Keck Adaptive Optics Note 745

NGAO System Calibration Unit

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1. Introduction

This note describes the design and performance of the AO system calibration unit. Its primary purpose is to provide reference point sources for system testing and calibration as well as uniform flat field and spectral line sources for the science instrument calibration. In other AO systems, such as the one currently in use at Keck, reference point sources are created by simply placing a single mode fiber at the input focal plane. Unfortunately in the NGAO system this is internal to the image rotator and is inaccessible. Since a simple fiber source will not work, an optical relay will be used to form an image of the reference sources at the input focal plane to the AO bench. The relay is designed to produce the correct f-ratio, pupil location and shape to mimic the telescope, while maintaining a very small wavefront error over the operational field.

2. Requirements

In this section is a brief summary of the key features and discussion of the variances from the requirements. Details of the implementation are in the following sections of this document. KAON 772 contains the complete compliance matrix.

Operational wavelength. <u>0.5 to 2.4 µm.</u> This matches the operating range given in FR-3276 for the NGS wavefront sensor and that in SR-22 for the science camera input. AO system throughput to the interferometer system is specified to a maximum of 3.9 µm but this long wavelength is currently unsupported by the calibration unit.

Calibration modes. <u>NGS and LGS point sources, flat field continuum, spectral line sources, astrometric grid.</u> These operational modes support the necessary calibrations for the AO system. NGS and LGS point sources are used for wavefront sensor and DM calibration as well as science camera image sharpening. Flat field continuum is used for flat fielding the science camera. The spectral line source is used for spectral calibration of the spectroscopy modes of the science camera. The astrometric grid is an accurate grid of unresolved sources that is used to measure the science camera field distortions.

NGS point source type. <u>Resolved and unresolved.</u> FR-1789 specifies both seeing limited and diffraction limited broadband NGS sources. The diffraction limited sources will be used for the science camera image sharpening routines that measure non-common path aberrations as well as for various wavefront sensor registration and calibration tasks. The resolved sources will be used for calibrations where the source size is a critical factor such as centroid gain measurements.

LGS point source type. <u>Resolved and unresolved.</u> FR-2151 only specifies resolved sources, however with the current plan that uses fiber optics it is a very small amount of additional work to include unresolved sources. As for the NGS case, resolved sources will be used for calibrations where the source size is critical such as centroid gain measurements while the unresolved sources will be useful for DM to lenslet registration.

Point source number and location. <u>Three NGS repositionable across the entire FOV, six LGS arranged in two equilateral triangles.</u> This is a combination of FR-1791, FR-3281and FR-1790. The goal of these requirements is to be able to test a range of tip/tilt star configurations. Providing three sources that are repositionable over the entire field implies a fairly complicated mechanical device with at least six motion control axes. To reduce the system complexity an arrangement of several sources in fixed locations is used instead of providing continuously variable locations. The source points for testing the tip/tilt sensors have collocated NGS and LGS sources, and the center of the field has a dual NGS/LGS source as well. There are LGS sources corresponding to the central LGS asterism, and a few other NGS sources in the central portion of the field. See section 4 for more details about the source distribution.

Flat field source. Broadband and spectral line uniform illumination. The flat field source will uniformly illuminate the image plane. FR-1773 requires a 0.6 to 2.5 µm spectral bandwidth over a 40 arcsecond diameter field of view. FR-1775 places a 0.2% uniformity requirement over the central 40 arcseconds of the field. The source needs to be stable to at least 5% over a 12 hour period according to FR-1780, with a goal of 1%. A calibrated photodiode will be placed in the system to monitor the light output and provide a feedback signal for source stabilization. For convenience, the spectral line sources will share the flat field illumination device to provide even coverage. The lamp types have not yet been chosen, but will likely be a combination of Xenon, Argon, Krypton, and Neon.

Astrometric grid. Uniform grid of unresolved sources. The astrometric grid will be a uniform grid of 5 milliarcsecond diameter holes spaced 0.5 arcseconds apart (FR-1783). It will be back illuminated by a broadband source with a 0.6-2.5 µm spectral bandwidth. FR-1785 requires it to have rotational and translational motion for calibration purposes.

Turbulence simulator. Optical phase aberration source. FR-1794 requires a method to simulate atmospheric turbulence. FR-1796 requires the greenwood frequency to be controllable between 10 and 60 Hz, and FR-1795 requires that the turbulence generated be from two screens and be matched to the Mauna Kea seeing model, r_0=16 cm and q_0=2.7 arcseconds. KAON 739 states that while it is desirable to have the turbulence generator be a permanent part of the calibration unit, it should not drive the cost or schedule. Due to space constraints the current design does not allow for permanent mounting of rotating phase plates that would also meet the requirement in FR-1798 for repeatable turbulence. Options are to include these phase plates in the calibration unit but only with the AO bench open, to substitute for a turbulence simulator outside the bench, or to include a hot air or other gaseous phase turbulence generator.

Wavefront error. Suggested 35 nm rms maximum. This is not explicitly specified in the Contour requirements database, but is addressed by KAON 568 and 739. The wavefront error requirement for the NGS source is not equal to the allowable AO system calibration error because the error is common path between the wavefront sensor and the science arm. It can therefore be removed during the calibration process. It must still be small enough, however, that any non-linear effects are smaller than the calibration error budget. The LGS source has a different wavefront error from the NGS source, and since it can not be calibrated using image sharpening it must use an external wavefront sensor that will be mounted on the same stage as the input fold mirror in front of the AO rotator.

Pupil mask. Removable. There is not currently a Contour database requirement for the pupil mask other than FR-1776 which sets the pupil shape uniformity requirement to 1% over a night of observing. Certain calibrations, such as the DM to lenslet registration, must illuminate the entire DM and wavefront sensor, while certain others, such as aligning components to the optical axis requires a pupil mask. Therefore the pupil mask must be removable.

3. Optical design

The combination of wide spectral bandwidth and small wavefront error across the full corrected AO field makes for a very challenging optical design. One major concern that was independent of the design chosen was the tolerance for figure error of the optical elements. During a recent discussion with a vendor, they indicated that for these optics 1/80 to 1/100 wave rms figure error would take some effort but was a reasonable specification. This results in a wavefront error of 16 to 12.5 nm, respectively assuming normal incidence. For the 1/100 wave case, this results in an overall wavefront error of 31 nm rms if there are six surfaces in the system. This amount of error is very large compared to the wavefront error goal. Note that this does not consider any other sources of error such as mounting effects or error inherent in the design.

