Keck Adaptive Optics Note 770

Keck Next Generation Adaptive Optics Preliminary Design Report

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Table of Acronyms Used in This Report

AO	Adaptive Optics
COO	Caltech Optical Observatories
DD	Detailed Design
FRD	Functional Requirements Document
IFS	Integral Field Spectrograph
KAON	Keck Adaptive Optics Note
LGS	Laser Guide Star
NGAO	Next Generation Adaptive Optics
NGS	Natural Guide Star
OOCD	Observing Operations Concept Document
PD	Preliminary Design
PDM	Preliminary Design Manual
PDR	Preliminary Design Review
PSF	Point Spread Function
SCRD	Science Case Requirements Document
SD	System Design
SDM	System Design Manual
SDR	System Design Report (this document)
SEMP	Systems Engineering Management Plan
SSC	W. M. Keck Observatory Science Steering Committee
UC	University of California
UCO	University of California Observatories
WFE	Wavefront Error
WMKO	W. M. Keck Observatory

1. Introduction

This document provides an overview of the work accomplished during Preliminary Design (PD) phase for the Keck Next Generation Adaptive Optics (NGAO) System. The PD phase is the second design phase for all W. M. Keck Observatory (WMKO) development projects. Successful completion of this phase will allow the project to move into the Detailed Design phase.

2. Recommended Reading and Background Information

The current document provides a high-level overview. We recommend that the Preliminary Design Phase reviewers also read the following key Keck Adaptive Optics Notes (KAON's):

- Science Advisory Team Report
- Preliminary Design Manual (KAON 768)
- Preliminary Design Performance Report (KAON 716)
- Programmatic and Technical Risk Evaluation (KAON 720)
- Systems Engineering Management Plan (KAON 769)

A list of all the NGAO-related KAON's produced through the system design phase can be found in Appendix A or at http://www.oir.caltech.edu/twiki_oir/bin/view/Keck/NGAO/NewKAONs. This web page is located within a TWiki shared website (http://www.oir.caltech.edu/twiki_oir/bin/view/Keck/NGAO/WebHome) that was established early in the System Design (SD) phase to serve the functions of management, information exchange, document sharing and document maintenance. The NGAO TWiki site is actively used by the project team, and has been an important factor in uniting researchers from WMKO, UC Observatories (UCO), and Caltech Optical Observatories (COO).

3. Keck Adaptive Optics Background

Keck I and Keck II are the world's largest optical and infrared telescopes. Because of their 10-m apertures, they offer the highest potential sensitivity and angular resolution currently available on the ground. Keck deployed the first natural guide star *and* laser guide star AO systems on 8-10 meter diameter telescopes. The Keck 2 and Keck 1 NGS AO systems were commissioned in 1999 and 2001, respectively. Keck 2's LGS AO capability became operational in 2004. The wavefront control computers and cameras were successfully upgraded on both systems in 2007. Keck 1's LGS AO capability should be operational in 2011. Four science instruments are used with Keck AO (NIRC2, OSIRIS, NIRSPEC and the Interferometer).

WMKO has a demonstrated track record in scientific leadership in high angular resolution astronomy. The two WMKO AO systems have amassed an impressive series of refereed science publications (259 total including 79 LGS papers as of April 2010). WMKO's dominance to date in LGS AO science is illustrated in Figure 1. The importance of achieving the full potential of the Keck telescopes is recognized in the Observatory's Strategic Plan, which identifies continued leadership in high angular resolution astronomy as a key long-term goal. To maintain leadership WMKO has recognized the need to pursue new AO systems and the science instruments to exploit them. NGAO represents the next major step in maintaining scientific leadership in high angular resolution for the WMKO community.

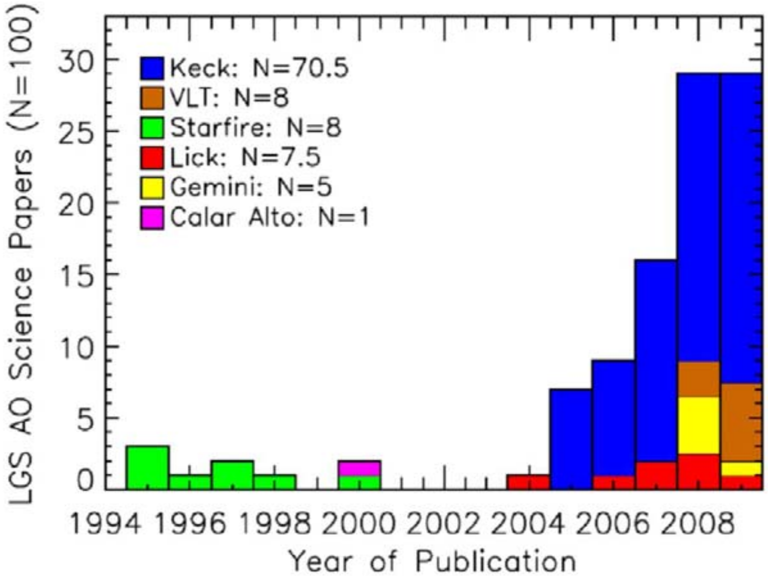


Figure 1: Refereed LGS AO science papers by year
(courtesy of M. Liu)

4. Major Milestones Leading up to the Preliminary Design Review

Table 1 lists the major completed project milestones leading up to the Preliminary Design Review (PDR).

Date	Major Completed Milestones	KAONs
Jun 2006	Proposal presented at WMKO SSC meeting	399 & 400 (Proposal)
Oct 2006	Start of System Design after approval of SEMP	414 (SEMP)
Apr 2008	System Design Review	575 (Report), 588 (Panel Report)
Nov 2008	TMT 1st Light AO Cost Comparison	625 (Report)
Mar 2009	Build-to-Cost Review	648 (Report), 650 (Panel Report)
Apr 2009	Astro2010 NGAO Activity Submission	649 (Submission)
Aug 2009	Laser Launch NSF MRI proposal funded	707 (Proposal)
Dec 2009	Laser Preliminary Design Reviews	706 (Report)

Table 1: Major completed NGAO project milestones

The proposal for NGAO was presented at the June 2006 Keck Science Steering Committee (SSC) meeting. This proposal was approved to proceed through System Design (SD) phase. A Systems Engineering Management Plan (SEMP) was subsequently prepared and approved for the NGAO SD phase which began in October 2006. The System Design Review (SDR) was held in April 2008 and work then began on the Preliminary Design. In response to the SDR panel report the NGAO cost estimate was reviewed in comparison to the TMT 1st light AO system. The result, presented at the November 2008 SSC meeting, largely justified the NGAO cost estimate in comparison to the TMT cost estimate except for a recommendation to hold more contingency for lasers.

In August 2008 the Directors provide the NGAO team with a build-to-cost cap of $60M then-year dollars including the science instruments. This direction required significant rework of the design choices, primarily the removal of deployable near-infrared integral field spectrograph units and their AO design implications. The team successfully completed a build-to-cost review in March 2009.

The NGAO team has had to be aggressive in seeking Federal funding due to the inability to find private funding for NGAO during the PD phase. The PD phase has been completely funded as a result of two TSIP proposals (monthly progress reports were provided to TSIP throughout the PD phase). A white paper to NSF/AURA received $300k in GSMT funds that allowed us to form a U.S. consortium to collaborate with ESO to fund preliminary designs from two laser vendors. The laser PDRs were successfully completed in December 2009. A proposal for a Keck 2 laser center launch telescope that will become part of NGAO was funded by the NSF MRI program in August 2009. Another MRI proposal was submitted in April 2010 for the first NGAO laser and this proposal is supported by collaboration agreements with ESO and TMT. An ATI proposal was submitted in November 2009 for a non-NGAO project, a near-infrared tip-tilt sensor for Keck 1, which will provide risk reduction for NGAO if funded.

In order to ensure that major subsystems were reaching a PDR level and to ensure that the subsystems satisfied their overall requirements the series of mini-reviews shown in Table 2 were held. In each case a set of documentation was distributed to the reviewers and colleagues prior to the review in order to get pre-review feedback. The reviewers were generally members of the NGAO team but in some cases we added external experts (the name of the review chair is in bold). The reviewer reports were documented as KAONs which were used as part of the input to update the designs and documentation.

Mini Design Review	Lead	Date	Reviewers
Software architecture	EJ	8/24/09	**Conrad**, Dekany, Gavel, Tsubota
LGS launch facility optics/mechanics	JC	10/30/09	Kupke, **Martin**, Velur
AO bench optics/mechanics	DG	11/17/09	**Dekany**, Delacroix, Stalcup
LGS WFS	VV	12/7/09	**Gavel**, Lockwood, Stalcup
RTC architecture	DG	12/10/09	**Boyer**, Troung, Johansson
Control electronics architecture	EW	1/26/10	Dekany, Krasuski, **Stalcup**
Motion control architecture	EW	3/11/10	Krasuski, Delacroix, **Gavel**
NGS WFS	VV	4/1/10	Lockwood, **Neyman**, Stalcup
LOWFS	KW	4/2/10	Adkins, **Gavel**, Kupke, Loop
Control system software	KT	4/16/10	**Conrad**, Dekany, Gavel, Cromer
NGAO instrument optical design	SA	4/19/10	Bauman, Gavel, **Larkin**, Lyke
Alignment & calibration	CN,TS	4/20/10	**Gavel**, Lyke
Performance budget	RD,MT	5/13/10	Gavel, Max, **Neyman**

Table 2: Mini design reviews during the NGAO preliminary design

5. NGAO Science and Science Requirements

The science case and science drivers for NGAO have continued to develop through the initial proposal phase, the SD phase and the PD phase.

The NGAO science advisory team has provided a fresh look at the strong science case for NGAO.

The NGAO project science team has continued to develop and refine two classes of science cases: "Key Science Drivers" and "Science Drivers". "Key Science Drivers" are those science cases that place the strongest or most technologically challenging demands on the performance of the NGAO system and its science instruments. These are the science cases that we have used to drive the performance requirements for the AO system and instruments. "Science Drivers" (not "Key") are included to assure that the NGAO system is sufficiently flexible to deal with the broad range of science that users will demand over the lifetime of the NGAO system. Typically, "Science Drivers" do not strongly push the state of the art of the AO system itself; rather they require specific types of coordination between the AO system, the instruments, and the telescope, or they help define parameters such as the full wavelength range or the required field of view of the instruments. The Science Case Requirements Document defines and analyzes 5 "Key Science Drivers" and 8 "Science Drivers." These cases were selected because they represented important astrophysics that would clarify the requirements on the NGAO system from different perspectives.

The "Key Science Drivers" are as follows, in order of distance from Earth:

- Galaxy Assembly and Star Formation History
- Nearby Active Galactic Nuclei
- Precision Astrometry: Measurement of General Relativistic Effects at the Galactic Center
- Imaging and Characterization of Extrasolar Planets around Nearby Stars
- Multiplicity of Minor Planets in our Solar System

The additional "Science Drivers" are as follows:

- Quasar Host Galaxies
- Gravitational Lensing
- Astrometry Science in Sparse Fields
- Resolved Stellar Populations in Crowded Fields
- Debris Disks and Young Stellar Objects
- Size, Shape, and Composition of Minor Planets
- Characteristics of Gas Giant Planets, their Satellites, and Rings
- Characteristics of Ice Giant Planets and their Rings

A first version of the Observing Operations Concept Document (OOCD; KAON 636) was produced during the PD phase. This document defines how the NGAO system will be used to carry out science observations.

6. Preliminary Design

The NGAO design is summarized in the Preliminary Design Manual (PDM; KAON 768). The PDM references a significant number of KAONs where more details can be found. The following sections are only intended to provide a very brief overview of the design.

