A comparison of astronomical performance metrics for potential Gemini-North Adaptive Optics systems

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Abstract. The next Gemini North Adaptive Optics (GNAO) system will have to be designed to deliver the greatest scientific impact to the Gemini user's community. There are many potential AO modes that could be implemented as part of GNAO. In this paper, we present five categories of astronomical performance metrics: 1) relative background-limited exposure times for point sources, 2) corrected field of view, 3) sky coverage, 4) astrometric and photometric limiting errors, and 5) survey efficiency. We compare potential GNAO implementations of different AO modes in terms of each of these performance metrics. The different systems we compare each have different strengths (and weaknesses). No one system will be optimal for each science case. The final choice of GNAO system will depend on the scientific priorities of the Gemini community.

1. Introduction

Adaptive Optics (AO), as a technical field, has advanced a great deal in the last decade [1]. These advances can be seen in:

- **Individual components**, such as quieter, larger and faster detectors for wavefront sensors (WFSs), large adaptive secondary mirrors (ASMs) [2], compact microelectromechanical (MEMS) deformable mirrors (DMs) [3], and higher power, more economical Sodium lasers.
- **On-sky demonstrations of "novel" AO techniques** including Multi-Conjugate AO (MCAO) [4,5,6], Ground Layer AO (GLAO) [7], Multi-Object AO (MOAO) [8], Laser Tomography AO (LTAO) [8], Extreme AO [9,10]. The differences between these methods are described in section 2 below.
- **Better understanding of how to use AO to achieve scientific ends**. Astronomers are pushing AO systems and AO data reduction techniques further to extract the most amount of information possible. Clear examples of this are found in the fields of planet imaging [11], PSF reconstruction [12], and improved AO astrometry [13].

In this paper, we look at potential Gemini-North AO (GNAO) upgrade paths, and give rough AO performance predictions. We have not attempted to model every variation in potential designs, and we are not promoting one potential system over another. Indeed, we are not basing this work on *any* opto-mechanical design. Rather, the characteristics of the systems we describe are based on results from the literature, results from other design studies, anchored by simulations of baseline systems. This paper is also not a review of the state of the art in astronomical AO. See Davies & Kasper for such an overview [1].

Having described what the paper is *not* about, this paper *will* compare the relative strengths and weaknesses of different AO system in terms of astronomical performance metrics. The next section describes the differences between the AO modes listed above. Section 3 then maps these AO modes onto potential GNAO systems. In section 4, we describe some key scientific performance metrics and use them to compare the potential GNAO systems. Finally, section 5 provides a short summary.

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2. AO Modes

There are several broad categories of AO modes that could be incorporated into a GNAO system. Some of these modes may be optimized for certain science cases (As an example, Extreme AO systems focus on planet detection), and there will be no one AO mode that will be best-suited to every science case.

- **Single Conjugate NGS AO mode:** This is the "classic" AO system that requires a bright guide star and a single DM. Altair operating in NGS mode is an example. Single conjugate NGS AO systems can produce quite high Strehl ratios, but they operate over limited fields of view (FOVs) with low sky coverage.

- **Extreme AO mode:** Extreme AO systems are usually one component in a planet finder instrument like GPI [14]. When coupled with a coronograph, and specialized calibration and focal plane instruments, dark holes (regions of high contrast) can be created near to the diffraction peak of the central PSF. Due to the high-order nature of the Extreme AO system, quite bright stars are needed for WFSing, and the sky coverage is correspondingly small.

- **Single conjugate, single LGS AO mode:** This mode is very similar to the Single Conjugate NGS AO mode, except that it takes advantage of a bright artificial star (usually a Sodium beacon). Using this LGS will increase sky coverage substantially. A fainter star is still usually needed to provide correction for atmospheric tip/tilt and windshake because the LGS is blind to this mode (and focus to some extent too). Astronomers willing to sacrifice performance can already use a LGS system without a NGS star and achieve 100% sky coverage on Gemini[2]. In this mode, Altair delivers a "seeing improvement" of a factor of 2-3 instead of delivering a PSF with a diffraction-limited core. Single LGS AO systems (like Altair with LGS) do suffer from poorer performance than a NGS AO system because of the cone effect. The cone effect refers to the fact that the Sodium layer at 90 km is not at infinity. Instead the light from the Sodium beacon that reaches the telescope fills a cone (rather than a cylinder coming from infinity). Atmospheric turbulence that falls in the cylinder of a science target but that is not included in the LGS cone cannot be corrected by the AO system. This leads to a significant degradation in performance. Using the TMT atmospheric profile [15] and an 8 m telescope looking at zenith, the wavefront error (WFE) due to the cone effect will be more than 250 nm.