One mitigating factor here is that on most optics the beam footprint for each field position will not cover the full clear aperture. This will serve to reduce the rms wavefront error contribution from that surface.

3.1 Alternative designs considered

A refractive design was briefly considered since it would likely be more compact, but the broad range of operating wavelengths made this design impractical. Multiple elements would be needed to control the chromatic effects to the necessary level which conflicts with the desire to keep the number of surfaces to a minimum. Index homogeneity is also a concern when dealing with transmissive elements at the nanometer tolerance level.

An off-axis parabola based relay was considered, but not chosen mainly due to packaging concerns. The area around the AO rotator is tight and any reasonable geometry required parabolas with a large off-axis distance. This drives up the cost of the optics and also makes it more difficult to meet the tight figure error specifications.

A few other designs were briefly considered and discarded. These included various forms of off-axis telescopes, either based on more traditional Cassegrain telescopes or more exotic three mirror telescopes such as a three mirror anastigmat. These either had packaging problems similar to the off-axis parabola systems or required higher order aspheric mirrors. Again, concerns about cost and figure accuracy eliminated these types of systems.

3.2 Offner relay design

After some investigation, a traditional Offner relay was chosen as the focus of the design. The biggest advantage is that it uses all spherical surfaces which will allow relatively cost-effective optical elements. Spherical surfaces are also somewhat easier to align. The main drawback to the Offner design is that the pupil plane is located at the secondary mirror, so it is more difficult to include pupil masks and there are limitations on the use of phase screens.

A typical Offner has a primary and secondary mirror with two reflections off of a monolithic primary. With this design, however, to obtain an exit pupil that matches the main telescope the pupil stop had to be displaced from the secondary. This presents a problem since any pupil mask placed there would also obscure the beam in the other arm of the relay. Splitting the primary into two parts allowed creating the desired exit pupil when the pupil stop was placed on the secondary.

The basic layout is shown in Figure 1. Folds are included to fit into the available space on the AO bench. These folds will be actuated in tip/tilt so that the calibration unit optical axis can be accurately aligned to the AO bench optical axis. This will allow correction of any errors that arise from the removal/replacement of the calibration unit as a whole and also for any thermal deformations that happen when cooling the AO bench to operating temperature.

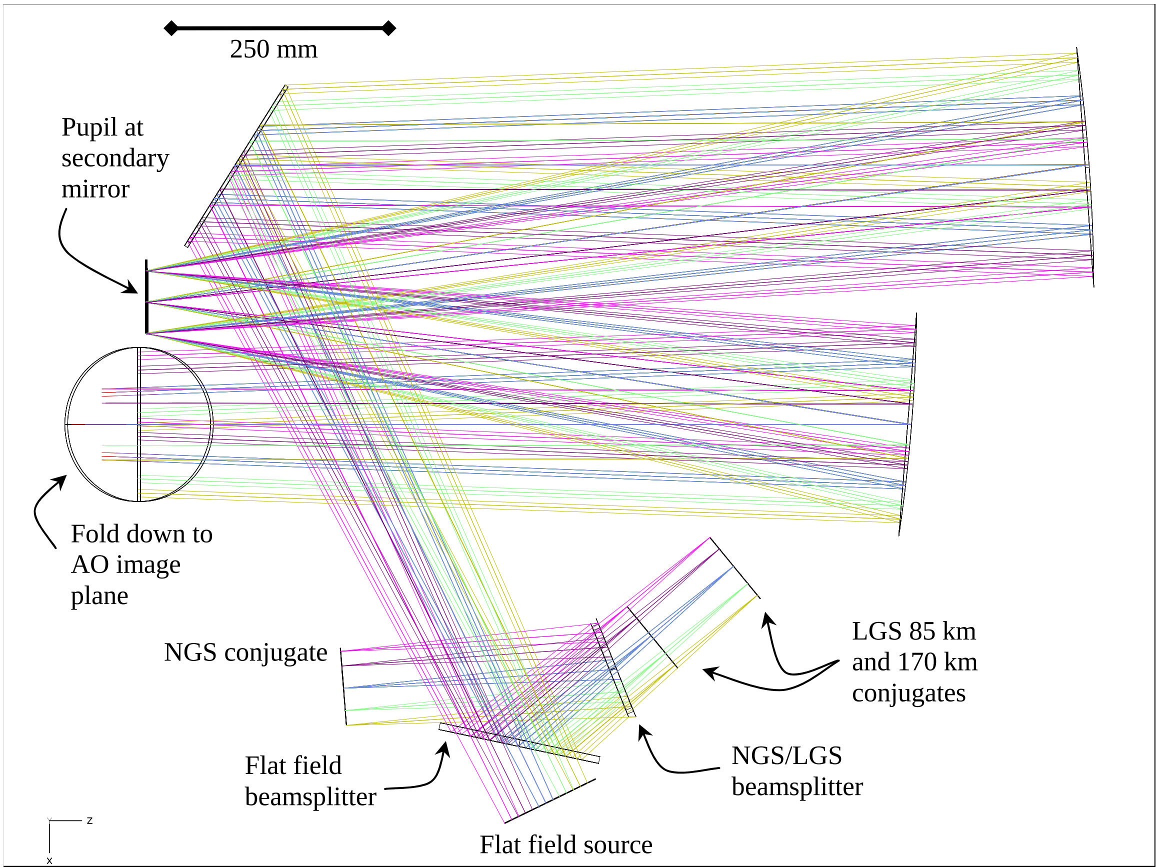
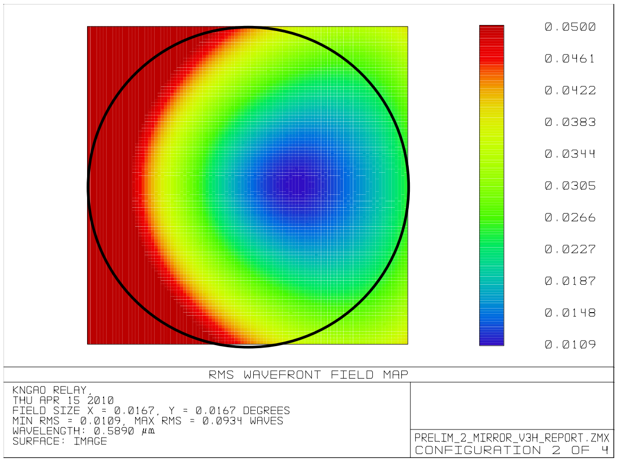


Figure 1. Offner relay optical layout.

