Keck Next Generation Adaptive Optics Preliminary Motion Control Design KAON 715

Ed Wetherell, Kevin Tsubota, Jason Chin

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With Alex's comments: p. 13 & 27

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1. Introduction

This document describes the preliminary motion control design for the NGAO system. We begin by describing the locations where motion control is needed and then break down the motion by location and type of control it will require. We then present some flow down requirements. The architecture is then introduced, including support equipment and the location of the controllers. Then we trace the optical path of the AO system and present the relevant information for each subsystem. Next we look at the Laser Guide Star facility followed by the science instruments. The final sections summarize requirements compliance and address risks.

This design is heavily dependant on the decisions made by the subsystem designers. As some of these designs are still evolving, parts of this document are lacking detail.

2. References

2.1. Referenced Documents

Documents referenced are listed in Table 1. Copies of these documents may be obtained from the source listed in the table.

Ref. #	Document #	Revision or Effective Date	Source	Title
1	KAON 105	24 APR 1996	WMKO	Servo vs. Stepper for AO Optics Bench
2	KAON 511	0.3	WMKO	NGAO System Design Manual
3	KAON 572	0.1	WMKO	Instrument Baseline Requirements Document
4	KAON 574	1.0	WMKO	NGAO Systems Engineering Management Plan
5	KAON 642	April 10, 2009	WMKO	NGAO Design Changes in Support of Build-to-Cost Guidelines
6	KAON 643	1.4	WMKO	Motion Control Architecture Study
7	KAON 659	1.1	WMKO	Laser Launch Facility Beam Generation System
8	KAON 661	1.1	WMKO	Laser Launch Facility Switchyard
9	KAON 662	1.1	WMKO	Laser Launch Facility Beam Transport Optics
10	KAON 668	2.0	WMKO	Device Control Architecture
11	KAON 682	1.2	WMKO	Master Device List
12	KAON 692	Dec09	COO	LGS WFS Preliminary Design

Table 1: Reference Documents

2.2. Acronyms and Abbreviations

Table 2 defines the acronyms and abbreviations used in this document.

Acronym/Abbreviation	Definition
ADC	Atmospheric Dispersion Compensator
AO	Adaptive Optics
BGS	Laser Beam Generation System
BTO	Laser Beam Transport Optics
COTS	Commercial Of The Shelf
DOF	Degree of Freedom
DM	Deformable Mirror
IF	Keck-Keck Interferometer
K1	Keck 1
K2	Keck 2
KAON	Keck Adaptive Optics Note
LGS	Laser Guide Star
LLF	Laser Launch Facility
LOWFS	Low Order Wave Front Sensor
LSE	Laser Service Enclosure
LVDS	Low Voltage Differential Signaling
MEMS	Micro Electro-Mechanical Systems
NGAO	Keck Next Generation Adaptive Optics System
NGS	Natural Guide Star
WFS	Wave Front Sensor
WMKO	W. M. Keck Observatory

Table 2: Acronyms and Abbreviations

3. Overview

3.1. System Description

The NGAO system is comprised of a cascade relay AO system, laser guide star facility, science instrument and support equipment, as illustrated in Figure 1. These systems combine to produce high Strehl performance over the near-IR wavelengths and modest Strehl into the visible for objects too faint to be used as guide stars. Multiple laser guide stars and tomographic reconstruction techniques are used to overcome the effects of focus anisoplanatism. Additional laser guide stars are used to sharpen the natural guide stars used to provide tip, tilt, focus and astigmatism information and to remove tilt anisoplanatism. Approximately 80 moving axes are needed to support the AO and Laser Guide Star systems.

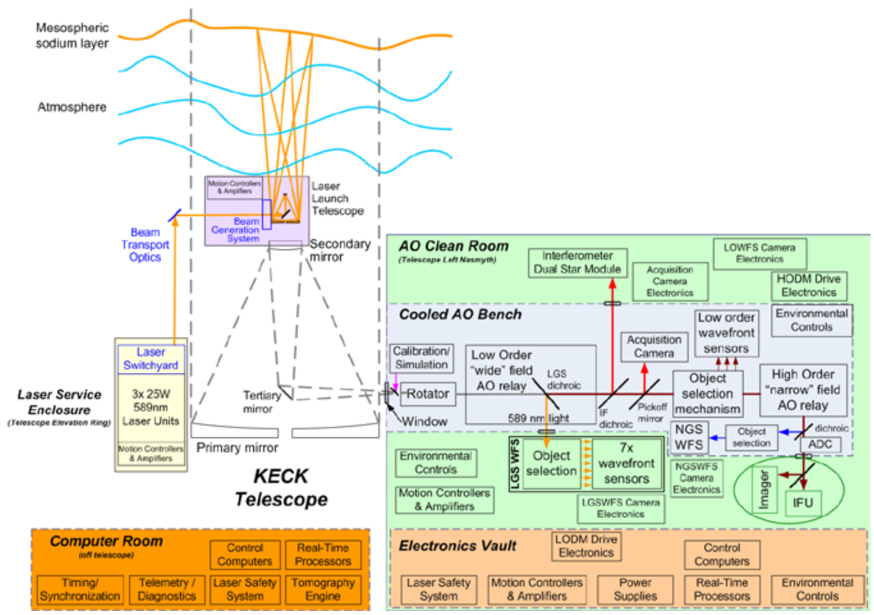

Figure 1: NGAO Block Diagram

3.2. Location of Motion Devices

The locations of these devices in the NGAO system are shown in Figure 2. There are four primary areas NGAO devices will be located. The devices on the cooled AO bench and those outside of the AO bench (AO Clean Room) will be located on the Left Nasmyth Platform. The devices for the Laser Switchyard will be on the elevation ring. The Beam Generation System (BGS) devices that control the asterism and steering of the patrolling guide stars will be in the secondary socket on the telescope.

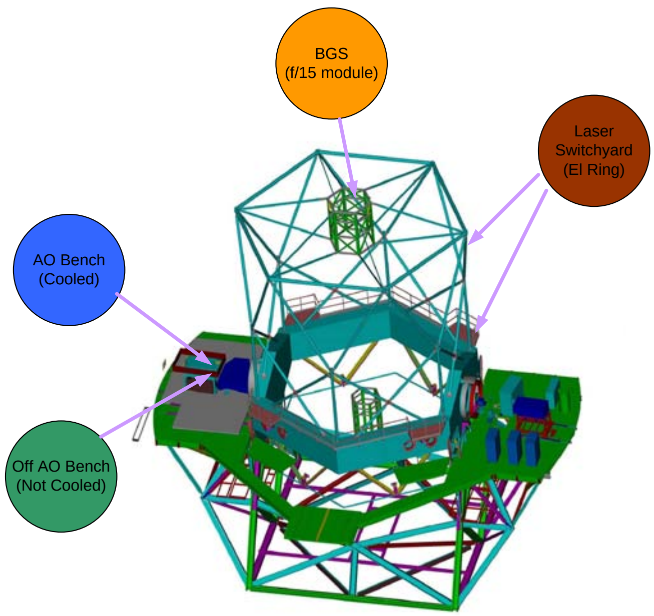

Figure 2: Motion Device Locations

3.3. Control Category

The concept of a control category, first introduced in KAON 643 (Motion Control Architecture Study), is used throughout this document. As a reference, the six categories are described below in order of complexity and difficulty, with 0 being straightforward and 6 being the most demanding.

0) Shutters
   - simple in/out devices with very loose positional requirements
   - actuators other than motors (e.g., solenoid, pneumatic, etc.) may be considered
   - switches or hard stops may be used to define positions, encoders are not required
   - knowledge of actual position and velocity, although desirable, is not required
1) Low precision, non-tracking
   - a dichroic or fold, for example, that is either in beam or out of beam
   - moved during configuration, not during an observation
   - position with encoder
2) Medium precision, non tracking
   - Higher precision, still primarily single axis devices
   - moved during configuration, not during an observation
   - likely combine this category with Type 1 devices

3) High precision, non-tracking
   - aligning a lenslet or focusing a unit
   - moved during configuration or acquisition, not during an observation
4) Tracking
   - position calculated from and synchronized to external information (telescope az/el, etc)
   - constantly moving during an observation, update rates from 25ms to 100s of seconds
   - various levels of precision required
   - ADC, rotators
5) Extremely high precision (non)tracking
   - coordinated motion with other DOF(s)
   - may be constantly moving during an observation, update rates ≥ 1Hz
   - precision generally requires a high precision actuator, not a servo motor
   - examples include steering mirrors and tip/tilt stages
6) Pickoff arms - coordinated high precision (non)tracking
   - most demanding DOF
   - position based on and synchronized to external information (telescope az/el, etc)
   - coordinated motion with other DOF(s)
   - spatial position constraints to avoid collision
   - may be constantly moving during an observation

3.4. Device Breakdown with Location and Type

A detailed break down of the devices and their control types is shown below in Figure 3. The devices are listed along the vertical axis, roughly corresponding to their position in the AO beam path, with the laser devices at the bottom. The name of each device is shown along with its type of motion in parentheses (x, y, z, θ, Φ). Groups of devices (by subsystem) are denoted by a solid black horizontal line across the chart, with the total number of devices shown in square brackets to the right of the group name (e.g., "Low-Order Relay [17]"). The control category for each device is shown along the horizontal axis, with type 0 on the left and type 6 on the right. The general location of these devices is indicated with a colored diamond. The total number of degrees of freedom (DOF) for a device is shown in square brackets to the right of the diamond.