6.1 Design Overview

Key New Science Capabilities

Near Diffraction-Limited in Near-IR (K-Strehl ~80%)
AO correction at Red Wavelengths (0.65-1.0 μm)
Increased Sky Coverage
Improved Angular Resolution, Sensitivity and Contrast
Improved Photometric and Astrometric Accuracy
Imaging and Integral Field Spectroscopy

The NGAO technical approach is shown schematically in Figure 2. The requirement of high Strehl over a narrow field is achieved using laser tomography (to correct for focal anisoplanatism; i.e., the "cone" effect) with an on-axis LGS and three uniformly spaced LGS on a 10" radius (as illustrated in Figure 3), a narrow field relay with a deformable mirror having 64 actuators across the telescope pupil and careful control of all wavefront errors especially tilt errors. High sky coverage is achieved by sharpening the three stars used to provide tip-tilt information with their own LGS AO systems including a movable LGS (shown in Figure 3) and a MEMS DM with 30 actuators across the telescope pupil (i.e., the low order wavefront sensors shown in Figure 2). High sensitivity at thermal wavelengths requires low emissivity which is achieved by cooling the science path optics (e.g., the cooled enclosure in Figure 2).

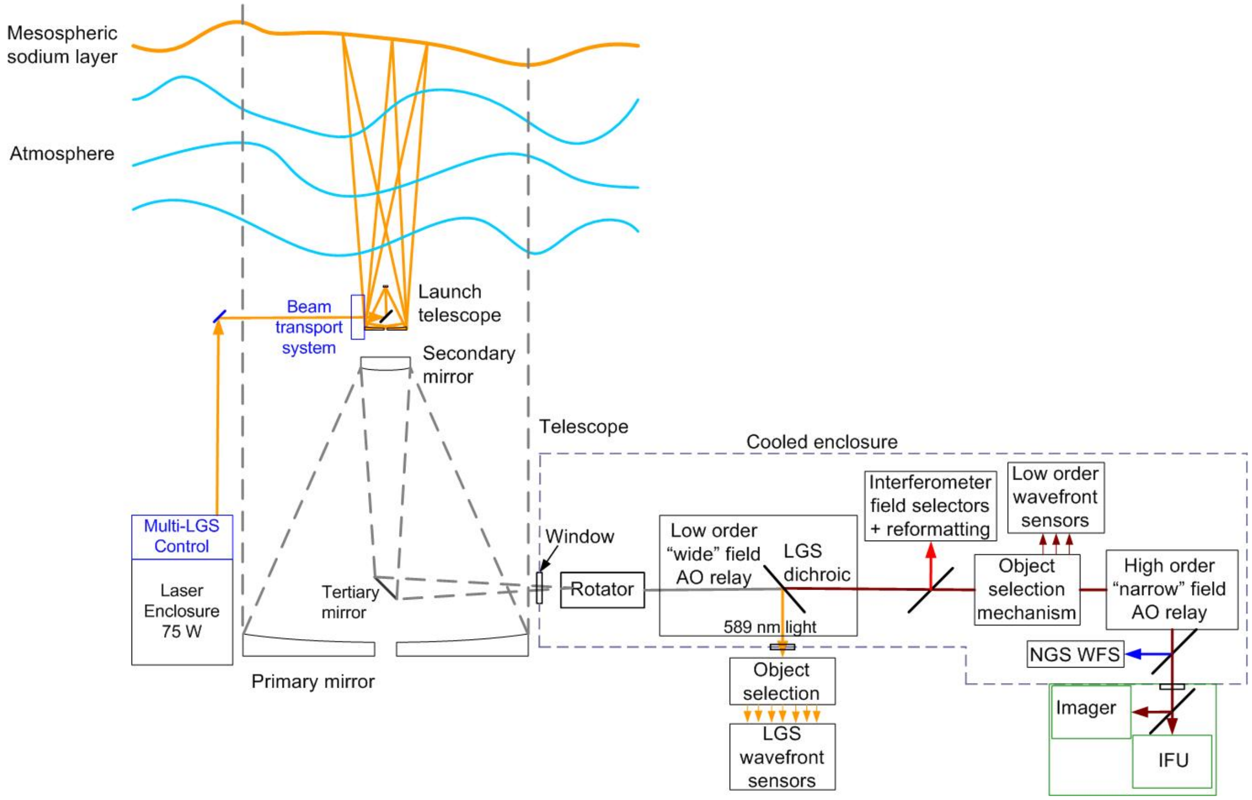


Figure 2: Schematic of the NGAO concept

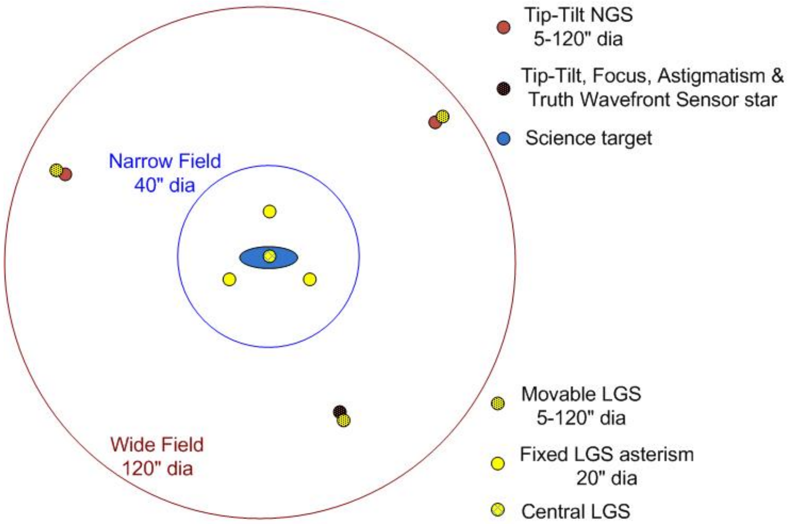


Figure 3: Schematic of the NGAO LGS asterism

The following is a brief summary of the key architectural features of NGAO and why they were selected (i.e., flowed down from the science requirements):

- Laser tomography to measure wavefronts and overcome the cone effect over the science field. This is supported by the fixed “3+1” LGS asterism and LGS WFS.
- LGS projection from behind the telescope’s secondary mirror to minimize perspective elongation.
- Location of the AO system on the Keck II telescope left Nasmyth platform to have sufficient space for the AO system and science instruments in a gravity constant environment.
- A cooled AO system to meet the near-infrared background requirements.
- A K-mirror rotator at the input to the AO system to keep either the field or pupil fixed. The AO system would need to be cooled even without a rotator and this approach allows the most stability for the AO system and instruments.
- A wide-field (120" diameter) relay to feed light to the LGS wavefront sensors and the three LOWFS.
- A conventional (5 mm pitch) DM was chosen to transmit a wide field in the wide-field relay.
- A low-order (20 actuators across the pupil) DM (LODM) was chosen for the wide-field relay to limit the size of the relay, to permit closed loop AO correction on the LGS wavefront sensors and to keep the LGS wavefront sensors in their linear range, reducing the requirement on downstream open loop correction.
- Open loop AO-corrected near-IR tip-tilt sensors to maximize sky coverage. This is supported by three patrolling laser beacons and LGS WFS.
- Open loop AO-correction to the narrow field science instrument(s) in LGS mode.
- MEMS DM’s for the AO-correction. These are very compact devices and have been lab demonstrated to accurately go where they are commanded. Small, modest-cost 32x32 element MEMS DM’s provide the required correction for the tip-tilt sensors. A 64x64 element MEMS, similar to that developed for the Gemini Planet Imager (GPI), is needed to provide the required AO correction to the narrow field science instrument(s).

- A high order, narrow-field (40"x60" diameter) AO relay to feed light to the narrow field science instrument(s) and NGS wavefront sensor. The science instruments fed by this relay only require a narrow-field (32"x32") and the narrow field facilitates the use of a single MEMS DM for all narrow-field instruments.

6.2 AO Opto-mechanics

Optical (Zemax) and mechanical (Solid Works) models of the AO bench have been produced. Figure 4 and Figure 5 provide views of the AO bench and instruments from the mechanical model.

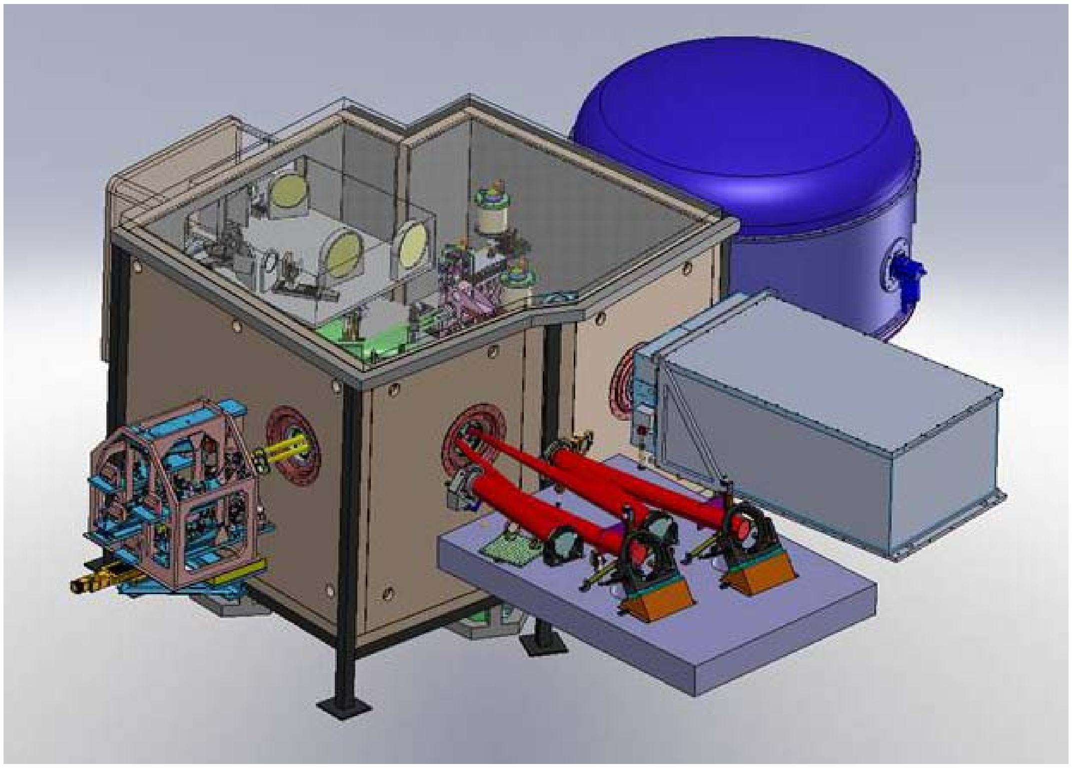


Figure 4: Perspective view of the NGAO system and science instruments at Nasmyth

The AO bench is shown with the cold enclosure ceiling removed. This enclosure is surrounded by four instruments. From left to right, the LGS WFS assembly, the interferometer dual star module, a future science instrument and DAVINCI.

