Keck Adaptive Optics Note 456

NEXT GENERATION ADAPTIVE OPTICS: SYSTEM REQUIREMENTS DOCUMENT

Version 1.18
March 26, 2008

Table of Contents

Summary Table of Contents

Table of Contents

Table of Contents

Table of Contents

Figures and Tables

Requirements Tables

Figures and Tables

1 INTRODUCTION

This document describes the requirements for the Next Generation Adaptive Optics (NGAO) system to be built for the W. M. Keck Observatory (WMKO).

The requirements in this document are intended to be at a level appropriate for the system design phase. Further development of the requirements will take place in the next phase of the project (preliminary design). In particular, parametric performance requirements given at this stage are intended to indicate the scope and format of the requirements, but do not in all cases establish final values for the specified parameters. In some cases values for these parameters have yet to be established and are given as TBD.

A more generic set of requirements for new WMKO instrumentation is described in the Observatory's "Instrumentation Baseline Requirements Document." These requirements are also applicable to NGAO. The NGAO System Requirements Document will take precedence over the "Instrumentation Baseline Requirements Document" in the event of a conflict.

It is important to understand that at this stage of development the requirements provide a basis for identifying the parameters that will be part of the system's specifications, but the values given are subject to change as the development continues. During the next phases of the project work will be done to refine the requirements for review at the preliminary design review. The final requirements to be reviewed at the detailed design review will form the basis for the acceptance test criteria for the instrument.

The purpose of this document is to define and communicate the requirements for the NGAO-specific design and implementation in terms of the needed scientific and technical performance. The document also expresses specific requirements for implementation or design where those requirements are essential to satisfactory integration and interoperation of NGAO with the observatory systems. The document avoids prescribing specific design or implementation solutions except for solutions that embody the Observatory's unique knowledge or experience. The document establishes requirements for the NGAO that will guide the design through the detailed design phase.

2 SCOPE AND APPLICABILITY

This document establishes requirements for all aspects of NGAO beyond those already specified in the "Instrumentation Baseline Requirements Document". This document also establishes requirements for changes to related Keck telescope subsystems and software where required.

This document does not address the requirements for the science instruments that will work with NGAO, although it does cover the NGAO interfaces to these instruments. Separate system requirements documents will need to be prepared for each of these instruments as part of their design process.

3 References

3.1 Related Documents

1. KAON 572. Instrumentation Baseline Requirements Document.
2. KAON 153. Coordination and Use of Laser Beacons for AO on Mauna Kea.
3. KAON 399. NGAO Proposal Executive Summary.
4. KAON 400. NGAO Proposal.
5. KAON 428. Implications and requirements for Interferometry with NGAO.
6. KAON 455. NGAO Science Case Requirements Document v2.0.
7. KAON 476. NGAO Science Operations Observing Model Trade Study
8. ANSI Z136.1 Safe Use of Lasers Indoors (2000).
9. ANSI Z136.6 Safe Use of Lasers Outdoors (2000).

3.2 Referenced Drawings

None at this time.

4 Revision History

Version	Date	Author	Reason for revision / remarks
0.1	Jan. 16, 2007	Wizinowich	Initial version
0.3	Feb. 1, 2007	Wizinowich	Multiple edits
0.4	Feb. 6, 2007	Wizinowich	Multiple edits. Included seeing & telescope environment in section 6.1.2
1.0	Feb. 21, 2007	Wizinowich	Added Dekany performance requirements input
1.1	Apr. 17, 2007	Wizinowich	Edited section 6
1.2	May 15, 2007	Wizinowich	Incorporated input from NGAO team meeting 6
1.3	May 22, 2007	Wizinowich	Miscellaneous
1.4	May 22, 2007	Wizinowich	Mods to the table in section 6.1.2
1.5	May 25, 2007	Wizinowich	Additions to 6.1.4 based on KAON 476
1.6	May 30, 2007	Wizinowich	Science requirement changes based on SRD telecom
1.7	May 31, 2007	Wizinowich	Solar system science requirement input with Le Mignant & Marchis + minor mods to science operation requirements
1.8	June 1, 2007	Wizinowich	Galactic Center & QSO host science cases. Mods to Observatory operational requirements
1.9	June 6, 2007	Wizinowich	AGN science case from Adkins, Le Mignant, Max & McGrath
1.10	June 19, 2007	Wizinowich	Added planets around low mass stars &

			gravitational lensing requirement tables. First cut at asteroid shape & size table. Added H-band to GR Galactic Center case. Minor edits to asteroid companions table.
1.11	June 29, 2007	Wizinowich	Minor edits to science performance requirements
1.12	August 15, 2007	Gavel	Review and edits, highlighting gaps in the flow down from the ScRD. Added a requirements numbering system.
1.13	August 22, 2007	Gavel	Continued edits, through all the science requirements tables and instrument requirements tables (to Table 13). Comments and questions are in red font.
1.14	Sept 4 thru 7, 2007	Max, McGrath, Le Mignant	Revised science requirements tables. We have scrutinized Tables 1, 2, 3, 4, and 6 thoroughly. Things to follow up on are highlighted in yellow.
1.15	Oct. 1 – 3rd, 2007	D. Le Mignant	Revised observatory requirements (section 6). Things to follow up on are highlighted in yellow. Updated Table numbering and TOC. Removed the obsolete performance requirement tables from optical performance section 7. Consolidated Telescope and Dome Environment requirements in Table 22 and included in section 6.2.3
1.16	Dec. 14 – 19, 2007	E. McGrath	Revised and re-ordered science requirements tables 1-17. Things to follow up on are highlighted in yellow.
1.17	March 13, 2008	D. Gavel	Follow up on traceability of requirements. Revised Science Requirements section (E. McGrath, C. Max)
1.18	March 26, 2008	D. Le Mignant	Check requirement for consistency with other documents, re-arranged sections and tables that are not complete.

5 Background

5.1 Purpose

The purpose of the background section of this document is to provide context and related information for the requirements defined in later sections of this document.

5.2 Motivation for the Development of NGAO

The Keck telescopes are the world's largest optical and infrared telescopes. Because of their large apertures the Keck telescopes offer the highest potential sensitivity and angular resolution currently available. WMKO has already demonstrated scientific leadership in high angular resolution astronomy with the first NGS and LGS AO systems on 8-10 m telescopes. The importance of achieving the full potential of the Keck telescopes is recognized in the Observatory's strategic plan which identifies leadership in high angular resolution astronomy as a key long-term goal.

In order to maintain our leadership in this field we must pursue new AO systems and the instrumentation to exploit them. We have examined, and are continuing to examine, a broad range of key science goals in order to identify the most compelling future science goals of our community and to determine what is needed to realize these goals. As a result we have identified that NGAO should provide the following suite of capabilities:

- Near diffraction-limited performance at near infrared wavelengths, producing a point spread function with unprecedented precision, stability and contrast;
- Increased sky coverage and a multiplexing capability, enabling a much broader range of science programs; and
- AO correction in the red portion of the visible spectrum (0.6-1.0 µm), delivering the highest angular resolution images available for filled aperture telescopes.

NGAO will be a broad and powerful facility with the potential to achieve major advances in astrophysics. It will provide dramatic gains in solar system and galactic science where AO has already demonstrated a strong scientific impact. NGAO will also allow for extraordinary advances in extragalactic astronomy, far beyond the initial gains being made with the Observatory's current AO systems.

To be clear NGAO need not be a single facility. It may be that the requirements are best met with multiple AO systems.

The NGAO proposal (KAON 400) and NGAO proposal executive summary (KAON 399) provide more background on the motivation for the development of NGAO. Further scientific motivation is provided in the NGAO science case requirements document (KAON 455).

5.3 Overview

The scientific and technical requirements for NGAO result in the following basic systems:

1. AO system. The AO system will likely consist of an AO enclosure, an opto-mechanical system, and software and electronics for both non real-time and real-time control.
2. Laser facility. The laser facility will likely consist of a laser enclosure, the laser(s), the launch facility including a beam transport system and launch telescope, safety systems and laser system control electronics and software.
3. Science operations facility. The science operations facility will primarily include the software and computers required to support operation of the AO system and science instruments. This includes operating the systems for nighttime observing as well as pre- and post-observing activities.
4. Science instruments. The three highest priority instruments are currently a near-IR imager, a visible imager and a deployable near-IR integral field unit (IFU). Three lower priority instruments have also been identified including a near-IR IFU and a visible IFU. There is also a requirement that the NGAO project be designed so as to allow the continued AO support of the Interferometer and the fiber injection module used for the 'OHANA (Optical Hawaiian Array for Nanoradian Astronomy) project.

The AO and laser facilities and the science instruments will have to interface with the telescope structure. Figure 1 shows a schematic view of a Keck telescope. The most likely location for the NGAO system and science instruments is on one of the Nasmyth platforms of the telescope. Nominally we have chosen the left Nasmyth platform of the Keck II telescope as our starting point. The most likely location for the projection telescope is behind the f/15 secondary mirror in the top end of the telescope.

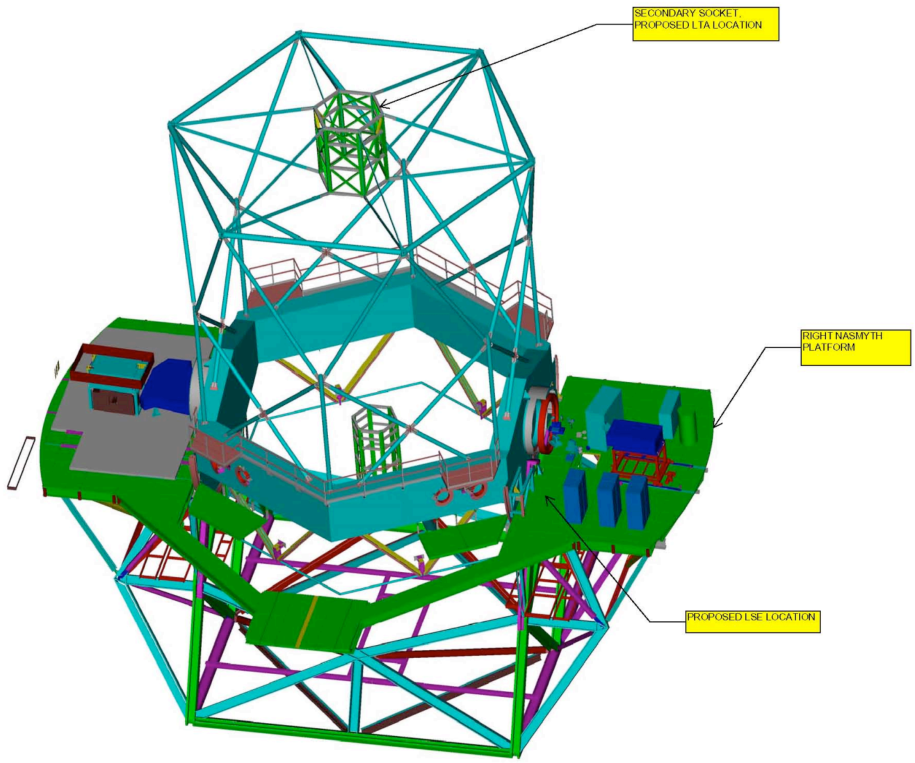

Figure 1 Keck telescope structure

6 Overall Requirements

6.1 Science Requirements

6.1.1 Purpose and Objectives

The purpose of the science overall requirements section is to summarize and convey requirements that apply generally to the overall NGAO system and its accessories. These are based on the NGAO Science Case Requirements Document (SCRD) (KAON 455), various trade studies undertaken and error budgets developed to meet these science requirements, general observatory instrument and interface requirements (KAON 572), and general observatory obligations (KAONs 428 and 153).

6.1.2 Science Performance Requirements

The performance requirements developed in the SCRD are summarized in the following tables. These will be updated as the science case requirements and performance budgets become better defined.

The relevant source of the requirement from the Science Requirements Document (SCRD), KAON 455, is referenced by section number. Some of the requirements have a source other than the SCRD. In these cases the additional source is listed.

We have categorized the various science cases into two classes: those that push the limits of AO system, instrument, and telescope performance (designated "Key Science Drivers"), and those that are less technically demanding than the "Key Science Drivers" but still place important requirements on available observing modes, instruments, and PSF knowledge. We shall call the latter category "Science Drivers."

In the remainder of this section we present tables showing the requirements that flow down from both of these categories of science cases. The cases we shall discuss are listed below, together with their designation as Key Science Drivers (KSD) or "Science Drivers" (SD).