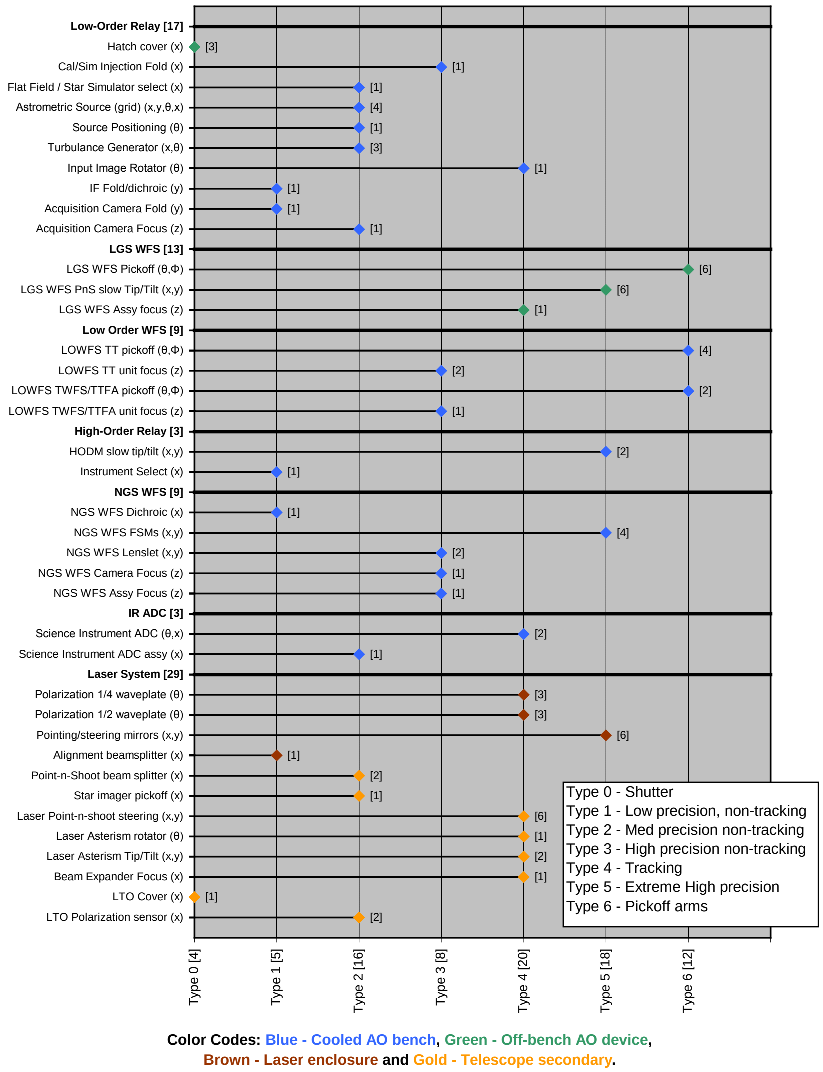

Figure 3: Summary of NGAO Devices

3.5. Requirements Flow-down

A number of system requirements, functional requirements and Keck standards apply to the motion control design. Based on the formal requirements and experience with the current AO system, Interferometer and telescope motion controls and standard practices for implementing large motion control systems, the following subsystem and device level requirements have been generated. Section 7 contains a compliance matrix for the formal (Contour) requirements. To avoid confusion, the term DOF is used to refer specifically to a single individual axis (channel) of control.

3.5.1. Subsystem Level Requirements

- The motion control system shall have the ability to position each device according to the following specifications:
  - Payload
  - Range of travel
  - Accuracy and repeatability
  - Maximum move time
- The motion control system shall be able to synchronize the motion of multiple DOF.
  - DOF within the NGAO system may require synchronous motion with respect to each other. This is referred to as move coordination. For example, pickoff arms must move both axes together in order to keep the desired field stable.
  - DOF may require synchronization with external devices/commands at a 40Hz+ (TBC) rate. This is referred to as a tracking device. The image rotator's position, for example, is a function of telescope azimuth and elevation.
  - NGAO devices may require both move coordination and tracking.
- The motion control system shall match the complexity, flexibility, and cost of hardware to the individual device requirements.
- The motion control system shall accept commands from the high level NGAO control system.
  - This should include over-ride commands such as to abort a move that is in progress or a change in destination.
- The motion control system shall provide feedback to the NGAO control system in the form of
  - Status and fault reporting
  - High rate (e.g. 40Hz, TBC) position feedback to facilitate control of tracking devices whose command may originate outside of the NGAO system.
- The motion control system shall incorporate controllers that support motion programs to perform computations and/or act on inputs. These tasks can be handled at a higher level (as is currently done), but are more efficient when performed in the controller. Given the size of the NGAO system, moving tasks to the controller level will reduce the load on the high level control system and reduce communication overhead.
- No device shall move when power is applied or removed, when the servo loop is closed, or when a controller is reset (KS-82).

- A local emergency shutdown (e-stop) system and/or interface to the telescope e-stop may be required to protect personnel (SR-209).
- Lockout/Tagout and local/remote capabilities are required to protect personnel working on devices that can be remotely controlled (KS-80).
- The motion control system shall protect motors, stages and payloads from physical damage (KS-82).
    - Typical protections include end-of-travel limit switches and hard stops to prevent physical collision; motor over-current detection to protect the motor; soft position limits, velocity and acceleration limits to protect the payload; and encoder failure detection to preserve servo loop integrity.
- The motion control system shall not contribute more than TBD minutes of lost time on a night
- The motion control system failures shall not exceed TBD % of total system downtime
    - NGAO System is required to have 95% up-time
        - Mean time between faults > 4 hrs
- The components shall have a 10 year life (SR-151)
    - 200 nights/yr * 12hrs/night = 2400 hrs/year
    - current AO system components specified at >5yr, 2500 hrs/yr
- The components of the motion control system shall operate in the environment present at the W.M. Keck Observatory on the summit of Mauna Kea (SR-254, KS-49, KS-88)
    - All components will operate within specification at an elevation of 4200m above sea level. Vendor advertised specifications will likely require de-rating and possibly dedicated cooling.
    - Operation, possibly with reduced performance, is also required at sea level for laboratory integration and test
- When required, components shall operate within specification in the cold box at a temperature around -15°C. This includes, but is not limited to, stages, motors, encoders and limit switches (FR-xx).
- When required, components shall operate within specification in the telescope dome environment, being exposed to temperatures from -10° to +10° C, and possibly wind and dust (SR-254?).
- When required, components shall operate within specification in the non-cooled area of the AO enclosure at temperatures ranging from -10° to +15° C (SR-254?).
- The motion control system shall minimize the thermal load on the cold box (FR-xx).
    - The thermal dissipation in the cold box shall be limited to TBD Watts per device, TBD watts total.
- The components of the motion control system located on the AO bench shall not emit light (IR or visible), KS-46.
- The motion control system shall limit generation of Electro Magnetic Interference (EMI), KS-43.
- The motion control system shall tolerate the presence of Electro Magnetic and Radio Frequency Interference (RFI), KS-43.

- The components of the motion control system, specifically cooling fans, shall not contribute vibration to the environment, SR-292.
- The motion control system shall be implemented with a workable and maintainable physical layout.
    - The architecture must consider the requirements for maintenance and troubleshooting the system.
    - The architecture should take into account the possibility of additions to the system.
- In order to reduce maintenance efforts, the motion control system shall provide interchangeable/swappable components where practical.
    - Ideally, a Plug-and-Play or in-system configurable approach will be used which requires no configuration prior to installation in the system.
- The motion control system shall include as much diagnostics as practical.
- In order to facilitate initial setup and ensure long term performance, servo tuning software should be available from the vendor of the motion control hardware

3.5.2. Device Level Requirements

From the architecture requirements listed above, we identify some more detailed requirements for each (DOF).

- The use of stepper motors is discouraged (KAON 643 §6.7, KAON 105).
    - An exception is made for devices located inside a cryostat where steppers or piezo actuators are preferred.
- End of travel limit switches shall be fail-safe, i.e. normally closed contacts that open when triggered. They should be optically isolated in the controller to prevent ground loops. Motion controller inputs should support both dry-contact and electrical type switches. Limit switches should be powered by the servo (or encoder if separate from servo) power supply (KS-82, KAON 643 §7.7)
- To achieve the positioning requirements, a DOF must be capable of being "homed"
    - The precision of homing should be consistent with the required device performance.
    - Optionally, a DOF can be moved to a specified offset after the physical reference position has been found. This allows use of protection (limit) switches or hard stops for homing.
    - Homing is not required if an absolute, load side encoder system is used
    - When possible, homing should be performed off of a fixed position of the load so changing motors (or actuators) does not require recalibration of the stage.
- "Soft" (software programmable) limits should be available to prevent a DOF from hitting the hard limits.
    - Soft limits allow deceleration and a controlled stop whereas hard limits require a more abrupt stop to prevent a collision.
- A number of status, error and fault reporting signals should be present. Some of these are primarily useful for setup or debugging, others are vital for system operation.
    - Current position/velocity

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  - Amplifier enable
  - Motion complete / 'in position'
  - Real-time limit switch status
  - Latched limit switch status (desirable, not required)
  - Output current / DAC output
  - Real-time following error (difference between actual and commanded position)
  - Maximum following error exceeded (fault)
  - Motor over current error (amp fault)
  - Over-temperature error
  - Communications errors
  - Controller watchdog fault
- The control system should support the option to fit a DOF with a shaft brake.
- Some high precision DOFs may require both drive side (motor) and load side (stage) encoders. A motor is usually fitted with an encoder and is referred to as the drive side encoder. Due to the nature of the mechanical coupling between the drive and the load, the actual position of the load may have an unpredictable relationship with the position of the motor. The use of two encoders allows the position to be controlled more precisely without sacrificing stability of the velocity (motor) control loop.
- In some cases, the load requirements on the motor are significantly different when moving in one direction as opposed to the other. Common examples are moving with or against gravity and moving with or against the force of a spring. Having a controller that includes a compensation factor for this effect is desirable.
- Coordinate systems (non-Cartesian may be required for some DOFs). Currently all of the conversions between a single DOF and the multiple DOFs required to position a device are done at a higher level. Some controllers are capable of creating 'coordinate systems' out of a number of channels. This allows tight trajectory control with reduced overhead. Coordinate systems can also help solve transformation problems when reversing moves or handling complex kinematics of multi axis devices.
- Debugging and device characterization benefit from the ability to send open-loop commands to a DOF. This eliminates the servo loop and higher level control.

3.6. Architecture

As suggested in KAON 643, the motion control architecture will be distributed in nature. The number of devices has decreased significantly as the subsystems have matured, making centralized control more practical, but there are still benefits to a distributed approach. In some cases, linear piezo devices for example, distributed controllers may be required given constraints on cable lengths.

3.6.1. Controllers and Actuators

The methods of actuation and control for the various device types are outlined below. This will be referenced throughout the design in later sections of this document. Refer to KAON 643 for background information on these selections.

The use of stepper motors is discouraged for several reasons: minimal cost difference if an encoder is required, easier diagnostics and performance monitoring with servo motors and more electrical noise and vibration with steppers. An exception is made for devices located inside a cryostat where steppers or piezo actuators are preferred. Reference KAON 643 and KAON 105.