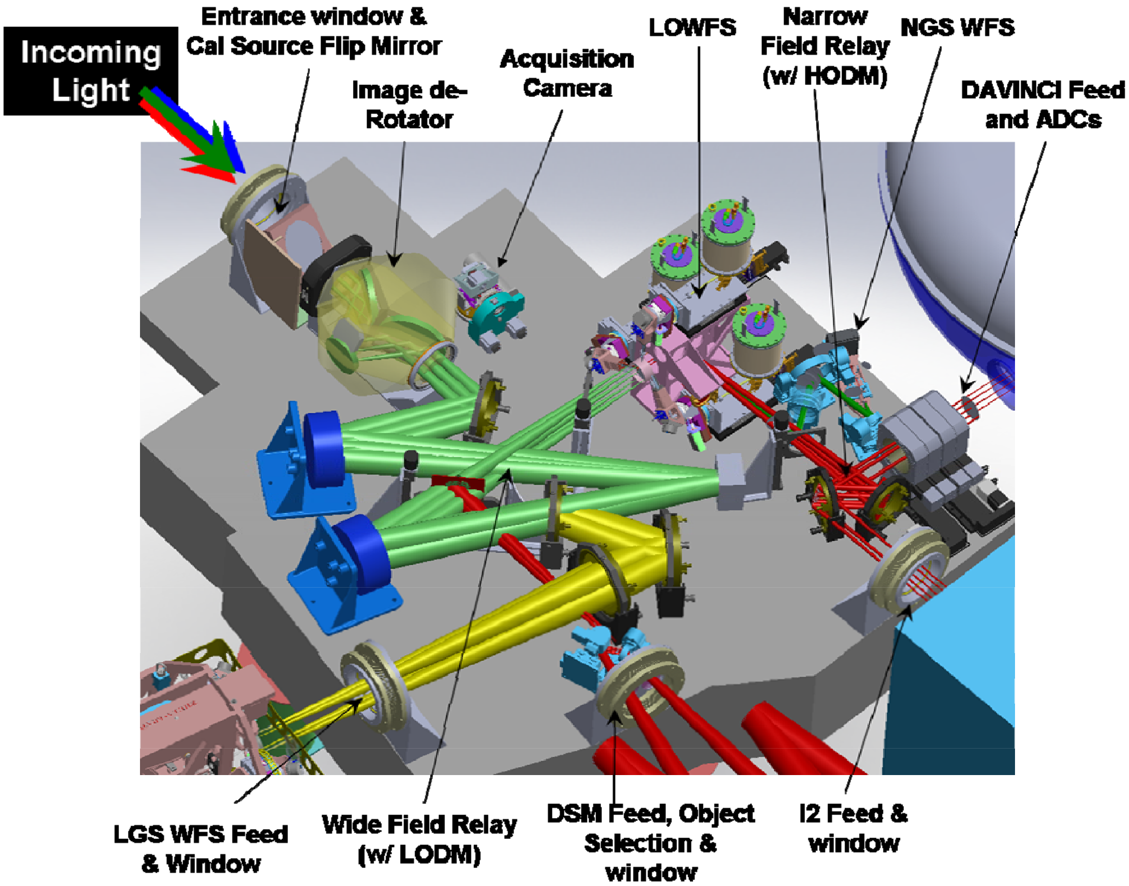


Figure 5: Perspective view of the AO bench with major components labeled

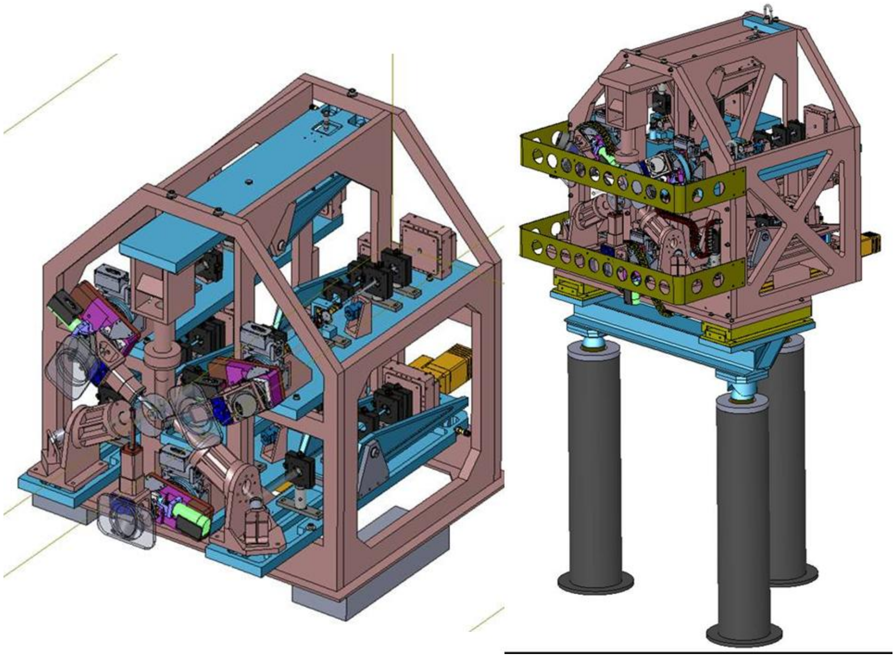


Figure 6: LGS wavefront sensor assembly (left) and mounted on Nasmyth platform (right)

Figure 6, Figure 7 and Figure 8 provide views of the LGS, NGS and low order wavefront sensor assemblies, respectively, from the SolidWorks model. Both the patrolling LGS wavefront sensors and the low order wavefront sensors use the same object selection mechanisms based on two rotational axes to insert a pickoff mirror anywhere in the 120" diameter field of view. The NGS wavefront sensor instead uses a pair of steering mirrors to keep the pupil fixed while selecting a star anywhere in a 40"x60" field.

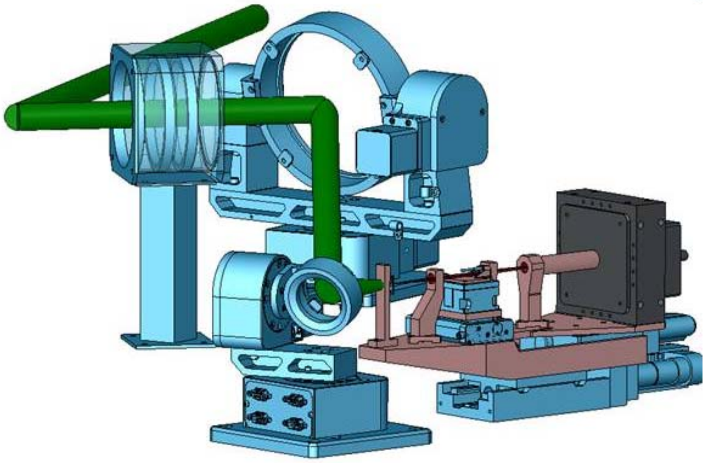


Figure 7: NGS wavefront sensor assembly

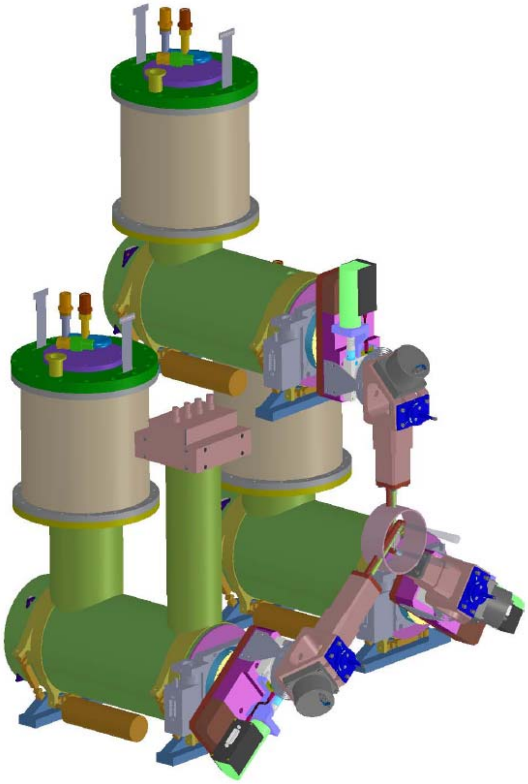


Figure 8: Low order wavefront sensor assembly

Figure 9 provides a partially transparent view through the Nasmyth platform enclosure that will house the AO bench, the science instruments and the electronics.

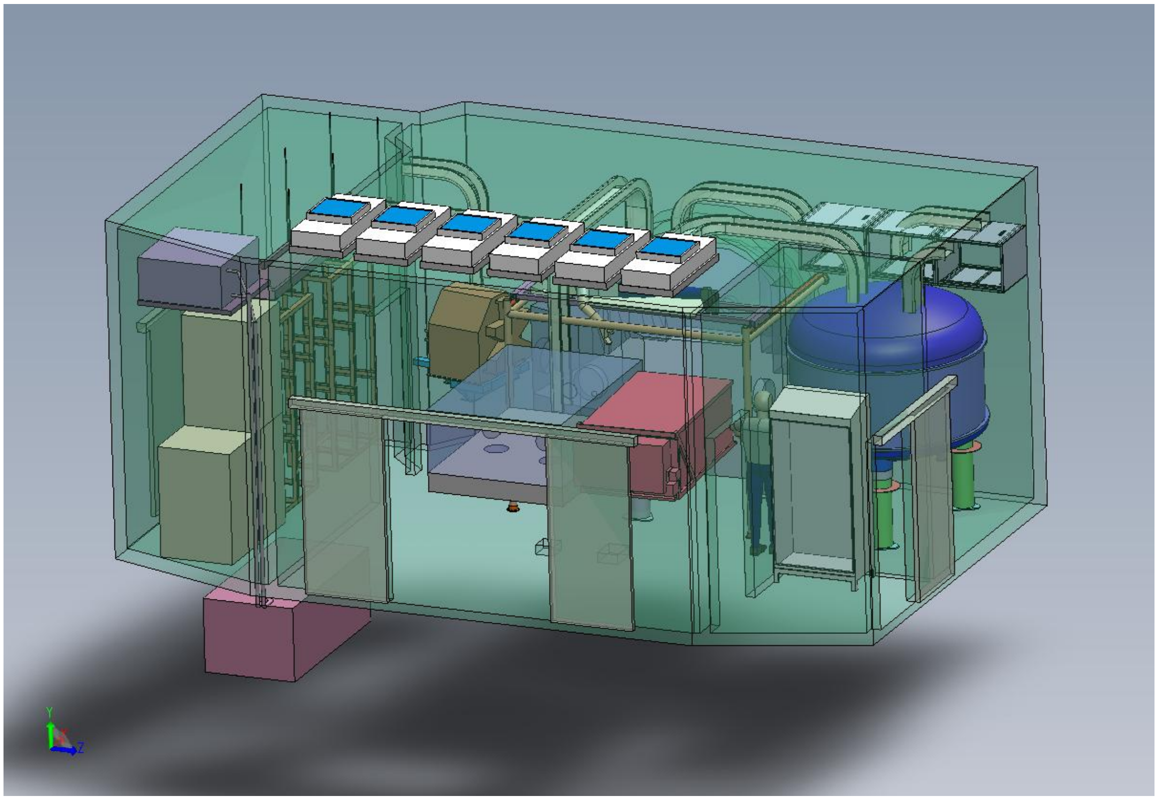


Figure 9: Transparent view of the Nasmyth platform enclosure

6.3 DAVINCI Science Instrument

DAVINCI, the Diffraction limited Adaptive optics Visible and Infrared iNtegral field spectrograph and Coronagraphic Imager is the first light science instrument for the Keck Next Generation Adaptive Optics system (NGAO) at the W. M. Keck Observatory (WMKO). DAVINCI is a fully cryogenic instrument providing imaging and integral field spectroscopy from 0.7 µm to 2.4 µm.

The imaging mode uses a fixed pixel scale of 7 mas and provides diffraction limited imaging with ≥2 pixel sampling in the I, Z, and Y bands, 3 pixel sampling in the J band, 4 pixel sampling in the H band, and >5 pixel sampling in the K band. The FOV is 28.7" x 28.7" using a Teledyne Hawaii-4RG detector with 4096 x 4096 pixels and a 2.5 µm cut-off wavelength. The imager emphasizes low distortion (~ 1%) and uses an all reflective optical design for the powered optics with the exception of a refractive field flattener and an additional lens to provide a pupil imaging mode. The imaging mode provides a selectable coronagraph mask and a large selection of photometric, continuum, and narrow band filters. A tracking cold pupil mask is provided for H and K band observations, and an additional selection of pupil masks is provided for the shorter wavelength bands and for the coronagraph mode. Predicted 5σ limiting magnitudes for the imaging mode are 26 in the H and K bands, 27 in J band, 28 in Y band, and ≥27.5 in the Z and I bands.

