NGAO Science Instrumentation

Baseline Capabilities Summary
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By Sean Adkins, James Larkin, Claire Max, and Elizabeth McGrath

INTRODUCTION

The Next Generation Adaptive Optics system (NGAO) is being developed by the W. M. Keck Observatory (WMKO) in order to advance the performance of AO systems and science instrumentation, providing improved performance for a broad range of science cases. The NGAO Science Case Requirements Document or SCRD ("Keck," 2008) defines a set of five science cases that are the "key science drivers" (p. 16) for the AO system and its science instrumentation. These science cases are understood to define particularly challenging performance requirements for the AO system or instrumentation, and because of their relative importance these science cases are also taken as defining the highest priority capabilities for the AO system and instruments. The SCRD also describes a number of other science cases that are intended to ensure that the AO system and science instrumentation have sufficient scope to reach the goal of making the system applicable to a broad range of science cases of interest to the WMKO observing community over a significant period of time.

The NGAO project also faces an important challenge resulting from a predetermined limit on the maximum cost of the complete NGAO system (AO and science instrumentation), commonly referred to as the "build to cost cap" or cost cap. Since achieving a system with the desired capabilities for a given cost starts with the design process, it is really a design and build to cost requirement.

Using the science driven requirements described in the SCRD, and taking into account the cost limit, we have developed a list of baseline capabilities for NGAO instrumentation. These capabilities were used to determine detailed cost estimates and make a comparison with TMT IRIS cost estimates in support of the NGAO design/build to cost (B2C) review. These capabilities are summarized here as a starting point for the development of the NGAO instrumentation.

SCIENCE REQUIREMENTS

The performance expected from the NGAO system (Dekany et al., 2009) includes Strehls of at least 20% in the NGAO z' passband and performance of ~70% in the K band (see Adkins, 2009 for the NGAO passband definitions). Detailed studies of the performance for various science cases and sky coverage fractions support the view that imaging capability suited to the diffraction limit will provide excellent results over the wavelength range of 0.818 to 2.4 µm. The combination of the AO system and imaging capability are expected to support high accuracy relative photometry and high accuracy astrometry. The imaging capability is also expected to have high throughput and appropriate background suppression in order to take advantage of the low backgrounds provided by NGAO, and the imaging capability must provide a coronagraph to support the detection and characterization of planets around nearby low mass stars.

An Integral field spectrograph (IFS) is recognized as an ideal way to take advantage of the image quality offered by NGAO because of its ability to provide spatially resolved spectroscopy of diffraction limited images without suffering from losses due to a mismatch between a long slit and the shape of a complex target object. IFS data can provide information essential for deconvolution of the point spread function (PSF) and offers a comprehensive tool for determining kinematics, mass distributions and velocity dispersions.

In this document we intended to focus on science driven performance requirements. However, in view of the requirement for design and build to cost we cannot avoid the need to evaluate performance requirements in the context of a well informed understanding of the most significant cost drivers. It should also be kept in mind that while this document focuses on the instrumentation's contribution to the quality of NGAO observations the actual performance is a product of AO system performance, instrument performance, and the observing conditions such as r_0.

NGAO Imaging Capability

The NGAO imaging capability represents a general purpose tool that will be expected to serve a wide range of scientific needs as well as provide a tool for characterizing the performance of the NGAO system. The imager's performance requirements are in turn defined from two viewpoints, the NGAO science cases, and a technical viewpoint that defines the requirements for performance measurement. Here we will consider the science driven performance requirements with an understanding that satisfying the most demanding of these will also provide the performance needed for AO system characterization.

The general purpose nature of the imaging capability is reflected in the number of NGAO science cases that require imaging. Based on a review of those science cases, the important performance parameters for the imaging capability are summarized by science case in Table 1. Several of these science cases identify the desirability of accessing wavelengths below 1 μm, either for specific diagnostic lines such as the Ca II triplet (~850 nm), or for the improved spatial resolution available at the shorter wavelengths. A number of the science cases also require high levels of performance from astrometric and photometric measurements obtained from NGAO observations.