For the lower precision, type 0 and 1 devices with intermittent motion, smart motors are recommended. A smart motor is a servo motor with an integrated controller. These devices can be chained together on a single communication port and power supply, providing a significant reduction in cabling. These motors have a NEMA17 or NEMA23 frame, so stages will need to be selected with that in mind.

Some type 2 devices may be grouped with the type 1 devices and controlled via smart motor. The remainder will likely be actuated with a conventional servo motor combined with a multi-axis controller.

Type 3 devices will be actuated with servo motors controlled from a multi-axis controller. Assuming electrical noise from PWM amplifiers is managed, linear amplifiers may not be required.

Type 4 devices will be actuated with a combination of motors and piezo actuators. These are required to track in some observing modes. This list may seem large given the possibility of observing non-sidereal objects. Motorized devices may require linear drive amplifiers. Piezo devices may not be suitable for use with a 3rd party controller. OEM controllers are available to match the specific actuator. These are provided with either a serial or analog interface. The interface and update rates will need to be carefully considered once the devices have been chosen to ensure that the tracking performance requirements are met.

Type 5 devices require precision stages due to the requirements on the accuracy of their position. Piezo actuators, servo motors and possibly voice coil actuators may be used. Servo motors will require linear amplifiers and be driven from a multi-axis controller. Other actuator types will likely use OEM controllers matched to the actuators. These devices will not require a high control bandwidth; tracking is used for flexure compensation and the rates are slow.

Type 6 devices are the rotational stages needed to position the object selection arms for the LGWFS and LOWFS. The requirements on the performance of these stages have relaxed since the initial classification, but the decision was made to keep them in their own category. These will be servo motors controlled from a multi-axis controller. The controller should support coordinate systems and allow the distributed control system to command the mechanism with a location in field coordinates, not the angles of each rotational stage.

Servo motors will be controlled via multi-axis motion controllers. Although a vendor has not been selected, the Delta-Tau PowerPMAC looks to be a good candidate given its programmability and scalability. Equipment will be located in standard 19inch equipment racks. Rack mountable equipment is preferred, although equipment with non-standard chassis can be placed on shelves within the rack.

3.6.2. Support Equipment

The motion control system is required to halt all devices in response to the observatory emergency stop. Circuitry will be required to remove power from the motion control amplifiers. Recovery from the e-stop event will be faster if the encoders and limits remain powered; re-initializing the devices would not be necessary.

Some digital inputs and outputs will be required to control and monitor the status of the motion controllers. Inputs will be required to monitor the health of the controllers. Outputs will be required to reset a controller.

Controllers will be connected to the Ethernet, either directly or via a protocol converter if their native protocol is RS-232 or USB.

Some controllers will need an analog setpoint and provide analog position feedback. Depending on the required bandwidth, either an Ethernet ready analog I/O module or an analog card in a control computer will be required.

3.6.3. Location of Equipment

The proposed architecture places controllers in the AO Electronics vault and either the Laser Service Enclosure or telescope Secondary. The use of smart motors puts some control on the AO bench.

The planned layout of the AO Bench, Clean room and Electronics vault is shown in Figure 4 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.

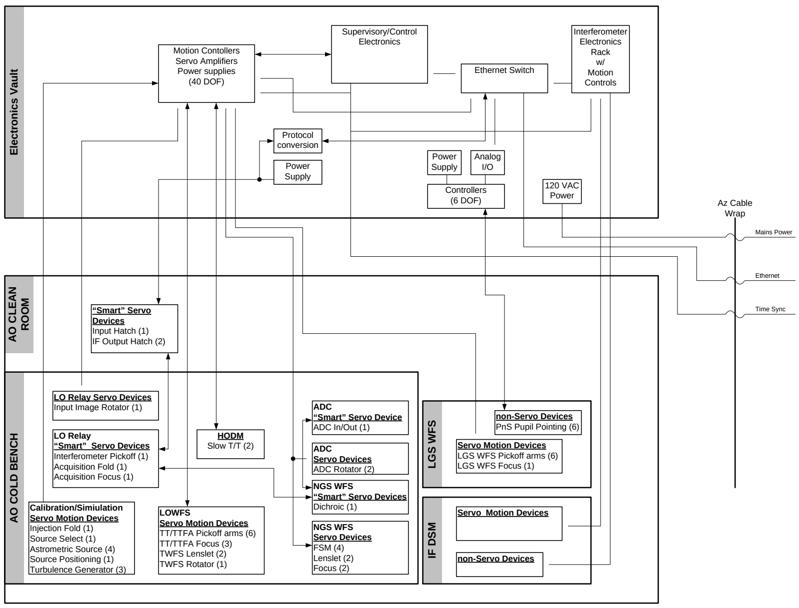


Figure 4: AO Motion Control Layout

Several possibilities exist for the Laser devices on the secondary and in the Laser Service Enclosure, each with its set of benefits and challenges.

One option, illustrated in Figure 5, is to locate distributed controllers on the secondary for the devices in the Laser Beam Generation System. This will significantly simplify the cabling, eliminating the need for ~15 long cables. This will address concerns about driving the piezo-linear stages, required for the asterism generation, through 40m cables. The down side is managing the heat and mass. Glycol is available on the secondary. The feasibility of this approach continues to be investigated.

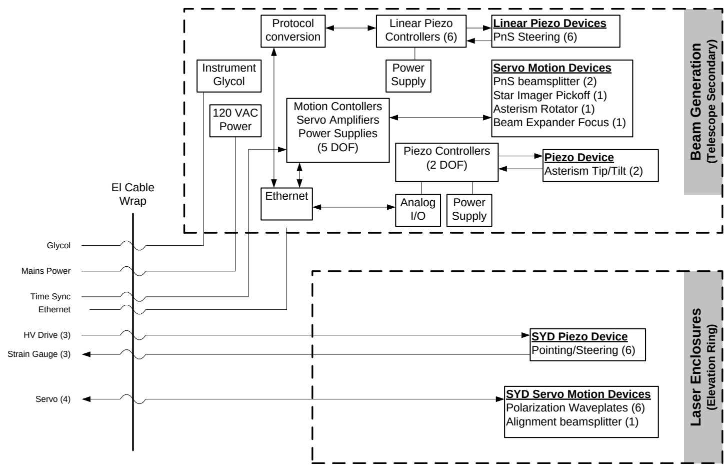


Figure 5: BGS Motion Controls on Secondary

An alternative, shown in Figure 6, is to locate the controllers in the Laser Service Enclosure (LSE). This helps by shortening the cable run and does not require significant use of the elevation cable wrap. This approach will also simplify 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.

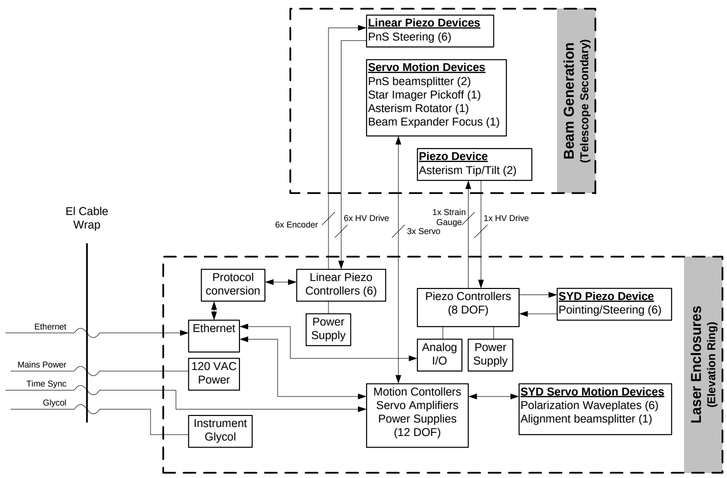


Figure 6: BGS Motion Controls in LSE

The least desirable approach is to place all of the laser motion controls in the AO electronics vault. Although this is a good location from the perspective of heat and mass, stages on the secondary must meet specification when driven through 40m of cable. This length is a concern for the linear-piezo devices. For all devices, the voltage drop across the cables must be managed and differential drivers will be required for serial (encoder) data. All of the cabling will need to fit in the elevation cable wrap.

One of the above options will be selected following a more detailed analysis of the costs, cabling, and the power dissipation, mass and volume of equipment required to support the motion devices.

The design of the motion control hardware is presented in the following sections.

4. AO System

The AO system and instrument(s) are located on the telescope's left Nasmyth platform at the f/15 focus. The AO system (optics bench) is enclosed and cooled to -15°C to reduce the thermal emissivity of the optical surfaces. Windows are provided to isolate this enclosure from the dome environment and AO clean room. The science path optics, acquisition camera, NGS wavefront sensor and Low Order Wave Front Sensor (LOWFS) assembly are located on the cooled AO bench. The entire AO system is located in a clean room that is maintained at dome ambient temperature, possibly with controlled humidity. The AO cold box, science instrument(s), the LGS WFS and the Interferometer Dual Star Module (DSM) are located in this clean room. An electronics vault and an ante-room to facilitate clean entry (similar to the existing AO enclosure) will be joined to the clean room. The electronics vault will have environmental controls, but not require the tight temperature and humidity controls present in the clean room or cooled bench.

The following sections trace the optical path and detail the motion control design for the various AO subsystems.

4.1. Hatches

The AO system input window will have an automated hatch to provide physical protection and also prevent any light from exiting the AO enclosure during non-AO observing. This hatch is located on the telescope side of the elevation journal.

Automated hatches will also be installed to seal the Interferometer output port(s) in the floor of the clean enclosure.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
Input Hatch	1	shutter	6"; in/out	low precision	No				off-bench	0	Smart Motor
Output Hatch	2	shutter	in/out	low precision	No				off-bench	0	Smart Motor

Table 3: Hatch Motion Channels

The mechanics of the input hatch assembly will likely not be changed from the current design. The mechanics of the output hatch assemblies will likely be similar to the existing AO hatch and coude mirror cover designs, using a rod-screw actuator to accommodate the long range of motion.

The state command will be provided by the NGAO control system, not the Interferometer control system as in the current implementation.