Title and Number in This Report	Reference in Summary Spreadsheet (KAON 548)
1. High-redshift galaxies (KSD)	X2
2. Nearby AGNs: black hole mass measurements (KSD)	X3
3. General Relativity at Galactic Center (KSD)	G2
a. Astrometric	G2a
b. Radial velocity	G2b
4. Planets around low-mass stars (KSD)	G1

5. Asteroid companions survey (KSD) S1a
6. Asteroid companions orbit determination (KSD) S1b
7. QSO host galaxies (SD) X1
8. Gravitationally lensed galaxies by galaxies (SD)
    a. Imaging X4b
    b. Spectroscopy X4a
9. Place holder for Gravitationally lensed galaxies by clusters (SD)
    c. Imaging X4b
    d. Spectroscopy X4a
10. Place-holder for Astrometry in sparse fields (SD) GX1
11. Place-holder for Resolved stellar populations in crowded fields (SD) GX2
12. Place-holder for Debris disks (SD) G3
13. Place-holder for Young stellar objects (SD) G4
14. Asteroid size, shape, and composition (SD) S2
15. Moons of the Giant Planets (SD) S3
16. Uranus and Neptune (SD) S4
17. Backup science (SD) O

6.1.2.1 High-Redshift Galaxies

The requirements for the *high-redshift galaxies* science case are summarized in the following table (see the Galaxy Assembly and Star Formation History section of KAON 455 (Release 2.1)).

Table 1. High-Redshift Galaxies derived requirements

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
1.1	*Sensitivity*. SNR ≥ 10 for a z = 2.6 galaxy in an integration time ≤ 3 hours for a spectral resolution R = 3500 with a spatial resolution of 50 mas [SCRD §2.1.4]	Sufficiently high throughput and low emissivity of the AO system science path to achieve this sensitivity. Background due to emissivity less than 30% of unattenuated (sky + telescope). [SCRD §2.1.5.1 and SCRD Figure 1]	

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
1.2	*Target sample size* of ≥ 200 galaxies in ≤ 3 years (assuming a target density of 4 galaxies per square arcmin) [SCRD §2.1.3]	Multi-object AO system: one DM per arm, *or* an upstream MCAO system correcting the entire field of regard. 6-12 arms on 5 square arc minutes patrol field.	Multiple (6-12) IFUs, deployable on the 5 square arc minute field of regard
1.3	Spectroscopic and imaging observing wavelengths = J, H and K (to 2.4 μm)[1] [SCRD §2.1.4, §2.1.5.3]	AO system must transmit J, H, and K bands[1]	Infrared imager and IFUs designed for J, H, and K.[1] Each entire wavelength band should be observable in one exposure.
1.4	Spectral resolution = 3000 to 4000 [SCRD §2.1.5.1, §2.1.5.3]		Spectral resolution of >3000 in IFUs
1.5	Narrow field imaging: diffraction limited at J, H, K [SCRD §2.1.5.3]	Wavefront error 170 nm or better	Nyquist sampled pixels at each wavelength
1.6	Encircled energy at least 50% in 70 mas for sky coverage of 30% (see 1.11) [SCRD §2.1.5.2]	Wavefront error sufficiently low (~170 nm) to achieve the stated requirement in J, H, and K bands.	IFU spaxel size: either 35 or 70 mas, to be determined during the design study for the multiplexed IFU spectrograph
1.7	Velocity determined to ≤ 20 km/sec for spatial resolutions of 70 mas	PSF intensity distribution known to ≤ 10% per spectral channel.	
1.8	IFU field of view ≥ 1" x 3" in order to allow sky background measurement at same time as observing a ~1" galaxy [SCRD §2.1.5.1]	Each MOAO IFU channel passes a 1"x3" field.	Each IFU unit's field of view is 1" x 3"
1.9	Simultaneous sky background	See #1.8	

[1] Note that z band (central wavelength 912 nm) and Y band (central wavelength 1020 nm) are of interest as well, since Hα falls in z (Y) band for redshift 0.4 (0.55). The importance of including these two bands in addition to J, H, K is currently being assessed.

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	measurements within a radius of 3” with the same field of view as the science field [SCRD §2.1.5.1]		
1.10	Relative photometry to ≤ 5% for observations during a single night	Knowledge of ensquared energy in IFU spaxel to 5%. Telemetry system that monitors tip/tilt star Strehl and other real-time data to estimate the EE vs. time, or other equivalent method to determine PSF to the required accuracy.	
1.11	Sky coverage ≥30% at 170 nm wavefront error, to overlap with data sets from other instruments and telescopes [SCRD §2.1.5.2]	Infrared tip/tilt sensors with AO correction of tip/tilt stars	
1.12	Should be able to center a galaxy to ≤ 10% of science field of view		
1.13	Should know the relative position of the galaxy to ≤ 20% of spaxel size		
1.14	Target drift should be ≤ 10% of spaxel size in 1 hr		
1.15	The following observing preparation tools are required: PSF simulation and exposure time calculator		
1.16	The following data products are required: calibrated spectral data cube [SCRD §2.1.5.3]		

6.1.2.2 Nearby AGNs: Black Hole Mass Measurements

The requirements for the Nearby AGN science case are summarized in the following table (see the Nearby AGN section of KAON 455 (Release 2.1)).

Table 2. Nearby AGNs derived requirements

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
2.1	Number of targets required: to be specified in future versions of the SCRD [SCRD §2.2.3]		
2.2	Required wavelength range 0.85 – 2.4 microns [SCRD §2.2.3]		
2.3	Required spatial sampling at least two resolution elements across gravitational sphere of influence. [SCRD §2.2.2]	50% enclosed energy radius < ½ gravitational sphere of influence. Wavefront error requirement to be specified in future versions of this document.	Spectral and imaging pixels/spaxels < ½ gravitational sphere of influence (in the spatial dimension)
2.4	Required field of view for both spectroscopy and imaging > 10 radii of the gravitational sphere of influence. [e.g., SCRD §2.2.4 Figure 3]		Will need to get sky background measurement as efficiently as possible. For IR, consider using a separate d-IFU on the sky.
2.5	Required SNR for spatially resolved spectroscopy of the central black hole region using stellar velocities > 30 per resolution element [SCRD §2.2.3]	PSF stability and knowledge requirements will be discussed in future releases of the SCRD	Spectral resolution R ~ 3000-4000 with at least two pixels per resolution element; detector limited SNR performance. Spatial sampling at least two resolution elements across the gravitational sphere of influence

2.6	Required observation planning tools: PSF simulation tools to plan for observations of Seyfert 1 galaxies which have strong central point sources		
2.7	Required data reduction pipeline for IFU		

6.1.2.3 General Relativity Effects in the Galactic Center

The requirements for the *Measurement of General Relativity Effects in the Galactic Center science case* on both precision astrometry and radial velocities are summarized in the following two tables, respectively (see the Precision Astrometry: Measurements of General Relativity Effects in the Galactic Center section of KAON 455 (Release 2.1)).

Table 3a. General relativity effects in the Galactic Center derived requirements

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
3a.1	*Astrometric* accuracy ≤ 100 µas for objects ≤ 5" from the Galactic Center [SCRD §2.3.8.1]	High Strehl to reduce confusion limit: rms wavefront error ≤ 170 nm at G.C. IR tip/tilt sensors. Means of aligning and measuring position of tip-tilt sensors so that they permit astrometric accuracy of ≤ 100 µas. Means of preventing WFS-blind field-distortion modes (if multi-DMs are in series). Will require ADC. Need astrometric error budget in order to determine ADC requirements.	Nyquist sampling at H and K. Instrument distortion characterized and stable to ≤ 100 µas.
3a.2	Observing wavelengths: H and K-band [SCRD §2.3.9]	Transmit H and K band to science instrument	
3a.3	Field of view ≥ 10" x 10" for imaging	Science path shall allow an unvignetted 10" x 10" field.	

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	[SCRD §2.3.9]		
3a.4	Ability to construct 40'x40" mosaic to tie to radio astrometric reference frame[2] [SCRD §2.3.5]		
3a.5	The following observing preparation tools are required: PSF simulation as function of wavelength and seeing conditions, exposure time calculator.		
3a.6	The following data products are required: Calibrated PSF, data reduction pipeline, accurate distortion map (see 3a.1) [SCRD §2.3.5]		

Table 3b. Radial velocity measurements derived requirements

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
3b.1	*Radial velocity* accuracy ≤ 10 km/sec for objects ≤ 5" from the Galactic Center [SCRD §2.3.8.2]	170nm wavefront error at G.C. PSF estimation sufficient to measure a radial velocity to 10 km/sec. [suggestions from SCRD §2.3.8.2]	Spectral resolution ≥ 4000 Calibration of one IFU relative to other ones sufficient to permit 10 km/sec radial velocity measurement
3b.2	Observing wavelengths H, K-band [SCRD §2.3.6]	Transmit H, K band to science instrument	
3b.3	Spatial sampling ≤ 20 mas (H) or 35 mas (K)		20 and 35 mas spaxel scales at H and K respectively

[2] Accuracy required needs to be determined

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	to control confusion within IFU field of view [SCRD §2.3.6]		
3b.4	Field of view ≥ 1" x 1" [SCRD §2.3.6]		Field of view ≥ 1" x 1"
3b.5	The following observing preparation tools are required: PSF simulation as function of wavelength and seeing conditions, exposure time calculator.		
3b.6	The following data products are required: IFU pipeline for wavelength/flux calibration [SCRD §2.3.6]		

6.1.2.4 Planets Around Low-Mass Stars

The requirements for the *planets around low-mass stars* science case are summarized in the following table. The key area in which NGAO will excel is the detection of planets around low-mass stars and brown dwarfs because Keck, unlike GPI, will be able to use a laser guide star. NGAO will also be able to search for planets around young solar-type stars where dust extinction is significant. JWST will have coronagraphic capability in the 3 to 5 μm window, but will have significantly lower spatial resolution than Keck NGAO. In terms of the types of solar systems that can be studied, this means that JWST will focus on older, nearby main sequence stars (since older giant planets will remain visible in 3 to 5 μm for a longer time). JWST may be more limited than NGAO in doing large surveys, because of its longer slewing time and possibly a lifetime limit on the total number of slews.

Note: this science will usually be in LGS mode. Depending on the target magnitude, may choose to use the parent star as one of the required tip-tilt stars.

Table 4. Planets Around Low Mass Stars derived requirements

	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
4.1	Target sample 1: Old	Observe 20 targets per night	Near infrared imager (possibly

	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	field brown dwarfs out to distance of 20 pc. Sample size several hundred, desired maximum survey duration 3 yrs (practical publication timescales). [SCRD §2.4.3]	(each with e.g. 20 min integration time). Guide on a tip-tilt star with H=14.	with coronagraph). Survey primary stars at J- and H-band.
4.2	Target sample 2: Young (<100 Myr) field brown dwarfs and low-mass stars to distance of 80 pc. Sample size several hundred, desired maximum survey duration 3 yrs. [SCRD §2.4.3]	Observe 20 targets per night (each with e.g. 20 min integration time).	Near infrared imager (possibly with coronagraph). Survey primary at J- and H-band. Could benefit from dual- or multi-channel mode for rejecting speckle suppression, but not essential for this program.
4.3	Target sample 3: solar type stars in nearby star forming regions such as Taurus and Ophiuchus, and young clusters @ 100 to 150 pc distance. Bright targets (on-axis tip-tilt generally possible: V=14-15, J=10-12). Sample size several hundred, desired maximum survey duration 3 yrs.	(May not require LGS if there is a good enough near-IR wavefront sensor available).	Possible dual- or multi-channel mode for speckle suppression. Alternatively an IFU would help, provided it is Nyquist sampled at H and has FOV > 1 arc sec. Min. IFU spectral resolution is R~100. May need IR ADC for imaging or coronagraphic observations (J or H bands); typical airmass is 1.7 for Ophiuchus.
4.4	Companion Sensitivity Sample 1: assume no companions beyond 15 AU. Targets at 20 to 30 pc; companion distribution peaks at 4 AU = 0.2"; this yields 2 $M_{Jupiter}$ planets at a 0.2" separation with contrast ⊗H = 10. Planets have H=24, J=24.7. Parent stars are	Excellent (<10nm) calibration of both initial LGS spot size and quasi-static non-common path aberrations, especially at mid-spatial-frequencies. Needs algorithms such as phase retrieval or speckle nulling (on a fiber source + good stability). Small servo-lag error (<30nm) to avoid scattered light at 0.2 arc sec. Source: Error budget and simulations by Bruce	Inner working angle of 6 λ/D general-purpose coronagraph with a contrast of 10^{-6}. Detailed design of coronagraph will take place during PDR stage. Speckle suppression capability (multi-spectral imaging); dual-channel imager; stability of static errors ~5nm per sqrt(hr) for PSF subtraction or ADI.