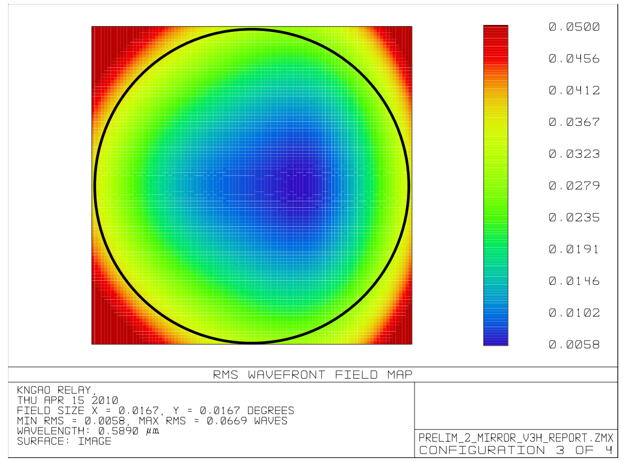
The zemax model was optimized simultaneously for the NGS conjugate and two LGS conjugates at 85 km and 170 km. These two sources are available concurrently through the use of a beam splitter, and were arranged such that the NGS source is in reflection. This avoids any chromatic effects in the NGS source from transmission through the beam splitter. Since the LGS source is monochromatic it was easily optimized to compensate for the small aberrations from the transmission through the beam splitter. The back surface of the NGS/LGS beam splitter has a long radius to help this compensation. A second beam splitter is included to provide a port for the flat-field and spectral calibration sources. These are non-imaging and so are minimally affected by the beam splitter transmission.

The pupil is at the secondary mirror. A hex mask matching the main telescope pupil will be mounted on a removable stage to allow illuminating the entire DM and WFS sensor areas when necessary. Some calibrations, such as camera flat-fields or pupil alignments, require a pupil mask, while others such as DM to lenslet registration must be done without a pupil mask to allow access to the entire DM.

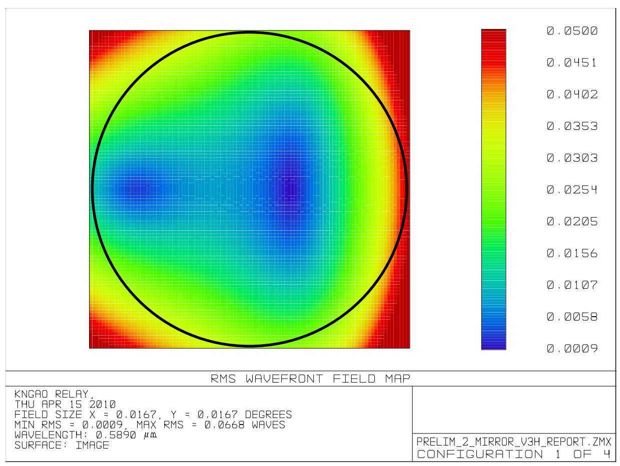
Figure 2 shows the rms wavefront error over the full 120 arcsecond field for the NGS and both LGS conjugates. The scale is in waves at 589 nm, so 0.034 waves corresponds to 20 nm and 0.05 waves corresponds to 30 nm. Figure 3 shows plots of the OPD for these configurations.



LGS 85km conjugate

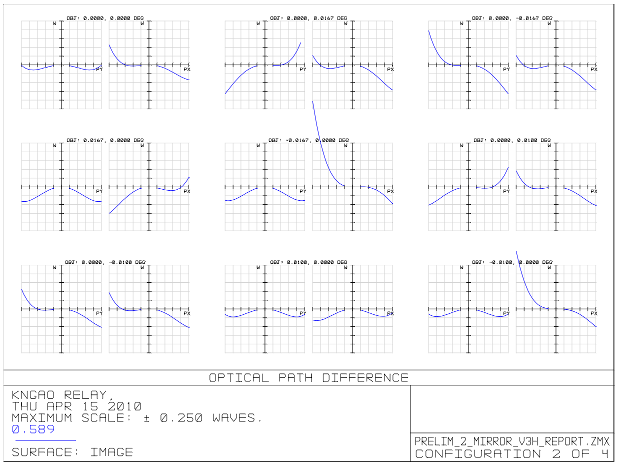


LGS 170km conjugate

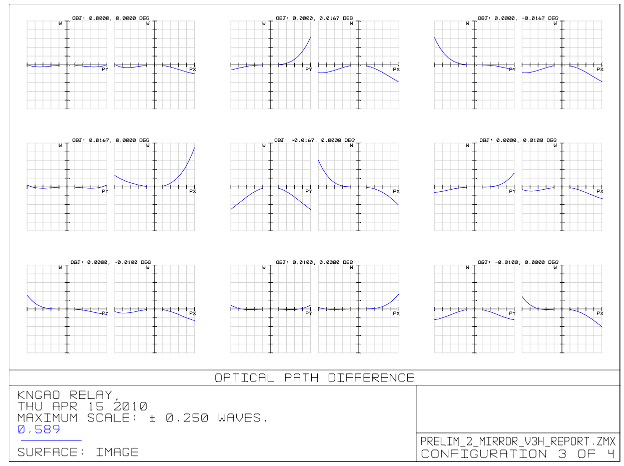


NGS conjugate

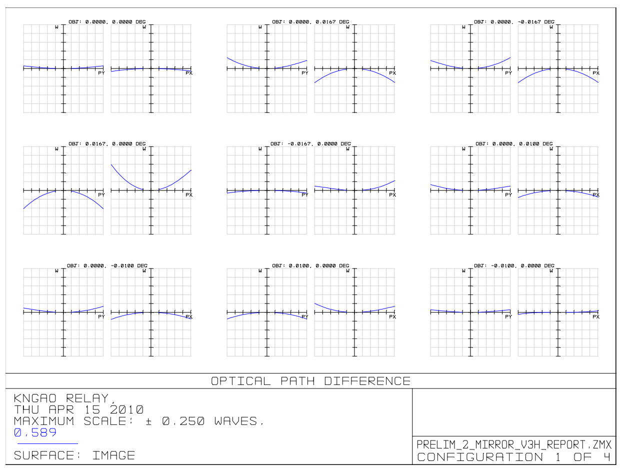
Figure 2. Field dependent rms wavefront error at different conjugates. Shown as waves at 589 nm, so 0.05 waves equals 30 nm and 0.034 waves equals 20 nm. The black circle denotes the full 120 arcsecond field of view.



LGS 85km conjugate



LGS 170km conjugate



NGS conjugate

Figure 3. OPD plots for different conjugates.