Photometric accuracy depends strongly on the stability of the point spread function (PSF). For observations of closely spaced targets, accurately modeling the PSF becomes critical to successfully employing deconvolution techniques to separate the flux contributed by each object. Britton et al. (2007) suggest that effects due to imperfect correction of atmospheric turbulence and field dependent aberrations will be dominant over effects due the instrumentation. Non-common path errors between the science instrument and the AO system will contribute to instability of the PSF at the instrument. Motion within the instrument structure during an observation (flexure) can also contribute to PSF variability. Flexure is not expected to be a problem for NGAO instruments as their structure is completely fixed, and there are no moving parts that can induce differential motion between parts of the optical path during an observation. We will not attempt an extended discussion of the instrumental contributions to photometric accuracy, but detector characteristics are expected to be the dominant factor in the instrument's photometric performance. Such effects are well understood and largely controllable with good design practices.

The accuracy of position determination or astrometry for a point source is ultimately determined by the width of the PSF and noise in the image due to photon statistics, sometimes referred to as the photonic limit. As with photometric accuracy, the performance of the AO system, including the Strehl and the quality of the PSF both affect the signal to noise ratio (SNR) of the observation. As discussed in Cameron et al. (2007) additional impacts on astrometric accuracy arise from AO performance issues such as variable angular displacement across the FOV due to differential tip-tilt anisoplanatism, and changes in plate scale that may result from blind modes in multi-conjugate AO (not currently a planned operating mode for the NGAO system).

Key Science Drivers	**Wavelength Coverage†**	**Field of View**	**Spatial Sampling**	**Sensitivity and SNR**	**Other requirements**
Measurements of General Relativity Effects in the Galactic Center*	H, K (1.49 to 2.37 μm)	10" x 10"	At least λ/2D sampling	Better than current AO system with NIRC2	Astrometric performance > 0.1 mas
Imaging and Characterization of Extrasolar Planets around Nearby Stars*	Y, J, H, K (0.97 to 2.37 μm) Also below Y to 0.9 μm	< 5"	Diffraction limited sampling. At least 1.5 x better than λ/2D sampling at J (goal Y)	10^{-4} contrast at 200 mas separations, goal of coronagraph with inner working angle of 70 to 100 mas. ΔH = 13 at 1" separation, H = 25 for σ = 5 in 20 minutes.	R ~100 spectroscopy? Relative photometry to accuracy ≤ 0.1 magnitudes, astrometric precision of 2 mas. 6 λ/D general purpose coronagraph.
Multiplicity of minor planets*	z, Y, J, H, K (0.818 to 2.37μm)	≤ 4"	Diffraction limited, λ/3D for J, H, and K-bands, or λ/2D for R and I-bands		
Gravitational Lensing	z, Y, J, H, K (0.818 to 2.37 μm)	≥ 15" dia., goal of 30" dia.	Diffraction limited, λ/2D		Relative photometry to accuracy ≤ 0.1 magnitudes
Size, shape, and composition of minor planets	z, Y, J, H, K (0.818 to 2.37 μm) i band to 0.7 μm desirable for asteroid shapes	≤ 4"	Diffraction limited, λ/3D for J, H, and K-bands, or λ/2D for R and I-bands	R = 29 for 5σ in 1 hour (from NGAO proposal, table 14)	R ~100 spectroscopy?
Characterization of Gas Giant Planets	J, H, K (1.17 to 2.37 μm)	≥ 30" dia. in K, ≥ 20" dia. in J,H	Diffraction limited, λ/2D or finer sampling	Moons are very bright, need a large dynamic range, short exposures	

Table 1: Summary of the primary science driven parameters for an imager
** = NGAO key science driver*
† = Photometric filter passbands

In addition to sensitivity, the primary effect of the instrument on astrometric accuracy will be the amount of distortion present in the optical system. In addition to minimizing the presence of distortion through careful design and construction a high performance approach to measuring the distortion across the field of the imager will be required. Such characterization has been shown to have a significant impact on the astrometric accuracy that can be achieved with the existing Keck II AO system and the NIRC2 instrument (Cameron et al., 2007). It should be noted that the Galactic center case makes the greatest demand on astrometric accuracy at < 0.1 mas, approaching the photonic limit.