	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	2MASS Brown Dwarfs with H=14. [SCRD §2.4.2.1]	Macintosh.	
4.5	Companion Sensitivity Sample 2: Parent stars are T Tauri, J=11. A 1 $M_{Jupiter}$ planet is at 300K, J=22, (2 $M_{Jupiter}$ is J=19.5). This distribution could have a wider distribution of binaries a) 0.1" separation, ⊗J = 8.5 (2M_J) b) 0.2" separation, ⊗J = 11 (1M_J) c) Goal ⊗J = 11 at 0.1" separation (1M_J) based on properties of the planets you want to look for. [SCRD §2.4.2.2]	Same as #4.4	a) 6 λ/D general-purpose coronagraph b) 6 λ/D general-purpose coronagraph c) (Goal) Not achievable with a general purpose coronagraph May need small Inner Working Distance (2 λ/D) coronagraph.[3] Speckle suppression capability (multi-spectral imaging); dual-channel imager; stability of static errors ~5nm per $\sqrt{hr}$ for PSF subtraction or ADI.
4.6	Goal: Companion Sensitivity Case 3: at 5 Myr , 1 M_{sun} primary; a) goal ⊗J = 13.5 to see 1 $M_{Jupiter}$ or b) goal ⊗J = 9 for 5 $M_{Jupiter}$. 0.07" is needed. For apparent magnitudes of parent stars see 4.3	Excellent (10-20nm) calibration of both initial LGS spot size and quasi-static non-common path aberrations, at both low- and mid-spatial-frequencies. Needs algorithms such as phase retrieval or speckle nulling (on a fiber source + good stability). Small servo-lag error (<30nm) to avoid scattered light at 0.2 arc sec. Tomography errors 20-30nm. Source: error budget and simulations by Bruce Macintosh.	Requires multi- λ speckle suppression; very small inner working angle coronagraph (2 λ/D); static errors in 5-10nm range.
4.7	*Sensitivity* of H=25 for	Sufficiently high throughput and	

[3] Non-redundant aperture masking is an interesting approach for this, limits currently unknown, probably requires low read noise in science detector.

	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	5-sigma detection in 20 minutes, at 1 arcsec separation from primary star. (Brown dwarf targets are limited by sky background at larger angles, of order ~1 arcsec). [SCRD §2.4.5.9]	low emissivity to permit detecting H=25 in 20 minutes at 5 sigma above background.	
4.8	H-band relative *photometry* (between primary and companion): accuracy ≤ 0.1 mag for recovered companions (to estimate mass of the companion); goal of measuring colors to 0.05 mags (0.03 mag per band) to measure temperatures and surface gravities sufficiently accurately (to ~10%). [SCRD §2.4.5.4]	Diagnostics on AO data to measure Strehl fluctuations if it takes a while to move on and off the coronagraph (a possible more attractive solution is a specialized coronagraph that simultaneously images the primary)	Induced ghost images of primary; or rapid interleaving of saturated and unsaturated images; or a partially transparent coronagraph
4.9	Requirement: Astrometric precision 2 mas (~1/10 PSF) relative between primary and planet, for initial rejection of background objects. [SCRD §2.4.5.5] Goal: For measuring orbits of nearby field objects, want 0.5 mas to measure masses to 10%. Note this gives you mass of primary star. Could be combined	Ways to do this: a) Position stability requirement for star behind coronagraph (e.g., stable to 0.5 or 2 mas over 10 min.). b) Induced ghost image method. Needs a wire grating ahead of the coronagraph, or use DM to induce ghost images. (papers by Marois et al. 2006, ApJ, 647, 612; Sivaramakrishnan & Oppenheimer 2006, ApJ, 647, 620).	Stability of distortion as required for 0.5 or 2 mas. Also want ghost images of primary (as for photometry #4.8) in order to locate it accurately relative to planet.

	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	with Doppler measurements if that's practical for the brighter objects.		
4.10	Efficiency: 20 targets per night (30 goal) [SCRD §2.4.6.2]	AO system must be able to absolutely steer objects so they land on the coronagraph. This implies 5 mas reproducibility of field steering –or lock the tip/tilt to this accuracy relative to coronagraph field stop. Final requirement will depend on the details of the coronagraph (5 mas is consistent with GPI modeling).	
4.11	Observing wavelengths JHK bands (strong goal: Y and z for companion temperature characterization) [SCRD §2.4.4, §2.4.7]	Transmit JHK to science instrument. Goal: Y and z.	JHK filters. Methane band filters for rapid discrimination, Y and z, and/or a custom filter for early characterization.
4.12	Able to register and subtract PSFs (with wavelength, time, etc.) for post-processing to get rid of residual speckles. Subtraction needs to be sufficient enough to meet req. #4.4.	PSF knowledge and/ or stability to meet req. #4.4.	At least 1.5 x better than Nyquist sampled at J (goal Y)
4.13	Field of view: must see companions at 100 AU scales at 30 pc (goal 20 pc) [SCRD §2.4.5.3]		Field of view 3" radius (goal 5" radius)
4.14	Characterization of companion [SCRD §2.4.4]		a) R ~150 IFU, sub-Nyquist sampling spectrograph, or if above not available, b) Nyquist spatial sampling IFU, R ~ 4,000, OH suppressing).

	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
			c) or narrow-band filters. All must be sensitive to J = 22 or 23 in ~3 hrs.
4.15	Sky Coverage >30%. (Survey several hundred Brown Dwarfs to H=15 of the ~1000 known targets.) [SCRD §2.4.7]	Technical field for low-order wavefront guidestar pickoff large enough to achieve 30% sky coverage at high galactic latitude. Ability to acquire and track 3 tip/tilt stars. (More lenient if parent star can be used as one of the three TT stars.) Or ability to measure everything sufficiently with a single H=15 TT star (pyramid sensors).	
4.16	The following observing preparation tools are required: guide star finder for high proper-motion stars		

6.1.2.5 Asteroid Companions Survey

The requirements for the *asteroid companions survey* science case are summarized in the following table (see also the Multiplicity of Minor Planets section of KAON 455 (Release 2.1)).

Table 5. Asteroid Companions Survey driven requirements

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
5.1	The *companion sensitivity* shall be ⊗J ≥ 5.5 mag at 0.5" separation for a V ≤ 17 asteroid (J≤ 15.9) (asteroid size < 0.2") with a proper motion of ≤ 50 arcsec/hour [ScRD §2.5.4.6]	The asteroid can be used as tip/tilt guidestar (proper motion of ≤ 50 arcsec/hour). The AO system has sufficient field of view for objects and for their seeing disks (>3 arcsec, see # 5.6). The tip-tilt residual error will be less than 10 mas (limited by resolved primary) while	Near-IR imager

		guiding on one V=17 (J =15.9) object with relative motion of 50 arcsec/hr (14 mas/sec). The AO system has sufficient Strehl to achieve this contrast ratio and sensitivity in 15 min exposure time. KAON 529 suggests that 170nm wavefront error will suffice.	
5.2	J-band relative *photometric* accuracy (between primary and companion) of 5% at 0.6" for ⊗J = 3 for a V ≤ 17 (J≤ 15.9) asteroid (asteroid size < 0.2") with a proper motion of ≤ 50 arcsec/hour [ScRD §2.5.4.4]		Near- IR imager (no coronagraph because many asteroids will be resolved)
5.3	Target sample ≥ 300 asteroids in ≤ 4 yr. [SCRD §2.5.3 ¶4] Leads to requirement of ≥ 25 targets per 11 hour night. [SCRD §2.5.5.2]	Assumes 3 good nights per year. Needs high observing efficiency: Able to slew to new target and complete the entire observation within 26 minutes on average.	
5.4	Observing wavelengths I through H bands, for optimum companion sensitivity [Source: KAON 529]. J band is best when seeing is good. H band could be used when seeing is poor. [SCRD 2.5.6.6]		Visible and IR imagers.
5.5	Spatial sampling ≤ Nyquist at each observing wavelength. [SCRD §2.5.6.4] Pixel		Spatial sampling ≤ Nyquist at the observing wavelength. Pixel sampling of λ/3D is

	sampling of λ/3D optimal for photometry and astrometry [KAON 529].		optimal at J through H-bands, and λ/2D at I through z-band for both photometry and astrometry [see KAON 529].
5.6	Field of view ≥ 3" diameter [SCRD §2.5.6.2]	AO system passes a >3" unvignetted field of view	Imager fields of view ≥ 3"
5.7	The following observing preparation tools are required: guide star finder for asteroids too faint to use as the only TT star, PSF simulation as function of wavelength and seeing conditions.	Guide star finder tool. PSF simulation tool (predict energy and width of central core to within 10%).	
5.8	The following data products are required: Access to archive with proper identification in World Coordinate System (to within 1 arc sec or better) and with associated calibrated PSF.	Calibrated PSF capability. Accuracy requirement will be discussed in future releases of the SCRD document. Ability to collect AO telemetry data to support the required PSF calibration.	FITS header system capable of handling non-sidereal offsets in reporting object coordinates in the World Coordinate System to within 1 arc sec or better.
5.9	Observing requirements: Observer present either in person or via remote observing rooms, because real-time observing sequence determination is needed.	Classical observing mode or service mode with active observer participation. Remote observing capabilities must allow frequent real-time decisions by observer.	

6.1.2.6 Asteroid Companions Orbit Determination

The requirements for the *asteroid companions orbit determination* science case are summarized in the following table (see also the Multiplicity of Minor Planets section of KAON 455 (Release 2.1)).

Table 6. Asteroid Companions Orbit Determination driven requirements

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
6.1	Companion sensitivity in the near-IR. Same as #5.1	Same as #5.1	Near-IR imager.
6.2	The *companion sensitivity in the visible* shall be ⊗I ≥ 7.5 mag at 0.75" separation for a V ≤ 17 (I ≤ 16.1) asteroid (asteroid size < 0.2") with a proper motion of ≤ 50 arcsec/hour [ScRD §2.5.4.6]		Visible Imager. Optimum visible wavelength is I through z bands per KAON 529. Note that if the near-IR imager extends down to I band, a separate visible imager would not be needed for this science case.
6.3	*Photometric accuracy*: Same as #5.2	Same as #5.2	
6.4	I-band relative *astrometric* accuracy of ≤ 1.5 mas for a V ≤ 17 (J ≤ 15.9) asteroid (asteroid size < 0.2") with a proper motion of ≤ 50 arcsec/hour [SCRD §2.5.4.5]	Non-sidereal tracking accuracy sufficiently small to achieve I-band astrometric accuracy ≤ 1.5 mas for a V ≤ 17 (J ≤ 15.9) asteroid with a proper motion of ≤ 50 arcsec/hour	Uncalibrated detector *distortion* sufficiently small to achieve I-band astrometric accuracy ≤ 1.5 mas for a V ≤ 17 (J ≤ 15.9) asteroid
6.5	Target sample size of ≥ 100 asteroids in ≤ 3 years. [SCRD §2.5.3 ¶4] Leads to requirement of ≥ 25 targets in an 11 hour night. [SCRD §2.5.5.2]	Needs high observing efficiency: Able to slew to new target and complete the entire observation within 25 minutes on average. Will generally only observe at one wavelength (the one that gives the best astrometric information).	
6.6	Observing wavelengths = I, z, J, H bands. (Note: R-band may become a future requirement if R-band		Imager(s) covering range I, z, J, H bands. Note that if the near-IR imager extends down to I band, a separate visible imager would not

	Strehl > 15%) [SCRD §2.5.6.6]		be needed for this science case.
6.7	Spatial sampling same as #5.5		Same as #5.5
6.8	Same as #5.6	Same as #5.6	Same as #5.6
6.9	Same as #5.7	Same as #5.7	
6.10	Same as #5.8	See #5.8	
6.11	Observing requirements: 7 epochs per target [SCRD §2.5.3 ¶4]	Observing model needs to accommodate split nights or some level of flexibility.	

