Alignment, Calibration, Diagnostics, Metrology, and Monitoring Subsystems for NGAO: Initial Requirements and Conceptual Design

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ABSTRACT

This note outlines the requirements and a design 'concept' for alignment, calibration, diagnostics, metrology and monitoring with the Next Generation Adaptive Optics (NGAO) system at Keck Observatory. This work was part of the system design phase of NGAO, a standard phase of new instrument development at W. M. Keck Observatory.

1. Introduction

Before adaptive optics observations can begin, the various NGAO wavefront sensors and science instruments should be calibrated and aligned including AO calibrations such as the calibration of wavefront sensor offsets to compensate for static aberration in the science instrument beam train. But radiometric calibration for the instruments also needs to be considered. During observations, several systems may be needed to record and analyze AO and instrument data and produce diagnostics and quality metrics. The topic of "alignment, calibration, diagnostics, metrology and monitoring" is quite broad. The NGAO management team [1] envisioned this study as being focused on the optical systems that support the calibration and diagnostics tasks. The task definition of reference 1 is:

> "Define the tools needed to support routine alignment and calibration and to provide the required routine metrology and diagnostics. Monitoring tools that are not part of the AO system, such as an external MASS/DIMM should be included under this category. Alignment, calibration, and diagnostics tools will likely include a telescope simulator with multiple NGS and LGS sources and a means of simulating turbulence, as well as arc lamps for science instrument calibration."

The atmospheric profiler in the original WBS is now part of a separate WBS element 3.2.3.10: Atmospheric Profiler. This study did not consider the monitoring of environmental conditions, such as temperature, humidity, and particle counts inside the AO enclosure. These functions are part of the design work for the AO enclosure and other releated studies. The low level software that gathers the required data from the AO real-time control systems for use in calibration, diagnostics and monitoring of the AO system is not considered in this study, but is part of the AO Real-time Control Software design. This study also does not consider the high level algorithms and associated software that would analyze the real-time data recorded for use in calibrating and determining AO performance. This is part of the AO Observing Tools task and the Real-time Control Software task.

The design team developed a plan [2] for accomplishing this task. The plan included:

- Requirements
- Description of interfaces to other parts of NGAO
- Design of an AO simulator at a conceptual level
- Design of instrument calibration sources at a conceptual level
- Discuss high cost items
- Discuss high risk items
- Highlight areas for further study during the preliminary design phase
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This document is the final report of the design effort for the alignment, calibration, and diagnostics task.

2. Overview of systems to support alignment, calibration, and diagnostics

The following systems are envisioned to provide alignment, calibration, and diagnostic information for NGAO:

- Standard sources for flux (flat field) and wavelength (spectral line) calibration of instruments
- Astrometric source for instrument field distortion calibration
- Simulated NGS and LGS sources for calibration, optical testing, and alignment of the AO system
- Wavefront measurement capability in each science instrument
- Atmospheric simulator

The standard sources for instrument calibration would likely be an integrating sphere with white light and spectral sources. These could be placed at an entrance of the AO bench as a facility that could be shared by all the instruments and provide calibration of the AO system detectors and instrument flat field correction simultaneously.

The current Keck NIRC2 instrument is equipped with a precision grid of small holes [3] at a focus inside the instrument. This point spread function (PSF) grid is used to map the optical distortion of the instrument across its field of view. A similar gird would likely be placed at the NGAO input focus for astrometric calibration of the AO and the instrument. Each instrument may also have its own internal grid source like the current NIRC2 instrument.

Simulated NGS and LGS sources would be located at the input focus at the front of the AO bench. These simulated sources are used for:

- Checking optical alignment (registration) between the AO system and instruments
- Point spread function and field aberration verification and calibration
- Testing atmospheric dispersion compensators (ADC)
- Calibrating chromatic aberrations
- Measure DM-to-lenslet registration
- Measure DM influence functions
- Non-common path aberration calibration
- Closed loop AO tests

The simulator would be designed to have several diffraction limited and seeing limited NGS sources. The LGS sources would attempt to mimic the elongation of laser guide stars, as closely as possible. These sources would be used in combination with the wavefront measurement capability of the AO system to calibrate each deformable mirror and each wavefront sensor. The point source is also used to verify the registration between wavefront sensors and deformable mirrors. The point source would also be used the measure instrument non-common path aberrations.