The pixel scale at the detector will determine the sampling of the delivered PSF and in turn will have an impact on both photometric and astrometric accuracy. The effects of sampling on the spatial frequency content of the PSF image can be appreciated using the techniques common to understanding the MTF of digital imaging systems. The loss of spatial frequencies due to sampling will translate directly to a reduction in the accuracy with which the original flux distribution is represented in the sampled image, and will also result in an increase in position uncertainty for well resolved image features.

For the specific case of imaging of multiple asteroid systems Baek and Marchis (2007) have undertaken simulations which indicate that pixel scales resulting in three pixel sampling across the diffraction limited image size (a pixel scale of λ/3D) results in the best representation of the flux ratio between the primary and the secondary in the J, H and K bands. For near-IR wavelengths for which the chosen object sizes are well resolved (J and H band) Baek and Marchis also report that three pixel sampling produces good results for position measurements. In the r and i bands the shorter wavelengths offer higher spatial resolution, but the decrease in Strehl reduces the SNR of the simulated observations, and as a result two pixel sampling (a pixel scale of λ/2D) provides the best representation of the flux ratio and the most accurate position measurements.

At a minimum two pixel sampling can be considered necessary for most other types of observations, but appropriate studies should be conducted for science cases that require high photometric or astrometric precision. It may also be appropriate to consider coarser plate scales for observations such as in K band where rising background levels will limit sensitivity. Finer sampling scales also imply a trade-off with FOV. Table 2 shows the FOVs that result from λ/3D and λ/2D sampling at various cut-on wavelengths when using either 2048 x 2048 or 4096 x 4096 pixel detectors.

The science case for imaging and characterization of extrasolar planets around nearby stars requires a coronagraph. In Flicker et al. (2007) various angular separations and magnitude differences between primary and secondary taken from an earlier draft of the NGAO SCRD (prior to the version referenced here) are evaluated in different wavelength bands and assuming 170 nm wavefront error. An apodized Lyot coronagraph with an occulting spot of 6λ/D, 10λ/D, and 14λ/D was analyzed using a numerical simulation for a 30 minute J band exposure. The analysis concludes with the observation that while not all of the science cases can be satisfied by this configuration it is capable of addressing a useful fraction (~50%) of the extrasolar planet observing scenarios. As a starting point we assume a 6λ/D coronagraph for the NGAO imaging capability, but further simulation work using the current predictions for NGAO performance are required.

		FOV in ", 2048 x 2048 pixel detector				
	Wavelength, nm	λ/D	λ/2D	λ/3D	λ/4D	λ/5D
K band cut-on	2030	85.8	42.9	28.6	21.4	17.2
J band cut-on	1170	49.4	24.7	16.5	12.4	9.9
Y band cut-on	970	41.0	20.5	13.7	10.2	8.2
z band cut-on	818	34.6	17.3	11.5	8.6	6.9
i band cut-on	728	30.8	15.4	10.3	7.7	6.2
r band cut-on	565	23.9	11.9	8.0	6.0	4.8

		FOV in ", 4096 x 4096 pixel detector				
	Wavelength, nm	λ/D	λ/2D	λ/3D	λ/4D	λ/5D
K band cut-on	2030	171.5	85.8	57.2	42.9	34.3
J band cut-on	1170	98.8	49.4	32.9	24.7	19.8
Y band cut-on	970	82.0	41.0	27.3	20.5	16.4
z band cut-on	818	69.1	34.6	23.0	17.3	13.8
i band cut-on	728	61.5	30.8	20.5	15.4	12.3
r band cut-on	565	47.7	23.9	15.9	11.9	9.5