6.1.2.7 QSO Host Galaxies

The requirements for the *QSO Host Galaxy* science case are summarized in the following table (see also the QSO Host Galaxy section of KAON 455 (Release 2.1)). The typical QSO that we are considering is at redshift 2. Typical galaxy sizes are 0.5 to 2 arc sec. Contrast ratios between the central point source and a galaxy region ½ arc sec away range from 50 to 200 or more. The scientific goals are the following: 1) measure colors and magnitudes for the point source; 2) measure morphology and surface brightness profile for the galaxy; 3) obtain spectrum of point source; 4) obtain spatially resolved spectrum of galaxy in order to study its kinematics and stellar populations. In order to accomplish these things, accurate PSF subtraction will be crucial.

Table 7. QSO Host galaxies derived requirements

Future releases of the SCRD will quantify the requirements for PSF subtraction and stability, required spatial resolution, and coronagraph design. The following table outlines the issues and should be viewed as a place-holder.

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
7.1	Number of targets required: to be specified in future versions of the SCRD	Sky coverage fraction >30% for 50% enclosed energy within 0.05 arc sec at J band	
7.2	Required wavelength range: 0.85 – 2.4 microns		Near IR IFU spectrograph; near IR and visible imagers.
7.3	Required spatial resolution will be discussed in a future release of this document. Will be determined by considerations of PSF	Desirable to use central QSO point source as one of the tip-tilt reference stars, if possible.	PSF must be oversampled in order to achieve required subtraction accuracy. Quantitative requirements will be discussed in future releases of the SCRD.

	subtraction accuracy. Hence required resolution will be higher than in the high-z galaxy science case.		
7.4	Photometric accuracy and PSF knowledge required for subtracting the central point source in order to characterize the host galaxy must be adequate to obtain host galaxy colors to 20% for a contrast ratio of up to 200 at a distance of ½ arc sec from the point source.	Requires excellent PSF stability and knowledge; future releases of the SCRD will discuss the quantitative requirements. Will have implications for required AO wavefront error, AO stability, and required signal to noise ratio.	Required calibration stability and accuracy, zero-point stability and knowledge, quality of flat-fielding will be discussed quantitatively in future releases of the SCRD. PSF must be oversampled in order to achieve required subtraction accuracy. Quantitative requirements will be discussed in future releases of the SCRD.
7.5	SNR for spatially resolved spectroscopy of the host galaxy will be determined by accuracy of PSF subtraction and by minimization of scattered light from the central point source.		May benefit from specialized coronagraph design to block light from central point source.
7.6	Required observation planning tools (e.g. guide stars); PSF simulation tools to plan for whether PSF subtraction will be good enough to see the host galaxy		
7.7	Required data reduction pipeline for IFU		

6.1.2.8 Gravitational Lensing

The requirements for the *gravitational lensing* science case are summarized in the following four tables (see the Gravitational Lensing section of KAON 455 (Release 2.1)).

Table 8a. Imaging studies of distant galaxies lensed by galaxies

Goal: screen potential lensed-galaxy targets for more detailed and lengthy spectroscopic study.

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
8a.1	Sensitivity: SNR ≥ 3 per pixel (100 per source) for a z = 1 – 2 galaxy in an integration time ≤ 1/2 hour.	Background due to emissivity less than 30% of unattenuated (sky + tel).	
8a.2	Target sample size of ≥ 200 galaxies, with density on the sky of 10 per square degree. Survey time ~ 3 years.	Overhead less than 10 min between targets.	10 per square degree implies that you will only be able to observe one target at a time – average of 1 in every ~19'x19' patch.
8a.3	Observing wavelengths = I through K (to 2.4 μm). Emphasis is on shorter wavelengths. Thermal part of K band less important. [SCRD §3.2.6.5]		
8a.4	Spatial resolution better than 50 mas at J band, for 30% sky coverage.	Need a good model of the PSF or a simultaneous image of a PSF star. Need a figure of merit for goodness of the PSF: how well the model fits the "real" PSF in two dimensions. Will quantify in future releases of the SCRD.	Nyquist sampling of pixels at each wavelength.
8a.5	Field of view > 15" diameter for survey. Bigger is better. Some degradation between center and edge of field is tolerable. Will quantify in future releases of the SCRD. [SCRD §3.2.6.2]		
8a.6	Relative photometry to ≤ 0.1 mag for observations during a single night [SCRD §3.2.4.4]		
8a.7	Absolute photometry ≤ 0.3 mag [SCRD §3.2.4.4]		
8a.8	Sky coverage at least 30%		

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	with enclosed energy radius within 0.07 arc sec at H or K. [SCRD §3.2.4.9]		
8a.9	Dithering and offset considerations: 1) Initially should be able to center a galaxy to ≤ 10% of science field of view. 2) Should know the relative position of the galaxy after a dither to ≤ 20% of pixel size.		
8a.10	The following observing preparation tools are required: PSF simulation and exposure time calculator		
8a.11	The following data products are required: accurate distortion map (to 1% of the size of the galaxy, or 0.01 arc sec rms)		

Table 8b. Spectroscopic studies of distant galaxies lensed by galaxies

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
8b.1	SNR ≥ 10 for a z = 1 – 2 galaxy in an integration time ≤ 3 hours for a Gaussian width 20 km/sec Gaussian width (50 km/sec FWHM) with a spatial resolution of 50 mas	Background due to emissivity less than 30% of unattenuated (sky + tel).	R ~ 5000 (or whatever is needed to achieve 20 km/sec sigma on these targets)
8b.2	Target sample size of ≥ 50 galaxies, with density on the sky of 10 per square degree. Survey time ~ 3 years.	Number of IFUs: at least one, plus preferably one to monitor the PSF and one to monitor the sky. The extra two IFUs could be dispensed with if there were	

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
		other ways to monitor the PSF and the sky background.	
8b.3	Observing wavelengths = J, H and K (to 2.4 μm) required, with emphasis on J band. Goal: also use z and I bands. [SCRD §3.2.6.5]		
8b.4	Spectral resolution: whatever is needed to get 20 km/sec radial velocity Gaussian sigma		
8b.5	Spatial resolution 50 mas at J band		
8b.6	Velocity determined to ≤ 20 km/sec Gaussian sigma for spatial resolutions of 50 mas	Required level of PSF knowledge will be assessed in future releases of the SCRD.	
8b.7	Field of view: Typical lens is 2 to 6 arc sec diameter. For IFU fields of view smaller than the lens size, one would use mosaicing. Desirable to take in blank sky in addition to the lens (if possible). Requirement: FOV ≥ 3" diameter. Goal: ≥ 4" diameter. [SCRD §3.2.6.2]		Requirement: IFU FOV ≥ 3" diameter. Goal: ≥ 4" diameter.
8b.8	Simultaneous sky background measurements		Preferably sky determination within the field of view of the IFU. Less preferably, through use of offsetting to sky or via a separate IFU looking at sky.
8b.9	Relative photometry to ≤ 0.1 mag for observations during a single night [SCRD §3.2.4.4]		

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
8b.10	Absolute photometry ≤ 0.3 mag [SCRD §3.2.4.4]		
8b.11	Sky coverage at least 30% with enclosed energy radius within 50 mas at J band. [SCRD §3.2.4.9]		
8b.12	Dithering and offset considerations: 1) Initially should be able to center a galaxy to ≤ 10% of science field of view. 2) Should know the relative position of the galaxy after a dither to ≤ 20% of spaxel size.		
8b.13	Target drift should be ≤ 10% of spaxel size in 1 hr		
8b.14	The following observing preparation tools are required: PSF simulation and exposure time calculator		
8b.15	The following data products are required: calibrated spectral data cube		

Table 9a. Imaging studies of distant galaxies lensed by clusters

Table 9b. Spectroscopic studies of distant galaxies lensed by clusters

6.1.2.9 Astrometry Science in Sparse Fields

Text and tables will be included in a future release of the SRD. This science case will be a driver for low and/or very well calibrated instrument distortions, compensation for atmospheric differential refraction, and good temperature control of the AO system.

Table 10. Astrometry Science in Sparse Fields derived requirements

6.1.2.10 Resolved Stellar Populations in Crowded Fields

Text and tables will be included in a future release of the SRD.

Table 11. Resolved Stellar Populations in Crowded Fields derived requirements

6.1.2.11 Debris Disks

Text and tables will be included in a future release of the SRD. This science case will be a driver for coronagraph design.

Table 12. Debris Disks derived requirements

6.1.2.12 Young Stellar Objects

Text and tables will be included in a future release of the SRD. This science case may be a driver towards having an infrared wavefront sensor.

Table 13. Young Stellar Objects derived requirements

6.1.2.13 Asteroid Size, Shape, and Composition

The requirements for the *asteroid size and shape* (characterize surface and orbital parameters) science case are summarized in the following table. In addition to the requirement of a high resolution visible imager, the slope of the visible spectrum is needed to determine the asteroid age or surface type. This case requires a spectral resolution of R ~ 100 for 0.7 – 1.0 µm wavelength with Nyquist sampling. If R ~ 100 is not available, some of this work can be achieved either with multiple narrow-band filters or with a higher-resolution spectrograph.

Table 14. Asteroid size, shape, and composition derived requirements

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
14.1	Target sample size of ≥ 300 asteroids in ≤ 3yrs years. < 10 targets in an 11 hour night [SCRD §3.6.3]	#6.5 is stricter requirement.	

14.2	Observing wavelengths 0.7 – 1.0 µm. Strong preference for R band because optimum to obtain shape of asteroid. [SCRD §3.6.6.6]	AO system must pass 0.7 to 1.0 micron wavelengths	Imagers (R through J band) with narrow-band filters or slit spectrograph (R~100), or possibly visible IFU (R~100).
14.3	Spatial sampling same as #5.5	Same as #5.5	Same as #5.5
14.4	Field of view ≥ 3" diameter [SCRD §3.6.6.2]	Same as #6.8	Same as #6.8
14.5	Ability to measure the spectral slope with R ~ 100 at 0.85-1.0 µm [SCRD §3.6.6.7]		
14.6	Ability to measure the SO_2 frost bands at R=1000 (R=5000 is acceptable) at 1.98 and 2.12 µm, crystalline ice band at 1.65 microns. [SCRD §3.6.6.7]		Spectroscopic imaging at R~1000 to 5000 in the H and K bands.
14.7	Same as #5.7	Same as #5.7	
14.8	Same as #5.8	Same as #5.8	

6.1.2.14 Gas Giant Planets

The requirements for the *Gas Giants* science case (all three goals) are summarized in the following table (see the section on Characterization of Gas Giant Planets of KAON 455 (Release 2.1)).

Table 15. Gas Giants derived requirements

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
15.1	*Capability of tracking a moving target* with rate up ≤ 50 arcseconds per hour (14 mas/second) [SCRD §3.7.5.1]		
15.2	*Capability of using at least one tip-tilt star*	Motion of low order wavefront sensor to track	

	that is moving with respect to the (moving) target planet. (For example, a moon of Jupiter or Saturn) [SCRD §3.7.5.1]	tip-tilt star.	
15.3	*Ability to acquire Io within 5" of Jupiter and to track it to within 2.5" of Jupiter.* Note that this is a goal but perhaps not a rigid requirement: we know we can acquire within 10" today.	May require either a diaphragm or a filter to attenuate the light from Jupiter.	See AO derived requirement.
15.4	*Sensitivity:* comparable to the current Keck system		
15.5	*Absolute Photometric accuracy:* comparable to the current Keck system (≤ 0.05 mag) [SCRD §3.7.4.4]	PSF knowledge	Detector flat-fielding requirements, linearity, etc will flow down from required photometric accuracy.
15.6	*Targets*: Jupiter and Saturn systems, with special focus on Io and Titan	AO system capable of working in the presence of scattered light from nearby extended objects; NGS option for bright moons	Jupiter & Saturn: near-IR imager from 0.8-2.4 μm Io: IFU 0.8-2.4 μ Titan: IFU 0.8-2.4 μm
15.7	*Observing wavelengths* I, z/Y, J, H, K [SCRD §3.7.6.5]	AO system must pass these wavelengths to science instruments.	Near- IR imager and IFU spectrometer, λ= 0.8-2.4 μm
15.8	*Spatial sampling:* for imager, ≤ Nyquist at the observing wavelength		For imager, spatial sampling ≤ Nyquist at the observing wavelength. For IFU, spatial sampling ~λ/D.
15.9	Imager field of view ≥ 30" diameter at K band, ≥ 20" diameter at J and H bands (goal 30") [SCRD §3.7.6.1]	AO system passes a >30" unvignetted field of view	Imager field of view ≥ 30" diameter at K band, ≥ 20" diameter at J and H bands (goal 30")
15.10	IFU field of view as		If IFU FOV is only a few

	large as possible, up to 15” (Jupiter’s diameter is 30”, Great Red Spot is 13” diameter) [SCRD §3.7.6.1]		arc sec, desirable to be able to place different IFUs as close together as possible. No firm numerical requirement.
15.11	Moons are very bright: do not allow saturation. Typical brightness: 5 mag per square arc sec.		Either need to use neutral density filters, or have a fast shutter, or have a detector with large wells or very short exposure times (and low read noise). Note: these observations will have high overhead.
15.12	The following observing preparation tools are required: PSF simulation, target ephemeris, exposure time calculator to enable choice of ND filter and exposure time.		
15.13	The following data products are required: Calibrated PSF.		
15.14	Observing requirements: Io and Titan are time domain targets; Io requires ≤ 1 hr notification of volcano activity. Typical timescales for clouds on Titan are of order days to weeks.		

