-4}$ on timescales of a night). Some AO architectures (i.e. MCAO) could yield significantly worse plate scale stability due to unsensed modes between deformable mirrors, which lead to overall field (de)magnification. The timescales over which these modes operate are currently unknown, and will likely be a function of the system architecture and control loop design. Such field magnifications will be an obstacle to high precision astrometry, particularly in spares fields where targets cannot be detected in a single image. Thus we require plate scale stability at the level of the current generation system.

- In order to achieve astrometric bias $\leq 0.1\,\mathrm{mas}$, our preliminary studies show that WFE $\approx 140\,\mathrm{nm}$ are required. Thus, NGAO should consider this level of WFE to achieve this particular science goal.

1.4 High Contrast

SciRD Sci. Case	Observing Wavelength	Requirement
Asteroid companions	0.7 - 2.4 μm	Δm = 5.5 at 0.5 asec separation
Planets around low-mass stars	0.9 - 2.4 (L band?) μm	ΔH = 13 at 1 asec separation
Galactic center	K band (L band?)	High (not clear yet how high)

SysRD Req. Number	Requirement	Requirement Met
10	The companion sensitivity shall be $\Delta H \geq 5.5$ mag at 0.5 asec separation for a $V \leq 17$ on-axis guide star	
11	The companion sensitivity shall be $\Delta H \geq 13$ mag at 1.0 asec separation for a $V \leq 16$ guide star ≤ 30 asec from science target	
12	Sensitivity? Does this just drive transmission?	

Table 7: Requirements from the NGAO SciRD (upper table) and SysRD (lower table) pertinent to the contrast performance budget.

So here's a summary of the one-shot contrast results and their implication on AO derived requirements.

The asteroid science goals (dH¿5.5@0.5", dI¿7.5@0.75") are achieved by a wide margin with the baseline NGAO configuration, and could realistically also be achieved by a much more modest AO system. Hence the astroid science cases do not appear to drive NGAO requirements beyond the point design, but rather can relax a number of design points, such as laser power.

The close companion (coronagraph) science cases are partially achieved by the same NGAO configuration:

- 1. dJ=10 @ 0.2" Achieved at a 8 sigma confidence level by either 6 or 10 lambda/D coronagraph Not achieved without coronagraph

- 2a. dJ=8.5 @ 0.1" Achieved at a 8 sigma confidence level by 6 lambda/D coronagraph

- 2b. dJ=11 @ 0.2" Not achieved at 8 sigma confidence level Achieved at 4 sigma confidence level by either 6 or 10 lambda/D coronagraph
- 2c. dJ=11 @ 0.1" Not achieved (factor 10 missing for 8 sigma level)
- 3. dJ=9-13.5 @ 0.07" dJ=9 could be achieved at 6 sigma level by the 6 lambda/D coronagraph (close to the occulting disk), but anything better will require a different instrument with multi-channel imaging and some pretty fancy speckle suppression strategies (or excellent PSF knowledge).

In round numbers, 50% of the stated companion science cases appear to be achieved at a 6-8 sigma confidence level by a standard coronagraph and the base line NGAO system configuration - maybe this is good enough? The margins are much tighter in this case, but it is also recognized that speckle noise in this simulation is pessimistic and that good PSF subtraction and speckle suppression strategies may improve the current margins and bring some of the other goals within reach. That being said, the tall tent poles that must be controlled and minimized for these goals to stay achievable are 1) excellent calibration of static non-common path aberrations, 2) keep a high bandwith ¿1kHz to minimize servo-lag, which has a strong impact on the contrast, and 3) effective application of speckle suppression techniques (whether by multi-channel differential imaging or highly precise PSF subtraction).

1.5 Polarimetric Precision

Polarimetric precision analysis is in a very preliminary state - only one power point slide.

Polarimetric Accuracy Performance Budget

- Science requirement input is polarimetric accuracy as a function of distance from the PSF core. E.g. 10^{-4} at 100 mas means the ability to detect a blob of dust 100 mas from a central source at 10-σ that scatters 1% of the incident radiation with 10% fractional polarization.
- 2 kinds of performance budgets, depending on polarimeter.
  - "Back-end" polarimeter: The entire polarimetry instrument is behind the entire NGAO system.
  - "Split" polarimeter: the polarization is modulated by an element (waveplate or variable retarder) downstream of only the primary, secondary and tertiary mirrors.
- "Back-end" budget :
  - How does the differential wavefront between different polarization states translate to a difference in PSF between polarization states?
    - Differential wavefront is due primarily to reflections off flat optics in converging beams, and is mainly astigmatic.
    - With no (quasi-) static aberrations, a pure astigmatism differential aberration translates to zero PSF difference. The PSF difference is dominated by a cross-term that is linearly proportional to (quasi-) static aberrations and linearly proportional to the differential wavefront. E.g. 0.1 radians static astigmatism and 0.1 radians differential wavefront gives a PSF difference which is10^{-2} of the diffraction-limited PSF: better than10^{-4} at 2nd Airy ring or beyond. Math to come in report…
  - At what level can an observer calibrate the PSF difference using a standard star and how does this relate to quasi-static aberrations?
    - It is difficult (impossible?) to completely correct for static aberrations if a standard star is observed after a K-mirror rotation or telescope elevation change. Obviously, quasi-static aberrations that change between observations can not be corrected.
- "Split" budget:
  - More complex. Will only be examined if the "back-end" budget can not deliver adequate performance for primary science goals.