Table 2: Imager sampling scales and FOVs at various wavelengths

NGAO IFS Capability

Using the approach of identifying the most demanding requirements, a detailed analysis of the NGAO SCRD science cases for IFS observations was performed as part of the preparation of our proposal (Adkins & Larkin, 2008) for the development of an advanced IFS. In that proposal we identified five science cases as the major drivers for the NGAO IFS. We also evaluated the key IFS performance parameters in order to determine which parameters are most critical to IFS science. These parameters are wavelength coverage including the placement of the short wavelength cut-off, spectral resolution, field of view, spatial sampling, and sensitivity. Table 3 gives the values of these parameters for each of the selected science cases.

In the IFS design one of the key performance trades is the relationship between spectral coverage, spectral sampling, and field of view (FOV). For a given number of detector pixels one can trade between these three parameters, finding that certain combinations are more efficient in using the available detector area than others. Our analysis indicates that the NGAO science cases requiring IFS observations are generally more concerned with obtaining a larger FOV than they are with full coverage of an entire IR or visible passband in one exposure.

For example, the Galactic Center case emphasizes the measurement of absorption lines in the H and K bands (such as HI absorption of Brγ emission at 2.166 μm) that fall within 5% band passes, while FOVs of 5" diameter are desirable for simultaneous measurements of multiple stars near the Galactic center to improve the strength of the orbital solutions. Measurements of GR effects at the Galactic center demand high SNR and diffraction limited spatial sampling. FOV and sensitivity are also important for population studies at the Galactic center (Lu et al., 2009).

Similarly, for emission line observations such as excitation temperatures, observations of molecular hydrogen emissions (Beck et al., 2008), and other spectral line features such as the CO bandheads, 5% band passes will suffice. For the galaxy assembly and star formation case the primary requirement is sensitivity, while FOV is less important provided that it is large enough that sufficient spatial pixels are available to accurately sample the sky background. For this science case since the targets are of known redshifts, and the key spectroscopic lines of interest for kinematics at redshifts of 1 < z < 3 are observable within ~5% passbands in the near-IR (J, H, and K) bands, a narrow band pass is also satisfactory.

Key Science Drivers	Wavelength Coverage	Spectral Resolution	Field of View	Spatial Sampling	Sensitivity and SNR
Galaxy Assembly and Star Formation History*	z, Y, J, H, K (0.818 to 2.4 μm), narrow band coverage acceptable since redshifts will be obtained before IFS observations	R >3000 (for OH line removal and discrimination of key diagnostic lines (Hα vs. NII)	1" x 3" or greater	Optimized for 50% ensquared energy, range of 50 to 100 mas acceptable	K band performance improvements needed (lower background). Seeking 5 times better sensitivity than OSIRIS on current Keck AO system
Nearby Active Galactic Nuclei*	z, Y, J, H, K (0.818 to 2.4 μm, or at least to below 850 nm for the Ca II triplet)	R ~3000 to 4000	≥ 5" dia.	20 mas in the near-IR, 8.5 mas in z	High spatial resolution and precision radial velocities
Measurements of General Relativity Effects in the Galactic Center*	H, K (1.475 to 2.4 μm), primarily narrow band observations of specific absorption lines	R ~4000	≥ 5" dia., goal of 10" dia.	20 mas (H band) and 35 mas (K band)	RV precision at least 10 km/s
Gravitational Lensing	J, H, K (1.10 to 2.4 μm, also would like i' and z, 0.702 to 0.922 μm)	R ~4000	> 4" dia., goal of 8" to 10" dia.	50 mas or smaller	RV precision at least 20 km/s (1 σ)

Table 3: Summary of the primary science driven parameters for an IFS
** = NGAO key science driver*