6.1.2.15 Ice Giants: Uranus and Neptune

The requirements for the *Ice Giants* science case (all four goals) are summarized in the following table (see the section on Characterization of Ice Giant Planets of KAON 455 (Release 2.1)).

Table 16. Ice Giants derived requirements

#	Science Performance	AO Derived	Instrument

	Requirement	Requirements	Requirements
16.0	*Capability of tracking a moving target* with rate up ≤ 5.0 arcseconds per hour (1.4 mas/sec) [SCRD §3.8.5.1]	• The planet can be used as tip/tilt guidestar (proper motion of ≤ 5.0 arcsec/hour). • The AO system requires sufficient field of view for planets and for their seeing disks (>5 arcsec). • The tip-tilt residual error will be less than 10 mas (limited by resolved primary) while guiding on one planet at 5.0 arcsec/hr (1.4 mas/sec).	
16.1	*Sensitivity:* comparable to the current Keck system		Near-IR imager, 0.8 - 2.4 μm
16.2	*Photometric accuracy:* comparable to the current Keck system [SCRD §3.8.4.5]		Near- IR imager
16.3	*Targets:* Uranus and Neptune systems. Observations of atmospheric vertical structure will require a near-IR IFU, to be described in more detail in a future release of the SCRD.	AO system (both LGS and NGS) capable of correcting on extended objects. • Uranus = 3.4 arcsec • Neptune = 2.3 arcsec	Near-IR imager, 0.8 – 2.4 μm, Near-IR IFU 1.0 – 2.4 μm
16.4	*Observing wavelengths:* J, H, K [SCRD §3.8.6.5]		Near- IR imager, Near-IR IFU
16.5	*Spatial sampling:* ≤ Nyquist at the observing wavelengths		Spatial sampling ≤ Nyquist at the observing wavelength
16.6	*Imager field of view:* ≥ 15” diameter [SCRD §3.8.6.2]	AO system passes a >15” unvignetted field of view	Imager fields of view ≥ 15”
16.7	*IFU field of view:* as large as possible, up to ≥ 15” diameter [SCRD §3.8.6.2]		If IFU FOV is only a few arc sec, desirable to be able to place different IFUs as close together as possible.

			No firm numerical requirement.
16.8	*Spectral resolution:* R ≥ 3000 to resolve methane absorption features. [SCRD §3.8.6.6]		Near-IR IFU with R~3000
16.9	*Observing requirements:* one run per semester with at least 4 contiguous (partial) nights; both targets can be studied during one run		
16.10	The following *observing preparation tools* are required: PSF simulation, target ephemeris, exposure time calculator to enable choice of ND filter and exposure time.		
16.11	The following *data products* are required: Calibrated PSF.		
16.12	*Observing requirements:* some science goals would be well suited to queue or service observing modes		

6.1.2.16 Other: Backup Science

This will primarily be NGS science that can be done when the lasers cannot be propagated (e.g. due to cirrus), or less-demanding examples of LGS science that can be done when the laser power available is lower than nominal due to hardware problems. The derived requirements for Backup Science will largely involve science preparation and operations issues.

Table 17. Backup Science Observing Modes: NGS

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
17.1	*NGS mode.* NGS as a backup observing mode for when conditions restrict propagation of the lasers.		
17.2	*Sky coverage* ≥5% to ensure at least one-sixth of the off-axis LGS targets will still be observable if it is necessary to go to an NGS backup mode.	Assuming *b=30º,* For 5% sky coverage: • R=14 mag guide star with 60" diameter field of regard (FOR) • R=15 mag guide star with 45" diameter FOR [Keck Observatory Report No. 208, p. 4-100]	
17.3	Capability to switch between NGS and LGS modes in ≤ 15 minutes (not including target acquisition) to enable flexibility if conditions change.		
17.4	*Sensitivity*. SNR ≥ 10 for a z = 2.6 galaxy in an integration time ≤ 3 hours for a spectral resolution R = 3500 with a spatial resolution of 50 mas	Sufficiently high throughput and low emissivity of the AO system science path to achieve this sensitivity. Background due to emissivity less than 30% of unattenuated (sky + tel).	
17.5	Observing wavelengths = J, H and K (to 2.4 μm)	AO system must transmit J, H, and K bands	Infrared single IFU and imager designed for J, H, and K.
17.6	*Spectral resolution* = 3000 to 4000		Spectral resolution of >3000 in IFU
17.7	*Imaging:* Nyquist sampled at H-band		Nyquist sampled IR imager (at H-band)
17.8	Encircled energy 50%	Wavefront error	Optimum spaxel size will

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	in 70 mas for a bright NGS guide star within 10 arc sec	sufficiently low (~170 nm) to achieve the stated requirement in J, H, and K bands.	be determined during a detailed study of the IFU instrument.
17.9	If a new instrument: IFU field of view ≥ 1" x 3" to allow simultaneous background measurements while observing a 1" galaxy. OSIRIS FOV would be adequate.	Narrow relay passes 1"x3" field	If a new instrument: IFU field of view ≥ 1" x 3" to allow simultaneous background measurements while observing a 1" galaxy. OSIRIS FOV would be adequate.
17.10	Imager FOV ≥ 10" x 10" for galactic center and gravitational lensing science		Imager FOV ≥ 10" x 10"
17.11	Relative photometry to ≤ 5% for observations during a single night, provided the night is photometric	Knowledge of ensquared energy in IFU spaxel to 5%.	
17.12	Should be able to initially center a galaxy to ≤ 10% of science field of view		
17.13	Should know the relative position of the galaxy to ≤ 20% of spaxel or pixel size		
17.14	Target drift should be ≤ 10% of spaxel size in 1 hr		
17.15	The following observing preparation tools are required: NGS guide star finding tool; PSF simulation and exposure time		

#	Science Performance Requirement	AO Derived Requirements	Instrument Requirements
	calculator		
17.16	The following data products are required: calibrated spectral data cube		

6.1.2.17 Atmospheric Seeing Assumptions

The atmosphere and telescope parameters assumed for achieving these numbers are summarized below.

The NGAO system shall provide its nominal performance when the atmospheric seeing is characterized by the following conditions. An evaluation of existing seeing data has been performed (KAON 303). The KAON 303 profile was modified to include a stronger ground layer and represent the median values for the seeing parameters (50^{th} percentile). The resultant baseline median C_n^2 profile is presented in Table 1. From this model we calculate the following turbulence parameters for 0.5 µm wavelength (note that r_0, θ_0 and $1/f_G$ increase as $\lambda^{6/5}$):

- Fried's seeing parameter $r_0 = 16$ cm
- Isoplanatic angle $\theta_0 = 2.7$ arcsec
- Turbulence characteristic frequency $f_G = 39$ Hz

In addition, we have adopted a standard deviation for r_0 of $\sigma_{r0} = 3$ cm with a characteristic evolution time of t = 3 min.

Table 17a. NGAO baseline Mauna Kea C_n^2 Profile

Altitude (km)	Fractional C	Wind Speed (m/s)
0.0	0.471	6.7
2.1	0.184	13.9
4.1	0.107	20.8
6.5	0.085	29.0
9.0	0.038	29.0
12.0	0.093	29.0
14.8	0.023	29.0

6.1.3 Science Instrument Requirements

The NGAO system must be capable of supporting the following science instruments (in rough order of priority), based on the NGAO proposal and SCRD:

- Visible imager. Wavelength range = 0.6 to 1.1 μm. Field of view = 20"x20". Image sampling = 6 mas pixels.
- Near-IR imager. Wavelength range = 1.0 to 2.45 μm. Field of view = 20"x20". Image sampling = 10 mas.
- Deployable near-IR Integral Field Unit (IFU). Wavelength range = 1.0 to 2.45 μm. Field of Regard = 1.5'x1.5' with 3x3.4" fields of view for each IFU. Image sampling = 100 mas.
- Near-IR IFU. Wavelength range = 1.0 to 2.45 μm. Field of view from 2"x1.25" to 16"x5". Image sampling = 20 to 100 mas.
- Visible IFU. Wavelength range = 0.6 to 1.1 μm. Field of view from 1.2"x1.36" to 12"x6.8". Image sampling = 20 to 100 mas.
- Future science instruments from the above list or completely new instruments. These future science instruments would need to be designed so as to fit at a movable port or to replace a fixed first generation instrument.

Table 18. Science Instrument Requirements

#	Science Instrument Requirement	Discussion	Based on
18.1	Visible Imager: the field of view shall be ≥ 2 arcsec diameter		SCRD §2.1.6.2, §2.5: asteroid shapes and companions
18.2	NIR Imager: the field of view shall be ≥ 2 arcsec		SCRD §2.1.6.2, §2.5: Io, Titan, debris disks and QSO host galaxies
18.3	NIR Imager: the field the field of view shall be ≥ 3 arcsec		SCRD §2.2.5.3: planets around low mass stars
18.4	NIR Imager: the field the field of view shall be ≥ 10 x 10 arcsec		SCRD §2.3.11: Galactic Center
18.5	NIR Imager: shall provide a coronagraph		SCRD §2.2.4, RollUp_v1 G5 : planets around low mass stars, debris disks and QSO host galaxies
18.6	NIR Imager: wavelength coverage shall be at least 0.9 to 2.4 μm		SCRD §2.2.4, RollUp_v1 B5: planets around low mass stars
18.7	NIR IFU: field of view shall be ≥ 2 arcsec	Only 1" is required for the Galactic Center	SCRD §2.1.6.2: Asteroids, Titan
18.8	Visible IFU: field of view		SCRD §2.5: Nearby AGNs

	shall be ≥ 2 arcsec		
18.9	Visible IFU: spectral resolution shall be R ~ 4000	What range is acceptable? Note: Asteroid size and shape prefers R=1000 but tolerates 4000 [SCRD §2.1.6.6]	SCRD §2.3.6: Galactic center radial velocity, Nearby AGNs
18.10	NIR deployable IFU: field of view shall be 1"x3" arcsec	1"x3" or larger required for high z galaxies. (see #9.8opt for an option to this) Galactic Center needs a dIFU.	SCRD §2.4.5.1: High z galaxies, gravitational lensing
18.11	NIR deployable Imager: field of view shall be ≥ 2 arcsec		SCRD §2.4.5.1:: high z galaxies

It is TBD whether the NGAO system will be required to support any of the existing science instruments (NIRC2, NIRSPEC or OSIRIS), however we are baselining a requirement that OSIRIS be fed by the narrow field (high Strehl) NGAO optical feed. The Interferometer and 'OHANA requirements are discussed in section 6.2.4.

It is a goal for NGAO to support visitor science instruments.

6.1.4 Science Operations Requirements

The top-level science operations goals for the NGAO system including the science instruments are the following (see KAON 476):

1. Science-grade quality of the raw data (i.e., image quality and completeness of observations).
2. Science-grade quality of the data products (i.e., photometry, astrometry, etc.).
3. Science impact from a given data product (i.e., number of publications and citations).

The requirements that support these top-level goals are defined in the following tables.