- **LTAO:** Laser Tomography AO uses multiple LGS to defeat the cone effect mentioned above. The Real-Time Computer (RTC) of a LTAO system will reconstruct the turbulence in the direction of the field center using tomographic methods and command the science DM to correct that turbulence. LTAO systems can provide AO corrections almost as good as those of a NGS AO system with a bright star, but with much higher sky coverage. The corrected field of view is no larger than for any other single conjugate AO system.

- **MCAO:** Multi-Conjugate AO systems also use multiple guide stars (usually LGSs) to sense the turbulence over a larger field of view, but then the correction is divided between two or more DMs which are each conjugate to different layers in the atmosphere. The Gemini community is of course familiar with MCAO due to the recent commissioning of GEMS on Gemini-South [6]. MCAO systems can provide near diffraction-limited performance over a much larger FOV than a single conjugate system. MCAO and LTAO systems will have similar sky coverages, unless near-infrared (NIR) WFSs are used, in which case MCAO systems can take advantage of guide star sharpening over a large field and provide a very high sky coverage.

- **MOAO:** Multi-Object AO systems are most similar to LTAO systems. MOAO instruments sense light from multiple LGSs and create a tomographic representation of the atmosphere. While in a LTAO system that tomographic model is collapsed only along the line-of-sight of the field center, in a MOAO system the tomographic model is collapsed along several lines-of-sight in the direction of multiple science targets. MOAO instruments also have individual pick-offs for each science target in which a DM is embedded to provide the optimal AO correction in that direction on-sky. All proposed MOAO instruments are meant to feed integral field spectrographs (IFSs),

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[2] http://www.gemini.edu/sciops/instruments/altair/lgs-p1-quotsuper-seeingquot-mode

and we treat a potential MOAO options for GNAO as strictly spectroscopic survey instruments. Since MOAO systems are meant to feed IFSs, the most important performance metric is the ensquared energy within the IFS spaxel from a point source. In this paper, we are only considering Strehl ratio and wavefront errors, but if the spaxels are relatively close to the diffraction limit of the telescope then Strehl ratio is a good proxy for ensquared energy.

- **GLAO:** Ground Layer AO systems also make use of multiple guide stars (NGS or LGS). If the widely-spaced WFS signals are simply averaged, that provides an estimate of the turbulence common to all the WFSs which corresponds to the turbulence at the ground (or within 1 km of the ground for the FOV of Gemini). Most of the turbulence is at the ground (up to 60% within 50 m of the primary mirror [16]), so a GLAO correction can be quite good. In the optical, the core of the PSFs become significantly narrower (although the wings of a GLAO PSF have been found to be more shallow than those of a seeing-limited PSF). In the NIR, the FWHM of GLAO PSFs have been observed to be the same as a diffraction-limited PSF [7]. GLAO should be usable with any visible or NIR instrument, and should have extremely high sky coverage if LGSs are used.

3. Potential GNAO Systems

Having introduced the various AO modes that could be used in GNAO, we describe a few ways those modes could be realized on Gemini.

- **Refurbished Altair:** In a refurbished Altair, the instrument would undergo a number of major changes. The field lens would be removed, the DM would be moved from its current 6 km conjugation to be ground conjugate, a tip/tilt WFS could be placed in the unit that could patrol a ~1 arcminute FOV, and the instrument could pass L-band light onto the scientific focal plane. In addition, work could be done to mitigate vibration issues. The refurbished Altair would be a classic single-conjugate AO instrument that could work in either NGS or LGS mode. The AO performance for a refurbished Altair was taken from previously defined specifications for an Altair upgrade.

- **Altair450:** In addition to the upgrades described above, one could also quadruple the actuator density on the Altair DM using existing DM technology. Again, Altair450 (450 refers to the number of actuators on the proposed DM) would be a single conjugate NGS/LGS AO system. We estimated the performance by subtracting the quadrature difference in generalized fitting error from the expected refurbished Altair system. This simple calculation is consistent with simulations.

- **ASM+Pyramid WFS:** The LBT with an Adaptive Secondary Mirror and pyramid WFS have produced some amazing results [2]. The pyramid WFS [17] is a focal plane WFS that is highly sensitive and linear, but over a limited dynamic range. Unlike a Shack-Hartmann WFS (SHWFS), a pyramid WFS can take advantage of the diffraction limit of the telescope (instead of being limited by the larger angular scale of the diffraction-limit of a single SHWFS subaperture). Another nice feature of a pyramid WFS is that the WFS detector can be binned which allows the pyramid to be used with fainter NGSs (while also sacrificing sensitivity). The ASM also appears to have some advantages over using an AO relay like Altair. The number of elements in the optical path is reduced so throughput increases, emissivity decreases, and long-lived speckles due to non-uniformities in optics should decrease dramatically. To be fair, there are drawbacks as well, including uncertainty in ASM lifetimes, a potentially more challenging calibration process, and a higher component cost. Determining the number of actuators in an ASM becomes a trade-off between power consumption, class thickness and actuator density. For this paper, we assumed a GNAO ASM would have ~700 actuators (30 across the pupil), similar to the ASM used on LBT. This higher actuator density can be used to full advantage (in terms of delivering high Strehl images) if one has a pyramid WFS with sufficient pixels that can be read fast enough. This system is another example of a single conjugate NGS AO system. We based our expectations of GNAO performance with an ASM+Pyramid on published results [18].