The central portion (~6") of the DAVINCI FOV can be sent to the IFS, allowing simultaneous spectroscopy and imaging. The IFS has a sampling format of 112 x 60 samples and is optimized for narrow band observations (~5% bandpass). The IFS uses a lenslet image slicer combined with novel reformatting optics to provide 6 virtual slits (680 pixels per spectra) on a Hawaii-4RG detector with a 2.5 µm cut-off wavelength. Three spatial sampling scales are provided, 10, 35, and 50 mas resulting in FOVs of 1.12" x 0.6", 3.92" x 2.1", and 5.6" x 3". Fixed gratings are provided for each major waveband, operating in the first order near the peak of the blaze function with R ~4,000. The IFS uses a refractive scale changer and all reflective optics for the collimator and camera. Predicted 5σ limiting magnitudes for the IFS mode in representative narrow bands with the 10 mas sampling scale are 24.8 in K band, 25.25 in H band, 26.63 in J band, 27.2 in Y band, 27.53 in Z band, and 26.85 in I band.

The DAVINCI instrument uses a single dewar based on heritage from the MOSFIRE instrument, and also takes advantage of significant design heritage from the mechanisms of OSIRIS and MOSFIRE. The electronics and software will be largely based on heritage from the MOSFIRE instrument.

A detailed discussion of DAVINCI is provided in the DAVINCI Preliminary Design Report (KAON 761). This report and other related KAONs may be found at this URL:

http://www.oir.caltech.edu/twiki_oir/bin/view/Keck/NGAO/DAVINCIPDRDocuments

6.4 Laser Guide Star Facility

The Laser Guide Star Facility (LGSF) is responsible for generating the asterism of seven laser beams shown in Figure 3. The LGSF is divided into four subsystems: 589 nm laser systems (3), a laser enclosure to house the lasers, a Laser Launch Facility (LLF), and a Safety System. A laser manufacturer, TOPTICA/MPBC has been identified through a down selection process that included committee members from ESO, TMT, and WMKO. During this phase, the manufacturer produced a lab demonstrator unit that meets the required laser performance levels and completed a preliminary design. The manufacturer will continue into the final design phase which includes a functioning prototype to meet the needs of all three institutions.

The 20 watt CW lasers can be partitioned into two areas, the laser heads producing the 589 nm generation, and the control electronics / pump diodes. The laser heads will be mounted within a laser enclosure located on the Keck II telescope's elevation ring. The electronics and pump diodes will be located in the temperature controlled AO electronics vault on the left Nasmyth platform. Fibers will be used to transfer the beams from the pump diodes to the laser heads. The laser enclosure currently supports the existing Keck II dye laser table. This table will be removed and replaced with the three laser heads as shown in Figure 10.

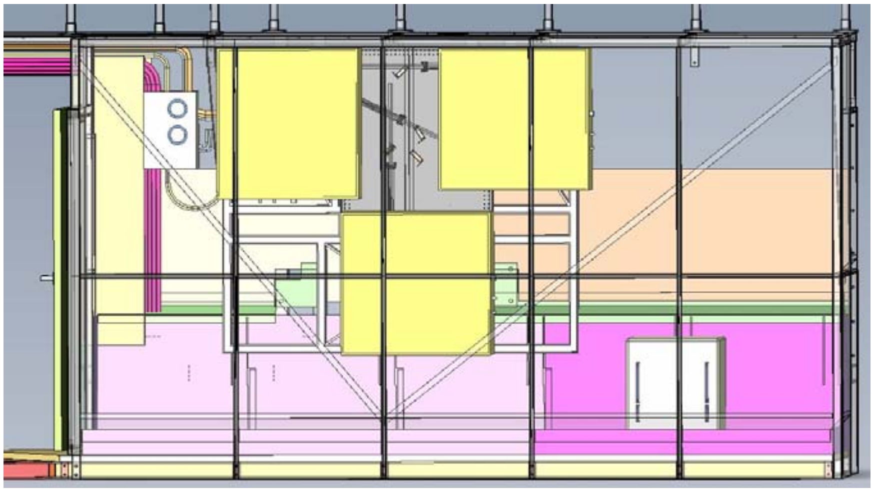


Figure 10: Laser enclosure layout to support three new laser systems

The LLF receives the three laser beams and generates the seven beams exiting the Keck II telescope. The first subsystem in the LLF is the Switchyard. The Switchyard formats and steers the three laser beams into Beam Transport Optics on the telescope and the Beam Generation System (BGS) located behind the prime focus location. The Switchyard compensates for telescope flexure as well as possible vibration in the telescope structure. The BGS receives the three laser beams and generates asterism through a series of beam splitters and mirrors (Figure 11). The BGS positions both the fixed and patrolling lasers and maintains their position via feedback from the LGS wavefront sensors. Included in the BGS and Switchyard are diagnostics to ensure optimum laser performance and asterism positions. The final element in the LLF is an f/1.4 Launch Telescope (LT) that sends the seven beams into the Mesosphere. A manufacturer has been contracted to provide this telescope, which is similar to the Keck I LGS AO System LT.

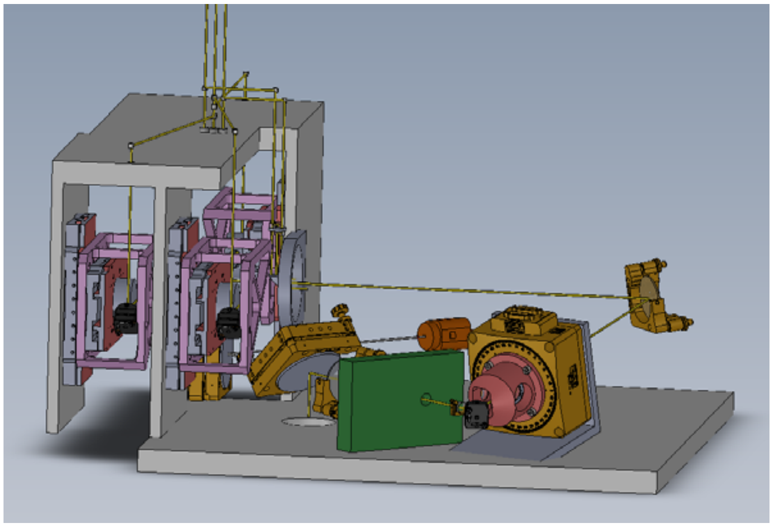


Figure 11: Beam Generation System

The final subsystem in the LGSF is the Safety System. This subsystem ensures the safety of personnel and equipment through a series of interlocks. The safety system uses a programmable logic controller which senses the laser environment, including aircraft spotters to terminate laser output if necessary. The safety system also works in conjunction with a Mauna Kea Laser Traffic Control System to minimize contamination of astronomical observations, the Laser Clearinghouse for satellite protection, and an Aircraft Safety System to prevent laser impact to aircrafts in the Mauna Kea airspace.

6.5 AO Controls

NGAO is a complex system that will require a controls architecture capable of coordinating and managing the execution of dozens of devices. Each device must be configured and operated in a coordinated and synchronized fashion to ensure the optimal performance and safety of the system.

A key to defining this device coordination is through the development of control sequences: a step-by-step breakdown of events and operations that a control system must perform to accomplish some task. In many cases a step can itself be divided into sub-steps allowing the developer to design a hierarchical command sequence. These hierarchies are critical for discovering the collaboration and communication between components within the system. Steps within a sequence can be executed serially, parallel or a combination of the two. A sequence or an operation within a sequence can be defined synchronously or asynchronously, where the execution of the sequence may depend on a specific system event.

All composites will reflect the overall state of its subcomponents: effectively the health and state of the entire laser system. The higher level composites will monitor these states to ensure its continued safe operation, and to respond to any errors that may occur. At the highest level the Multi-System Command Sequencer is the interface between the science operations tools and the NGAO facility as well as the science instruments and telescope. The NGAO system is divided into two main sequences: The AO and laser control sequences.

6.5.1 AO Control Sequence and Hardware Architecture

The AO control sequence is implemented by the *AOFacilityComposite*, which is the main interface between the various AO controls functions and the rest of the NGAO system. The composite executes these sequences by directing commands to each of the dependent subsystems depicted in Figure 12.

The planned layout of the AO Bench, AO room and Electronics vault is shown in Figure 13 below. Although a single block is shown for the servo controllers, this may not reflect the final hardware implementation with all DOF on a single controller. The use of smart motors will also put some control on the AO bench.