4.1.1. Requirements

Other than FR-1834 that indicates an input hatch should be provided; no requirements have been identified for this hatch. It is assumed that a constraint on the open/close time will flow down from the configuration/setup time allocations. It is also assumed that the hatch will not vignette the telescope primary in either the open or closed positions. The system will be designed to have a default state on power up, likely open. At a minimum, the open/closed/traveling/faulted state (based on limit switches) will be provided to the control system. If an encoder is present, velocity and current position will be available. No requirements have been identified for the output hatches. Verbal discussions indicate that they are required. The implementation will be similar to that of the input hatch.

4.1.2. Architecture / Design

The hatch is a low precision, Type 0 device. Encoder position feedback is not required. Two architecture options exist, 1) use the existing centralized open-loop drive system or 2) upgrade to a distributed system based on a smart motor.

The current implementation uses a custom Keck designed box that interfaces a COTS motor controller to the motor, its limits, and the discrete I/O of the control system. There is no position feedback; the hatch position is only known when a limit switch on the rod-screw actuator is triggered at full open or full closed. The input hatch is currently cabled and operating under command of the Interferometer control system.

This control method could be upgraded by replacing the motor with a smart motor. The actuator uses a NEMA 23 motor, so mechanically this would be an easy changeover. A risk that would need to be addressed is the small amount of heat (~1W) generated by the controller in the idle state. The benefits of this upgrade would be to provide continuous position feedback when the actuator is in motion and not require any digital I/O to command the hatch.

The input hatch will likely use smart motors as this will be more cost effective than reusing the existing design. Some of the components are obsolete and a redesign would require more effort than integrating the smart motor which will be used elsewhere in NGAO. Heat from the motors will need to be investigated.

4.1.3. Interfaces

i. Mechanical
   The rod-screw actuator requires a NEMA 23 motor.
   Input hatch: Refer to drawing 1632-C0200 and the 1632 drawing series

ii. Electrical/electronic
   Open-loop controller:
      Motor drive: 32VDC with a 20 kHz PWM frequency
      Motor controller: 15A continuous and 30A peak
      Limit switches: 15V, current limited to ~5mA
      Two digital inputs (command) opto-isolated, 5V, 2mA sinking
      Three digital outputs (feedback), opto-isolated 5V
      5V supply to power the opto-isolators
   Smart Motor:
      20-48 VDC, 200W
      Terminal server port
   Local/remote capability
   E-stop interface

iii. Software
   Open/close control

State feedback

4.2. Calibration/Simulation

This subsystem is still in the early design phase and there is not enough information available to provide a design of the motion controls. The devices listed below are expected, based on the current understanding of the design. This section will be completed prior to the PDR.

The calibration/simulation subsystem will provide the necessary equipment for alignment, calibration and diagnostics: standard sources for flux and wavelength calibration of instruments; astrometric source(s) for instrument field distortion calibration; simulated NGS and LGS sources for calibration, testing and alignment; and atmospheric simulation. Motion stages will be needed to select between the modes, position the output and control the atmospheric simulation (turbulence generation). The module is located above the AO rotator inside the cold enclosure. An actuated fold mirror will be located in front of the rotator to direct the light into the AO system.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
Cal/Sim Injection Fold	1	Linear	in/out	5 um	No			150mm	bench	3	servo
Flat Field / Star Simulator select	1	Linear	in/out	low precision	No				bench	2	servo
Astrometric Source (grid)	4	Linear Rotational Linear	in/out	micron level	No			50mm	bench	2	
Source Positioning	1	Rotational	+/-180 deg	arc-sec	No				bench	2	
LGS Source	(?)	Linear	in/out		No				bench	2	
Turbulence generator	3	Rotational linear	index+speed+dir in/out	low precision	No				bench	2	

Table 4: Cal/Sim Motion Channels

4.2.1. Requirements

FR-1786 states that the astrometric source shall be inserted/removed from the AO beam in 60 seconds or less. FR-1776 places TBD tolerances on the movement of the mechanisms.

4.2.2. Devices

With the exception of the injection fold, these devices are expected to require moderate positioning accuracy. Some of this equipment may be COTS and be supplied with the necessary controllers. Servo motors should be able to provide the required motion for these stages.

4.2.3. Interfaces

i. Mechanical
Motion control cables through the Cold Box wall
Space for rotator motion controls in e-vault

ii. Electrical/electronic
Motor/encoder/reference location signals (low voltage)
Local/remote control
E-stop interface

iii. Software

4.3. Low-Order Relay / Switchyard

The automated stages in the low-order relay include the image rotator, the interferometer pickoff dichroic translation stage, the acquisition fold mirror and acquisition camera focus stage. These stages will all be on the cooled optical bench.

These devices are summarized in the table below and discussed in the following sections.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
Input Image Rotator	1	Rotational	360 deg	15 arc-sec (1) (72 urad)	Yes	1.8 deg/sec	3 deg/sec (1)		bench	4	servo
IF Fold/dichroic	1	Linear	in/out	1mm(?)	No		50 mm/s	200mm	bench	1	Smart Motor
Acquisition Fold	1	Linear	in/out	1mm(?)	No		50 mm/s	200mm	bench	1	Smart Motor
Acquisition Focus	1	Linear	300mm	0.25mm (1)	No				bench	2	Smart Motor

Table 5: Low-order Relay Motion Channels

4.3.1. Image Rotator

The rotator is a precision device that requires special attention. The rotator is required to track in order to correct for the rotation induced by the motion of the telescope and keep the orientation of either the science field or the telescope pupil stable at the output of the AO system. The commanded position is a function of telescope elevation and azimuth. The rotator may also be stationary. If mechanical balance is not achieved, the stage will need to servo in position.

4.3.1.1. Requirements

FR-71 requires that the rotator will have fixed field, fixed pupil modes and stationary modes. FR-1896 requires a TBD slew rate which we anticipate to be at least 3 deg/sec. FR-1897 requires the rotator to have the capability of rotating 360°.

4.3.1.2. Architecture / Design

The current opto-mechanical design is based on the Newport RV240 high performance precision rotation stage. Versions of this stage are available with an incremental load-side encoder, eliminating the need for an additional encoder. The stage will rotate +/- 170°; it does not provide continuous rotation. The motor is a brushed servo design with a tachometer. The cable for the motor/encoder signals will be required to pass through the wall of the cold box. A bulkhead connector will be used to maintain the integrity of the enclosure wall. Operating temperature may be an issue for this stage.

An alternative stage, the Aerotech ALAR-250, is based on a direct-drive brushless servo motor design, providing low torque ripple and zero backlash. The stage includes a sin/cos encoder for position feedback and hall effect sensors for commutation. The operating temperature is also a concern for this stage.

This stage will likely require a linear amplifier to meet the requirements. The torque jitter and errors due to digital to frequency conversion present in PWM drive systems could introduce problems for this stage.

In the current design, all of the position calculations are performed by the distributed control system. The motion controller does not perform any calculations to determine the trajectory of the stage. For NGAO, it is envisioned that the motion controller will contribute more to the positioning of the stage.

4.3.2. Interferometer Dichroic

A pickoff dichroic will be mounted on a translation stage to allow the optic to be inserted during interferometer observing. This will move vertically at a fixed angle to the beam.

4.3.2.1. Requirements

No specific requirements were identified on this stage. It is likely to require millimeter level accuracy. Speed is not a concern as this will only move when changing instruments.

4.3.2.2. Architecture / Design

Given the intermittent nature of the motion and the low precision, a smart motor is suggested for this stage. This smart motor will be chained with the other smart motors on the AO bench.

4.3.3. Acquisition Fold

A pickoff mirror will be mounted on a translation stage to allow the optic to be inserted during acquisition of the science field. As this pickoff sends the entire field to the acquisition camera (and completely blocks the beam from entering the LOWFS and narrow-field relay), it is only inserted during the acquisition phase of the observing sequence.

4.3.3.1. Requirements

FR-68 specifies that the fold mirror will be remotely actuated. A portion of the time allocated for acquisitions in FR-1808 will be taken moving the fold mirror out of beam. This may occur in parallel with a telescope move to the science target. 10 seconds are allocated for that slew. Given the length of travel required to remove the large optic, motion will probably take 5-10seconds. The mirror will be inserted as the telescope slews to a new field and speed is not a major concern. FR-1903 requires the field on the acquisition camera to be repeatable within 40mas. This will be mostly a function of the mechanical design and alignment. The stage will move vertically out of the optical beam and the angle will be fixed. Motion repeatability on the order of a millimeter should be sufficient.

4.3.3.2. Architecture / Design

The pickoff stage and the camera focus mechanism will require motion control channels, as detailed in the motion control design document. This smart motor will be chained with the other smart motors on the AO bench.

4.3.4. Acquisition Camera Focus

The acquisition camera will be mounted on a linear stage to allow adjustment of its focus. Focusing on both a science object and a LGS are needed.

4.3.4.1. Requirements

No specific requirements were identified on this stage. It is likely to require 0.25mm accuracy. From the existing AO system, we anticipate the travel to be around 300mm to accommodate the needed range of focus.

4.3.4.2. Architecture / Design

Given the intermittent nature of the motion and the moderate precision, a smart motor is suggested for this stage. This smart motor will be chained with the other smart motors on the AO bench.

4.3.5. Interfaces

i. Mechanical
   Image Rotator motion cable though the cold box wall (bulkhead connection)
   Smart motor Power/Comms cable through cold box wall (bulkhead connection)
   Space for rotator motion controls in e-vault
   Space for Smart motor DC power supply in e-vault

ii. Electrical/electronic

Image rotator motor/encoder/tach/reference location signals (low voltage)
Smart motor power 20-48 VDC, 600W (may be combined with hatches)
Smart motor terminal server port (may be combined with hatches)
Local/remote control
E-stop interface
Remote power control
Time synchronization signal (?) for image rotator

iii. Software
Motion control
Rotator: tracking
IF dichroic: in/out
Acquisition Fold: in/out
Acquisition camera focus: linear, 0.25mm accuracy
Telescope position information from DCS (for image rotator)

4.4. Laser Guide Star Wave Front Sensor (LGS WFS)

The LGS WFS assembly is located in the AO clean room, adjacent to the cooled AO bench. A window assembly in the cold box allows light to enter the WFS assembly. The function of the LGS WFS is to make wavefront phase measurements of the turbulence-induced distortions seen by the set of seven 589 nm LGS as they propagate downward back to Earth. Reference KAON 692 – LGS Wavefront Sensor Preliminary Design.