3.3 Tolerance analysis

A preliminary tolerance analysis in zemax was performed on a simplified system consisting of the powered elements. As the mechanical design progresses, data from finite element analysis will be used to refine the performance numbers and also provide feedback about any areas of the mechanical design that need improvement.

The perfect system has a wavefront error of 0.026 waves at 589 nm wavelength when averaged across the field. A monte carlo analysis was performed with the tolerances in Table 1, with the result that 90% of the systems had a wavefront error less than 0.043 waves and 50% of the systems had less than 0.030 waves.

Table 1. Optical tolerance specifications.

Element	Tilt (degrees)	Decenter (mm)	Radius (%)	Spacing to next element (mm)
M3	0.0056	0.100	0.1	0.5
M4	0.0100	0.100	0.1	0.5
M5	0.0056	0.100	0.1	0.5

3.4 Alignment

The Calibration Unit will be aligned as a subsystem prior to integration with the AO bench. The Zemax model will be updated and optimized based on the as-built data for the optics. From this model updated element positions will be used to finalize the mounting hole locations on the baseplate. Figure 4 shows features relevant to the alignment procedure. Note that there are three main axes that are important. The system optical axis between M2 and M3 is parallel to that between M4 and M6, and the red line in Figure 4 is halfway between these two and parallel to them. This line contains the center of curvature of all three powered mirrors in the system, M3, M4, and M5.

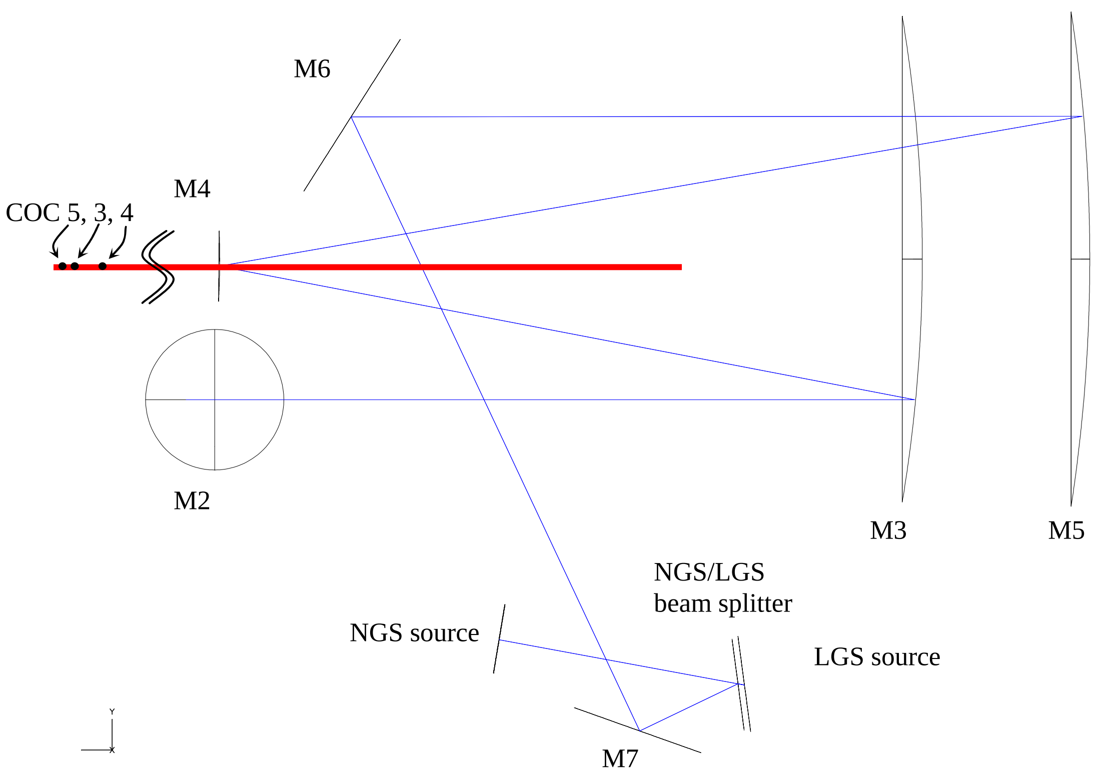


Figure 4. Detail of alignment features. Elements are the same as Figure 1, however the full “parent” size of the two concave spherical mirrors are shown. The blue line is the optical axis for the system, and the red line is a reference that is parallel to the input and output optical axes and contains the center of curvature for M3, M4, and M5.

This is a preliminary alignment procedure for the calibration unit. More details will be added during the detailed design phase.

- Mark lines to represent the optical axis location between M2 and M3 and between M5 and M6. Also lay out a line that corresponds to the red line in Figure 4.
- Place M3 and M5 on the optical bench. Place the point source formed with an interferometer with an f/8 or faster diverging lens at the desired position for the center of curvature of M3 or M5 and adjust the mirror to bring its center of curvature into the correct location. When this is true, the interferometer will measure zero tip, tilt, and power.
- Place the NGS source stage assembly, the beamsplitters, and the LGS source assembly on the baseplate. Use an alignment telescope to ensure that the NGS and LGS sources are aligned to the desired optical axis, and that the focus stage travel is also aligned to the optical axis.
- Place M6 on the bench and use the alignment telescope to adjust M6 such that the optical axis matches the marked line.
- Place M4 and adjust to align the optical axis to the marked line between M3 and M2.
- Use a Shack-Hartmann wavefront sensor to measure the beam exiting the calibration unit. Fine tune the position of M4 to minimize aberrations. Check the wavefront quality at other field points and use M4 adjustments to correct.

3.5 Turbulence generator

It is possible to place a phase plate to simulate turbulence at two places in the optical system. One is at the pupil formed on M4 and is conjugate to the ground layer, while the other is at M5 and is conjugate to 11.5 km. The ground layer plate will be small enough to fit in the enclosure, but there may not be room to include a mechanism to move it in and out of the beam since that area is very tight. The 11.5 km conjugate is at M5, and the plate would have to be at least 750 mm in diameter. This will not fit inside the AO enclosure and could only be used with the enclosure removed and the bench warm. The 11.5 km conjugate wheel could be reduced in diameter somewhat at the expense of some field. If the field is limited to 30"x30", the 11.5 km wheel could be reduced to roughly 500 mm in diameter.