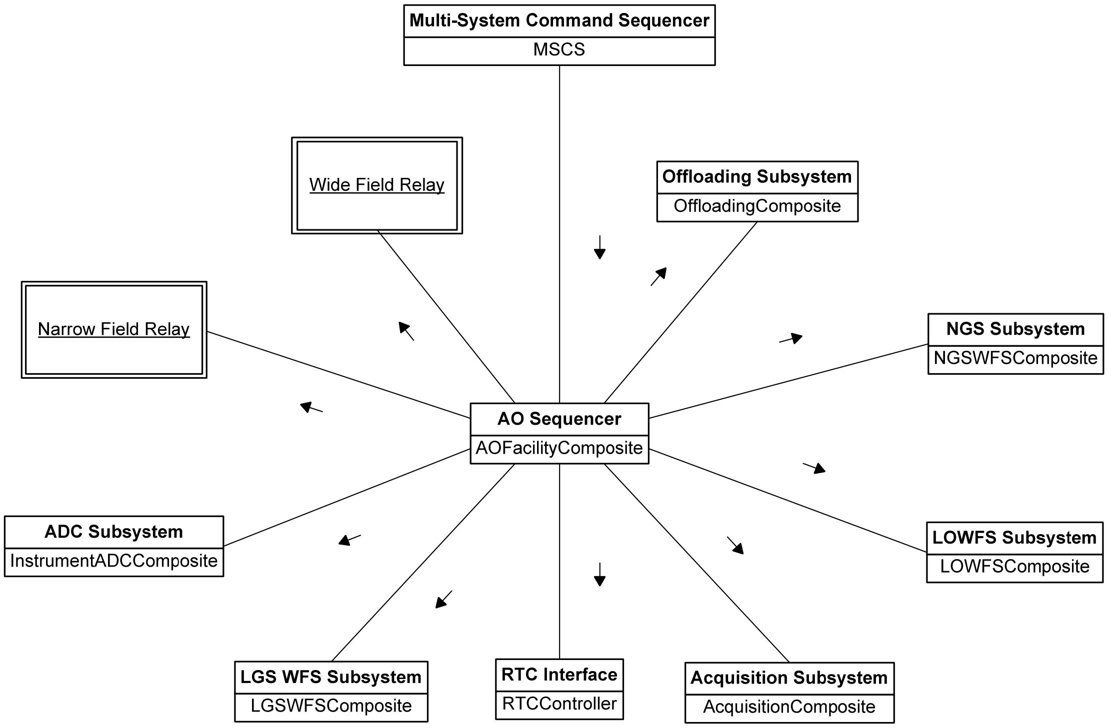


Figure 12: AO Control Sequencer Diagram

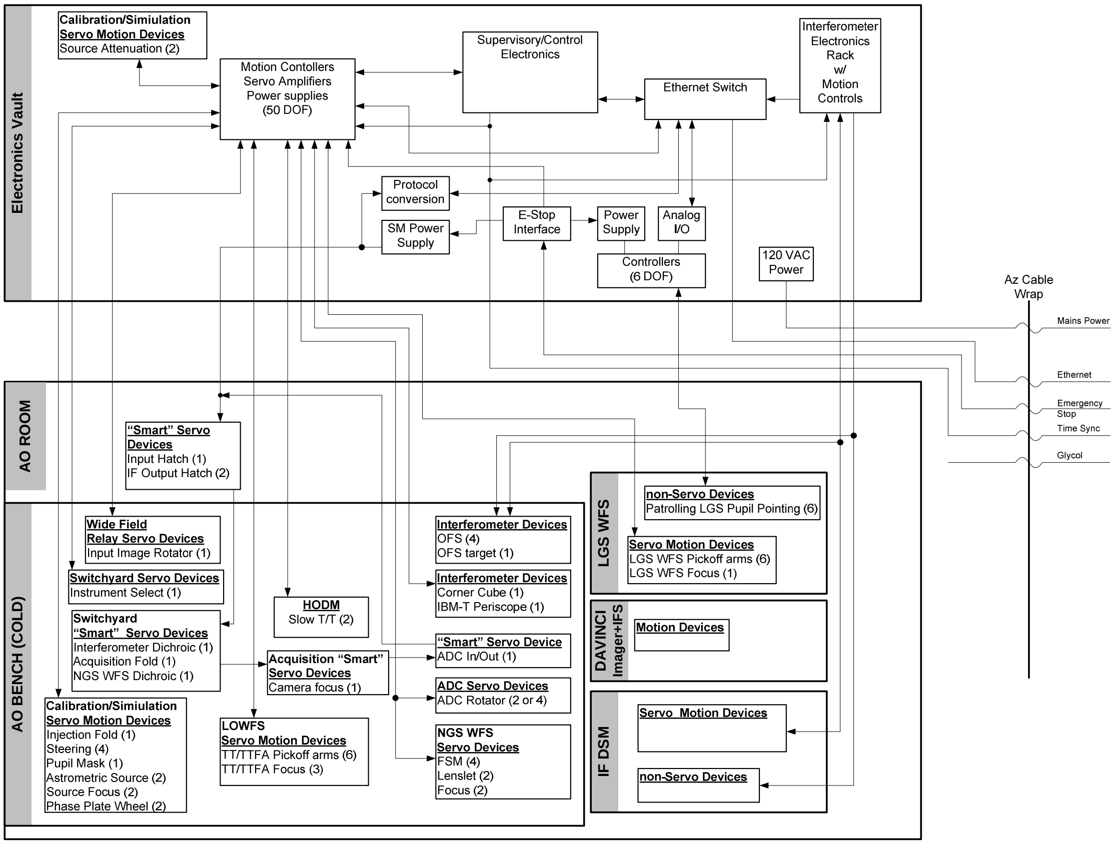


Figure 13: AO Motion Control

6.5.2 Laser Control Sequence and Hardware Architecture

The Laser Control Sequencer is implemented by the *LaserFacilityComposite*, and is responsible for managing and configuring the entire laser guide star facility, and executing the various sequences. The composite sits above all of the other laser system components, and coordinates their state and task execution during observing. The Laser Sequencer is under the direct control of the MSCS, and is the primary interface to the laser system.

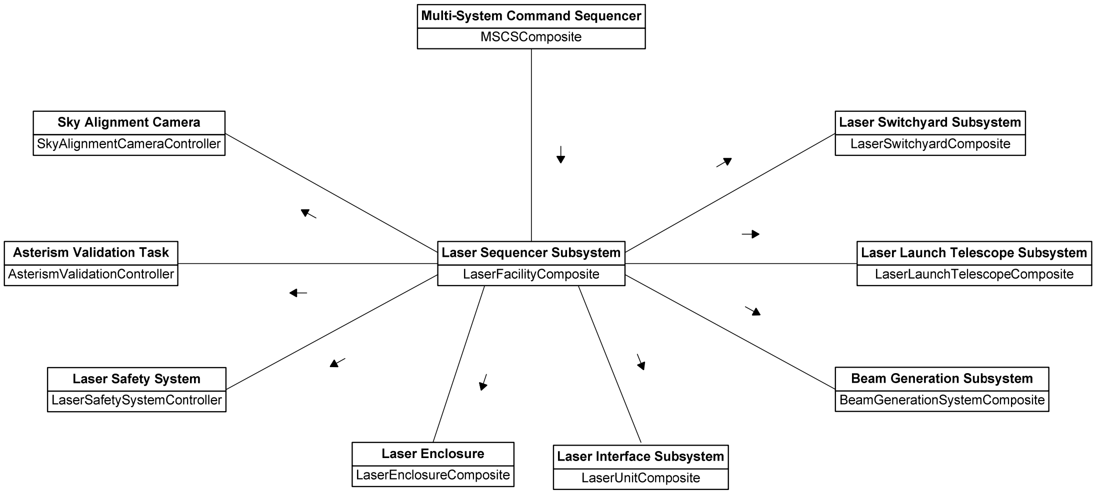


Figure 14: Laser Control Sequencer Diagram

The Laser Sequencer exposes a simple set of high level actions to the MSCS. These actions provide the Command Sequencer with the ability to initialize and configure the laser facility; acquire LGS targets; and shutdown the system. The composite in-turn takes the action data and distributes it among the relevant subcomponents; invoking their corresponding initialization, configuration, acquisition, and shutdown actions.

Several possibilities exist for the Laser devices on the secondary and in the Laser Service Enclosure, each with its set of benefits and challenges. The baseline design will place motion controllers in the LSE as outlined in Figure 15.

Locating the controllers in the Laser Service Enclosure (LSE) helps by shortening the cable run and does not require significant use of the elevation cable wrap. This approach also simplifies integration of the laser switchyard devices. Cabling between the LSE and secondary should be designed to include two or more devices per cable, where possible. This architecture is quite feasible. The present LSE design will accommodate the volume of the equipment and glycol cooling is already required.

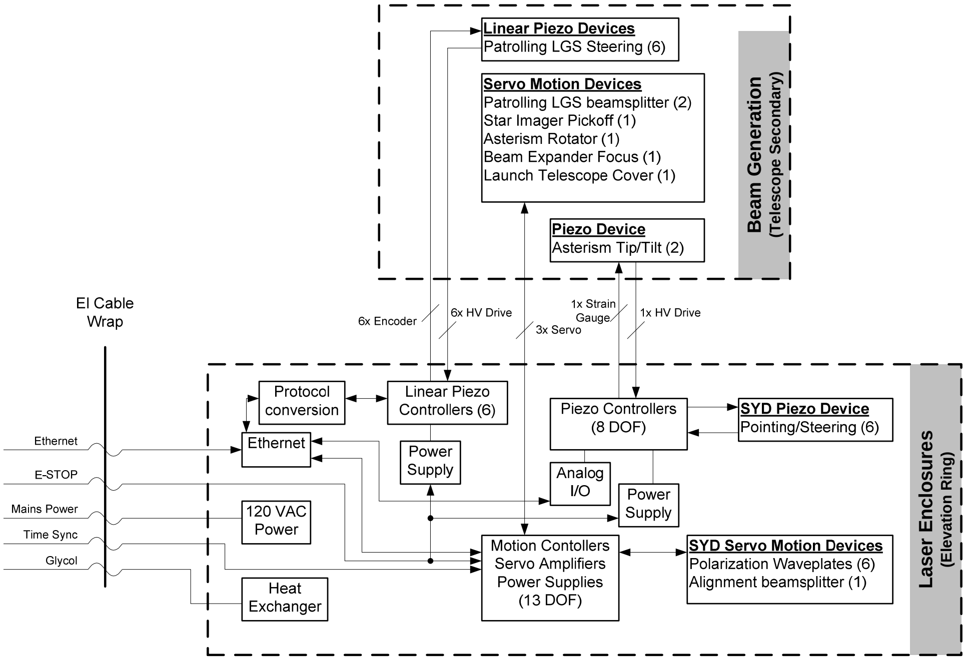


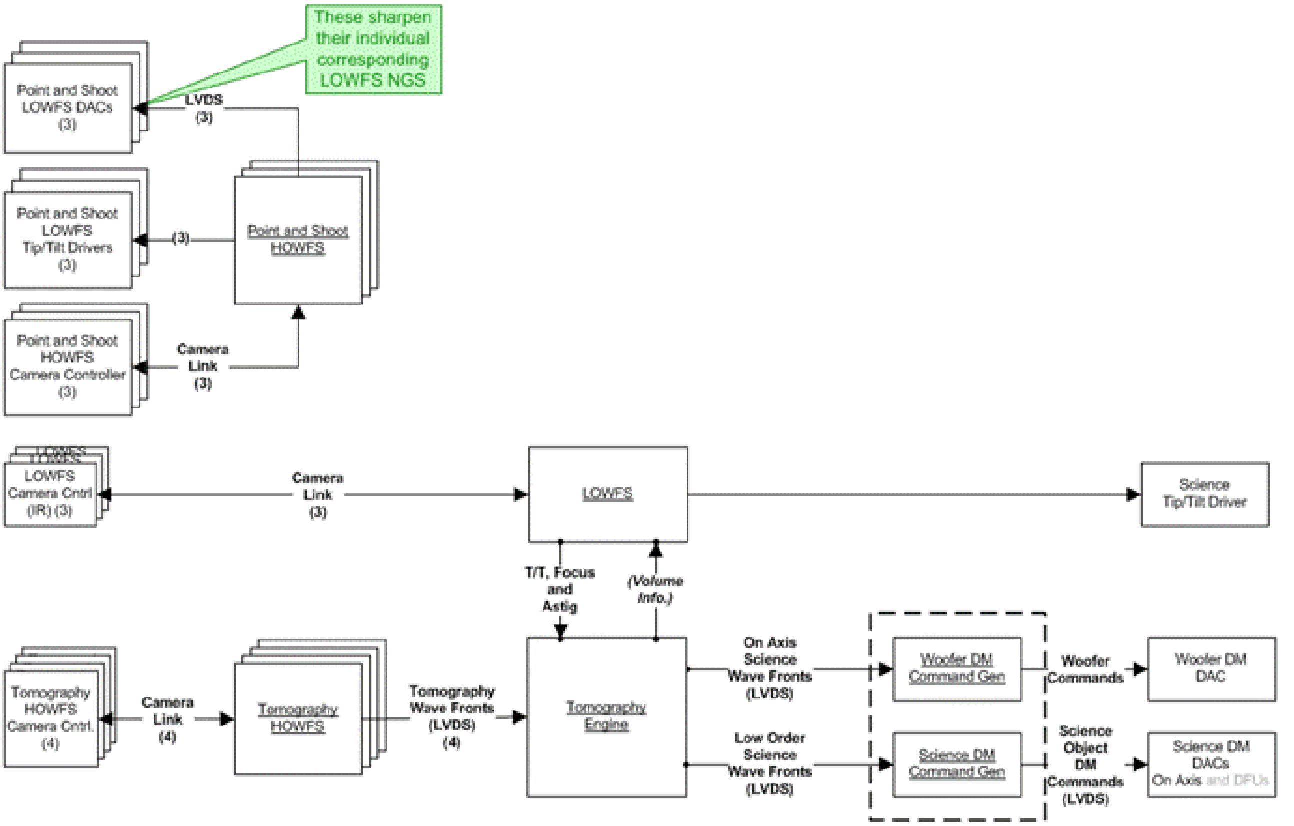
Figure 15: BGS Motion Control

6.6 Real-time Control

The Real Time Controller (RTC) is a specialized computer system designed to perform all of the wavefront sensing, tomography calculations, and deformable mirror control processing at rates that keep up with atmospheric turbulence induced optical aberrations. The RTC data flow and computer architectures have been designed to achieve the tomography precision, noise suppression, and bandwidth requirements implied by the science-case driven wavefront error budgets.