Figure 1: Powerpoint slide from the polarimetric precision performance study.

SysRD Req. Number	Requirement
1	Telescope plus NGAO transmission to the input of the science instruments $\geq 70\%$ at 0.7-2.4 μm
2	Goal: Telescope plus NGAO transmission to the input of the science instruments $\geq 70\%$ at L band
3	NGAO background, including the science instrument shall be $\leq 100\%$ of the sky plus telescope at K band
4	Goal: NGAO background including the science instruments shall be $\leq 100\%$ of the sky plus telescope at K band

Table 8: Requirements from the NGAO SysRD pertinent to the transmission and background performance budget.

1.6 Transmission and Background

- An adaptive secondary designs start with an 0.30 limiting magnitude advantage at K band (0.25 in L band).
- Once AO is cooled to <263 K, the thermal background is dominated by the telescope. We may want to consider higher reflectivity telescope coatings.

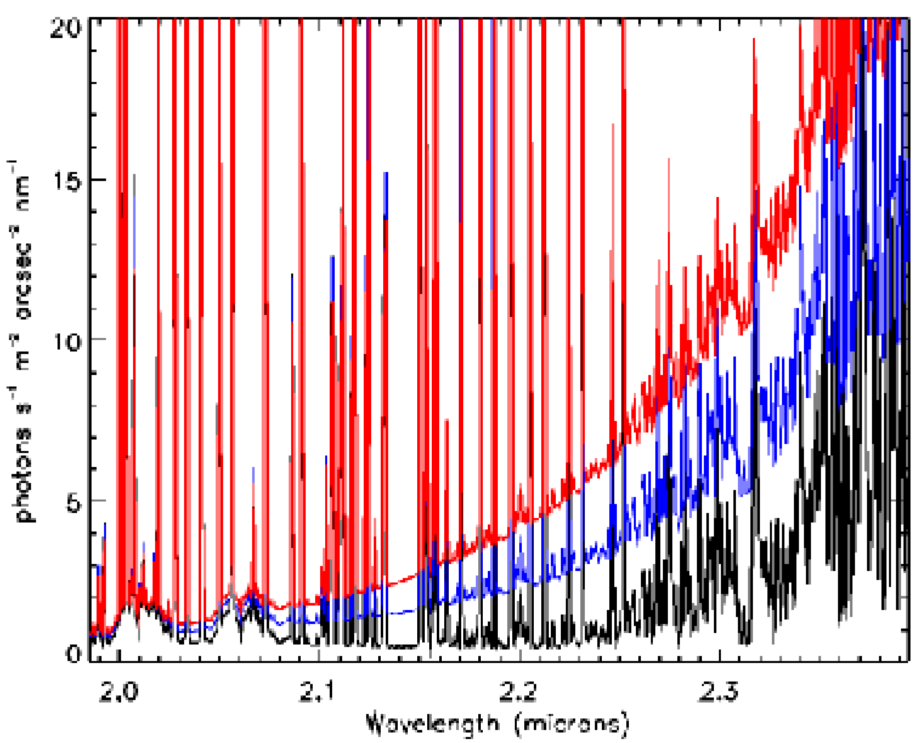

Figure 2: OAP relay design, $T_{AO} = 263$ K, $\lambda/\Delta\lambda = 4000$ Background after telescope M3 in blue. (Questions - what is black, what is red)

SysRD Req. Number	Requirement
19	Overheads between targets $\leq$ 10 min

Table 9: Requirements from the NGAO SysRD pertinent to the observing efficiency and system uptime performance budget.

1.7 Observing Efficiency and System Uptime

Full reports on observing efficiency and system uptime budgets for NGAO have been postponed by the project. KAON 463 summarizes lessons learned from the Keck laser guide star adaptive optics program. The issue of system uptime raised in this report will be extremely important for NGAO.

The existing laser guide star system at Keck has an open shutter science fraction of 25%. The largest single loss of observing time is due to operational overhead (37%). NGAO will be a much more complex system, with multiple lasers and wavefront sensors. The project has very little latitude to slip on this statistic. This calls for significant attention to the operational model for NGAO. (e.g. parallel sequencing of hardware, reducing overhead on guide star acquisition, minimization of detector readout time.)

Loss due to weather is the second largest component of system downtime. The only effect that I can think of that would result in a marginal loss of observing time between existing LGS system and NGAO would arise from LGS fratricide, which could make a multiple LGS system less robust against observing through clouds. However, it is not clear whether this will be a significant effect. (Don Gavel wrote a report for Gemini on LGS fratricide - we should ask him for his opinion.)

The third largest source of system downtime is from system faults. Given its multiple lasers and wavefront sensors, NGAO has a much larger probability to experience system faults. NGAO will need to be designed with careful attention to fault tolerance and fault recovery.

Table 9 summarizes the single requirement placed on observing efficiency by the SysRD.

1.8 Loose Ends

One requirement from the NGAO system requirements document was not addressed in any performance study. This requirement appears in Table 10.

SysRD Req. Number	**Requirement**	**Requirement Met**
18	Radial velocity accuracy $\leq$ 10 km/sec at K band for objects $\leq$ 5 asec from the Galactic Center	Unknown

Table 10: The remaining requirement from the NGAO SysRD not addressed by any of the above studies.