6.1.4.1 Science-grade quality of the raw data

Table 19. Science Operations Requirements, Raw Data Quality

#	Science Operations Requirement	Discussion	Based on
19.1	Provide an extensive set of tools for instrument performance simulation and observing preparations	The requirement is that an observer should be able to prepare the observing sequences and simulate the science performance in terms of SNR, EE, SR and total observing time given a set of observing parameters and observing conditions. The suite of functions from the planning tools includes: resolve target, check observability, find suitable NGS, select and simulate instrument setup, simulate AO and instrument performance for various parameters, simulate observing sequence and efficiency, exposure time calculator, save target information, save observing setup. The tools should be designed with the end user in mind: user friendly, configurable, stand-alone and available at the observing site.	Required by most Science Cases. See e.g., #1.7, #6.16, #12.9. KAON 476 Observing Models Study, section 6.2.1.
19.2	Document the instrument performance at an appropriate level to support observing preparations	This is both a development and operations requirement, since a continued effort will be required to characterize, monitor and document the performance. This should be based on an extensive science verification phase.	KAON 476, section 6.2.1 and 6.2.3

#	Science Operations Requirement	Discussion	Based on
19.3	Provide a semi-real-time level 1 data reduction pipeline for each instrument to at minimum perform background subtraction, cosmetic correction and shift-and-add of images.	This is an operation requirement to support # 14.2 and # 14.4 for any science instrument as well as a science requirements for IFU instruments.	KAON 476, section 6.2.1
19.4	Provide semi-real-time tools to perform an assessment of the image quality on the level 1 data including SNR, Strehl and encircled energy.	It is required that the observing support team as well as the observer have the tools to check the image performance at the focal plane of the science instrument.	KAON 476, section 6.2.1
19.5	Provide a science operations paradigm that optimizes the completion rate for a significant fraction (TBD) of observing programs.	It is ** not required ** to develop a plan for queue scheduling and service observing. Yet, it is required to provide the necessary tools to 1) simulate, prepare and run the observing sequences; 2) assess the science-grade quality of the data on-the-fly and subsequently 3) decide (or not) to switch to a different observing sequence, a different observing program either by the same observer or not. Particularly, a goal is to develop a science operations paradigm that allows for (and encourages?) flexible scheduling per TAC, to optimize the match between required observing conditions for a science program and real conditions.	KAON 476, section 6.2.1

6.1.4.2 Science-grade quality of the data products

Table 20. Science Operations Requirements, Data Products Quality

#	Science Operations Requirement	Discussion	Based on
20.1	Provide the required calibration methods and tools to achieve the astrometry performance requirements	This requires four important steps: 1) the tools and methods to calibrate for the astrometry are specified and designed, 2) the tools and methods are implemented, demonstrated, and optimized during the science engineering and verification phase, 3) the tools and methods are handed over to the observing support team, and 4) the performance is regularly documented and posted using the tools and methods.	KAON 476, section 6.2.2
20.2	Provide the required calibration methods and tools to achieve the photometry performance requirements	Same as above	KAON 476, section 6.2.2
20.3	Provide the required calibration methods and tools to achieve the PSF characterization requirements	This is in support of # 15.1, 15.2. as well as 14.1 to 3;	KAON 476, section 6.2.2

6.1.4.3 Science impact from a given data product

Table 21. Science Operations Requirements, Archiving and Retrieval

#	Science Operations Requirement	Discussion	Based on
20.1	Develop a plan for data archival	Data archival is critical for 1) science programs such as proper motion studies, transient phenomena (GRB, SN, Titan, etc), 2) the semi-automated monitoring of instrument performance and 3) the long-term visibility of Keck NGAO (either from direct science impact, or the use of the archive by the general public, e.g. CADC, google sky). It's very likely that the archive may not be supported at first, but it's essential to develop a plan for it and understand the requirements for the FITS information, the data storage format, etc	Science Case Requirement #1.8 KAON 476, section 6.2.3
20.2	Develop a plan for data retrieval from the data archive	Same as above	KAON 476, section 6.2.3
20.3	Document the on-sky science performance of each science instrument with NGAO		KAON 476, section 6.2.3

6.2 Observatory Overall Requirements

6.2.1 Purpose and Objectives

The purpose of the overall requirements section is to convey requirements that apply generally to the overall instrument and its accessories based on the Observatory's requirements.

Note that the Observatory's standard requirements for all new instrumentation are summarized in the Instrumentation Baseline Requirements Document. Additional Observatory requirements specific to NGAO are listed in the following sections.

6.2.2 Facility Requirements

The following are requirements imposed by the nature of the existing facility.

Table 21. Facility Requirements

#	Facility Requirement	Discussion	Based on
21.1	The NGAO system must be facility-class	Facility-class has many implications on safety, operability, reliability, maintainability, lifetime, documentation, configuration management, etc.	KAON 572 (Baseline Instrument Requirements), KAON 463 and 476
21.2	The NGAO system & science instruments should be located on the Nasmyth platform of one of the Keck telescopes	The Keck telescope foci and Nasmyth deck storage locations are already heavily utilized. The current AO systems occupy the left Nasmyth platform locations of both telescopes. HIRES occupies the right Nasmyth on Keck I while DEIMOS and NIRSPEC share the right Nasmyth on Keck II. The Cassegrain foci are occupied by LRIS (and MOSFIRE in the future) on Keck I and by ESI on Keck II. The bent Cassegrain ports are believed to have inadequate space and weight capacities. The prime focus could potentially be available but there would be many constraints on an	System architecture decision by NGAO engineering team (see KAON 499)

		instrument at this location. The most viable option is in the location of an existing AO system. Alternatives would be to decommission HIRES or for the existing AO system and the NGAO system to be able to share the same platform.	
21.3	The NGAO system should accommodate the entire Keck pupil	The Keck primary has a maximum edge-to-edge diameter of 10.949 m.	System architecture decision by NGAO engineering team (see KAON 499)
21.4	If the existing f/15 or f/40 secondary mirrors are used then the NGAO system will be constrained by the resultant f/#, focal plane and pupil location	Both telescopes have f/15 secondary mirrors, as well as chopping secondary units that can accommodate f/25 and f/40 secondary mirrors. The choice of f/15 secondary mirrors for the current AO systems was largely driven by the resultant reduced size of the AO systems and the availability of PCS (Phasing Camera System) via a rotation of the tertiary mirror. The inability of the current systems to chop at the telescope pupil has been a limitation for thermal IR observations. The focal length of the telescope with the f/15 secondary mirror is 150 m. The 10.949 m primary corresponds to an f/13.66 beam with an exit pupil diameter of 1.460 m located 19.948 m in front of the focal plane.	Engineering decision to avoid the cost of constructing another secondary

21.5	The NGAO facility must not compromise the performance of a non-NGAO instrument when that instrument is being used for science or engineering	This requirement is intended to ensure that the NGAO facility, when not in use, does not introduce vibrations or stray light that might impact the performance of another science instrument or an engineering instrument such as PCS.	KAON 572 Baseline Instrument Requirements, e.g. §8.2.2.2, §9.3.2.1
21.6	The NGAO facility must not compromise the performance of the telescope when the telescope is used for non-NGAO observations.	The NGAO system should not impact the dynamic performance of the telescope through vibrations or different telescope dynamics. If NGAO hardware is to be mounted in the top-end then it must be designed/implemented not to compromise the secondary mirror performance.	KAON 572 Baseline Instrument Requirements
21.7	The NGAO facility / science instrument combination should provide compensation for science field rotation	The Alt-Az telescope design requires compensation for field rotation in order to keep the science field fixed on the science instrument.	KAON 455 Science Case Requirements Document (various science case observing modes)
21.8	The NGAO facility / science instrument combination should provide compensation for pupil rotation	The Alt-Az telescope design and the irregular shape of the Keck primary mirror require that NGAO system provide appropriate compensation for pupil rotation. Examples: The existing Keck AO system updates the reconstructor to compensate for pupil orientation. The NIRC2 coronagraph mask rotates to match the rotating pupil.	KAON 455 Science Case Requirements Document, high contrast imaging mode §2.1.4.4

21.9	The NGAO facility should provide compensation for LGS projector rotation	The Alt-Az telescope design will cause the laser projector (and the resultant LGS asterism) to rotate with respect to the Nasmyth platform. Compensation will be required to maintain the off-axis LGS on the corresponding wavefront sensor.	Practical requirement in order to accommodate LGS wavefront sensors' Nasymth location (see requirement 21.2)
21.10	The NGAO facility should accommodate access for routine maintenance of the telescope	For example, access to the elevation journal, elevation wrap, bent Cassegrain platform and stairwell to the mirror cell	KAON 572 Baseline Instrument Requirements, section 15
21.11	The NGAO facility should not routinely require more than 30 minutes of daytime telescope restriction on an NGAO science night.		KAON 463 and 476 (Observing model studies)
21.12	The NGAO system must operate within specifications under the normal summit temperature and humidity conditions	See the conditions specified in the Instrument Baseline Requirements Document.	KAON 572 Baseline Instrument Requirements, §6.2.1.2.3

6.2.3 Telescope and Dome Environment Requirements:

The NGAO system shall provide its nominal performance when the telescope and dome environment can be characterized by the following conditions.

Table 22. Telescope and Dome Environment Requirements

#	Observatory Instrument Requirement	Discussion	Based on
22.1	Dome & telescope seeing less than 0.1”	The Keck dome and telescope environment degrades the intrinsic seeing by less than 0.1 arcsec, in quadrature, as measured from the effective increase in image FWHM (this change corresponds to decreasing the r_0 parameter from 18 cm to 17.8 cm).	KAON482, Keck Telescope Wavefront Error trade study, and references therin
22.2	The phasing errors will be 10 nm rms wavefront or less before NGAO correction.	Standard performance is 60 nm rms currently. Currently available algorithms have demonstrated 10 nm rms. This error interacts with the segment figure error discussed next. We may want to place an error on the overall telescope wavefront figure PSD instead.	KAON482, Keck Telescope Wavefront Error trade study, and references therin
22.3	Segment figure : The wavefront error of the 36 segments will be less than 80 nm rms wavefront after warping, but before NGAO correction.	This number is an average over all 36 segments segment. As a goal the wavefront error shall be 80 nm rms over each segment.	KAON482, Keck Telescope Wavefront Error trade study, and references therin
22.4	Stacking: The segment stacking errors will contribute less than 20 nm rms wavefront to the overall wavefront error before NGAO correction.		KAON482, Keck Telescope Wavefront Error trade study, and references therin

22.5	Line of sight jitter: The aggregate line of sight jitter (wavefront tip and tilt) resulting from motion of the primary, secondary and tertiary mirrors will be less than 0.020 arc seconds rms before correction by the NGAO.	This vibration is known to currently be largely dominated by a narrow resonance at ~29 Hz.	KAON482, Keck Telescope Wavefront Error trade study, and references therin
22.6	Segment motion: The motion of each segment as a solid body will be less than 0.015 arc seconds rms before correction by the NGAO.	This vibration is known to currently be largely in a narrow resonance at ~29 Hz.	KAON482, Keck Telescope Wavefront Error trade study, and references therin

6.2.4 Observatory Science Instrument Requirements

In addition to the science instrument requirements specified in section 6.1.3 the NGAO facility must allow the Observatory to continue supporting Interferometer science with the two Keck telescopes. The requirements for these instruments are developed in KAON 428 and are further specified in later sections.

Table 23. Observatory Science Instrument Requirements

#	Observatory Instrument Requirement	Discussion	Based on
23.1	The NGAO facility should support the Keck Interferometer (KI) with performance as good or better than provided by the pre-NGAO Keck AO systems	The KI dual star modules (DSM) currently move into both AO enclosures on rails to feed the KI. The requirement to feed the KI requires that collimated and f/15 light can be fed to the DSM and that the field rotation, pupil rotation, longitudinal dispersion and polarization from the NGAO system and the AO system on the other telescope be identical. See KAON 428 Implications and Requirements for Interferometry with NGAO.	Existing Keck Observatory commitments to NASA and NSF
23.2	The NGAO system	Injection modules are currently	Existing Keck Observatory

	should support the 'OHANA interferometer with performance as good or better than provided by the pre-NGAO Keck AO systems	placed on each AO bench to feed an optical fiber that goes to the KI. In future the output from these fibers will be interfered with those from multiple telescopes.	commitments to NASA and NSF

6.2.5 Observatory Operational Requirements

The purpose of this section is to document the Observatory's overall requirements for the support of science operations. These requirements can be divided into the following categories:

- Percent of time collecting science quality data.
- Capability to support a certain number of nights per year of science operations.
- Operational costs.
- Impact on daytime and nighttime operations.
- Compliance with regulations, including safety, Mauna Kea policies, FAA and U.S. Space Command.

Each of these categories is represented in one of the following tables. In addition, all of the above categories require a facility-class NGAO system and science instruments, and this requirement is reflected in the final table.