An equally important consideration in the RTC design is the need to keep the cost and complexity manageable. Simply scaling earlier implementations of single conjugate AO RTC reconstructors using traditional central processing units (CPUs) is infeasible because of the multiplying effect of multi-guidestars and multiple deformable mirrors on computer speed requirements. To address this issue, we have taken advantage of the parallelizability of wavefront reconstruction and tomography algorithms and mapped them on to a massively-parallel processing (MPP) compute architecture. This architecture scales in size and complexity much more favorably than doing the same calculations on CPUs, and can be readily implemented with commercial off the shelf technology building blocks called field programmable gate arrays (FPGAs).

As shown in the Figure 16 schematic, large chunks of compute tasks are associated with either wavefront sensors or DM’s and thus can be parallelized across them. Furthermore, algorithms running within the sensor and actuator subunits, as well as within the tomography engine, are highly parallelizable when implemented in the Fourier domain, and thus will each map onto an MPP architecture.



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15 October, 2009

Figure 16: Multi-guide star tomography data flow and parallel processing

6.7 Performance Overview

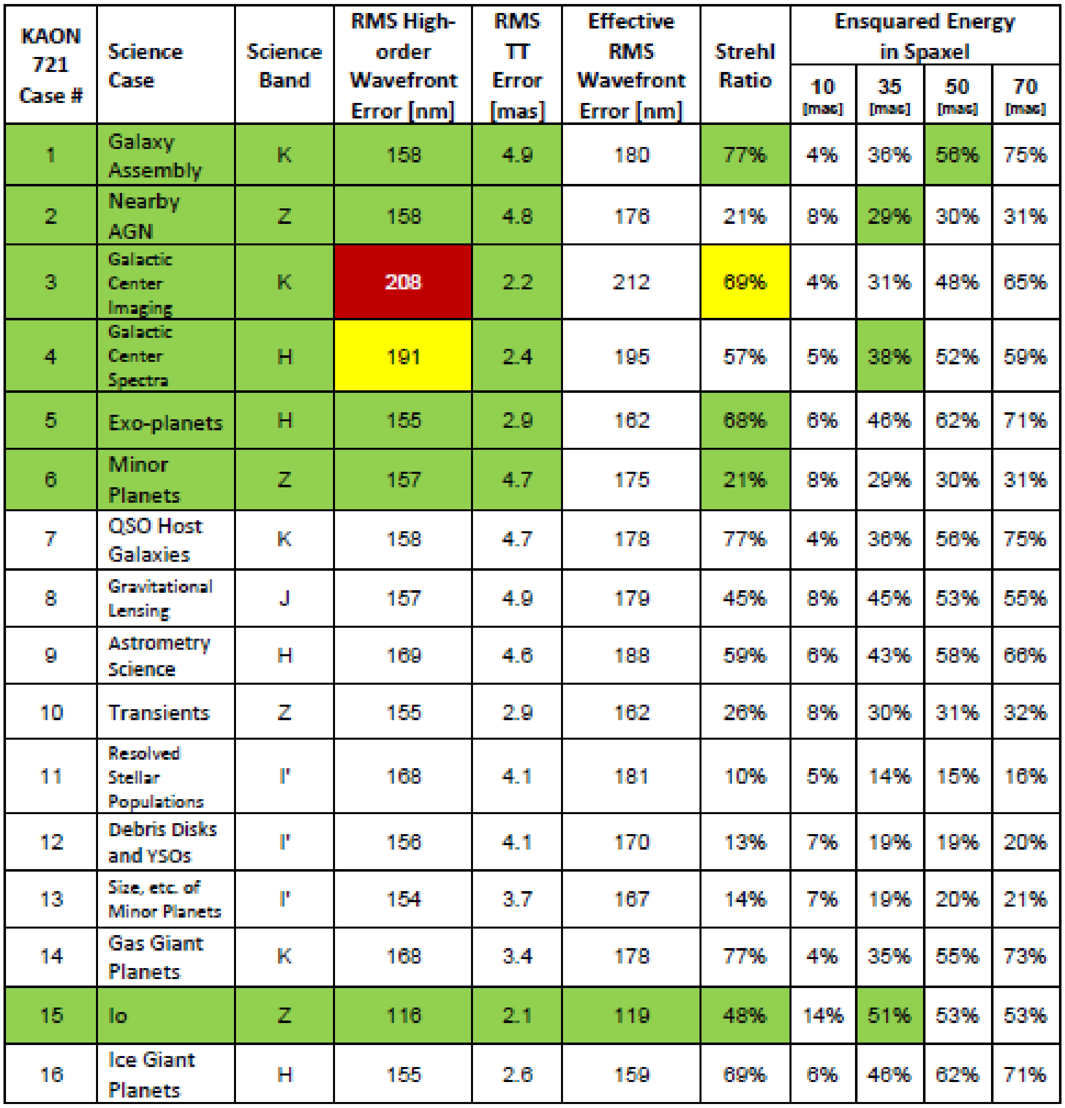
NGAO performance predictions, in terms of wavefront error and ensquared energy, for each of the key and non-key NGAO science cases are reported in KAON 716. Other performance budgets are discussed in section 4 of the PDM (KAON 768).

The performance summary from KAON 716 is summarized here in Table 3. KAON 716 also provides a description of:

- The tools, primarily a MS Excel spreadsheet (maintained as KAON 721), and input assumptions used to generate these predictions
- How the spreadsheet tool has been anchored against both detailed wave-optics simulations and as-built measurements of existing AO systems,
- The results of several studies describing the sensitivity of NGAO performance to varying conditions, demonstrating the robustness of NGAO performance.

Table 3: Predicted performance for all NGAO science cases

Cases 1 to 6 are the key science cases. The colors indicate whether the requirement has been met (green), almost met (yellow) or not met (red). Uncolored cells have no explicit performance requirement. The case 3 high order wavefront error requirement is 190 nm rms.



KAON 721 Case #	Science Case	Science Band	RMS High-order Wavefront Error [nm]	RMS TT Error [mas]	Effective RMS Wavefront Error [nm]	Strehl Ratio	Ensquared Energy in Spaxel			
							10 [mas]	35 [mas]	50 [mas]	70 [mas]
1	Galaxy Assembly	K	158	4.9	180	77%	4%	36%	56%	75%
2	Nearby AGN	Z	158	4.8	176	21%	8%	29%	30%	31%
3	Galactic Center Imaging	K	208	2.2	212	69%	4%	31%	48%	65%
4	Galactic Center Spectra	H	191	2.4	195	57%	5%	38%	52%	59%
5	Exo-planets	H	155	2.9	162	68%	6%	46%	62%	71%
6	Minor Planets	Z	157	4.7	175	21%	8%	29%	30%	31%
7	QSO Host Galaxies	K	158	4.7	178	77%	4%	36%	56%	75%
8	Gravitational Lensing	J	157	4.9	179	45%	8%	45%	53%	55%
9	Astrometry Science	H	169	4.6	188	59%	6%	43%	58%	66%
10	Transients	Z	155	2.9	162	26%	8%	30%	31%	32%
11	Resolved Stellar Populations	I'	168	4.1	181	10%	5%	14%	15%	16%
12	Debris Disks and YSOs	I'	156	4.1	170	13%	7%	19%	19%	20%
13	Size, etc. of Minor Planets	I'	154	3.7	167	14%	7%	19%	20%	21%
14	Gas Giant Planets	K	168	3.4	178	77%	4%	35%	55%	73%
15	Io	Z	116	2.1	119	48%	14%	51%	53%	53%
16	Ice Giant Planets	H	155	2.6	159	69%	6%	46%	62%	71%

A more conceptual view of how NGAO is expected to improve performance with respect to the existing Keck AO systems is shown in Figure 17.

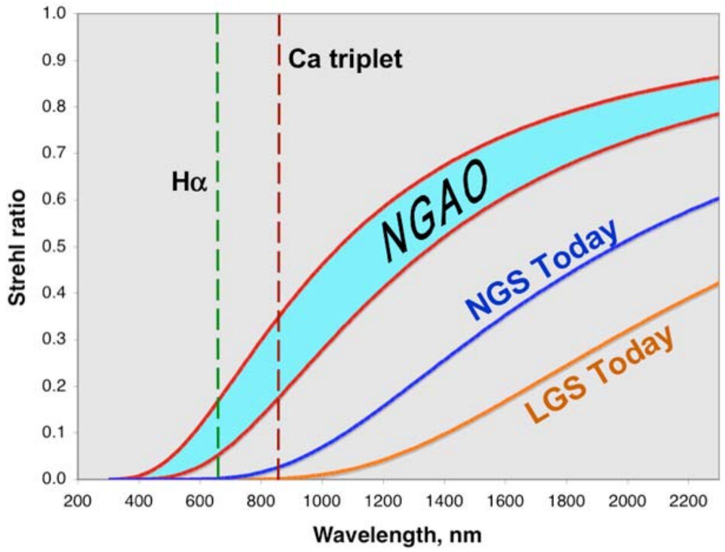


Figure 17: NGAO versus current Keck II NGS and LGS AO performance
(for the case when a bright natural guide star is available for NGS AO or for tip-tilt correction with LGS AO).

6.8 Requirements, Interfaces and Configuration Control

The requirements are managed within the Contour database purchased from Jama software. This database is under configuration control. The requirements in the database include the science case requirements from the SCRD, the system requirements that include the flowed down science case requirements and additional observatory requirements on the overall NGAO system, the flowed down functional requirements on NGAO subsystems organized by the NGAO product breakdown structure (PBS), and a set of WMKO instrument baseline requirements applicable to all subsystems.

The requirements database and interface control approach (KAON 741) also reference a number of additional documents that are under configuration control:

- The system configuration spreadsheet (KAON 550) which defines the NGAO observing configurations.
- The observing operations concept document (KAON 636) that defines how observations are performed with the NGAO system
- The Master device list (KAON 682) that documents all of the parameters of the devices requiring control.
- Keck drawing 1410-CM0010 that defines the mapping of the Keck primary mirror to each deformable mirror.
- The AO control loops document (KAON 705) that provides a high-level definition of all of the required control loops external to the real-time control systems.
- The power budget (KAON 709) that compiles the power dissipation by device.
- The wavefront error budgets as documented in KAON 716.
- The wavefront error budget tool (KAON 721) used to produce Strehl and ensquared energy predictions.
- The high-contrast error budget tool (KAON 722).

- The performance flowdown requirements spreadsheet (KAON 723) that distributes the error terms between subsystems and components.
- The SolidWorks model (KAON 726) that documents the mechanical design.
- The Zemax optical design (KAON 727) that documents the optical design.

Our adopted approach to configuration control for the requirements and documents is defined in KAON 638.

Requirements compliance matrices were prepared for each of the subsystems toward the end of the preliminary design. The result of the system requirements evaluation for each of the subsystems is shown in Table 4. The results of the evaluation of the overall AO functional requirements are listed in Table 5. The results of the evaluation of the subsystem specific functional requirements are listed in Table 6 by subsystem. None of the no, partial or goal non-compliance items are considered to represent significant issues.

Table 4: System requirements compliance summary

	N/A	DD	Yes	No	Partial	Goal
Compliance of 11 subsystems for all 102 System Requirements	568	378	170	1	2	3
% excluding N/A		68%	31%	0.2%	0.4%	0.5%

N/A = Not Applicable. DD = Compliance will be determined during Detailed Design. Yes = compliant. No = Not compliant. Partial = Partially compliant. Goal = Compliant as a goal.