The LGS WFS assembly contains seven similar WFS units. Four are used to sense the fixed asterism, three for the patrolling guide stars. Each unit has a fast tip/tilt mirror (controlled by the RTC), relay optics, lenslet array and detector. Unique to each patrolling WFS is a theta-phi pickoff arm required to direct light from an arbitrary location in the field into the sensor optics. The patrolling WFS may also require an additional (slow) tip/tilt stage to position the pupil on the detector. This would not be under RTC control. The entire assembly must be translated along the optical axis to adjust for focus changes induced by variation in the distance to the atmospheric sodium layer. This effect is due both to a natural drift in the sodium layer altitude and the current zenith angle of the telescope.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
LGS WFS ObjectSelect Assy	6	Rotational	180 deg 180 deg	115 arc-sec (560urad) 300 arc-sec (1.5mrad)	No				off-bench	6	servo
LGS WFS PnS slow Tip/Tilt	6	Linear	10mrad	.05 urad	No				off-bench	4	piezo?
LGS WFS Assy focus	1	Linear	205 mm	50 um	Yes				off-bench	4	servo

Table 6: LGS WFS Motion Channels

4.4.1. Requirements and compliance

FR-2408 has an incorrect list of the LGSWFS devices and a list of TBDs for mechanism performance. FR-2406 states that the AO motion control system is responsible for the controlling the mechanisms in the LGS WFS.

4.4.2. LGS WFS Pickoff mechanism

A motorized assembly is needed to direct the light from the patrolling guide stars into their respective wavefront sensors. The design starts with a fixed 'crank' motor to which an arm is attached. To the end of the crank arm, a second, lever, motor and arm are attached. At the end of the lever arm is a mirror. There are several more fold optics mounted to the arms to fold the light through the assembly. The result is a pickoff mechanism that can be positioned in the field using two COTS rotation stages. The three probe arms will be in different planes, so collision of the probe tips is not possible. A switch mechanism has been recommended to constrain the motion of the probe arm to the optical field and prevent any part of the assembly from colliding with the supporting structure of the WFS. If the switch triggers, automatic recovery will take some thought, and perhaps trial and error, as incorrect position feedback could have lead to the fault and the safe operating zone is a complex shape.

Comment [AD2]: The development of a custom wobble switch with direction and distance indication is proposed HERE to ensure safe arm retraction from any unknown position.

These stages will be controlled via a mulit-axis controller and linear amplifiers. Each pair of axis should be controlled from the same controller to provide tight coordination of movement. It is highly desirable that the controller support coordinate systems to help translate the two rotational motions into the field position. The kinematic equations for the field position can be solved in the controller, allowing the AO control system to send commands in field coordinates rather than encoder counts or stage angles. The controllers will be located in the electronics vault.

4.4.3. LGS WFS PnS slow Tip/Tilt

A slow tip/tilt mechanism may be required to keep the patrolling guide stars centered on the WFS lenslets. These precision mechanisms will likely not be actuated with a servo motors. Piezo or voice coil stages are being considered. Depending on the actuator choice, controllers should be located in the e-vault. If there are constraints on the cable length, controllers may need to be located at the WFS.

4.4.4. LGS WFS Assembly Focus

The entire WFS assembly will need to translate along the beam to provide a focus adjustment. This will require constant updates to handle changes in the distance to the atmospheric sodium layer. The update rate should be reasonably slow and tight synchronization to other events is not required. This will be controlled using a linear amplifier and a multi-axis controller located in the electronics vault.

4.4.5. Interfaces

i. Mechanical
   - Cabling for 7 DOF to motion controllers in the e-vault
   - Space for 7 DOF of servo motion controllers in the e-vault
   - Space for slow tip/tilt controllers, likely in the e-vault

ii. Electrical/electronic
   - T/T actuator signals, 100VDC (?)
   - Low voltage T/T command signals (0-10 VDC)
   - 7 channels of motor/encoder/limit switch signals (low voltage)
   - Local/remote control
   - E-stop interface

iii. Software
   - Motion control
     - Patrolling LGS probe arms
     - Assembly focus – tracking
     - Patrolling LGS pointing

4.5. Low Order Wave Front Sensors (LOWFS)

The LOWFS assembly includes two NIR tip-tilt sensors, a NIR tip-tilt-focus-astigmatism sensor (TTFA) and a visible truth wavefront sensor (TWFS). Light from three natural guide stars feeds these four sensors. The T/T sensors each have their own star; the TWFS will use the visible NGS light while the TTFA uses the NIR light from the same NGS. Each star will be AO corrected using a MEMS DM internal to the assembly. This correction is maximized using the patrolling LGS beacons positioned near each star. The TWFS is used to calibrate biases that arise when using LGS in an AO system. This assembly is located on the cooled AO bench.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
LOWFS TT ObjectSelect Assy	4	Rotational	180 deg 180 deg		Yes				bench	6	servo
LOWFS TT unit focus	2	Linear			Yes				bench	3	servo
LOWFS TWFS/TTFA ObjectSelect Assy	2	Rotational	180 deg 180 deg		Yes				bench	6	servo
LOWFS TWFS/TTFA unit focus	1	Linear			Yes?				bench	3	servo

Table 7: LOWFS Motion Channels

4.5.1. Requirements

FR-1834 indicates that there will be 14 DOF in the LOWFS. This is incorrect; the current design only requires 9 DOF. FR-190 the control for these devices will fall under AO controls, not the RTC. No other requirements have been identified.

4.5.2. LOWFS Pickoff mechanism

The object selection mechanisms will be similar, if not identical, to the LGS WFS selection mechanisms described in section 4.4.2, using two rotational stages to position a small fold mirror in the field. As in the LGS WFS case, these stages are controlled by a precision multi-axis servo controller programmed to treat the two axes as a coordinate system. These cables will need to pass through the wall of the cold box. It should be possible to combine the two axes of each pickoff mechanism on a single cable.

4.5.3. LOWFS Unit Focus

Each LOWFS unit will require a focus motor. The current design suggests the use of a Physik Instrumente heavy-duty precision linear actuator. These are based on a servo motor include an encoder with 16nm resolution. These actuators will be controlled via linear amplifiers from a multi-axis controller located in the electronics vault. These cables will need to pass through the wall of the cold box.

4.5.4. Interfaces

i. Mechanical
   Cabling to motion controllers, through cold box wall (bulkhead)
   Space for 9 DOF of servo motion controllers

ii. Electrical/electronic
   9 motion control channels

iii. Software
   Motion control

Object Selection probe arms
Focus stages – tracking

4.6. High-order Relay

The High-order relay, as the name implies, provides high order correction to the science beam. The corrective element is a 4k-actuator MEMS (Micro Electro-Mechanical System) deformable mirror, produced by Boston Mircomachines. This deformable mirror is mounted on a slow tip/tilt stage for field steering.

The DM and tip/tilt stage are mounted on the cooled AO bench. The tip/tilt electronics can most likely be located in the electronics vault. A mechanism will be provided to select between two science instruments.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
HODM slow tip/tilt	2	tip/tilt	> 2170" (10.5mRad)	4.34"/1.09" (21urad/5urad)	yes	3.0"/sec			bench	5	?
Instrument Select	1	Linear	in/out		No				bench	2	Smart Motor

Table 8: High-order Relay Motion Channels

4.6.1. Tip/Tilt Platform

The range suggested for this stage is on the edge of what is possible with a COTS piezo tip/tilt platform. It is possible that a stage using voice-coil technology could be used. Limited work has been done on this part of the opto-mechanical design.

4.6.1.1. Requirements

FR-2154 requires the HODM to be on a tip/tilt stage.

4.6.1.2. Architecture / Design

Assuming a piezo tip/tilt platform will provide enough motion and support the mass of the DM, it would be a good option. Feedback, likely strain gauge, would be required.

4.6.2. Instrument Select

The design of the AO bench is not complete in this area. The assumption is that an optic will be inserted to redirect the beam to an alternate instrument.

4.6.2.1. Requirements

FR-71 states that an instrument selection mechanism will be located at the exit of the high order relay. No additional requirements were identified. Speed is not a major concern as this would only be moved when changing instruments. Hopefully the mechanical design will tolerate a low or moderate precision when positioning this optic.

4.6.2.2. Architecture / Design

4.6.3. Interfaces

i. Mechanical
   2 motion cables through cold box (bulkhead connection)
   Space in electronics vault for T/T electronics

ii. Electrical/electronic
   T/T actuator signals, 100VDC (?)
   T/T drive signals

iii. Software
   HV power supply interface

4.7. Natural Guide Star Wave Front Sensor (NGS WFS)

This subsystem is still in the early design phase and there is not enough information available to provide a design of the motion controls. The devices listed below are expected, based on the current understanding of the design. This section will be completed prior to the PDR.

The NGS WFS assembly is comprised of a pickoff dichroic (to send visible light to the WFS), a field selection mechanism, lenslet assembly and a camera with a motorized focus mechanism. This subsystem is located after the narrow-field relay.
The motion controls associated with the pickoff dichroic, field selection mechanism, lenslet assembly and focus mechanism.

The camera head and motion stages will be mounted on the cold AO bench. The servo electronics will either be in the clean room or the electronics vault.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
NGS WFS Dichroic	1	Linear	3 positions		No		50 mm/s	200 mm	Bench	1	Smart Motor
NGS WFS FSMs	4	Tip/tilt			Yes				Bench	5	servo
NGS WFS Lenslet	2	Linear			No				Bench	3	servo
NGS WFS Camera Focus	1	Linear			No				Bench	3	servo
NGS WFS Assy Focus	1	Linear			No				Bench	3	servo

Table 9: NGS WFS Motion Channels

4.7.1. Devices

4.7.1.1. Requirements

FR-142 is an incomplete requirement on the NGS WFS motion devices. FR-1834 states there are 8 DOF in the NGS WFS, the dichroic is not counted.

4.7.1.2. Architecture / Design

The motion stages will require cables for the motor/encoder signals. These cables will be required to pass through the wall of the cold box.