Table 24. Observatory Operational Requirements

#	Observatory Operational Requirement	AO Derived Requirements	Instrument Derived Requirements	Based on
24.1	Assuming a classical observing model* and adequate observing conditions for the science program, more than 80% of the observing time is spent on collecting science-quality data for the deployable science instruments. *See KAON 476 for definitions of observing models	Observing model should allow flexible scheduling and quick-and-easy switching of observing modes and instrument. Observing overhead is minimized, particularly by being able to center multiple targets and reference guide stars with a < 0.3" accuracy. Observing reliability is critical to avoid canceling long integration: there should be less than 2 faults per night (one system fault is equivalent ~ 20-30 min lost time on faint targets for the worst cases). Observing tools should allow for automated observing sequences.	The deployable instrument are used for faint object spectroscopy with much longer time on target, hence less observing setup overhead. One should be able to stop, abort and restart an integration on command.	KAON 455 (ScRD) science target samples and survey durations, combined with efficiency analyses given in KAON 476

24.2	Assuming a classical observing model and adequate observing conditions for the science program, more than 70% of the observing time is spent on collecting science-quality data for the narrow-field science instruments.	Same as above. In addition, observing efficiency is critical for survey mode (see Science Case 1) Acquisition sequences must be fully automated. Overhead must be reduced by allowing parallel sequences between telescope, AO, laser and science instrument.	The narrow field science instruments are used on brighter targets in imaging, coronagraphy and spectroscopy modes. The science instrument interface command must allow for parallel sequences, e.g, start a nod/dither sequence immediately after the pixel readout.	KAON 455 (ScRD) science target samples and survey durations, combined with efficiency analyses given in KAON 476
24.3	The NGAO system must be capable of supporting 200 nights/year of science operations and keep the total annual operational personnel within the 5-year plan Observatory operation budget, including non-personnel costs.	Observatory currently willing to support 140 nights/year.		KAON 455 (ScRD) science target samples and survey durations, combined with efficiency analyses given in KAON 476
24.4	The NGAO facility should not require more than TBD engineering nights per year for system maintenance.			KAON 572 Baseline Instrument Requirements, section 13

24.5	The Mauna Kea laser projection requirements must be satisfied	This includes requirements on laser power, wavelength, laser traffic control participation, aircraft safety and space command. See KAON 153. The current policy only accepts sodium wavelength lasers, and requires that a single laser beacon not exceed 50W and that a maximum of 200 W be projected from a single facility, and that laser beacons not be projected below 70º zenith angle.	Mauna Kea laser projection requirement	KAON 153 Requirements on laser traffic control participation, aircraft safety, and space command compliance for satellite safety.

6.2.6 Observatory Implementation Requirements

Table 25. Observatory Implementation Requirements

#	Observatory Implementation Requirement	Discussion	Based on
25.1	The NGAO system and instruments must complete the Observatory standard design review process.		Sean Adkins, "An Overview of the WMKO Development Phases," WM Keck Observatory Instrument Program Management Memo, December 8, 2005 link

25.2	The time between decommissioning an AO capability on the telescope where the NGAO system is to be installed and making NGAO available for limited shared-risk science must be agreed upon with the Observatory Director.	Minimize down time impact on Interferometer and AO science at the Observatory. It is suggested that it should not be longer than 6 months.	Director's discretion
25.3	The telescope downtime required to implement NGAO must not be longer than an amount agreed upon with the Observatory Director.	Minimize down time impact on Interferometer and AO science at the Observatory. It is suggested that it should not be longer than 5 days.	Director's discretion
25.4	The NGAO system must complete an operations transition review where operational responsibility is transferred from development to operations	This has implications on defining transition requirements and on training.	Sean Adkins, "An Overview of the WMKO Development Phases," WM Keck Observatory Instrument Program Management Memo, December 8, 2005 link

7 Optical Requirements

7.1 Purpose and Objectives

The purpose of this section is to describe optical requirements for the performance, implementation and design of the NGAO optical system.

7.2 Performance Requirements

The following performance requirements are duplicated from the Science Performance Requirements in section 6.1.2 since these are direct optical performance requirements.
The following performance requirements are derived from the Science Performance Requirements in Section 6.1.2 and the relevant performance budgets.

7.3 Implementation Requirements

Table 26. Implementation Requirements

#	Optical Implementation Requirement	Discussion	Based on
26.1	The NGAO optical axis shall be coincident to the telescope's elevation axis to ≤ TBD.	This assures that the telescope achieves its nominal performance requirements delineated in Table 22.	See Table 22

7.4 Design Requirements

NGAO is required to provide an AO corrected beam to each of the science instruments, including the Interferometer and 'OHANA fiber injection module. This may be accomplished with one or more AO systems. The following requirements are valid for all of these science instruments.

Table 27. Optical Design Requirements

#	Optical Design Requirement	Discussion	Based on
27.1	The focal ratio provided to the science instruments should be TBD	These requirements will be deferred pending an interface definition between KNGAO and new instruments, OSIRIS, and the interferometers, to be written during Preliminary Design Phase	

27.2	The exit pupil location provided to the science instruments should be TBD	These requirements will be deferred pending an interface definition between KNGAO and new instruments, OSIRIS, and the interferometers, to be written during Preliminary Design Phase	
27.3	The NGAO system and science instrument combination should be capable of keeping the field or pupil fixed on the science instrument.		See requirements 21.7 and 21.8
27.4	The NGAO system shall have ≤ TBD of non-common path aberration delivered to the science instruments.	These requirements will be deferred pending an interface definition between KNGAO and new instruments, OSIRIS, and the interferometers, to be written during Preliminary Design Phase	
27.5	The NGAO system should be capable of correcting ≥ TBD nm of low spatial frequency (Zernikes 4 to 15) non-common path aberration in the science instruments.	Image sharpening can be used to correct for aberrations in the science instruments. New science instruments should be designed to have small optical aberrations. The interferometer and possible legacy instruments such as NIRC2 or OSIRIS may be allowed larger aberration budgets.	Keck NGAO Error Budget requirements (KAON 471) in support of Science Case Requirements (KAON 455)

27.6	The peak-to-peak range of tip/tilt correction provided by NGAO shall be ≥ 3" on sky.	The existing Keck AO systems have a peak-to-peak range of 1.6" which has proven to be inadequate in windy conditions.	See section 6.1.2.17 Atmospheric Seeing Assumptions and Table 22 Telescope and Dome Environment AssumptionsAtmospheric Seeing AssumptionsAtmospheric Seeing AssumptionsAtmospheric Seeing AssumptionsAtmospheric Seeing AssumptionsAtmospheric Seeing Assumptions

The following design requirements are duplicated from the Science Performance Requirements in section 6.1.2 since these are direct optical performance requirements.

Table 28. Science Instrument Optical Design Requirements

#	Science Instrument Optical Design Requirement	Discussion	Based on
28.1	Unvignetted contiguous fields shall be provided to the NIR and visible science imagers and single field IFUs. The maximum field size is 20"x20".		Science requirements on the contiguous field science instruments. (KAON 455, Tables 1-17)
28.2	Multiple unvignetted contiguous fields shall be provided to the NIR d-IFU. Each field should be ≥ 4" in diameter.		Science requirements on the NIR d-IFU. (KAON 455, Tables 1-17)
28.3	The unvignetted field of regard provided to the NIR d-IFU shall have a total area of ≥ 6 arcmin^2 and shall have a maximum off-axis distance of ≤ 1.5' with respect to the telescope's		Science requirements on the NIR d-IFU. (KAON 455, Tables 1-17)

	optical axis.		
28.4	NGAO shall provide appropriate outputs to ≥ TBD science instruments.		Science Cases Requirements - KAON 455

The following design requirements are imposed by the non-interferometric science instruments.

Table 29. Non-Interferometric Science Instrument Optical Design Requirements

#	Science Instrument Optical Design Requirement	Discussion	Based on
29.1	A wavelength range of 0.7 to 1.0 µm must be provided to the visible science instruments (imager and IFU)		Science Case Requirements Document (KAON 455), and KAON 548.
29.2	A wavelength range of 1.0 to 2.45 µm must be provided to the NIR science instruments (imager, IFU and deployable IFU)		Science Case Requirements Document (KAON 455), and KAON 548
29.3	A wavelength range of 3.0 to 5.3 µm must be provided to the thermal NIR imager	This is currently low priority and should be discussed if this drives the design.	Requirement deleted
29.4	An unvignetted field of view ≥ 20"x20" must be provided to the science imagers (visible and NIR)		Science Case Requirements Document (KAON 455), and KAON 548
29.5	An unvignetted field of view ≥ 12" diameter must be provided to the visible IFU		Science Case Requirements Document (KAON 455), and KAON 548
29.6	An unvignetted field of view ≥ 16" diameter must be provided to the NIR IFU		Science Case Requirements Document (KAON 455), and KAON 548
29.7	A field of regard of ≥ 1.5' diameter must be provided to the NIR deployable IFU with		Science Case Requirements Document (KAON 455), and KAON 548.

	vignetting by all sources ≤ TBD over TBD % of the field of regard		
29.8	A field of view of 25”x25” must be provided to the L and M-band imager	Low priority.	Requirement deleted
29.9	An unvignetted science target field ≥ 3” x 3.4” shall be provided to each channel of the NIR deployable IFU		Science Case Requirements Document (KAON 455), and KAON 548
29.10	The NGAO + deployable IFU system shall support simultaneous observations of at least two science targets separated by ≤ 5”	There is no requirement for simultaneous nearest-neighbor target distances less than 5”.	Requirement deleted
29.11	The NGAO + deployable IFU system shall support simultaneous observations of at least six science target fields inscribed within a 5 square arcminute field		Science Case Requirements Document (KAON 455) requirement 1.2.
29.12	NGAO shall be capable of compensating for focus changes due to changing filters or modes		Wavefront error requirement (SCRD KAON 455) coupled to NGAO Error Budget

The following design requirements are imposed by the Interferometer and/or ‘OHANA support requirements.

Table 30. Interferometry Science Instrument Optical Design Requirements

#	Interferometry Optical Design Requirement	Discussion	Based on
30.1	A wavelength range of 1.1 to 14 μm must be provided to the Interferometer		KAON 428 Requirements for Interferometry with NGAO

30.2	A wavelength range of 1.1 to 2.45 µm must be provided to the OHANA injection module		KAON 428
30.3	A field of view of ≥ 1' diameter must be provided to the Interferometer		KAON 428
30.4	A field of view of 5" diameter must be provided to the OHANA injection module		KAON 428
30.5	NGAO must be able to support a chopping mode for the interferometer.	The nuller requires small amplitude chopping with the AO loops closed at each end of the chop for alignment purposes.	KAON 428
30.6	The interferometer output of NGAO must be polarization matched to the interferometer output of the AO system on the other telescope in order to produce ≤ 3º of differential s-p phase shift	The current KI achieves polarization matching by keeping the number, angle and coatings of all reflections the same in the beam trains from each telescope. The differential s-p phase shift in the current KI is measured at 6º resulting in a loss in V^2 of 0.003.	KAON 428
30.7	The interferometer output of NGAO must have the same image rotation as the interferometer output of the AO system on the other telescope		KAON 428
30.8	The interferometer output of NGAO must have the same pupil rotation as the interferometer output of the AO system on the other telescope		KAON 428

30.9	The interferometer output of NGAO must have the same longitudinal chromatic dispersion as the interferometer output of the AO system on the other telescope	Transmissive optics fabricated from different materials can have different amounts of longitudinal chromatic dispersion resulting in the loss of fringe visibility	KAON 428
30.10	The ratio of the Strehls from the interferometer output of NGAO and the interferometer output of the AO system on the other telescope must be $\leq$ 1.2 and $\geq$ 0.9.	A Strehl mismatch of 22% or an intensity ratio of 1.22 results in a V^2 loss of 0.010.	KAON 428
30.11	NGAO must be able to accommodate the accelerometers needed to support the Interferometer	On the current AO bench one accelerometer is placed near the telescope focus and another near the output to the DSM. These are used to measure vibration along the optical path and are used in the fringe tracker control system. The accelerometer acquisition system is housed in an electronics rack in the AO electronics vault.	KAON 428
30.12	NGAO or NGAO in combination with a modified DSM must be capable of supporting the laser metrology beams from the interferometer	These metrology beams are a potential source of background light on the wavefront sensors	KAON 428
30.13	NGAO must incorporate the required tools and tolerances to support alignment to the interferometer	For example, the current AO bench hosts a corner cube to aid in aligning the interferometer to the optical axis of the AO system and telescope	KAON 428

30.14	NGAO or NGAO in combination with a modified DSM must provide a collimated 100 mm diameter beam to the interferometer	In the current AO system a removable (on a translation stage) dichroic beamsplitter, located between the deformable mirror and second off-axis parabola, folds the collimated beam to the DSM	KAON 428
30.15	The rms residual tilt at the NGAO system output to the interferometer should be ≤ 0.007” for TBD guide star.		KAON 428

8 MECHANICAL REQUIREMENTS

8.1 Purpose and Objectives

The purpose of this section is to describe mechanical requirements for the performance, implementation and design of the NGAO mechanical systems.