The instrument should be able to determine the aberration differences between the AO system and the instrument optical trains, the so-called "non-common path" aberrations. At present, AO systems meet their performance specifications by placing a shape on the deformable mirror that cancels instrument aberrations; this shape is the "zero point' for dynamic correction of the atmospheric distortion. An alternative would be to require much tighter tolerance on the optical quality of the instrument. The measurement of these wavefront errors and correction by the AO system has proven adequate in present AO systems [4-6] and appears to work at tolerances typical of extreme AO systems [7]. A number of techniques are available for measuring these aberrations including, phase diversity algorithms, fiber optic interferometers, point-diffraction interferometers, and 'on-instrument' wavefront sensors. Most of these techniques would make use of an optical source located at the input focus of the AO optical system.

In order to test the AO systems ability, to correct atmospheric turbulence during the daytime and other times when the sky is not available the AO system would be equipped with a means to simulate atmospheric distortions. This simulator would also be useful during the assembly, integration, and test phase of the AO system. In current AO practice, turbulence simulators pass a reference beam through a distorted optical surface that mimics atmospheric turbulence or through a turbulent fluid (mixing cold and hot air). Both these aberrating media could be used in a source simulator which would be placed close to the input focus of the AO system.

Although the original study plans [1] suggest that a metrology system might be needed to measure alignments between the NGAO system and its instruments, the author did not have enough detailed information to consider it at this time. A "metrology like" alignment system [8] was proposed originally for the Keck AO system. Some parts were installed in the NIRC-2 camera but it was later decided not to be needed. A laser metrology system for the Palomar AO system was also considered [9] but was not installed.

In the next section, we list our proposed performance requirements on the above systems. These requirements are high level and do not include standard WMKO instrument baseline requirements such as the ability to operate at high altitude, etc. These requirements will change as the project matures. Please consult the current requirements document and the electronic database for the most up-to-date requirements.

3. Requirements

3.1. Instrument radiometric calibration source (IRCS) requirements

Flat field images
The instrument radiometric calibration source shall provide uniform illumination (flat fields) over the wavelength range from visible to near IR, covering at least the wavelength range 0.6-2.5 μm and over a field of view up to 150 arc seconds diameter. It is possible to have separate sources (lamps) covering the visible and near IR parts of the spectrum.

Spectral line sources
The IRCS spectral source lamps shall have enough strong emission lines so that at least 1 spectral line per 1 nm wavelength interval will reach a SNR of 100 in 60 second exposure.

Uniformity
The assumption when flat-fielding a detector is that the flux falling in each pixel is the same. The calibration beam at the output of the stand source shall be smoothly varying and the spatial profile understood. These requirements could be achieved by a combination of intrinsic uniformity of the beam and subsequent calibration of the beam profile with reference to a standard source such as the twilight or nighttime sky. The standard source shall be uniform to 0.2% over 40 arc seconds scales at the center of the AO field of view and uniform to 3% over a 180 arc second field of view, a random 10 arc second patch over this field shall be uniform to 0.5%.

Stable pupil shape
The pupil shape shall be constant to 1% over the course of a night of observing. This places limits on the mechanical stability of the IRCS and on the repeatability of its insertion mechanism. The tolerance on the relative motion of optical components is to be determined (TBD)

Intensity
The IRCS shall have a signal to noise ratio of 1000 per pixel in a 60 second exposure with the proposed science instruments.

Time to deploy and remove
The IRCS shall be able to be inserted and removed from the AO beam in 60 seconds or less. The warm-up time for lamps to reach stable operational output shall be less than 30 seconds. This will likely require feedback control of the intensity from the source.

Control of lamps
The IRCS lamps shall have an on and off intensity control as part of the AO non real-time software. It can also be control by the instrument control software either directly or through an interface to the AO software

Temporal stability
The intensity of the continuum sources shall be stable to 5% (with a goal of 1%) during any 12-hour period.

3.2. Instrument astrometric calibration source requirements

Astrometric grid spacing, size, and uniformity
The astrometric reference source shall have sources covering a 40 arc second field of view with an inter hole spacing of about 0.5 arc seconds. The diameter of the holes shall correspond to 0.005 arc seconds with a tolerance of plus minus 700 nano arc seconds. The random error in the inter-hole distance (center to center) shall vary by no more than plus or minus TBD nano arc seconds. These tolerances are typical of the current NIRC2 astrometric grid [3] and are suitable for near IR instruments. Tighter tolerance may be need for NGAO near-IR and visible instruments.