4.7.2. Interfaces

i. Mechanical
   8 motion control cables though the cold box wall (bulkhead connection)
   Dichroic smart motor chained with other smart motors on bench
   Space for motion controllers in e-vault

ii. Electrical/electronic
   Motion stage motor/encoder/limit switch signals

iii. Software

4.8. Science Instrument Atmospheric Dispersion Compensator

An Atmospheric Dispersion Compensator (ADC) is required for the science instrument. This is the last component along the optical path located on the cooled AO bench.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
Science Instrument ADC	2	Rotational linear	360 deg		Yes				Bench	4	servo
Science Instrument ADC assy	1	Linear	in/out	1 um	No				Bench	2	Smart Motor

Table 10: Science ADC Motion Channels

4.8.1. Requirements

FR-71 indicates the ADC can be removed from the science beam and will be positioned based on telescope elevation. FR-2345 requires a 30second setup time on new targets.

4.8.2. Devices

A motion control channel is required to insert/remove the ADC and two more channels are required to rotate and translate the optical elements.

A smart motor is suggested for the in/out mechanism based on its intermittent motion. The accuracy of positioning this assembly may be on the edge of what is achievable with smart motors. A lot depends on the choice of translation stage. This smart motor would be chained with the other smart motors on the bench. A fall back would be to use a traditional servo motor coupled with linear drive amplifier.

The prism stages will require cables for the motor/encoder signals. These cables will be required to pass through the wall of the cold box. It may be possible to combine these two DOF on a single cable.

4.8.3. Interfaces

i. Mechanical
   3 motion control cables though the cold box wall (bulkhead connection)
   Space for motion controllers (where?)

ii. Electrical/electronic
   Motion stage motor/encoder/limit switch signals

iii. Software

5. Laser Guide Star Facility

The Laser Guide Star Facility provides the facilities for propagation of the laser beams. The LGSF includes the lasers, Laser Service Enclosure, Laser Launch Facility, Launch Telescope and any safety related system for propagation of laser beams. The Laser Service Enclosure(s), housing the laser systems, are located on the elevation ring of the telescope. The Laser Launch Facility receives the laser beams and generates the asterism and propagates the beams from the behind the secondary. Some of the electronics required for this system, such as the Laser Safety System Programmable Logic Controller may be located in the AO electronics vault.

5.1. Switchyard

The Switchyard is located within the Laser Enclosure attached to the elevation ring. It receives the beams from the laser systems, formats them and sends them on to the Beam Transport Optics (BTO). The Switchyard ensures the laser beams are properly formatted and aligned to the BGS. The Switchyard compensates for pointing errors due to the changing gravity vector as the telescope moves in elevation. It also provides polarization controls, safety shutters, and a switchable element to dump most of the beam power to produce a low power alignment beam.

Thirteen axes of motion control are required for the Switchyard steering mirrors, wave plates and beam splitter

Reference the Laser Launch Facility Switchyard Preliminary Design (KAON 661) for more details.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
Polarization waveplates	6	Rotational	360 deg	urad	Yes?	Sidereal	min: 10 deg/s goal: 30 deg/s		laser_enc	2	servo
Pointing/steering mirrors	6	tip/tilt	100 urad	1 urad (35nm)	Yes	slow/ flexure			laser_enc	5	piezo
Alignment beamsplitter	1	Linear	in/out, 50mm	1mm	No		1mm/s		laser_enc	1	servo

Table 11: LGS Switchyard Motion Channels

5.1.1. Requirements

FR-2131 defines the basic functionality required for the laser devices. FR-2149 has in incorrect list of require laser devices. FR-2150 states that the laser devices will be controlled by the LGS control system.

5.1.2. Devices

As presented in section 3.6.3, there are two preferred options for locating the controls of the switchyard devices. If the BGS controllers are on the secondary, the switchyard controls will likely be in the electronics vault. This will require that all of switchyard cables run through the elevation wrap.

The motion devices will require motion controllers and amplifiers. Both servo amplifiers and high-voltage PZT amplifiers will be needed.

Motion control cabling for six rotators and one linear stag will be required. These will all be servo motors. To control the three tip/tilt mirrors, motion control cabling will be needed for six peizo actuators. Depending on the architecture, these cables might be short – within the laser enclosure, or longer – running through the elevation wrap to the AO electronics vault.

The analog signal from the calorimeter will need some cabling.

5.1.3. Interfaces (controllers in e-vault)

i. Mechanical
   7 servo motion cables through el wrap
   6 peizo motion cables through el wrap
   Space for motion controllers in AO e-vault
   Space for analog input or COTS controller in AO e-vault (2U)

ii. Electrical/electronic
   Servo motor / encoder / limit switch (low voltage)
   Peizo actuator (0-120VDC)
   AC Mains
   AC remote control

iii. Software
   Motion control
   AC mains remote control

5.1.4. Interfaces (controllers in LSE)

i. Mechanical
   7 servo motion cables; short, within LSE
   6 peizo motion cables; short, within LSE
   Fiber for motion controller through el wrap
   Space for motion controllers in Laser Enclosure
   Space for analog input or COTS controller (2U)

ii. Electrical/electronic
   Servo motor / encoder / limit switch
   Peizo actuator (0-120VDC)

iii. Software
   Motion control
   AC mains remote control
   AC Mains
   AC remote control

5.2. Beam Transport Optics

The Beam Transport Optics (BTO) subsystem is responsible for delivering the laser light from the Switchyard to the Beam Generation System. In the current design, there are no actuated components in this system. All of the actuated steering mirrors are located in either the Switchyard or Beam Generation System. Reference the Laser Launch Facility BTO Preliminary Design (KAON 662) for more details.

5.3. Beam Generation System

The Beam Generation System (BGS) is located within the secondary f/15 module on the telescope. It receives the laser beams from the Beam Transport Optics (BTO), formats them into the required asterism, directs them into the launch telescope and provides the beam pointing on the sky.

The BGS requires a number of movable optics to divide the three incoming beams into the seven beams required for the sky beacons, position the beams into the required asterism and then reformat the result to be compatible with the Launch Telescope Assembly.

There are 16 motorized actuators in the BGS. The cabling requirements for the motion control aspect of this subsystem depend heavily on the location of the motion controller(s) and amplifiers. A number of the motion stages will require piezo actuators. The piezo actuators will require different controls and cabling than the servo motors.

Reference the Laser Launch Facility Beam Generation System Preliminary Design Document (KAON 659) for more information on the BGS.

Device	TL DOF	Type	Range	Accuracy / Repeatability	Tracking Device?	Tracking Rate	Slew Rate	load size/ mass	Device Location	Control Category	Actuator Type
Point-n-Shoot beam splitter	2	Linear	in/out, 12.5 mm	60 um	No		1 mm/s		secondary	2	servo
Star imager pickoff	1	Linear	in/out, 50 mm	30 um	No		5 mm/s		secondary	2	servo
Laser Point-n-Shoot steering	6	linear	80 mm	30 um	Yes	slow UTT offload	10 mm/s		secondary	4	linear piezo
Laser Asterism rotator	1	Rotational	360 deg	0.05 deg	Yes	Sidereal	min: 10 deg/s goal: 30 deg/s		secondary	4	servo
Laser Asterism Tip/Tilt	2	tip/tilt	3 mrad	3 urad	Yes	slow/ flexure			secondary	4	piezo
Beam Expander Focus	1	Linear	5 mm	10 um	Yes	Elevation (100um from 90 to 20 el)	100 um/s		secondary	4	servo
LTO Cover	1	?		Low precision	No				secondary	0	Smart Motor
LTO Polarization sensor	2	Rotational	360 deg	0.1 deg	No		min: 20 deg/s goal >50 deg/s		secondary	2	servo

Table 12: LGS Beam Generation Motion Channels

5.3.1. Requirements

FR-2131 defines the basic functionality required for the laser devices. FR-2149 has in incorrect list of require laser devices. FR-2150 states that the laser devices will be controlled by the LGS control system.

5.3.2. Devices

As presented in section 3.6.3, there are two preferred options for locating the controls of the BGS devices. Placing the controllers on the secondary will simplify the cabling at the expense of adding a conditioned enclosure on the secondary. This would require a single cable, likely fiber, for communications. Short cables will then connect the amplifiers to the motion stages.

Placing the controllers in the LSE would require, 16 motion cables will need to be run to the telescope secondary. These cables are on the order of 20m in length. The benefit of this approach is to reduce the cabling for the LSE devices and reduce the volume needed in the cable wrap. There would be no additional weight (of controller/amps) on the secondary.

The bulk of the DOF are straight forward servo devices requiring moderate precision. The stages used to position the patrolling LGS are unique. Linear piezo stages were selected to keep the design compact and lightweight. These stages require a specific controller supplied by the stage manufacturer. Two vendors for this stage have been identified, Physik Instrumente and SmarAct. Both vendors use a similar 'walking' piezo technology. The interface to the controller will likely be RS-232 or USB. This will require protocol conversion to interface with the distributed control system.

5.3.3. Interfaces (controllers in LSE)

i. Mechanical
14 servo motion control cables from Secondary to LSE
2 piezo motion control cables from Secondary to LSE
Glycol to cool motion controllers

ii. Electrical/electronic
Motion stage motor/encoder/limit switch signals
HV drive for piezo stages
120VAC power for motion amps
AC power control

iii. Software
Motion control
AC mains remote control

5.3.4. Interfaces (controllers on Secondary)

i. Mechanical
14 servo motion control cables to local controllers
2 peizo motion control cables to local controllers
1 fiber-optic cable for motion controller to AO e-vault
1 Ethernet cable for piezo motion controller to AO e-vault
Custom enclosure w/ heat exchanger for motion controllers
Glycol to cool motion controllers

ii. Electrical/electronic
Motion stage motor/encoder/limit switch signals (low voltage)
HV drive for piezo stages
120VAC power for motion amps
AC power control

iii. Software
Motion control
AC mains remote control

5.4. Launch Telescope

The laser launch telescope is a vendor supplied unit that accepts the formatted laser beams from the BGS and projects them on the sky. There are no actuators associated with this subsystem.

6. Instrument

For this document, two instruments are considered: the Interferometer and the Narrow-field Imager + Integral Field Spectrograph. The following sections provide an overview of both instruments and details of (or references to) their interface with the NGAO system.

6.1. Interferometer

The NGAO system is required to support the Keck-Keck Interferometer. The preliminary NGAO design will support the ASTRA mode by providing a focused beam to the DSM.

The NGAO system is not responsible for controlling any Interferometer specific devices, other than the fold dichroic discussed in section 4.3.2 and the output hatches discussed in section 4.1. Approximately 30 devices are currently located on the DSM and AO bench. The IF Ancillary control rack, located in the AO electronics vault, also controls ~15 devices in the coudé optical path. Refer to Interferometer electronics document 120-00-03: Master Device List for a complete description of the controlled devices.