- **ASM+Single LGS:** The ASM can also be used with a single LGS (as exists at Gemini North). In this system, we assume the LGS is sensed by a SHWFS. Pyramid WFSs do not gain as great an advantage over SHWFS when LGS are used because the size of the on-sky spot is set by the size of the small laser launch telescope and the thickness of the Sodium layer. The pyramid's limited dynamic range can then become a liability. The performance of a single LGS system for GNAO is limited by the cone effect described above. The AO correction for an ASM+single LGS was estimated by simply adding in quadrature the cone effect error to the total ASM+pyramid WFE. This was matched by a performance estimate from LBT [18].

  As we shall continue to see in this section, the ASM can be used with a variety of different AO subsystems to deliver a range of AO modes. Figure 1 diagrams how these AO subsystems map onto different modes.

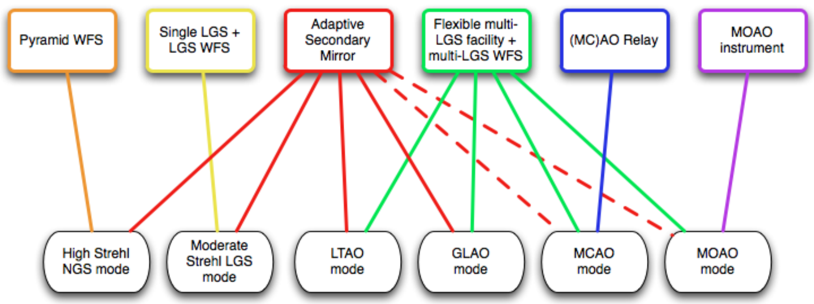

Figure 1. Diagram of different AO components (top row) and how they map onto AO modes (bottom row). The dashed lines represent AO modes for which an ASM is not required, but for which it would offer benefits. All these components could be included in a comprehensive GNAO facility.

- **LTAO:** Laser Tomography AO, as mentioned above, defeats the cone effect by using multiple LGS cones to fill in the "cylinder" of light from an on-axis science target. Using tomographic techniques, the turbulence in one direction can be estimated quite accurately. Keck's NGAO system was designed to yield moderate Strehl ratios even in the visible [19]. One could build a LTAO system using an AO relay, but if GNAO includes an ASM, it would be natural to include the LGS WFSs in the Gemini Instrument Support Structure (ISS) / Acquisition and Guide Unit (AGU). LTAO would also require multiple LGSs (Figure 1). Here, we assumed that GNAO would include 5 LGSs in a configuration similar to GEMS (4 LGSs on a square with one in the center). As we shall see, our predictions for LTAO performance are somewhat reduced from the ASM+Pyramid predictions. This reduction in performance is due to two factors: 1) For simulations of LTAO with ASM, we assumed the LGS SHWFSs have 0.5 m diameter subapertures (16 across the Gemini pupil). If there were enough return flux from the Sodium layer, the number of subapertures could be increased thereby reducing aliasing in the WFSs. 2) We included 120 nm RMS of implementation error in our LTAO performance estimate that is not present in the ASM+Pyramid estimate, because of extra error sources in LGS systems (e.g. added windshake in laser launch telescope, spot elongation, uncertainties in the distance to the Sodium layer and Sodium profile asymmetry errors [20]). LTAO performance here has been estimated through simulation using MAOS [21].

- **MCAO:** Multi-Conjugate AO systems can certainly be built without an ASM, as GEMS clearly shows, but in this paper, we have estimated the performance of a MCAO system that includes an ASM and a single AO relay (like Altair). Indeed, if Altair were restored to its original state with a a DM conjugate to 6 km and passing a 2 arcminute field, it may be possible to use Altair with an ASM to create a double-conjugate MCAO system. However, if a double conjugate self-contained MCAO system were implemented for GNAO, the only difference in performance would be a reduction in throughput and an additional small implemetation error (due to the presence of more optical surfaces). As with the LTAO system described above, we assume Gemini North MCAO includes 5 LGSs. MCAO performance estimates were simulated using MAOS. We included an additional 120 nm RMS implementation error based on NFIRAOS (NFIRAOS is the proposed facility MCAO system for the Thirty Meter Telescope) design work [22,23].