Intensity
The light source used to illuminate the astrometric grid shall be intense enough to produce a signal to noise ratio of 100 per spot in a 20 second exposure.

Translation and rotation of source grid
It must be possible to rotate and translate these astrometric grid elements. This allows the use of numerical techniques that simultaneously solve for the positions of the holes and the distortions of the optical system.

Time to deploy and remove
The astrometric grid shall be able to be inserted and removed from the AO beam in 60 seconds or less.

3.3. Instrument wavefront error calibration requirements

Measure science instrument wavefront error
The science instrument shall be able to measure the wavefront errors from the telescope Nasmyth focus to instrument focal plane to better than 22 nm rms. The current NGAO AO error budget [10] allocation for “uncorrectable instrument aberrations” is 32 nm rms. We have allocated half this error in a RSS sense to measurement. The remainder of this error is the residual (fitting error) after the AO system and instrument aberrations are corrected by positioning the deformable mirror actuators to the correct position. The error is a combination of intrinsic optical quality and the use of the various deformable mirrors to compensate for them. Allocation of this error to on-axis versus field aberrations is TBD and likely will vary on an instrument by instrument basis. The exact methods of wavefront sensing will be determined on an instrument by instrument basis.

3.4. AO wavefront error calibration requirements

Source simulator
The AO system shall have white light (visible and NIR) artificial sources that simulate both seeing and diffraction limited NGS sources. The AO system shall have narrow line (~580-600 nm) LGS sources that are approximately the same size and elongation as the expected LGS spot size on the sky.

Number and location of LGS sources
The LGS sources shall be arranged in two asterisms of 5 stars in a regular pentagon. The pentagon diameter shall be equivalent to either 15 arc seconds or 100 arc seconds. A single LGS source shall be located at the center of the pentagons.

Number and location of NGS sources
The number and location of the NGS sources is TBD.

RMS wavefront error for NGS sources
The NGS sources that are sized at the diffraction shall produce ‘clean beams’ for wavefront calibration of the AO system and the instruments. The rms wavefront error of these sources shall be 1 nm rms or less or the wavefront error will be able to be calibrated to this level.

DM-to-lenslet misregistration
The current NGAO AO error budget [10] allocation for “DM-to-lenslet misregistration” is 15 nm rms. The current NGAO AO error budget [10] allocation for “DM-to-lenslet Pupil Scale error” is 15 nm rms. This is an overall requirement on the NGAO system the specification of the AO point sources must be consistent with it.

3.5. AO turbulence simulator requirements

Seeing values and isoplanatic angle
The atmosphere shall be simulated by at least two phase screens that can be independently moved (rotated). The phase screen shall be matched to the median (50%) r_0 and θ_0 of the Mauna Kea Ridge [11] model. These values are respectively 16 cm and 2.7 arc seconds at a wavelength of 0.5 μm.

Greenwood frequency
The two phase screen shall be movable with variable speeds and direction of rotation, such that they can simulate Greenwood frequencies between 60-10 Hz.

Transmission for NIR wavelengths
The phase screens shall have transmission of 80% or better for wavelengths of 0.5-2.5 μm.

Repeatable turbulence
The turbulence phase screens shall be repeatable in position, when static, such that the AO performance can be measured repeatability to an error of 10 nm rms or less.

3.6. AO to instrument stability requirements

Mechanical drift
The science instrument to AO system mechanical drift shall amount to 7.50 milli arc seconds or less in a 30 minutes exposure [10].

Field rotation errors
Long exposure field rotation error on the science instrument shall be 15 milli arc seconds or less in a 30 minute exposure [10].

These two requirements are overall NGAO requirements. Any metrology or active alignment system must be consistent with these specifications

4. AO NGS and LGS source simulator conceptual design

The next sections contain conceptual designs for AO and instrument alignment, calibration, and diagnostics systems. The designs make the assumption that current state of the art methods for calibrating current single conjugate [4-7] AO systems and multi conjugate AO systems are sufficient. However, the NGAO design features some “open loop” multiple object AO (MOAO) elements. It is one task of the upcoming preliminary design to verify that these assumptions about calibration are justified.