6.2. Narrow-field Imager + Integral Field Spectrograph

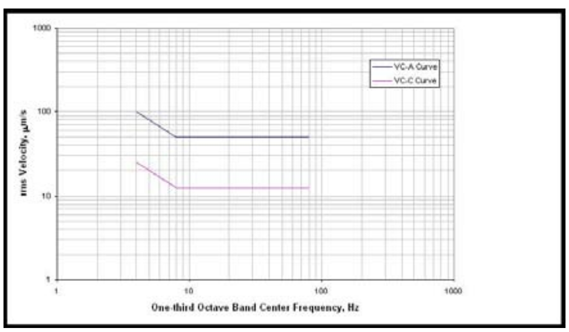
This instrument is being designed/built as part of the NGAO project and falls under the build to cost guidelines (KAON 642). This instrument will be located in the AO clean enclosure with electronics in the e-vault.

The instrument will be self contained and not require any motion control channels from the NGAO system.

7. Requirements compliance

A number of the "Keck Standards and Best Practice" requirements apply to the motion control design. The table below lists the requirements that were identified and references a section of this document that shows compliance with the requirement. Note: a major review of the requirements is in progress by the systems engineering team and the impact on this not yet known.

<table>
<tr><td>Short Name</td><td>ID</td><td>Description</td><td>Compliance</td></tr>
<tr><td>Operating Environment</td><td>SR-254</td><td>The NGAO system shall meet all performance requirements, while the NGAO system is subjected to the operating environment conditions given in the table below.
<table>
<tr><th>Parameter</th><th>Min.</th><th>Typ.</th><th>Max.</th><th>Units</th><th>Notes</th></tr>
<tr><td>Altitude</td><td>0</td><td>-</td><td>4300</td><td>m</td><td></td></tr>
<tr><td>Temperature</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Range</td><td>-10</td><td>0</td><td>20</td><td>ºC</td><td>1</td></tr>
<tr><td>Rate of change</td><td>-0.8</td><td>-</td><td>0.8</td><td>ºC/h</td><td></td></tr>
<tr><td>Humidity</td><td>0</td><td>-</td><td>90</td><td>%</td><td>2</td></tr>
<tr><td>Gravity orientation</td><td>-</td><td>-1</td><td>-</td><td>g</td><td>3</td></tr>
<tr><td>Vibration</td><td>-</td><td>-</td><td>$1x10^{-5}$</td><td>g^2/Hz</td><td>4</td></tr>
<tr><td>Acceleration</td><td>-</td><td>-</td><td>1</td><td>g</td><td>5</td></tr>
</table>
Notes:
1. Typical value is the average annual temperature.
2. Relative, non-condensing.
3. Normal to the earth's surface.
4. 20 Hz to 1000 Hz, 6db/oct drop- off to 2000 Hz.
5. All axes, due to telescope drive system fault conditions.</td><td>3.5</td></tr>
<tr><td>Vibration (observing and non observing)</td><td>SR-292</td><td>Vibration isolation shall be employed as required to isolate sources of vibration within the NGAO system due to moving components such as fans, pumps and motors. The NGAO system shall meet all performance and operating requirements when installed in a vibration environment that conforms to the Generic Vibration Criteria Curve[1] "C" as shown in the figure below. The NGAO system shall not produce vibrations that result in rms velocities in excess of those given in curve "C" of the figure below.

[1] Gordon, Colin G. Generic Criteria for Vibration-Sensitive Equipment. Proceedings of the SPIE Vol. 1619, pp. 71-85, Vibration Control in Microelectronics, Optics, and Metrology. Gordon, Colin G. editor. SPIE 1992.

</td><td>Noted</td></tr>
</table>

Short Name	ID	Description	Compliance
Thermal dissipation into observatory dome	SR-65	NGAO shall dissipate less than or equal to 100 W into the dome environment from the telescope Nasmyth platforms, less than or equal to 50W fom the telescope elevation ring and less than or equal to 50W from the telescope top end.	Noted
Electrical power usage	SR-78	The NGAO system shall use less than or equal 50 kW of electrical power.	
Azimuth wrap cabling	SR-79	The NGAO facility cabling through the azimuth wrap must not require an area of more than TBD.	All
Left elevation wrap cabling	SR-80	The NGAO facility cabling through the left Nasmyth elevation wrap must not exceed an area of more than TBD.	All
Right elevation wrap cabling	SR-81	The NGAO facility cabling through the right Nasmyth elevation wrap must not exceed an area of more than TBD.	All
Emergency Stop Input	SR-209	The NGAO shall stop all motion of NGAO components and turn off all lasers when the observatory emergency stop signal is activated.	3.5
System Lifetime	SR-151	The NGAO system shall have a ≥10 year lifetime.	3.5
Time to deploy and remove astrometric source	FR-1786	The astrometric source (grid) shall be able to be inserted and removed from the AO beam in 60 seconds or less (TBC).	4.2
Stable pupil shape	FR-1776	The pupil shape shall be constant to 1% (TBC) over the course of a night of observing. This places limits on the mechanical stability of the radiometric calibration source and it sets limits on the repeatability of its insertion mechanism. The tolerance on the relative motion of optical components is TBD.	4.2
Image rotator slew rate	FR-1896	The image rotator shall be capable of slewing between any two field or pupil orientations (a physical rotation of 90 degrees), including the time to switch out of tracking and back into tracking, in less than TBD seconds.	4.3.1
Image rotator range of motion	FR-1897	The image rotator shall be capable of being in any orientation over a full 360 degrees, and shall be capable of going from any orientation to another orientation via the shortest path (i.e., the rotator can rotate continuously).	4.3.1

Short Name	ID	Description	Compliance
Motion control	FR-71	The motion control system for the AO relay shall provide the following: 1. The input K mirror shall provide image or pupil rotation compensation as well a stationary mode, which is selectable by the AO control software. 2. There shall be a moving optical element which will select between the two instruments located at the output of the second stage relay. 3. The AO facility atmospheric dispersion compensator shall be able to move into and out of the optical beam from the second relay. 4. The atmospheric dispersion compensator shall be driven based on the telescope elevation and the direction of the Keck zenith on the AO bench. 5. The LGS dichroic shall be fixed	4.3.1 4.6.2 4.8
Minimal time overheads	FR-1808	The NGS acquisition shall take less than 90 seconds for NGS in the range V ~ 18-20, less than 50 seconds for NGS in the range V < 17, with the goal of achieving less than 20 seconds for the brightest targets. This requirement includes time for telescope moves for repointing, camera exposure, and analysis. It does not include the initial slew of the telescope to the target. Typical slewing time is 120 seconds. It it assumed that the slewing time is used to configure the acquisition system hardware and software systems and other NGAO system that support the acquisition task.	4.3.3
Acquisition camera fold	FR-68	A fold mirror (or possibly a beamsplitter) will be located at the output of the first relay preferably before the LOWFS pickoffs in order to reflect the 120" diameter field of view to the acquisition camera. The fold mirror must be on a stage to allow it to move in and out of the beam.	4.3.3
Acquisition camera fold positioning repeatibility	FR-1903	The acquisition camera fold mirror shall move to the same position in the optical beam to ensure that the image does not move on the acquisition camera by more than 40 mas.	4.3.3
LGS WFS Mechanism Degrees of Freedom	FR-2408	Device and degree of freedom are as follows: Patrolling LGS WFS Unit Focus: 1 Patrolling LGS WFS Unit Rotation: 1 Patrolling LGS WFS OSM 2 LGS WFS Assembly Focus 1 Motion Control Requirements for LGS WFS Number and Type of Mechanism is TBD Speed of Mechanism motions is TBD Accuracy of mechanism motions is TBD Focus tracking accuracy is TBD	4.4
LGS WFS Motion Controller	FR-2406	Motion control for the LGS WFS mechanisms shall be provided by the AO Controls subsysetm	4.4
Mechanism motions	FR-177	[TABLE of LOWFS devices OMITTED] All entries in above table need to be confirmed.	4.5
Mechanism controller	FR-186	Control of all mechanisms in the LOWFS subsystem shall be performed by the AO Controls function.	4.5

Short Name	ID	Description	Compliance
[LOWFS] Interface to AO non real-time control	FR-190	The mechanism control and other status information (temperature, humidity, etc.to be listed as a table when fully identified) shall be reported to the AO non real-time control system. Tracking of the input optical pickoffs shall be controlled by the AO Controls function.	4.5
HODM Slow tip-tilt stage	FR-2154	The HODM shall be mounted on a slow tip-tilt stage to implement dithering.	4.6.1
Mechanism motions	FR-72	The speed and accuracy of the opto-mechanics in the optical switchyard are TBD.	4.7
Mechanism controller (NGS WFS)	FR-151	Control of all mechanisms inside the NGS WFS assembly shall be done by the AO Controls system.	4.7
Mechanism motions (NGS WFS)	FR-142	a) The NGS WFS shall be able to pick off a star in its field and guide on it in 14 sec by positioning the sensor. b) The accuracy of the mechanisms shall position the NGS WFS to (1/20)th of the finest sub-aperture plate scale. c) NGS WFS mechanisms shall facilitate on-chip dithers of 5 milli-arcsec. Motion control requirements for NGS WFS (need to add travel range, accuracy etc.) --- TABLE OMITTED ---	4.7
Interface to AO Controls (NGS WFS)	FR-155	The NGS WFS shall have an interface to the AO Controls system. All motion control and configuration of the NGS WFS subsystem (including plate scale selection, camera setup, frame rate, input optical pickoff, etc.) shall be done by AO Controls. Subsystem health and status information shall be reported to the AO Controls system.	4.7
Science ADC slew rate	FR-2345	The science ADC mechanisms shall allow setup on a new science target RA and Dec, attaining the required dispersion compensation on the new target (see FR-73), within the time 30 seconds (TBD) for motions between any two positions within 60 degrees of zenith.	4.8