- **MOAO:** Multi-Object AO systems also do not require an ASM, but they do benefit from its presence. An ASM in a MOAO system will act as a woofer that will correct for the turbulence common to all the WFSs (like a GLAO system). This will decrease the dynamic range required on the LGS WFSs and the stroke required on the DMs in each science channel. We have modeled the performance for 5 LGSs projected on a square (with a central LGS) of 3 and 4 arcminutes in diameter with MAOS. At these wide separations, the performance drops because the light from the LGSs is not fully sampling all the atmospheric turbulence over the entire field of regard (FoR). This leads to a large tomographic WFE (or shear WFE) [24]. Performance for a MOAO system could be improved substantially if more beacons could be projected. Based on some target density estimates for IRMOS on TMT [25], we estimated that the optimal number of MOAO targets (for a 30 m telescope) in a 5 arcminute FoR was ~20. For a 3 arcminute FoR, that translates into roughly 6 arms and for a 4 arcminute FoR, that translates into roughly 13 arms. The multiplexing advantage of a Gemini North MOAO system we found was based on the number or arms for a given field size.
- **GLAO:** A Ground Layer AO system that could be part of GNAO would benefit greatly from an ASM. Given that the Gemini Cassegrain focal plane is only 10 arcminutes in diameter, a GNAO GLAO system will be able to correct turbulence to an altitude of several hundred meters [26]. So even though the GNAO ASM would be conjugate to -150 m, the GLAO performance does not suffer greatly [27]. As Figure 1 shows, a GLAO system and a LTAO system require the same basic hardware (although there would be different requirements on the LGS asterism), so a GLAO system would come with little added cost. GLAO also is expected to work well even in the optical as it "improves seeing." In reality, the GLAO PSF is different than a seeing limited PSF. Both are well-fit by Moffatt profiles [28], but the GLAO PSF has a tighter core and broader wings. In the NIR, the GLAO PSF has a core with the same FWHM as the diffraction-limited PSF, but the Strehl ratio is small. New simulations of Gemini North GLAO were performed using instantGLAO [29].
- **Extreme AO:** We have not simulated an extreme AO system for GNAO, but we do note that the ASM+Pyramid will deliver a very high Strehl ratio image in L-band for bright stars (with minimum additional emissivity). If coupled with a suitable coronograph and science instrument, an ASM+Pyramid could be part of a L-band GNAO planet imager. We do not consider Extreme AO performance metrics (like contrast) in this paper.
- **AO Science Instruments:** Besides the MOAO option described above which would feed multiple IFSs, the science instruments which would receive the light from these potential GNAO systems are not specified. It will be important to develop a plan for AO-fed instrumentation, as well as defining the GNAO system itself. In this paper, we assume that NIFS will continue to exist, and that generic imagers that match the field delivered by GNAO will come into being. Other options, like multi-object spectrographs for a potential Gemini-North MCAO system are not considered here, but could be of interest.

4. Scientific Performance Metrics

Instead of comparing the potential GNAO systems listed above using just Strehl ratios, isoplanatic angles, and wavefront errors, we instead wanted to try and compare the differences between systems in terms of astronomical performance metrics like relative background-limited exposure times, FOV, sky coverage, astrometric and photometric errors and survey efficiency. By comparing AO systems on this basis, it should make it easier for the Gemini community to evaluate which AO system is best suited for different science cases.

4.1. Exposure Time

In Table 1, we compare 9 AO modes (plus 2 different FOVs for the MOAO option) in terms of Strehl ratio, throughput and relative exposure time.

Table 1. Strehl ratio, throughput and background-limited exposure time ratios for select potential GNAO systems. *The MOAO system $1/t_H$ estimates include the multiplexing advantage of a factor of 6 or 13 described in the previous section.

System	Strehl (I-band)	Strehl (H-band)	Strehl (L-band)	Through-put	$1/t_H$	$1/t_L$
Refurbished Altair - NGS	NA	40%	75%	77%	1	1
Refurbished Altair – LGS	NA	20%	NA	77%	0.25	NA
Altair450	10%	50%	82%	77%	**1.6**	1.2
ASM+Pyramid	**40%**	**75%**	**92%**	90%	**4.1**	**4.7**
ASM+LGS	NA	30%	NA	90%	0.7	NA
LTAO	15%	55%	NA	90%	**2.2**	NA
MCAO	10%	50%	NA	77%	**1.6**	NA
MOAO – 3'	NA	35%	NA	77%	**5.4***	NA
MOAO – 4'	NA	25%	NA	77%	**5.9***	NA
GLAO	0.21" (0.45")	3%	NA	90%	<0.01	NA