There are a few possible alternatives to the rotating phase plate. The most straightforward is to inject a disturbance signal onto the LODM. This would produce an easily controllable ground layer turbulence simulation, but would be limited to the spatial scales achievable with the DM. Additionally, since it is impossible to introduce turbulence that is not in the control space of the DM it is not a good model of true atmospheric turbulence.

One other method that could be investigated is a turbulent gas system, where two gases with different refractive indices are mixed. This is traditionally done with hot air, however a heat source in the AO enclosure is not a good idea. Instead, it should be possible to use a gas such as helium that has a different index of refraction. The helium could be injected through an outlet underneath the region where the turbulence is desired. The speed of the airflow can be varied to change the modeled wind speed, while the index of the helium can be adjusted by mixing it with air prior to injection to give the correct amount of optical phase. This method would require testing during the detailed design phase to determine if it would be a practical solution. A phase plate at the ground layer conjugate would likely still be needed to meet the requirement for repeatable turbulence.

4. Sources

All light sources will be outside the cold enclosure and coupled via fiber optics to the calibration unit. This reduces the amount of heat dissipated inside the cold enclosure and also makes it much easier to replace failed lamps.

The NGS and LGS sources in the image plane will not be mounted on an x-y stage, but rather multiple sources will be mounted at fixed locations across the field. This pattern can then be rotated by using the image rotator on the AO bench to access more field points. The combination of multiple sources and the image rotator will allow calibration at a large enough set of points to sufficiently cover the field. These sources will include a mixture of both unresolved sources and larger fibers to simulate a seeing limited spot. Figure 5 shows a conceptual layout for the sources in the image plane. The NGS and the LGS sources will have very similar arrangements. The on-axis source will be an unresolved source for the NGS pattern to allow good accuracy when using it to measure the position of the optical axis. The LGS on-axis source, however, will be a resolved source so that the on-axis LGS WFS can have a properly sized object during testing.

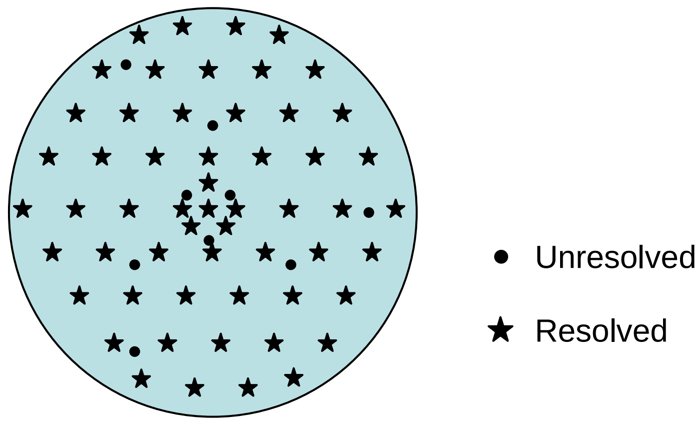


Figure 5. NGS and LGS source arrangement.

To simplify the coupling of the fibers to the light sources individual control of the brightness of the fibers will not be included. The fibers will be sufficiently spaced in the image plane to minimize crosstalk during the calibrations, and will be grouped into a few sets that can be controlled independently.

For all of the sources except the LGS source, there will be a single, large diameter fiber bundle that carries the light from the lamps to the calibration unit. These will be identical assemblies that use the same connector type. The LGS source will use a single, large core fiber instead of the fiber bundles. At the calibration unit, each main fiber from the lamps will be split into the individual fibers that are then routed to correct locations. The individual source fibers will be gathered into a bundle for coupling to the main fiber. If the source fiber bundle is small enough, it may be possible to simply butt it up against the incoming large fiber bundle. Otherwise, some simple re-imaging optics may be necessary.

All sources except for the spectral line lamps will be able to provide a wide range of illumination levels. While it may be possible to pre-select one or a few levels to handle the typical calibration procedures, experience with the current Keck AO systems has shown that it can be useful during system engineering and troubleshooting to have access to a wide range of brightness levels.

4.1 NGS

The baseline light source for the NGS fibers is a Xenon arc lamp such as the 66476 Oriel Research Series from Newport[1]. The controller for this source includes intensity control via RS232. The output will be focused onto a fiber bundle for transport to the NGS focal plane. The fibers will include both single mode fibers with a 4.3 µm core for the unresolved sources and fibers with a 400 µm core to provide seeing limited sources. This corresponds to 6 milliarcseconds and 550 milliarcseconds. For comparison, the current Keck AO system uses a 400 µm resolved fiber source and a 10 µm unresolved source. A shutter will be included to allow completely blocking the output for dark calibrations while maintaining stable lamp operation.

Since the lamp will fail with little to no warning, the current design includes two lamp sources each with their own fiber bundle. This will provide redundancy and prevent problems caused by a lamp failing at inopportune moments. Although it is only possible to provide a central fiber from one of the two fiber bundles, this position is used primarily for gross system alignments that are not repeated on a nightly basis so the loss of the lamp supplying the central fiber position will not hamper normal nightly calibrations.

One alternative to using a grid of fibers is to use an arrangement similar to the astrometric grid, where small holes in a plate are backlit to produce the point sources. This plate could use a common backlight with the astrometric grid and realize some savings in overall complexity. However, this would result in a uniform brightness for all of the NGS sources which would prevent testing the system with different brightness tip/tilt stars. The current design that uses two lamps and two fiber bundles allows for two different brightness tip/tilt stars.

4.2 LGS

The LGS sources will be formed from fibers coupled to a laser operating at 589 nm. Diode pumped solid state (DPSS) lasers are now available with powers ranging from 5 to 15 mW at a price of about $4,000[2,3]. These units have adjustable power, and the unit from Crystalaser has an analog modulation input which will make it easy to adjust the output power without the need for a motorized filter wheel.

As with the NGS fiber bundles, the LGS fiber bundles will also include both single mode fibers with a 9 µm core for the unresolved sources and fibers with an 800 µm core to provide seeing limited sources.

It is possible to include two lasers powering separate fiber bundles to add a degree of redundancy to the system. The unit reliability will be examined during the detailed design phase to determine if the cost of this option is justified. The current Keck AO systems do not use a source at the laser conjugate at all during the current calibration routine, however an important difference is that the current wavefront sensor has sufficient travel to reach the NGS conjugate. The current NGAO LGS wavefront sensor design does not have enough travel to reach the NGS focus, although this could be provided through either increasing its travel range.