Short Name	ID	Description	Compliance
Basic Functionality	FR-1837	AO Controls shall provide the following basic functions for the AO system: 1. A control system, supporting: Simple and complex commands Synchronous and asynchronous commands Command completion monitoring Error detection, handling, notification and recovery User interfaces supporting graphical, command line, and script modes 2. Device control for all controllable devices in the AO system. 3. Motion control for all controllable opto-mechanical devices in the AO system. 4. Configuration and control of the RTC. 5. Support for AO system configuration, calibration and operations. 6. Logging of all telemetry data to the data server. 7. Monitoring the health of all AO subsystems and providing notification to other systems as required. 8. Control of the AO enclosure environment. 9. Interfaces to the other NGAO and observatory subsystems: Laser System LTCS Science Instruments Telescope Control System Data Server Atmospheric Tools Multi-System Command Sequencer These items are detailed in the requirements that follow.	4
Motion control coordination	FR-471	AO controls will coordinate the motion control and other tasks needed to perform dithering, offsetting and chopping for science observations.	4
Motion Control	FR-1834	AO Controls shall provide a motion control function for all opto-mechanical devices requiring remote computer control. The control function shall include basic device control (initialize, standby, start, stop, etc.), configuration control, position control, tracking control for those devices that require it, and support coordinated moves of multiple devices. As of this writing, the opto-mechanical devices requiring motion control are as follows (number of degrees of freedom shown in parentheses): Hatch cover (1 DOF); Vibration sensor (4 DOF); Calibration sources (14 DOF); Rotator (1 DOF);Wyko (3 DOF); LGS WFS assembly (31 DOF); Interferometer pickoff, pointing and centering (5 DOF)Acquisition camera pickoff, focus (2 DOF); LOWFS assembly (14 DOF); NGS WFS (8 DOF); NIR imager (3 DOF) As more information is known about the motion control needs for these devices and subassemblies, individual requirements will be added to address them.	4

Short Name	ID	Description	Compliance
Pointing reference	FR-2000	The Beam Transport System shall have a mean to initialize its motion control devices to known fiducial.	N/A – no motion devices in Beam Transport System
Basic Functionality	FR-2131	LGS Controls shall provide the following basic functions for the LGS facility: 1. A control system, supporting: Simple and complex commands Synchronous and asynchronous commands Command completion monitoring Error detection, handling, notification and recovery User interfaces supporting graphical, command line, and script modes 2. Device control for all controllable devices in the LGS facility. 3. Motion control for all controllable opto-mechanical devices in the LGS facility. 4. Configuration and control of the laser system. 5. Support for LGS facility configuration, calibration and operations. 6. Logging of all telemetry data to the data server. 7. Monitoring the health of all LGS facility subsystems and providing notification to other systems as required. 8. Control of the Laser enclosure environment. 9. Interfaces to the other NGAO and observatory subsystems: AO System LTCS Telescope Control System Data Server Multi-System Command Sequencer These items are detailed in the requirements that follow.	5
Motion Control	FR-2149	LGS Controls shall provide a motion control function for all opto-mechanical devices in the LGS facility requiring remote computer control. The control function shall include basic device control (initialize, standby, start, stop, etc.), configuration control, position control, tracking control for those devices that require it, and support coordinated moves of multiple devices. As of this writing, the opto-mechanical devices requiring motion control are as follows (number of degrees of freedom shown in parentheses): Laser Shutter (1 DOF); Polarization waveplates (3 DOF); BTO bottom mirrors (4 DOF); BTO mid mirrors (4 DOF); BTO top mirrors (4 DOF); Shutter (1 DOF); Point and shoot beam splitter (2 DOF); Star imager pickoff (1 DOF); Point and shoot steering (6 DOF); Asterism rotator (1 DOF); Asterism tip/tilt (2 DOF); Fast shutter (1 DOF); Beam expander focus (1 DOF); LTO cover (1 DOF); LTO polarization sensor (1 DOF); LTO focus lens (1 DOF) As more information is known about the motion control needs for these devices and subassemblies, individual requirements will be added to address them.	5

Short Name	ID	Description	Compliance
Motion control coordination	FR-2150	LGS controls will coordinate the LGS facility motion control and other tasks needed to perform dithering, offsetting and chopping for science observations.	5
Stray Light	KS-46	The NGAO system should not produce stray light from LED or lamp indicators, optical switches or optical shaft encoders. LED or lamp indicators should not be used on the exterior of NGAO system or any major NGAO subsystem. Any indicators required for service should be concealed behind a cover or access door. Optical switches or shaft encoders must be optically baffled or enclosed so that no stray visible or infrared light is emitted into the telescope optical path or dome environment. All exterior parts of the NGAO system should be examined for stray light emissions with a night vision device with a light gain of at least 50,000[1]. A person known to have normal photopic and scotopic visual sensitivity should conduct the examination under dark adapted conditions. [1]This is a typical specification for generation III night vision monoculars such as the ITT 160 Night Mariner.	3.5
Cable and Wire Ratings	KS-49	All wire and cable will be rated for an ambient temperature range of -30 °C to 100 °C.	3.5
Power Ratings	KS-88	All power dissipating components to be cooled by free air convection must be derated to 80% of their sea level absolute maximum average power dissipation ratings.	noted
Local Control	KS-80	Mechanisms internal to the NGAO system will not be accessible during normal operation. However, during servicing a means shall be provided to ensure that all mechanisms are under local control and remote control is locked out.	3.5

Short Name	ID	Description	Compliance
Safety, Moving Parts	KS-82	No part of any mechanism should move when AC mains power is applied to or removed from the NGAO system or subsystems. The motion control hardware should inhibit all motion during a power on or reset. If closed loop or servo systems are used in the motion control systems these servo loops should be designed so that loss of the encoder signal or disconnection of the motor cannot result in a "wind up" of the servo position command. Software features should be implemented to inhibit motion when the position error measured by the servo controller exceeds the smallest reasonable margin that reflects all of the expected operating conditions. Limit switches should be closed when not actuated (N.C. contacts). Motion control software should be designed so that a disconnected limit switch will appear to be active, inhibiting further motion towards that limit. Motion control software should also be designed so that movement away from an active limit switch is restricted to a reasonable distance past the limit switch actuation point after which motion is stopped and an error indicated due to the apparent failure of the limit switch to open.	3.5
Electrical/Electronic Documentation	KS-61	The following documentation for all electrical and electronic assemblies and modules in the NGAO system shall be provided in the formats listed in KS-58 Drawing Standards and in the native format if translated to one of the specified formats: 1. A top level system block diagram. 2. An interconnection diagram showing all interconnecting cables and connected assemblies and modules in the NGAO system. 3. An interconnection diagram showing the external connections to the NGAO system. 4. Cable drawings including cable reference numbers, pinouts, wire color codes and assembly information for all internal and external cables. 5. Schematics, assembly drawings, bills of material, printed circuit board designs and printed circuit board artwork for all custom printed circuit boards in the NGAO system. 6. Programmable device source code and binary (programming) image files for all programmable devices used on custom printed circuit boards in the NGAO system. 7. Configuration, set up and/or switch/jumper setting information for all custom components. 8. Programmable device source code and binary (programming) image files for all programmable devices used in COTS components where the programmable device source code has been modified or customized for the NGAO system. 9. Configuration, set up and/or switch/jumper setting information for all COTS components.	Noted

Short Name	ID	Description	Compliance
Grounding and Shielding	KS-39	The enclosures of AC line connected components shall be grounded in conformance with the requirements of the National Electric Code and any local codes. Grounding conductors shall be continuous and bonded to the enclosure (or other designated grounding surface) in at least one point. The grounding point shall be specifically provided for the purpose and shall not be a screw or nut used for mounting components or covers. Any paint or surface treatment that acts as an insulator shall be removed in order to ensure a good electrical contact for the ground connection. All components capable of generating electromagnetic emissions in excess of the limits established in the standards referenced in KS-43: Electromagnetic Compatibility will be shielded and the shielding grounded to limit electromagnetic emissions to the levels allowed by the standards referenced in KS-43: Electromagnetic Compatibility. All components susceptible to externally generated electromagnetic emissions in excess of the limits established in the standards referenced in KS-43 Electromagnetic Compatibility will be shielded and the shielding grounded to protect those components from unintended operation due to external electromagnetic emissions of the levels established in the standards referenced in KS-43: Electromagnetic Compatibility.	Noted
Electromagnetic Compatibility	KS-43	Standards exist that specify the test conditions and limits for electromagnetic emissions and electromagnetic immunity. They do not give information on how to achieve compliance. In the absence of such information WMKO believes that a satisfactory level of electromagnetic emission and immunity compliance can be achieved by following the requirements given in requirements,KS-22: Continuity of Shielding and Grounding, KS-21: Electrical Assemblies and Enclosures, KS-39: Grounding and Shielding. For information on the permitted level of emissions and the required level of immunity the following standards may be consulted: 1. The conducted and radiated emissions limits for unintentional radiators are specified in Title 47 CFR Part 15, sections 15.107 and 15.109 for class B devices. 2. Electromagnetic immunity requirements are given in the Council of the European Communities Directive EMC 89/336/EEC, and the reference standard of the European Committee for Electrotechnical Standardization (CENELEC) EN 50082-1:1997 “Electromagnetic compatibility-Generic immunity standard-Part 1: Residential, commercial and light industry” published in the Official Journal of the European Community on March 1, 1998.	Noted
Connector and Cable Mounting	KS-37	Cable and wiring strain reliefs should be designed so that strain relief and wiring integrity is not compromised by opening access doors or removing service access covers. Connectors should not be mounted on service access covers or on access doors.	Noted

8. Risks and mitigation

8.1. Suitability of Smart motors

Research into smart motors was done and presented in KAON 668. The results showed that they were a strong candidate for lower precision devices with intermittent motion. Some testing is needed to gain experience with their behavior, their idle power dissipation and whether or not they will function reliably at the operating temperature of the cold box.

8.2. Piezo-linear stages for LGS PnS beacon steering

Two vendors were identified for these stages. Some testing is required once the architecture is chosen to be sure they will meet our requirements. The concerns are the operating temperature and the cable length. The interface to the controller needs to be tested for reliability and speed.

8.3. Uncertainty in device list

As the subsystem designs mature, the devices change. It has been difficult to know if the list is correct. In order to solidify the motion control design, there needs to be confidence in the device list and the requirements on DOF.

8.4. Requirements

The requirements have been in a state of flux. A major review was performed the week of 1-March, the results of which have not been reviewed. Hopefully this has produced a more useable set of requirements.

9. Plans/schedule for Detailed Design Phase

This section must be completed for PD.