The **Strehl ratio** is a measure of how diffraction-limited a PSF is. It can be thought of as the ratio of an observed PSF's peak flux to the peak flux of a perfect diffraction-limited PSF. As stated above, some of the Strehl ratio numbers come from simulation (with additional implementation errors based on AO design studies – in particular the NFIRAOS design studies [22,23]), some come from the literature (ASM+Pyramid & ASM+LGS [18]), and some are based on design specificiations (Refurbished Altair). Despite the range of sources, all the Strehl ratios listed below are consistent with simulations. To calculate some of the PSFs, we use the Maréchal approximation: SR = $exp(-\sigma^2)$ where σ^2 is the wavefront variance in radians. This approximation is no longer valid below 10%, so in many cases we do not report an I-band Strehl ratio (but note the high I-band Strehl ratio that could be achieved by the ASM+Pyramid option). In an era that will include JWST, we believe L-band science cases are confined to observing single, bright stars, so we assume that the science target can serve as the NGS in these cases, so we do not consider the performance of LGS or wide-field AO systems in L-band. In almost all cases the Strehl ratios quoted are for the field center. Only for the MOAO option is the number a mean Strehl ratio over the FOR quoted. Under the I-band Strehl column for GLAO, we report the FWHM of the corrected PSF and seeing-limited PSF (in parenthesis) for R-band.

The H-band **throughput** of the telescope plus AO system is listed. For any option with an additional AO relay, we have assumed that it would have 87% throughput (the throughput measured for Altair). We assumed the telescope plus a dichroic in the ISS have a 90% throughput.

We calculated the H and L-band background-limited **relative exposure times for point sources**[3] assuming $S/N \propto SR \sqrt{(t \cdot \tau)}$ in H-band where the background is due primary from the sky (S/N=Signal to Noise Ratio, SR=Strehl Ratio, t=exposure time, τ=through-put) and $S/N \propto SR\, \tau \sqrt{[t / (1-\tau)]}$ in L-band because the background will be dominated by the emissivity ($1-\tau$) of the telescope and AO system. Table 1 shows the inverse of the exposure time scaled to a refurbished Altair NGS AO system. As an example, the ASM+LTAO GNAO system would reach the same depth in H-band 2.2 times faster than a refurbished Altair. The MOAO numbers are inflated by the multiplexing advantage (x6 for a 3' FoR; x13 for a 4' FoR). High actuator density NGS AO systems (Altair450 and ASM+Pyramid) and tomographic AO systems (LTAO, MCAO, and MOAO) all show large improvements in relative exposure times over a refurbished Altiar (which would show a significant gain over the existing Altair AO system in this metric).

4.2. Field of View

[3] If one compares the performance of the systems for astronomical extended targets, the $t \propto SR^2$ advantage will decrease depending on the structure of the extended target.

Another critical astronomical GNAO performance metric is the corrected FOV (Table 2). This FOV of all the single conjugate AO systems will be limited by the isoplanatic angle of the atmosphere. For most observed profiles the isoplanatic angle is a few arcseconds as measured at λ=500 nm. The isoplanatic angle has a $\lambda^{6/5}$ dependence. For single conjugate AO systems, the performance will fall off smoothly with radius (Figure 2). In MCAO, MOAO and GLAO systems the performance can be relatively constant over a wider area before falling off at larger radii. However, performance is usually higher in the center, even for MCAO and MOAO systems, when a central LGS is used. In MCAO systems, the FOV is set by the generalized isoplanatic angle which is determined by the structure of the turbulence and the conjugate altitude of the DMs. For these MCAO simulations, we assumed that the high-layer DM was conjugate to 8 km. The FOV of the simulated GNAO MCAO system is 9 times greater than that of a single conjugate AO system. The FoR of a MOAO system is set by the LGS asterism diameter. In every direction in that FoR, the MOAO system provides the best possible AO correction given the tomographic WFE arising from shearing of the LGS cones. GLAO systems can correct very large FOVs [30]. For a GNAO GLAO system, the FOV would be limited by the field passed from the telescope.

Table 2. Corrected FOV of different potential GNAO systems.

System	**Strehl (H-center)**	**Strehl (H-edge)**	**FOV diameter (I-band) arcsec**	**FOV diameter (H-band) Arcsec**
Refurbished Altair - NGS	40%	20%	NA	20
Refurbished Altair – LGS	20%	<10%	NA	20
Altair450	50%	30%	10	20
ASM+Pyramid	75%	40%	10	20
ASM+LGS	30%	10%	NA	20
LTAO	55%	35%	10	20
MCAO	50%	30%	30	**60**
MOAO – 3’	40%	30%	NA	**170**
MOAO – 4’	40%	20%	NA	**250**
GLAO	3%	2%	500	**500**