4.3 Astrometric grid

The astrometric grid will be formed from a grid of micro-machined holes in a plate, very similar to the one currently used in NIRC2. It will have a 80 x 80 grid of holes with a diameter of 3.6 µm and spaced 360 µm on center. This corresponds to 5 milliarcsecond diameter holes on a 0.5 arcsecond grid. The light source will be a woven fiber optic panel[4] placed behind the grid supplied by a lamp source[1]. The throughput of this setup should be checked during the detailed design phase. If it is insufficient, an alternative could use large core optical fibers to supply light into a diffusing chamber behind the hole grid.

The current design places this assembly on an in/out stage at the NGS focus. It could also be placed just in front of the flat field source, however the flat field source is not at the NGS focus in the current design to save space. Moving the flat field source to the NGS focus would add another 325 mm of path length after the flat field beamsplitter. It is not clear if there is room to do this, however this will be an option considered during the detailed design phase.

It is possible to use the AO bench rotator to rotate the astrometric grid pattern instead of including a separate rotation stage. This would simplify the assembly and reduce the overall actuator count. This would, however, change the field dependent aberrations as seen by the science instrument. The impact of this on the astrometric grid calibration will be evaluated during the detailed design phase. If it is acceptable then the rotator for the astrometric grid will be removed.

4.4 Flat field/spectral lamps

A typical flat field setup uses an integrating sphere to obtain very uniform illumination. Since the flat field source in the current design is not at an image plane, the flat field source size needed is larger than what would be required at the image plane. A science field that is 32”x32” would require a minimum port diameter of 71 mm to fully cover the science field. Both Labsphere and Sphereoptics offer this size port only in a 300 mm diameter sphere, and claim a 2% uniformity specification for this configuration.

While a 300 mm diameter sphere would fit, a more compact solution will be tested during the detailed design phase. It uses a woven fiber optic backlight panel to generate a uniform illumination. These panels can have up to eight layers each with their own sources, so some would be dedicated to the flat field lamps and the rest to the spectral lamps. The manufacturer claims that these panels are “very uniform,” but there are no numbers associated with that claim. Some experimentation will be needed to verify the uniformity of the output, but even if the panel is natively poor a diffuser spaced a few centimeters away should correct the problems.

If the woven fiber optic panels are not sufficient, then another compact alternative would be side emitting fiber used along with a diffuser to create the same effect. Yet another alternative is to build a diffuser box[5] that uses the output from multiple fibers reflected off of a Lambertian scattering surface. The referenced unit was made to flat field a CCD directly, but in this case the CCD could be replaced with either an opal or ground glass diffuser and used as the output aperture.

5. Mechanical design

All components will be mounted on a common baseplate with the exception of the motorized fold mirror just in front of the AO rotator. This will allow assembly and testing as a unit prior to integration with the AO bench. A light tight enclosure and possibly internal baffling will be used to minimize the stray light seen by the AO bench during calibrations.

Since the calibration unit is mounted on a part of the AO bench that is inside the telescope elevation bearing access for maintenance is very limited, and it also blocks access to other items below it on the main AO bench. A system of rails will be used to slide it into and out of the elevation bearing. There will be enough travel on the rails to move the calibration unit to a location where it can be picked up with a small overhead crane in the AO room. A three point kinematic mount will be used to ensure a repeatable alignment for the calibration unit when it is removed and replaced. Figure 6 through Figure 10 show views of the unit and its placement on the AO bench.

A finite element analysis will be performed on the mechanical design during the detailed design phase to determine the overall performance and any stiffening that is required for the baseplate. Thermal analysis will also be performed to ensure that the unit will stay within spec when the AO bench is cooled to its operating temperature.

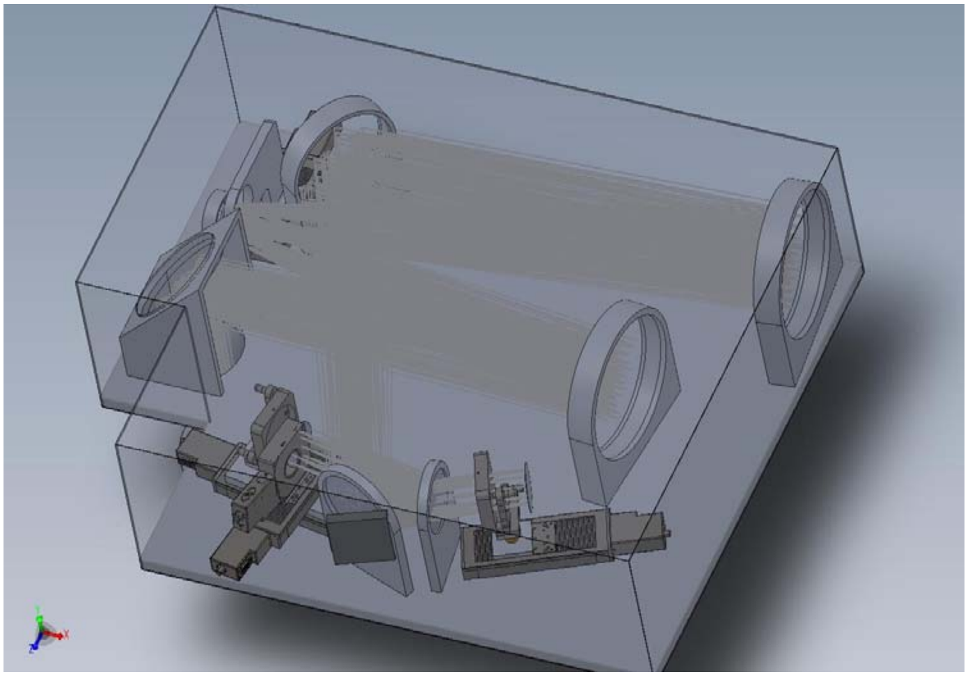


Figure 6. Calibration unit.