The AO system will have NGS and LGS source simulators located in front of the AO bench. The current AO design [12] places the infinity focus inside the K-mirror between the first and second mirrors. The location of the LGS focus is even further inside the K-mirror. If single mode fibers or pinholes are used to generate a reference wavefront for the AO system, some means will be needed to relay these optical “clean beams” from their source to the AO focus. This optical design task may prove challenging with regards to the requirements for RMS wavefront error for the NGS sources. Non diffraction limited sources will have somewhat relaxed requirements. If the same optical relay is used for both NGS and LGS sources then some means will be needed to correct of the focal difference between LGS and NGS sources. A schematic is shown in Figure 1. This relay is shown as two lenses. However, the need to operate across both visible and NIR wavelengths may require a reflective optical design. Since the aberrations resulting from the LGS source passing through the 1-to-1 optical relay is static, predictable, and of relatively low spatial order, small optical correctors could be built into each LGS source. A novel method [13] used at the Gemini telescope, is inclusion of a low cost 19 channel deformable mirror inside the point source generator used to calibrate its active optics wavefront sensors.

5. Design of an atmospheric simulator conceptual design

The point source simulator can serve as an atmospheric simulator if rotating phase plates are inserted into the system as shown in Figure 1. In order to meet the requirement on operation to a wavelength of 2.5 μm the phase plates will need to be made of etched IR grade fused silica similar to those made by Silios in France. If transmission to 1.6 μm is acceptable then plastic materials may be used, at a considerable cost savings, similar to phase screens made by Lexitek in Massachusetts.

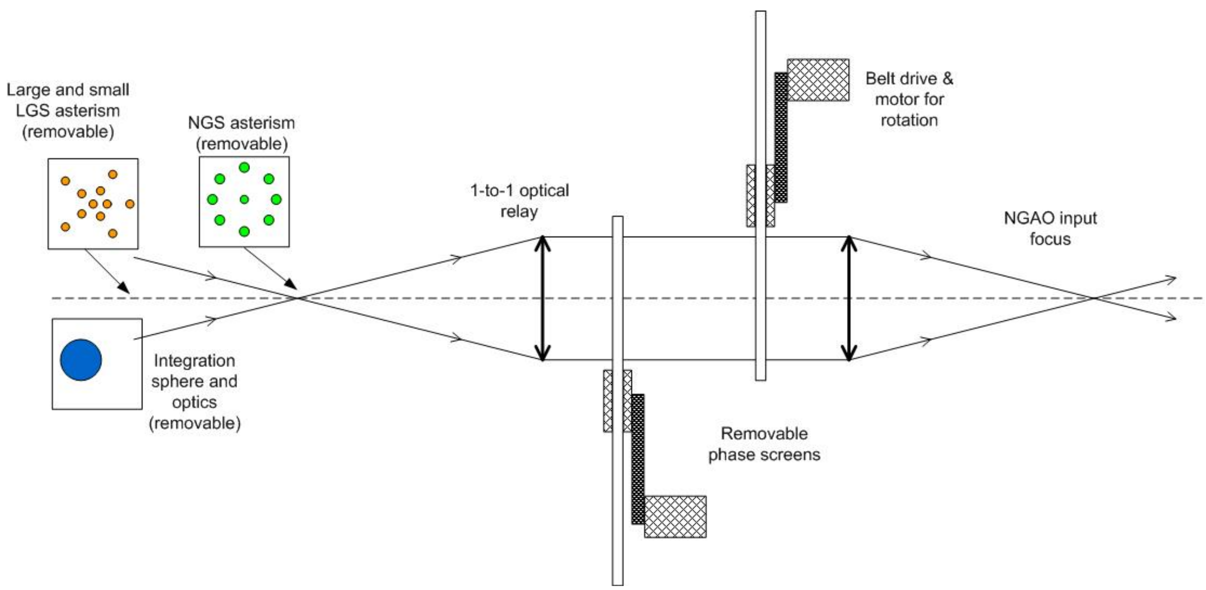

Figure 1: A schematic diagram of a combination atmospheric simulator, LGS and NGS source simulator, and radiometric calibration source.