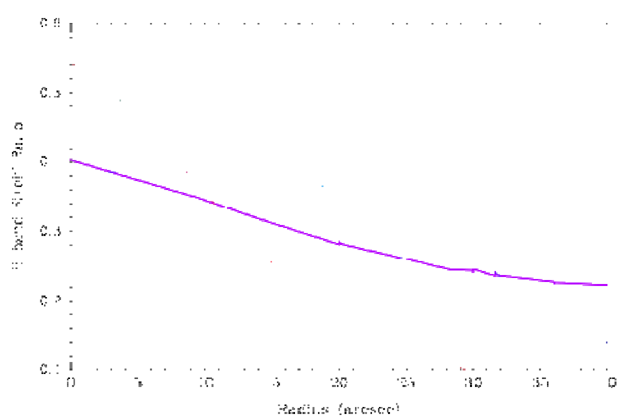

Figure 2. H-band Strehl ratio versus radius for LTAO (red line), and MCAO optimized to correct 40” (cyan) and 60” (blue) FOVs. The MOAO (purple) Strehl ratios are shown for the 4 arcminute field of regard. The mean performance drops for the larger field because there were only 2 DMs in the modeled GNAO MCAO system.

4.3. Sky Coverage

Classical NGS AO systems are limited in use to a very small fraction of the sky near bright guide stars. One reason new AO modes have been developed has been to increase the effective sky coverage of AO instruments. Table 3 contains the estimated sky coverage of the different potential GNAO modes for a

Galactic latitude of 60° and a Galactic longitude of 0°. We estimated the stellar densities at these Galactic coordinates using the Besançon model of the Galaxy [31]. Even with quiet detectors that allow NGS AO systems to use stars with limiting magnitudes of 14, the sky coverage of these systems is low at high Galactic latitudes. As the table shows, LGS AO systems have significantly higher sky coverage because they can use a significantly fainter star from a larger FoR to supply the tip/tilt (T/T) correction. As mentioned above, one can forego the use of a T/T WFS altogether and accept a "seeing-improvement" of a factor of 2-3 in return for 100% sky coverage. LTAO and MCAO systems can have slightly higher sky coverage by alternatively using 3 faint T/T WFSs from an even larger area. MOAO systems can cover more than half of the sky for fields with stellar densities comparable to those at Galactic coordinates (*b*=60°, *l*=0°) because the FoR is so large. Even a NGS-only GLAO system has ~20% sky coverage because the field is 10 arcminutes across. A LGS GLAO system at Gemini would essentially have complete sky coverage.

Table 3. Sky coverage for potential GNAO systems at Galactic coordinates of (*b*=60°, *l*=0°). For entries with 2 lines, the numbers in paranthesis show the sky coverage if performance is sacrificed. A pyramid WFS detector can be binned, which sacrifices performance, but allows it to be used with significantly fainter stars [18]. MCAO and LTAO systems could be used with a single T/T + Focus WFS over a large FoR, but some performance will be sacrificed.

System	**Patrol Radius (arcsec)**	**Limiting Magnitude**	**Visible light WFS**	**NIR sharpened WFS**	**MOAO WFS**
Refurbished Altair - NGS	10	14	0.4%	NA	NA
Refurbished Altair – LGS	20	18	12%	NA	NA
Altair450	10	14	0.4%	NA	NA
ASM+Pyramid	10	12 (16)	0.1% (1%)	NA	NA
ASM+LGS	20	18	12%	8%	NA
LTAO	1x20+3x40 (1x45)	18 (16)	15% (25%)	20%	**90%**
MCAO	1x20+3x40 (1x45)	18 (16)	15% (25%)	**50%**	**90%**
MOAO – 3'	3x90	18	**50%**	NA	**95+%**
MOAO – 4'	3x150	18	**80%**	NA	**95+%**
LGS GLAO	3x300	18	**95+%**	NA	NA
NGS GLAO	4x300	14	20%	NA	NA

One way to improve sky coverage is to use low noise NIR T/T WFSs [32][4]. In the NIR, the WFS can benefit from the sharpening of the PSF. This allows the T/T WFS to operate with much fainter guide stars. For a LTAO system, the gain (if there is any) due to sharpening would be modest, as the corrected FOV is small even though the guide star magnitude can be significantly fainter. MCAO systems, however, would benefit a great deal as T/T NGSs would be sharpened over a much larger FOV. The sky coverage of a GNAO MCAO system with NIR T/T WFSs is roughly 50%. If one includes DMs in the T/T WFS probe arms and apply a MOAO correction to the WFSs, then both LTAO and MCAO systems could achieve sky coverages of roughly 90%. MOAO instruments with MOAO NIR T/T WFSs would have almost complete sky coverage.

[4] We assumed NIR detectors that could reach 3 e^- readnoise.