Because the solution for black hole mass requires having a good model for the larger-scale structure of the galaxy the nearby AGN science case has a need for larger FOVs of 3" to 5" diameter, but again the observations required for the stellar and gas dynamics around the central black hole are based on absorption lines for stellar dynamics and emission lines for gas dynamics, all of which can be observed within 5% band pass or less in the z through K bands. This science case in particular identifies the benefits of high angular resolution observations below 1 μm wavelength where the more compact PSF core at the shorter wavelength and the reduced sky background will enable BH detection over greater distances. Gravitational lensing also requires high SNR and a FOV of at least 4" to 5". The lensing science case can also benefits from observations below 1 μm for access to diagnostic lines for the lensed source and for redshifted lines of the lensing galaxy.

In cases where observations of multiple lines are required, if the IFS field is suitably matched to the object size, such that the entire PSF of the object is imaged, then image motion can be detected and discounted using simple PSF fitting techniques (Roth, 2006). This allows multiple narrow band exposures to be a practical alternative to a single broad band exposure.

BASELINE CAPABILITIES SUMMARY

Table 4 lists the proposed baseline capabilities for the NGAO near-IR instrumentation. The values of relevant parameters are given for the two desired modes, integral field spectroscopy, and imaging. The parameters are listed this way for clarity; it is not necessarily true that there will be two separate instruments. In fact, cost considerations are such that at present we are planning to build a single instrument offering both capabilities.

Capability	Integral Field Spectrograph	Imager
Wavelength Coverage	z, Y, J, H, K (0.818 to 2.4 μm)	z, Y, J, H, K (0.818 to 2.4 μm)
Filters	Narrowband in z, Y, J, H, K, nominally 5% band pass per filter, number of filters as required to each band	See Table 5.
Spectral Resolution	~4000	1
FOV	~ 4" x 4" with 50 mas sampling ~ 2" x 2" with 10 mas sampling	≥ 15"
Spatial Sampling	3 scales maximum: • 10 mas • 50 to 75 mas, spatial sampling selected to match 50% ensquared energy delivered by NGAO narrow field relay • Intermediate scale, possibly 20 or 35 mas, selected to balance FOV/sensitivity trade off	≤ λ/2D, possibility of multiple pixel scales
Throughput (instrument only)	~40%	> 60% (without coronagraph)
Detector	4096 x 4096 (Hawaii-4RG)	4096 x 4096 (Hawaii-4RG)
Detector Performance	Background limited	Background limited or detector limited depending on observing band

Table 4: Near-IR instrumentation capabilities

Filter #	Filter Name	Cut-on λ (μm)	Cut-off λ (μm)	Notes
1	NGAO Y	0.970	1.07	UKIDSS photometric
2	NGAO J	1.170	1.330	UKIDSS/Mauna Kea photometric
3	NGAO H	1.490	1.780	UKIDSS/Mauna Kea photometric
4	NGAO K	2.030	2.370	UKIDSS/Mauna Kea photometric
5	Ks	1.991	2.302	Similar to NIRC2
6	Kp	1.948	2.299	Similar to NIRC2
7	J continuum	1.2033	1.2231	Similar to NIRC2
8	H continuum	1.5688	1.592	Similar to NIRC2
9	K continuum	2.2558	2.2854	Similar to NIRC2
10	Bracket γ (1)	2.1523	2.1849	Similar to NIRC2
11	Bracket γ (2)	2.1426	2.178	Similar to NIRC2
12	CO	2.2757	2.3024	Similar to NIRC2
13	CH_4S	1.5295	1.6552	Similar to NIRC2
14	CH_4L	1.6125	1.7493	Similar to NIRC2
15	FeII	1.6327	1.6583	Similar to NIRC2
16	He 1 B	2.04	2.0726	Similar to NIRC2
17	H2, v = 1-04	2.04	2.0726	Similar to NIRC2
18	H2, v = 1-04	2.2428	2.2816	Similar to NIRC2
19	Pa β	1.2807	1.3	Similar to NIRC2

Table 5: Imager filter set

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