8.2 Performance Requirements

Table 31. Mechanical Performance Requirements

#	Mechanical Performance Requirement	Discussion	Based on
31.1	The NGAO AO system shall not exceed a thermal dissipation budget, into the dome environment, of 100 W		Instrument Baseline Requirements, KAON 572, requirement 8.2.1.3
31.2	The NGAO laser system shall not exceed a thermal dissipation budget, into the dome environment, of 100 W		Instrument Baseline Requirements, KAON 572, requirement 8.2.1.3
31.3	The NGAO AO system shall not exceed a thermal dissipation budget at the top-end of the telescope, into the dome environment, of 50 W		Instrument Baseline Requirements, KAON 572, requirement 8.2.1.3

8.3 Implementation Requirements

Table 32. Mechanical Implementation Requirements

#	Mechanical Implementation Requirement	Discussion	Based on
32.1	The NGAO facility must allow a means to install the new science instruments delineated for NGAO optical feed, and to install the OSRIS instrument to the NGAO optical feed.	Refer to KAON 531 for a discussion of instrument interface issues, and to KAON 493 for a discussion of OSIRIS instrument reuse.	See Table 18 (which is derived from KAON 455, Science Case Requirements Document, Instrument Requirements sections for each science case.)

8.4 Design Requirements

Table 33. Mechanical Design Requirements

#	Mechanical Design Requirement	Discussion	Based on
33.1	The maximum weight of the AO system on the Nasmyth platform shall not exceed 10,000 kg	The weight requirements are imposed by limits on what the telescope can support at various locations without changing its performance.	Instrument Baseline Requirements, KAON 572
33.2	The maximum weight of the laser facility on the azimuth rotating part of the telescope shall not exceed 10,000 kg		Instrument Baseline Requirements, KAON 572
33.3	The maximum weight of the beam transport system on the elevation portion of the telescope shall not exceed 150 kg		Instrument Baseline Requirements, KAON 572
33.4	The maximum weight of the laser launch facility in the top-end module shall not exceed 150 kg		Instrument Baseline Requirements, KAON 572

33.5	If mounted behind the f/15 secondary mirror, the launch telescope facility must allow for the removal, storage and installation of the f/15 secondary module		Required to support regular observatory science operations with alternative secondary mirrors.
33.6	If mounted behind the f/15 secondary mirror, the launch telescope facility must 1) not extend beyond the module in the x,y-directions and 2) must not extend more than 1 m beyond the top of the telescope structure.		1) Error and emissivity budgets KAON 501 do not allow for an increased secondary obscuration 2) The dimensions of the telescope structure, dome, and allowance for safety clearance – refer to drawing or document number XXX
33.7	The NGAO facility must fit within the mechanical constraints of a Nasmyth platform (nominally the Keck II left Nasmyth platform)		Observatory standards for safety clearance when moving the telescope. Instrument Baseline Requirements, KAON 572
33.8	The NGAO facility must provide access and space for the installation of each science instrument and a mechanical interface on which to mount each instrument		Instrument Baseline Requirements, KAON 572
33.9	The NGAO facility must provide access for routine maintenance of the elevation bearing, elevation wrap, bent Cassegrain platform and mirror cell stairwell		Instrument Baseline Requirements, KAON 572, Section 15
33.10	The required glycol flow rate and pressure for cooling the NGAO facility shall not exceed TBD and TBD, respectively		Instrument Baseline Requirements, KAON 572

9 Electronic/Electrical Requirments

9.1 Purpose and Objectives

The purpose of this section is to describe electronic and electrical requirements for the performance, implementation and design of the NGAO electronic and electrical systems.

9.2 Performance Requirements

9.3 Implementation Requirements

9.4 Design Requirements

Table 34. Electrical Performance Requirements

#	Electrical Performance Requirement	Discussion	Based on
34.1	The entire NGAO facility must not exceed a total electrical power requirement of 30 kW		Instrument Baseline Requirements, KAON 572
34.2	The NGAO facility cabling through the azimuth wrap must not require an area of more than TBD		Instrument Baseline Requirements, KAON 572
34.3	The NGAO facility cabling through the left Nasmyth elevation wrap must not exceed an area of more than TBD		Instrument Baseline Requirements, KAON 572
34.4	The NGAO facility cabling through the right Nasmyth elevation wrap must not exceed an area of more than TBD		Instrument Baseline Requirements, KAON 572

10 Safety Requirements

10.1 Purpose and Objectives

Safety is the paramount concern for all activities at the observatory. The purpose of this section is to provide requirements related to specific safety concerns during the operation and handling of NGAO.

10.2 Scope

The general Observatory safety requirements that are also applicable to NGAO are already contained in the Instrumentation Baseline Requirements Document. This section covers the additional laser safety and laser projection safety requirements.

Adequate earthquake restraints are also required for all systems.

10.3 Laser Safety Requirements

A safety system will be implemented to ensure the safe use of the laser. This safety system will include both engineering and administrative/procedural controls to assure safe operations. The system will apply ANSI Z136.1 and Z136.6 standards for safe use of laser for indoor and outdoor.

The NGAO system will conform to OSHA and local codes in addition to codes specified for each subsystem.

10.4 Laser Projection Safety Requirements

This section covers the additional requirements on safety for projecting the laser beams outside the dome.

10.4.1 Aircraft Safety

An aircraft safety system compliant with FAA requirements must be implemented and approved by the FAA.

10.4.2 Space Command

A system must be implemented to facilitate effective communication with U.S. Space Command of projection dates and targets, and to ensure that no projection occurs on a target without Space Command approval. This requirement may be deleted if it is determined that Space Command approval is no longer required.

11 SOFTWARE REQUIREMENTS

11.1 Purpose and Objectives

The software requirements section describes requirements for performance, implementation and design. The software requirements for the W. M. Keck Observatory are described in the Instrument Baseline Requirements (KAON 572).

11.2 Scope

Unless otherwise indicated all of the requirements of this section apply to all software components of NGAO.

11.3 Performance Requirements

Table 35 presents the software requirements for NGAO. The performance requirements will be detailed during the Preliminary Design phase.

Table 35. Software Performance Requirements

#	Software Design Requirement	Discussion	Based on
35.1	The NGAO system must be able to support the external interfaces supported by the existing AO systems	The external keywords and EPICS channels used by the existing AO systems are documented in KAON 315, Summary of External Interfaces in the Current WFC and Implications for the NGWFC Design"	KAON 315
35.2	The NGAO system must be able to accept tip/tilt offloads from the science instrument		Science Case Requirments KAON 455 (wavefront error and tip/tilt error requirements)

11.4 Implementation Requirements

The implementation requirements will be documented during the Preliminary Design phase.

11.5 Design Requirements

Some of the design requirements for the non-RTC software, the acquisition camera, the science operations have been documented in KAON 567, 569 and 511. The implementation requirements will be completed during the Preliminary Design phase.

12 Interface Requirements

12.1 Purpose and Objectives

This section is reserved for interface requirements that are not addressed by other portions of the document.

12.2 Design Requirements

12.2.1 Optical Interface

The optical interface requirements for NGAO are described in the Instrument Baseline Requirements (KAON 572) and in the "AO to Instrument Interface Definitions" KAON 555.

12.2.2 Mechanical Interface

Table 36. Mechanical Interface Requirements

#	Mechanical Interface Requirement	Discussion	Based on
36.1	An agreed upon kinematic interface between the NGAO opto-mechanical systems and the telescope structure must be provided	Kinematic interfaces are proposed so that thermal changes do not distort optical benches.	Instrument Baseline Requirements, KAON 572
36.2	NGAO must be compatible with the interferometer dual star module (DSM) or replicate its functionality	The current Keck AO systems interface to the interferometer via an opto-mechanical system known as the DSM.	KAON 428 Requirements for Interferometry with NGAO
36.3	An agreed upon mechanical interface between the NGAO electronics and the telescope must be provided		Instrument Baseline Requirements, KAON 572
36.4	An agreed upon mechanical interface between any NGAO enclosures and the telescope must be provided.		Instrument Baseline Requirements, KAON 572
36.5	An agreed upon mechanical interface between any NGAO glycol cooled systems and the telescope instrument and/or facility glycol systems must be provided		Instrument Baseline Requirements, KAON 572

36.6	An agreed upon mechanical interface between any NGAO CCR-cooled systems must be provided		Instrument Baseline Requirements, KAON 572

12.2.3 Electrical/Electronic Interface

Table 37. Electrical Interface Requirements

#	Electrical Interface Requirement	Discussion	Based on
37.1	An agreed upon electrical interface for power between NGAO systems and the Observatory /telescope must be provided	The Observatory is responsible for providing power to the various NGAO system locations.	Instrument Baseline Requirements, KAON 572
37.2	An agreed upon interface for communication between NGAO systems and the Observatory/telescope must be provided	The Observatory is responsible for the implementation of all cables between NGAO system locations. The Observatory must in particular approve all cabling required to go in the elevation or azimuth wraps.	Instrument Baseline Requirements, KAON 572

12.2.4 Software Interface

Table 38. Software Interface Requirements

#	Software Interface Requirement	Discussion	Based on
38.1	An interface should be provided to offload tip/tilt errors to telescope pointing through the telescope drive and control system (DCS)		Science Case Requirments KAON 455 (wavefront error and tip/tilt error requirements) and NGAO error budget assumptions
38.2	An interface should be provided to offload focus errors to the secondary mirror piston through DCS		Science Case Requirments KAON 455 (wavefront error and tip/tilt error requirements) and NGAO error budget assumptions
38.3	An interface should be provided to offload coma errors to the secondary mirror tilt through DCS		Science Case Requirments KAON 455 (wavefront error and tip/tilt error requirements) and NGAO error budget assumptions
38.4	An interface should be provided to offload segment stacking errors to the active control system (ACS)		Science Case Requirments KAON 455 (wavefront error and tip/tilt error requirements) and NGAO error budget assumptions

13 Reliability Requirements

13.1 Purpose

A process should take place to confirm that the NGAO system will provide a high level of reliability for a 10 year lifetime.

13.2 Scope

Unless otherwise indicated all of the requirements of this section apply to all components of NGAO.

13.3 Performance

System downtime should be minimized by a combination of component reliability, ease of repair, maintenance and appropriate sparing.

Table 39. Reliability Performance Requirements

#	Reliability Performance Requirement	Discussion	Based on
39.1	≤ 5% of observing time lost to problems	This includes any loss to an exposure in progress and the time to start the next exposure after recovering from a fault	Science Case target sample size and survey durations (KAON 455). Analysis of current LGS system efficiency (KAON 463).
39.2	The median time between faults during observing time should be ≥ 4 hrs	Frequent short duration faults are not acceptable since they have a high impact on science productivity	Science Case target sample size and survey durations (KAON 455). Analysis of current LGS system efficiency (KAON 463).

14 Spares Requirements

The spares requirements will be documented during the preliminary design phase.

15 Service and Maintenance Requirements

Refer to Instrument Baseline Requirements, KAON 572.

16 Documentation Requirements

The documentation requirements are defined in the Instrumentation Baseline Requirements Document, KAON 572

17 GLOSSARY

Table 2 defines the acronyms and specialized terms used in this document.

Table 2 Glossary of Terms

Term	Definition
ACS	Active Control System
ANSI	American National Standards Institute
AO	Adaptive Optics
DCS	Drive and Control System
DSM	Dual Star Module
FAA	Federal Aviation Administration
FOV	Field Of View
FWHM	Full Width at Half Maximum.
IFU	Integral Field Unit
KAON	Keck Adaptive Optics Note
KI	Keck Interferometer
LGS	Laser Guide Star
MTBF	Mean Time Between Failures
NGAO	Next Generation Adaptive Optics
NGS	Natural Guide Star
NIR	Near InfraRed
NIRC2	NIR Camera 2
NIRSPEC	NIR SPECtrometer
‘OHANA	Optical Hawaiian Array for Nanoradian Astronomy
OSHA	Occupational Safety and Health Administration
OSIRIS	OH-Suppression InfraRed Integral field Spectrograph
TBC	To Be Completed
TBD	To Be Determined
WMKO	W. M. Keck Observatory