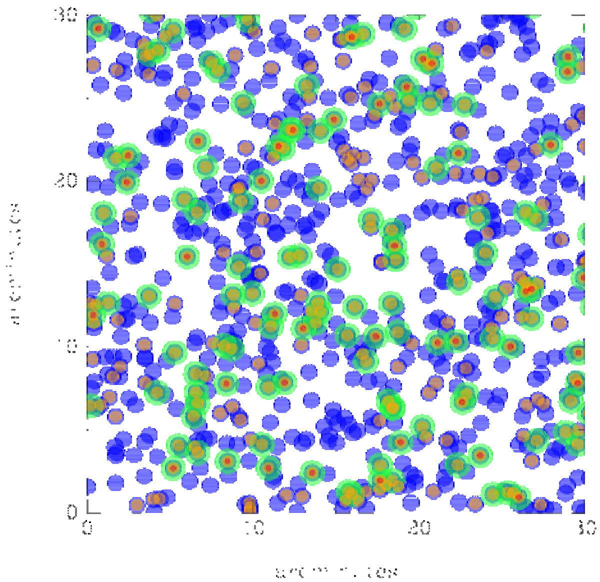

Figure 3. Simple simulation of sky coverage at Galactic coordinates (*b=60°*, *l*=0°). Red points are areas of the sky which could be observed by a NGS system. Areas shaded yellow-orange could be observed with a LGS system A LTAO system could observe the ~20% of the sky shaded green, while an MCAO system (blue) could observe roughly 50% of the sky at these Galactic coordinates.

4.4. Astrometry and Photometry

Tracking the orbits of stars around the super-massive black hole at the Galactic Center [33, 34] has been one of the highlights of AO astronomy to date. The twin problems of measuring an object's position and its brightness require an accurate knowledge of the PSF. A highly variable PSF introduces large astrometric and photometric errors. A high Strehl PSF is preferable in most cases because the difficult to model halo of the PSF will contain a much smaller fraction of the energy.

Assessing the astrometric and photometric performance of AO systems is difficult and is not a general problem. In general, the better the PSF is understood, the more precise the photometry. The field of PSF reconstruction is advancing [12], so irrespective of the AO system, there will be advances in the astrometric performance delivered for AO systems. Neverthelss, an AO system delivering high Strehl, uniform PSFs across the field will yield the smallest astrometric errors. An excellent reference that quantifies the different astrometric errors for observations at the Galactic Center [13] helped guide our work here. But the most important error terms and the optimal AO solution are dependent on the individual science case. In this paper, we qualitatively assess the astrometric and photometric performance for a number of general conditions (Table 4).

In crowded narrow fields, the halo noise is dominant. Halo noise refers to the centroding or photometry errors due to overlapping PSF halos; any light not corrected by the AO system will be spread out over a halo of roughly the size of the seeing-limited PSF. Therefore, a PSF with a high Strehl will have more energy in its core and less in the halo. If the source counts are not high and the field is larger, the major error terms shift to uncorrected image distortion and PSF non-uniformities. The optimal AO system that could address science cases under these conditions would produce high Strehl ratio images with excellent PSF uniformity. Depending on the details of the science case, either a LTAO or MCAO system may work best. It is worth noting that the MCAO field size can be optimized to match the science field, i.e., one can sacrifice some FOV in a MCAO system in return for higher Strehl ratios over the specific field of interest (and *vice versa*). For larger fields, MCAO seems to emerge as the best compromise in terms of providing high Strehl ratios over moderately large FOVs. For multi-arcminute FOVs, GLAO systems may outperform MCAO systems as long as crowding is not an issue.

MOAO instruments will typically not be used for astrometric and photometric research, because the AO correction is applied to only small patches of a large field of regard. MOAO is therefore not considered here.

Table 4. Limiting astrometric and photometric error terms for four different regimes of FOV and source density. For each case, we identify the most important AO performance metrics and suggest the optimal AO mode.

Science Case	Major Error Terms	Relevant AO Performance Metrics	Optimal AO solutions
Crowded narrow field (<10 arcsec)	Halo noise, residual image distortion	High Strehl (reduces halo noise)	NGS AO, LTAO
Moderate density, 10-15 arcsec FOV	Residual image distortions, PSF uncertainty	PSF uniformity (larger FOV), High Strehl	MCAO, LTAO (depends on detailed science case)
Larger field (15-30 arcsec FOV)	PSF uncertainty, residual image distortions	PSF uniformity (larger FOV), High Strehl	MCAO
Wide Field (multi-arcminute FOV)	PSF uncertainty, residual image distortions, SNR, position uncertainty, coordinate transforms, confusion/halo errors	PSF uniformity (larger FOV), High Strehl/improved image quality	GLAO, MCAO (depends on detailed science case)