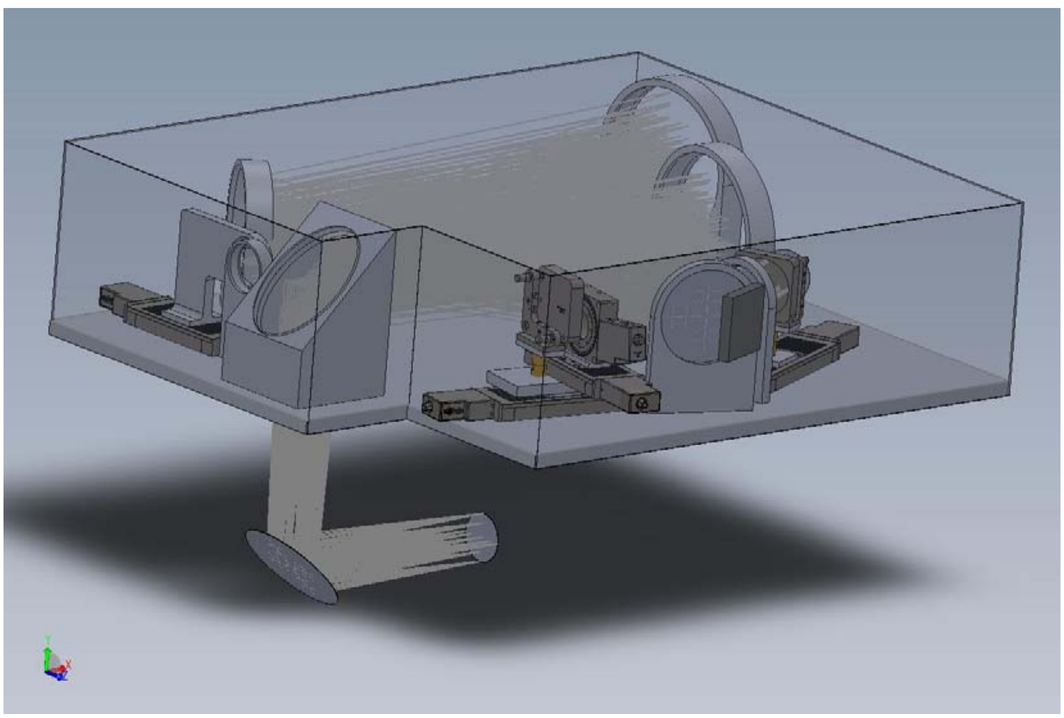


Figure 7. Calibration unit showing fold into AO bench rotator.

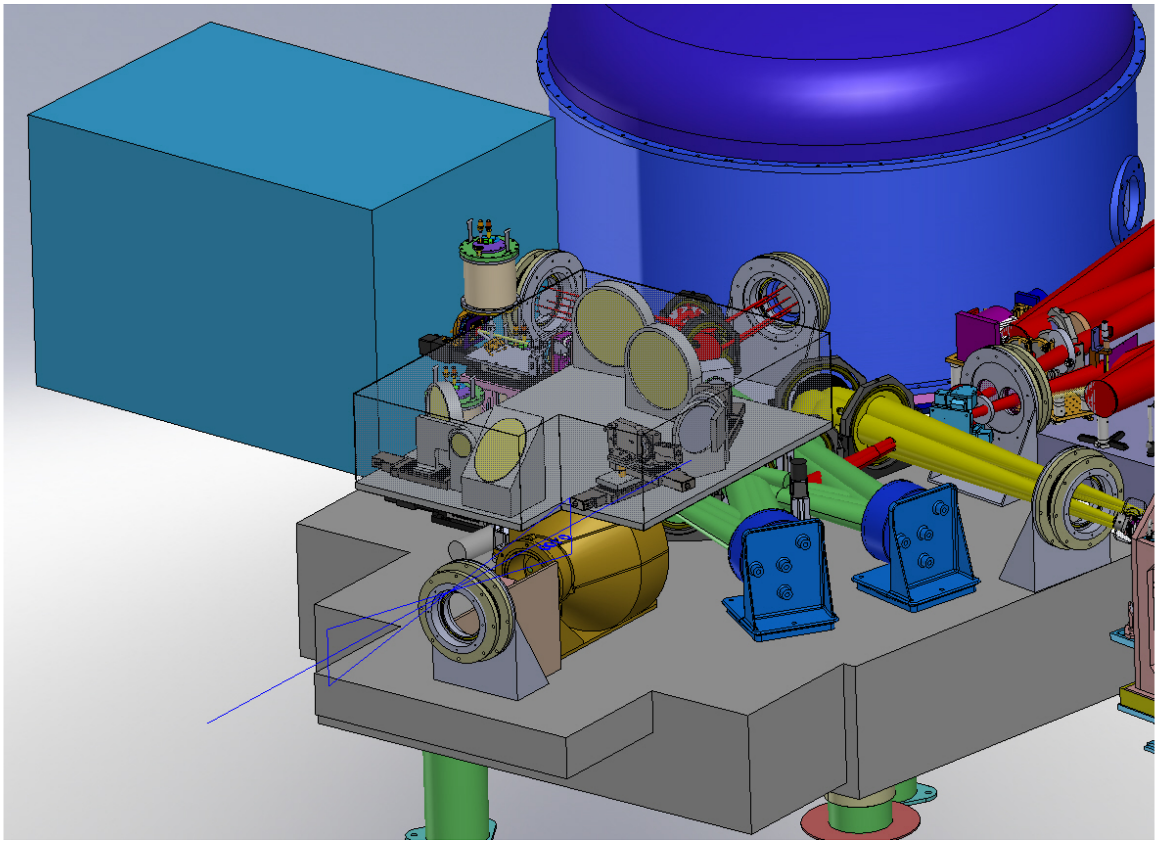


Figure 8. View of calibration unit on AO bench.