Table 5: Overall AO requirements compliance summary

	N/A	DD	Yes	No	Partial	Goal
Compliance of 8 major AO subsystems for all 30 Overall AO functional Requirements	102	80	56	0	1	1

Table 6: Subsystem Specific functional requirements compliance summary

Subsystem Specific Functional Requirements	DD	Yes	No	Partial	Goal
AO Enclosure	12	18	0	0	0
AO Bench	21	47	0	2	0
LGS WFS	11	24	1	0	0
NGS WFS	10	12	1	0	0
LOWFS	5	11	0	0	0
Acquisition Camera	5	11	0	7	0
Alignment & Calibration	2	39	0	0	0
LGS Facility	26	103	1	1	0
Controls	8	48	1	0	0
Science Operations Tools	8	38	0	3	0

7. Risk Assessment

The results of a programmatic and technical risk evaluation and the approaches to mitigating these risks are documented in KAON 720. The changes to the risk matrices between SDR and PDR are presented and discussed. Some funding related programmatic risks identified at the SDR have grown due to the poor economic environment for private fund raising. On the other hand we have made good progress on reducing some of the key technical risks (see the following text block) through simplifications to the NGAO design resulting from the build-to-cost changes and through collaborations.

Key Technology Drivers

Sodium Wavelength Lasers
Laser Guide Star Tomography
Low Order Wavefront Sensing with LGS AO-Corrected Guide Stars
Open Loop AO Correction with MEMS Deformable Mirrors
Improved Science Measurement Accuracy and PSF Knowledge

In order to achieve the required science performance NGAO must offer improved performance in a number of key technology areas that have not yet been demonstrated. The NGAO design process has therefore been one of finding solutions to the reduction of numerous error terms while simultaneously finding ways to minimize risk and cost.

7.1 Laser Guide Star Tomography

NGAO will use four LGS beacons (Figure 3) to perform tomography of the atmosphere in a narrow volume around the science field. The primary purpose of tomography is to reduce focal anisoplanatism (i.e., the cone effect); the single largest wavefront error term for the current Keck 2 LGS AO system. Laser tomography has not yet been demonstrated on the sky despite the fact that it is planned as a key part of future AO systems on existing telescopes as well as future extremely large telescopes. We have compared multiple tomography simulation codes, followed the results of NGS tomography demonstrations and performed experiments at the UCSC Laboratory for AO to better quantify the tomography error.

The data from multiple wavefront sensors are combined to determine the wavefront error as a function of altitude and direction. In the NGAO system this information will be used to provide the optimal on-axis correction. This information could alternatively be used to optimize the performance at any given field point within the tomographic volume. We also intend to use the tomographic information in support of providing PSF calibration data versus field position.

Laser tomography requires the availability of high return sodium wavelength lasers. The availability of affordable and reliable commercial sodium wavelength lasers continues to be a major issue for the astronomical community.

Mitigation during PD phase: We collaborated with ESO, GMT, TMT and AURA to fund two companies to develop preliminary designs for commercial lasers. ESO subsequently selected TOPTICA/MPBC to provide four 20W fiber Raman amplifier based lasers. WMKO has signed an agreement with ESO to continue to participate during the final design and pre-production phases for this laser. WMKO with TMT collaboration has submitted a NSF MRI proposal to procure one of the three lasers that will be needed for NGAO. TOPTICA/MPBC produced a demonstrator for the PDR that operated at up to 30W and with a variable gravity vector.

7.1.1 Near-IR Low Order Wavefront Sensing

The NGAO low order wavefront sensors (LOWFS) are a key element in achieving high Strehl with high sky coverage. Two of these LOWFS just provide tip and tilt based on measurements from natural guide stars in the 120" diameter field. A third LOWFS also measures focus and astigmatism. Three tip-tilt measurements are necessary to determine low order modes which the LGS wavefront sensors cannot measure. The use of AO-sharpened tip-tilt stars has not been demonstrated on the sky to date. A number of challenging technologies need to be incorporated into these LOWFS to achieve the required performance. These include:

- Pickoff arms to accurately acquire and track the tip-tilt stars with respect to the science field. Mitigation during PD: our preliminary design meets the requirements.
- MEMS deformable mirrors to open loop sharpen the image of the tip-tilt star based on the wavefront sensor data from the LGS pointed at the tip-tilt star. Mitigation: UCO has demonstrated accurate go-to performance in the lab and on the sky using NGS (Villages experiment).
- Near-infrared low order wavefront sensor cameras. Mitigation: COO has demonstrated the required read noise and we have submitted a joint ATI proposal to field a camera on Keck I.

7.1.2 Science Measurement Accuracy

Astronomers are interested in such key performance issues as sensitivity, spatial resolution, spectral sensitivity, contrast, astrometric accuracy and photometric accuracy. AO developers have traditionally designed and assessed their system performance versus wavefront error (or encircled energy) and transmission/emissivity budgets. In order to move to another realm of science performance the AO developers now need to develop error budgets for, and improved understanding of, the other relevant performance parameters impacting science with AO.

One key parameter is the point spread function (PSF) of the images delivered by the AO system; this needs to be determined in the absence of a PSF star in the science data. The structure of this PSF and its dependence on time and field position strongly impacts the accuracy of astrometric or photometric measurements, the ability to detect faint sources next to bright sources and the ability to characterize the structure of astronomical objects. Improving the stability of the PSF and knowledge of the PSF versus time and field position will directly improve the science achievable with AO.

Mitigation: In the process of developing NGAO we have begun to develop additional error budgets, for such areas as companion sensitivity, astrometry and photometry, in order to determine their impact on the NGAO design. We began the process of implementing PSF characterization tools with the existing Keck AO system, based on existing wavefront sensor data supplemented by atmospheric turbulence monitoring data, as a stepping stone to developing the more complex tools that will need to be implemented with NGAO's laser tomography system. This effort was stalled for much of the PD but has recently been restarted in collaboration with Gemini and Groningen. PSF characterization tools have not yet been implemented anywhere for LGS AO science or for NGS AO with Shack-Hartmann wavefront sensors.

8. Systems Engineering Management Plan

A SEMP (KAON 769) has been produced for the remainder of the project. The project plan includes a work breakdown structure with task definitions, cost estimates, management plans including risk management, major milestones, and an MS Project plan.

Some key excerpts from the SEMP are summarized here:

- Organization. The project personnel are distributed between Caltech, UCO and WMKO. Key personnel include the project manager, P. Wizinowich (WMKO), who reports to the WMKO directorate, the project scientist, C. Max (UCSC), and the senior management team, R. Dekany (Caltech), D. Gavel (UCSC) and S. Adkins (WMKO), who manage major elements of the NGAO project.
- A Work Breakdown Structure (WBS) and Product Breakdown Structure (PBS) have been defined for the project. The high level WBS is shown in Figure 18. The top level structure reflects the transition from Design (1.0) through Full Scale Development (4.0 to 8.0 and 11.0) to Delivery and Commissioning (9.0 and 10.0). WBS 9.0 includes Science Verification and WBS 10.0 covers the handover to Facility Class Operation. Management (2.0) and Systems Engineering (3.0) are ongoing items through both Full Scale Development and Delivery and Commissioning.
- A high level project milestone schedule is shown in Table 7. The 24-month DD phase is driven by the need to allow time to significantly increase the number of personnel at the start of this phase. Eighteen months between the end of the detailed design and the start of lab I&T will be adequate if long lead procurements can be placed during the detailed design. The telescope integration and test schedule will need to be carefully coordinated with the observing semester schedule and decision dates in order to minimize the down time for AO (AO will however be available on the Keck I telescope during this period). In this schedule NGAO shared-risk science would begin in semester 15A.
- A very detailed bottoms-up cost estimation process was performed, modeled on the TMT process with the additional improvement of producing even more detailed MS project plans. The cost sheets include WBS dictionary definitions, deliverables, labor, non-labor, travel and contingency estimates along with their bases of estimation. These costs were also compared to the costs for similarly complex systems. As a result we have a good degree of confidence in the cost estimate. The bottom line estimate is $44.7M plus $9.1M in contingency in FY10 dollars. A summary of this cost estimate in then-year dollars by major phase is provided in Table 8. The then-year dollar total cost is $58.5M.
- We have evaluated and documented the programmatic and technical risks (KAON 720) to NGAO and our proposed mitigation approaches. Our approach to risk evaluation follows the model used at JPL where risks are ranked according to likelihood and consequence.
- An approach to requirements management using a database management tool has been defined and is in use.
- An approach to integration and test has been defined and is integrated with our WBS and schedule.
- A detailed design phase MS project schedule has been produced that is consistent with the cost estimate and with the available Observatory budget. Personnel assignments have been made to each task in the schedule.

- A brief summary is provided of how the team performed during the PD phase in terms of deliverables, schedule and budget.

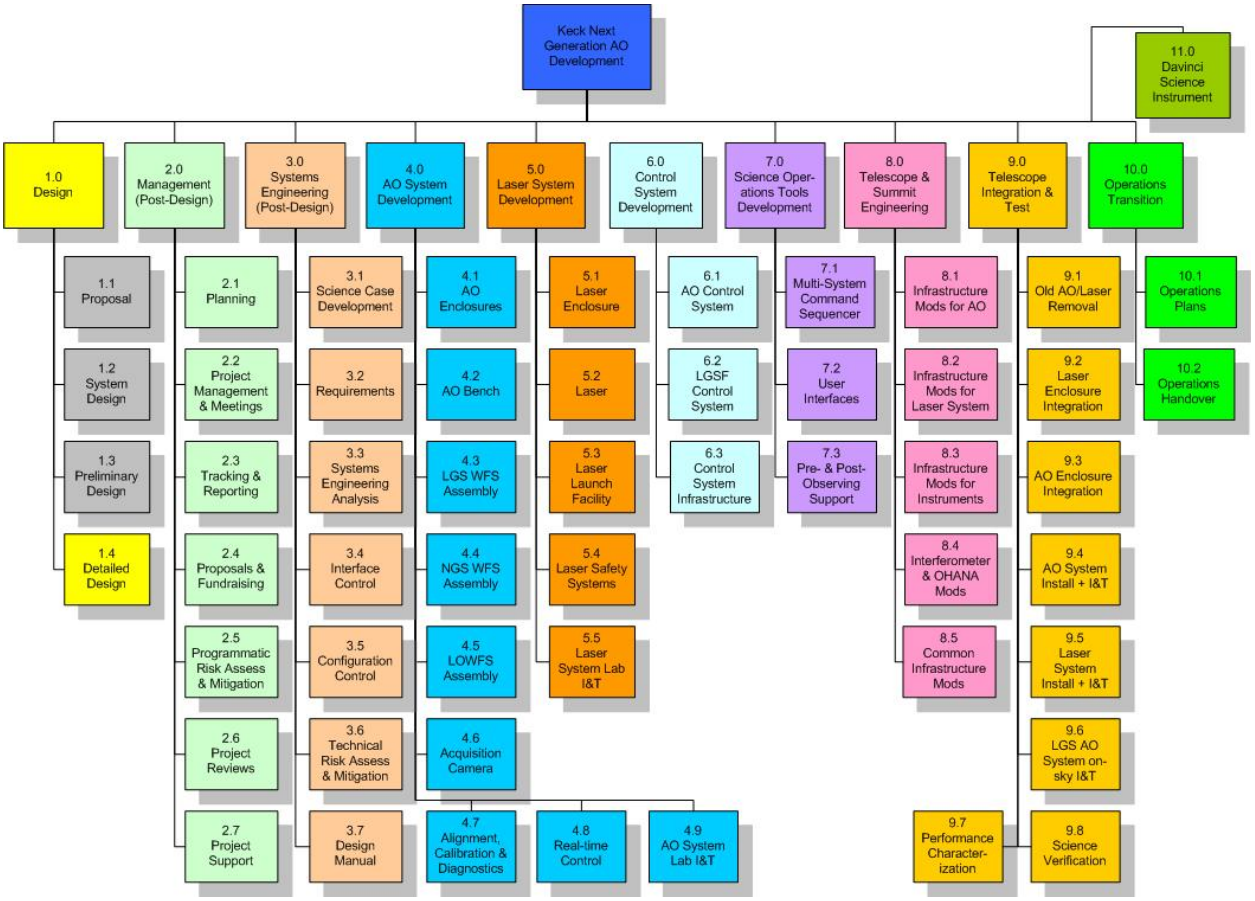


Figure 18: NGAO Work Breakdown Structure (WBS)