6. Design of an instrument calibration source conceptual design

Based on the OSIRIS experience, it is suggested that a flat field source can be constructed from an integrating sphere and optics that project the sphere's output port onto the telescope exit pupil. Both a white light and spectral lamps could be used with the same sphere. The OSIRIS lamps are listed in Table 1. These are typical of the spectral lamps used for wavelength calibration of NIR spectrographs. The OSIRIS source use an 8-inch diameter integrating sphere with Infragold coating manufactured by Labsphere. Coatings of this type are ideal for NIR applications. However, they produce less illumination in the visible (< 1 μm) part of the spectrum. NGAO will need to evaluate the cost and benefits of having a separate flat field source for visible and NIR detectors.

Table 1: The OSIRIS lamps

Lamp manufacture and model number	Element
Pen-Ray B-191605	Xenon
Pen-Ray B-172636	Argon
Pen-Ray B-172904	Krypton
Pen-Ray B-173023	Neon

7. Conclusion and recommendations

The sections above contain an outline for calibration sources for NGAO assuming that calibration methods used on current AO systems can be adapted to NGAO use. A more detailed analysis of the calibration errors and resulting design tolerance is needed. This might include some computer simulation of incorrect AO calibrations on NGAO performance. The placement of the atmospheric simulator, LGS and NGS source simulator, and radiometric calibration source all at the entrance to the NGAO optical bench will likely present challenges for packaging the system into the existing space. The "clean beam" sources used for non-common path aberration calibration should be placed directly at the NGAO input focus, if possible. However, this area is inaccessible in the current optical design. The need to relay these diffraction-limited sources will place tighter tolerance on the source simulator optical design. The need to use the atmospheric simulator at NIR wavelength up to 2.5 μm requires the use of expensive glass phase plates. The NGAO project needs to verify this wavelength requirement in the next phase of design.

Recommendations for future work include the following:

1. Analysis of calibration methods for NGAO and resulting design tolerances
2. Detailed opto-mechanical design of source simulator including its mechanical packaging
3. Verify requirement on atmospheric simulator operation to 2.5 μm (might 1.6 μm be acceptable)

References

1. P. Wizinowich, R. Dekany, D. Gavel, C. Max, S. Adkins, D. Le Mignant, "Keck Next Generation Adaptive Optics: System Design Phase Systems Engineering Management Plan", Keck Adaptive Optics Note (KAON) 414, September 29, 2006.
2. C. Neyman, "NGAO System Design Phase: Work Scope Planning Sheet WBS Element 3.2.3.9 Alignment, Calibration, Diagnostics, Metrology and Monitoring", http://www.oir.caltech.edu/twiki_oir/pub/Keck/NGAO/WorkProducts/3.2.3.9_AlignCalibDiagMetrMont.doc.
3. P. Cameron, "NIRC2 Geometric Distortion", http://www.astro.caltech.edu/~pbc/AO/distortion.pdf.
4. Keck AO Calibration Procedures: http://www.keck.hawaii.edu/realpublic/optics/pages/operations.html. note: this reference page is probably not reachable from outside the Keck network firewall
5. M. van Dam, et al, "The W. M. Keck Observatory Laser Guide Star Adaptive Optics System: Performance Characterization", **118**, 310-318, 2006.
6. M. Oliker, "Alignment Techniques for DM, Lenslet, and WFS Camera at the SOR", SPIE 3126,
7. J. Sauvage, "Calibration and pre-compensation of non-common path aberrations for extreme adaptive optics", JOSAA, **24**, 8, pp. 2334-2346, 2007.
8. T. Gregory ,"Adaptive Optics Bench to NIRC-2 Alignment", Keck Adaptive Optics Note (KAON) 35, 1995.
9. E. Bloemhof and R. Deknay, "Metrology for the Adaptive Optics System at the Palomar 200" telescope", Proc. SPIE Vol. 3353, p. 638-648, 1998.
10. R. Dekany and M. Britton, "NGAO wavefront error budget", Keck Adaptive Optics Note (KAON) 471, 2007.
11. R. Dekany, "Mauna Kea Ridge (MKR) Turbulence Models", Keck Adaptive Optics Note (KAON) 503, 2007.
12. R. Kupke, et al., "Opto-Mechanical Design for the Keck NGAO Cascaded Relay", Keck Adaptive Optics Note (KAON) 549, 2008.
13. M. Boccas and T. Vucina, "Performance and upgrades of active optics on Gemini telescopes", Proc. SPIE, 6273, 2006.