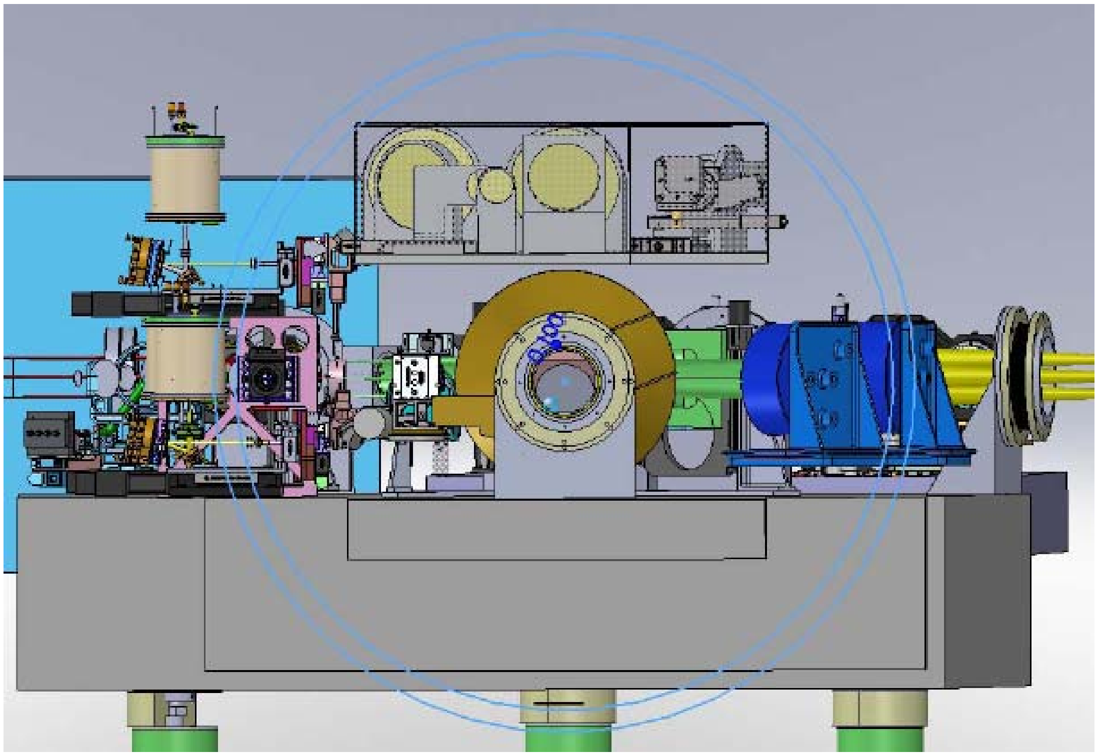


Figure 9. View of calibration unit on AO bench through elevation bearing. The largest blue circle is the inner surface of the elevation bearing and the smaller blue circle is the maximum size for the calibration unit.

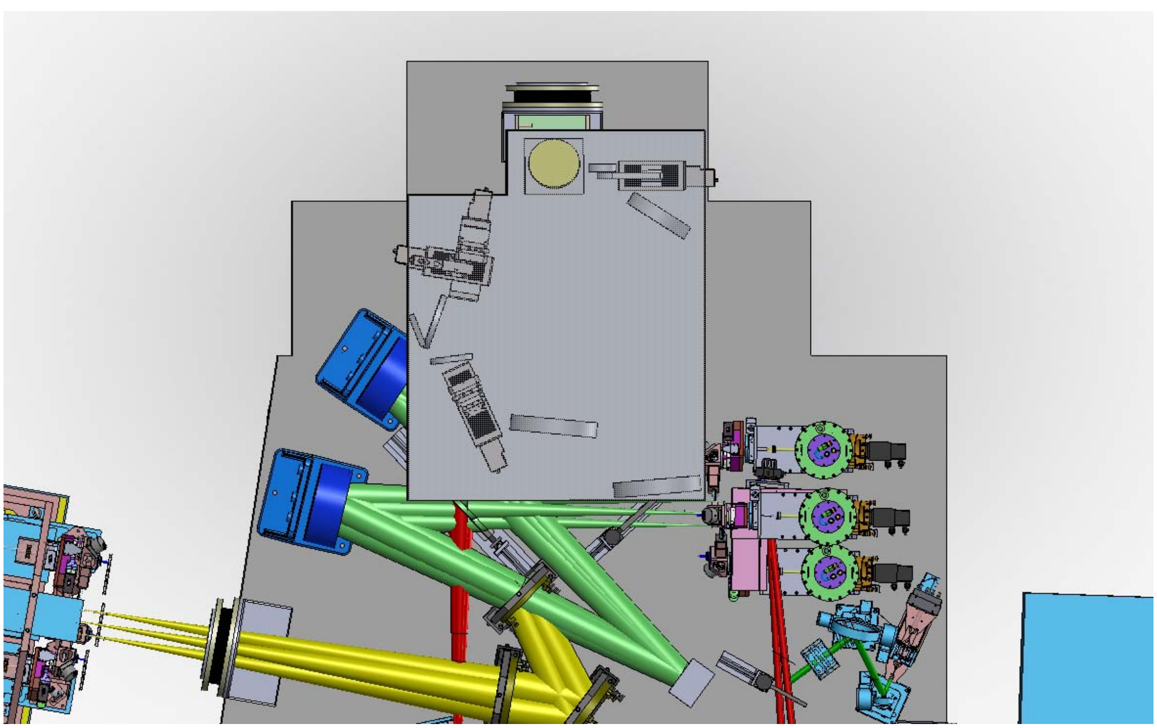


Figure 10. View from above of the Calibration Unit on the AO Bench.

Not shown in these figures is the cold enclosure. The area inside the elevation bearing is tight, however with the indicated envelope for the calibration unit there is 5 cm of clearance at the closest corner. This corner does not need to be square as drawn, and truncating it will increase the clearance available. At the expense of a slightly more complicated baseplate design, the layout of the calibration unit could be adjusted to conform better to the cylindrical shape of the rotator volume below it and so increase the clearance for the cold enclosure. This would result in a non-planar optical system which would complicate the fabrication and testing somewhat, so unless it is necessary the planar design shown will be used.

6. Device control summary

These devices are also shown in the master table of motion devices where more detailed information is available.

6.1 Motion devices

Device	Motion Type	Range	Accuracy
NGS source focus	Linear	25 mm	10 µm
NGS target selector	Linear	100 mm	1 µm
Astrometric grid rotation	Rotation	90 degrees	0.01 degree
LGS source focus	Linear	150 mm	10 µm
Output fold mirror	Tip/tilt	+- 1 degrees	1 arcsecond
Fold mirror at AO rotator	Tip/tilt	+- 1 degrees	1 arcsecond
AO rotator fold mirror in/out	Linear	175 mm	50 µm
Pupil mask in/out	Linear	100 mm	1 µm
Source ND filter wheel	Rotation	360 degrees	5 degrees
Shutter	In/out	25 mm	

6.2 Other devices

Device	Interface type
NGS Quartz Halogen source 1	RS232
NGS Quartz Halogen source 2	RS232
LGS 589 laser source 1	Analog 0-5V
Flatfield Quartz Halogen lamp	RS232
Spectral lamp source	TBD

[1] Arc Lamp Source, 50-200W, F/2.2 Fused silica, 0.5-3mm focus, available from Newport Optics, http://search.newport.com/?q=*&x2=sku&q2=66476

[2] 589nm DPSS laser model CL589-015 with datasheet at http://www.crystalaser.com/CL584-593.pdf

[3] 589nm 10mW DPSS laser model RLTMGL-589-10 is $4,060 at http://www.roithner-laser.at/All_Datasheets/Pricelists/roithner-pricelist-c-100319.pdf

[4] Woven fiber optic panels available from http://www.lumitex.com/machine_vision.html

[5] http://www.ing.iac.es/Astronomy/observing/manuals/ps/tech_notes/tn108.pdf