Year	Month	NGAO Project Milestone
2008	April	System Design Review
2010	June	Preliminary Design Review
2010	September	Detailed Design Phase Begins (if approved)
2012	September	Detailed Design Review
2013	May	1st AO Subsystem Acceptance Review
2013	July	1st Laser Pre-Telescope Readiness Review
2014	January	1st Laser First Light with Keck II AO
2014	February	Last AO Subsystem Acceptance Review
2014	March	DAVINCI Pre-ship Review
2014	November	AO Pre-Ship Readiness Review
2015	February	NGS First Light
2015	June	LGS First Light
2015	October	Operational Readiness Review

Table 7: NGAO Project milestones

	Actuals ($k)				Plan (Then-Year $k)							
NGAO System	**FY07**	**FY08**	**FY09**	**4/30/10**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**Total**
System Design (WMKO)	725	513	6									1244
Preliminary Design (TSIP)		150	1153	1007	535							2845
Detailed Design					100	2691	5115					7906
Full Scale Development								9303	9629			18932
Delivery & Commissioning									695	2086	121	2903
Contingency						581	1220	1660	3190	600		7251
NGAO Total =	725	663	1159	1007	635	3272	6336	10963	13515	2686	121	**41080**
MRI Laser Launch Telescope				49	213	1222	50					1535
MRI Laser					1323	611	940	339				3214
NGAO Proposal Total =	0	0	0	49	1537	1833	990	339	0	0	0	**4748**
DAVINCI Prel. Design (TSIP)				137	108							245
DAVINCI PD & DD					98	787						885
DAVINCI FSD & DC						421	6073	1774	333	103	4	8708
Contingency					10	362	1822	532	100	31	1	2858
NGAO Instrument Total =			0	137	216	1570	7895	2306	433	134	5	**12696**
Overall Total =	725	663	1159	1193	2387	6675	15220	13608	13948	2820	126	**58524**

Table 8: NGAO cost estimate by project phase, in then year dollars

9. Conclusion

We believe that we have successfully completed the Preliminary Design phase and are confident that the presented NGAO design will offer a very powerful scientific capability to the WMKO community. We are looking forward to continuing into the Detailed Design phase and beyond.

Appendix A. NGAO Keck Adaptive Optics Notes (KAONs)

KAON	Title	Program Mgmt	Requirements	Model Validation	Performance	AO System Design	LGS Facility Design	Controls Design	Instrument Design	System Architecture	Configuration Controlled	External Reports
455	Science Case Requirements Document		x									
550	System Configurations Spreadsheet		x								x	
593	Response to NGAO SDR Panel	x										
594	NGAO Plan to Address Phased Implementation and Descope Options (draft)	x										
595	NGAO Preliminary Design Phase Replan	x										
596	NGAO SDR: SSC Recommendations and Response	x										
597	WMKO's NGAO Facility (SPIE 2008)									x		x
599	WMKO NGAO Facility: Science Operations (SPIE 2008)							x				x
600	NGAO Preliminary Design Phase Project Report #1	x										x
601	Sharpening of NGS for low-order wavefront sensing using patrolling LGS (SPIE 2008)			x		x						x
604	Concept for the Keck Next Generation Adaptive Optics System (SPIE 2008)					x						x
605	The Science Case for the NGAO System at W. M. Keck Observatory (SPIE 2008)		x									x
606	Low-order wavefront sensing in					x						x
607	NGAO PD Project Report #2	x										x
611	PSF reconstruction at WMKO: Develop-	x								x		x
612	NGAO PD Project Report #3	x										x
618	NGAO PD Project Report #4	x										x
621	The Noise Propagator for Laser Tomography Adaptive Optics			x								
622	NGAO PD Project Report #5	x										x
625	Cost Comparison with First Light TMT AO	x										
626	PSF Reconstruction for Keck AO – Phase 1 Final Report									x		
627	NGAO PD Project Report #6	x										x
628	NGAO Optical Relay Redesign Evaluation					x						
629	Wavefront Error Budget Comparison between Keck NGAO and TMT NFIRAOS			x								
630	NGAO PD Project Report #7	x										x
634	NGAO PD Project Report #8	x										x

KAON	Title	Program Mgmt	Requirements	Model Validation	Performance	AO System Design	LGS Facility Design	Controls Design	Instrument Design	System Architecture	Configuration Controlled	External Reports
635	Sharpening of Natural Stars Using Deployable Laser Guide Stars for NGAO			x	x							
636	Observing Operations Concept Document		x								x	
637	NGAO PD Project Report #9	x										x
638	Requirements Approval & Change Process	x	x									
642	Design Changes in Support of Build-to-	x	x			x	x	x	x	x	x	
643	Motion Control Architecture Study							x				
644	NGAO Build-to-Cost Architecture Performance Analysis				x							
645	NGAO Guidelines for the Initial Review of the Functional Requirements	x	x									
646	NGAO PD Project Report #10	x										x
647	Software Standards Proposal		x									
648	Build-to-Cost Review Presentation	x										
649	ASTRO 2010 NGAO Activity Report	x										x
650	Build-to-Cost Review Report	x										
652	Real Time Computer Interface Concept							x				
653	NGAO PD Project Report #11	x										x
656	NGAO PD Project Report #12	x										x
658	Science Advisory Team Charter	x										
659	Laser Launch Facility Beam Generation System Preliminary Design						x					
661	Laser Launch Facility Switchyard Preliminary Design						x					
662	Laser Launch Facility Beam Transport						x					
665	NGAO PD Project Report #13	x										x
666	NGAO Fixed Pupil Mode									x		
667	NGAO Science Instrumentation Baseline Capabilities Summary								x		x	
668	Device Control Architecture							x				
669	A Slow Tip-Tilt Mount for the Narrow-Field Deformable Mirror									x		
670	NGAO PD Project Report #14	x										x
671	Container Component Model							x				
672	Software Architecture Connection Service							x				
673	Software Architecture Logging Service							x				
674	Software Architecture Sequencer Architecture Design							x				
675	Software Architecture Tasks							x				
676	Software Architecture Configuration Service							x				
677	Alarm Subsystem and Service							x				
678	External (CA/KTL) Interfacing							x				
679	Control Software Architecture							x				
680	Telescope Vibration Mitigation for NGAO									x		
681	NGAO PD Project Report #15	x										x

KAON	Title	Program Mgmt	Requirements	Model Validation	Performance	AO System Design	LGS Facility Design	Controls Design	Instrument Design	System Architecture	Configuration Controlled	External Reports
682	NGAO Master Device List							x			x	
683	NGAO PD Project Report #16	x										x
684	Uptime and Reliability Analysis for NGAO				x							
685	Optical Relay Design					x						
686	Laser Launch Facility System Performance Preliminary Design						x					
687	NGAO PD Project Report #17	x										x
688	Software Architecture Review Report	x						x				
689	Laser Launch Facility Review Report	x					x					
690	Technical Specification for the Laser System of the Next Generation Adaptive Optics Facility on the Keck II Telescope						x					
691	NGAO PD Project Report #18	x										x
692	LGS Wavefront Sensor Preliminary Design					x						
694	Opto-mechanical Review Report	x				x						
695	NGAO Real Time Controller Algorithms Design Document					x						
696	NGAO Real Time Controller Design Document					x						
697	Real-Time Controller Review Report	x				x						
698	NGAO PD Project Report #19	x										x
699	LGS WFS Review Report	x				x						
700	Real Time Controller Testing Document					x						
701	Preliminary Electronics Design							x				
703	NGAO PD Project Report #20	x										x
704	Opto-mechanical Registration Tolerances for "go-to" AO		x		x	x						
705	AO-Level Control Loops							x			x	
706	AURA Laser Subaward Summary	x					x					x
707	NSF MRI Proposal "Development of an	x										
708	Limits to AO Observations from Altitude-				x							
709	Power Budget		x								x	
710	Latency, Bandwith and Control Loop				x							
711	Control Electronics Architecture Review Report	x						x				
712	NGAO PD Project Report #21	x										x
713	LTCS URL Interface Specifications							x				
714	AO Control System Design							x				
715	Preliminary Motion Control Design							x				
716	Preliminary Design Wavefront Error Budgets		x		x						x	
717	Keck 2 Telescope Tube Flexure Measurements			x			x					

KAON	Title	Program Mgmt	Requirements	Model Validation	Performance	AO System Design	LGS Facility Design	Controls Design	Instrument Design	System Architecture	Configuration Controlled	External Reports
718	NGAO LGS and NGS Wavefront Sensor Cameras					x						
719	AO System Alignment Plan					x						
720	PDR Risk Evaluation	x										
721	Wavefront Error Budget Tool		x		x						x	
722	High Contrast Error Budget Tool		x		x						x	
723	Performance Flowdown Budgets		x		x						x	
724	Mass Budget (place holder available during DD phase)		x								x	
725	DAVINCI Interface Control Document		x						x		x	
726	SolidWorks Model (not linkable at this time)					x					x	
727	Optical Design (Zemax)					x					x	
728	NGAO PD Project Report #22	x										x
729	NGS WFS Design					x						
730	TT and TTFA WFS Design					x						
731	Motion Control Architecture Review Report	x						x				
732	Data Server Preliminary Design Document							x				
733	Controls Software Review Report	x						x				
734	LOWFS Review Report	x				x						
735	Main AO Sequence							x				
736	Main Laser Sequence							x				
738	NGS WFS Review Report	x				x						
739	AO Calibration Methods					x						
741	Interface Control	x	x									
742	NGAO PD Project Report #23	x										x
743	DAVINCI Review Report	x							x			
744	Science Operations Tools							x				
745	Calibration Unit					x			x			
746	Alignment & Calibration Review Report	x				x			x			
747	DAVINCI Pupil Registration		x						x			
748	NGAO & the Keck Interferometer					x			x		x	
749	Laser Enclosure Design						x					
750	Laser Systems Support						x					
751	LGSF Subsystem Control Sequencing						x					
752	LGSF Safety System Controller Assembly						x					
753	LGSF Safety System Interface Control Spreadsheet						x					
754	NGAO Laser Traffic Control System						x					
755	NGAO Laser Clearinghouse Planning						x					
756	NGAO Aircraft Safety System						x					
757	NGAO PD Project Report #24	x										x
758	Keck II Laser Removal Plan						x					
759	NGAO System Facility & Cooling					x	x					

KAON	Title	Program Mgmt	Requirements	Model Validation	Performance	AO System Design	LGS Facility Design	Controls Design	Instrument Design	System Architecture	Configuration Controlled	External Reports
760	NGAO PDR Charge and Design Review Process	x										
761	DAVINCI Overview and Optical Design Report								x			
762	NGAO PSF Metrics, Characterization and Reconstruction		x							x		
763	DAVINCI Pixel Scales and Sensitivities								x			
764	DAVINCI Background and Zero Point Estimates								x			
765	Requirements for DAVINCI		x									
766	AO Bench Cold Enclosure											
767	AO Enclosure											
768	Preliminary Design Manual	x										
769	Systems Engineering Management Plan	x										
770	Preliminary Design Report	x										
771	System Requirements Documents PDR		x									
772	PDR Compliance Matrix		x									