4.5. Survey Efficiency

One final performance metric we consider here is the ability of potential GNAO systems to undertake large imaging or spectroscopic surveys. We have constructed an imaging "survey efficiency" performance metric as the survey area (based on the corrected FOV) multiplied by the mean 1/t (in H-band). Survey efficiency is inversely proportional to the time required to create background-limited imaging of a large field (much larger than any individual pointing) to a given depth and S/N *for unresolved sources* (Table 5). One sees that for surveys of unresolved sources, MCAO clearly has the highest survey efficiency. For unresolved, but small sources, GLAO would be competitive with MCAO. We also looked at the survey efficiency multiplied by the sky coverage (at Galactic coordinates of b=60°, l=0°) normalized to the Refurbished Altair+NGS system, because often times surveys cover a contiguous area and the survey location may not be chosen based on the suitability of potential guide stars. With this metric, we see the advantage of using LGS systems. For LTAO, we considered a 25% sky coverage for a single T/T Focus WFS in a 45" patrol radius (and in parenthesis a 90% sky coverage with MOAO T/T WFSs; Table 3). For MCAO, we considered a 50% sky coverage for 3 sharpened NIR T/T WFSs (and in parenthesis a 90% sky coverage with MOAO T/T WFSs).

Table 5. Relative survey efficiency (inversely proportional to the exposure time needed to image unresolved sources over a large field to a given depth and S/N).

System	FOV (arcsec diameter)	Mean 1/t (H-band)	Relative Survey Efficiency	Survey Efficiency x Sky Coverage
Refurbished Altair + NGS	20	1	1	1
ASM + LGS	20	0.6	0.6	18
LTAO	20	2.5	2.5	160 (560)
MCAO	60	1.7	**15.3**	1900 (3400)
GLAO	420	0.01	**5.6**	1400

GLAO can also be used in the visible. Table 1 shows that the FWHM of the GLAO PSF is more than 0.2" smaller than the seeing-limited PSF in R-band. This tight core should prove to be useful for astrometric studies using GLAO, but the broader wings of the PSF mean that GLAO survey efficiency in the visible will not be as high as one would guess from the FWHM alone. Instead, we use the Noise Equivalent Angle (NEA) which is defined as the pixel area ($arcsec^2$) divided by the sum of fluxes squared in each pixel normalized by the total flux [35]. This metric is inversely proportional to exposure time. In R-band, a GLAO system on Gemini would have a NEA 1.4 times smaller than the seeing-limit, meaning the GLAO relative survey efficiency in the visible will be roughly 1.4 times that of a seeing-limited instrument. Detractors of GLAO systems have argued that this gain in survey efficiency is lost in the overhead associated with configuring an AO system, however, an observation with a GLAO system can begin as soon as the field is acquired even before the GLAO correction is applied. Once the GLAO loop closes, the performance improves dramatically, but observations taken before would still not be lost. Another advantage of GLAO systems that we found was that the efficiency of a GLAO survey relative to a seeing-limited survey increased when the seeing-limited image quality is poor [27]. This is because poor seeing is often times due to very strong ground layer turbulence.

For spectroscopic surveys using IFSs, Table 1 gives an indication of survey efficiency. Most AO systems would feed just a single IFS. Only the MOAO (and possibly GLAO) systems in that table would feed multiple IFSs. The MOAO multiplexing advantage is already included in that table. MOAO could be used for a large spectroscopic survey more than **5** times more efficiently than a refurbished Altair, and 2 times more efficiently than a LTAO system feeding a single IFS. If we again multiply survey efficiency by sky coverage, one finds that a MOAO system has a factor of **~8.5** advantage over a LTAO system using this metric.

5. Summary

In this paper we described several distinct AO modes that should be discussed in the context of the next GNAO system. To further that discussion, we have compared these different modes as they could possibly be implemented on Gemini in terms of a number of different astronomical performance metrics, including:

- Relative exposure times
- Corrected fields of view
- Sky coverage at a fiducial point on the sky at high Galactic latitude
- Astrometric and photometric limiting errors
- Relative survey efficiency.

In short, the choice of the next GNAO system should be driven by the highest priority science. For example, one could conclude that a LTAO system has some favorable attributes that make it the most suitable system for narrow-field extragalactic studies. For mid-infrared observations or studies of brighter sources at red optical or NIR wavelengths, an ASM with a Pyramid WFS would probably be the optimal AO architecture. If sky coverage and wider fields are important for a science case, a MCAO system may be best. An MOAO system would be best suited for the telescope if the Gemini community thinks spectroscopic surveys should receive the highest priority. It should be noted that several of these modes are enabled if the GNAO system architecture includes an ASM and a flexible LGS system. A MCAO or MOAO system could be a modular upgrade to this base architecture.

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