Next Generation Adaptive Optics System

KAON 659

# Laser Launch Facility Beam Generation System

# Preliminary Design

**Nov 4, 2009**

**VersionV1.2**

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## REVISION HISTORY

| Revision | Date | Author (s) | Reason for revision / remarks |
|---|---|---|---|
| 1.0 | Oct 19, 2009 | All | Initial release |
| 1.1 | Oct 20, 2009 | EW | Add KAON number (was TBD) |
| 1.2 | Nov 04, 2009 | JC | Updated risk summary |

# TABLE OF CONTENTS

# 1 INTRODUCTION

As part of the Next Generation Adaptive Optics System (NGAO), a Laser Launch Facility (LLF) System is needed to generate and propagate the laser beams. One component of the LLF System is the Beam Generation System (BGS). The BGS is located within the secondary f/15 module on the telescope. It receives the laser beam(s) from the Beam Transport Optics (BTO), formats them into the required asterism into the LT, and provides the beam pointing on the sky. This document provides the preliminary design for the BGS. Some sections of the document have not been completed to the level required for PDR; these sections will be modified prior to the PDR.

## 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 510 | 1.0 | WMKO | NGAO Technical Risk Evaluation |
| 2 | KAON 511 | 0.3 | WMKO | NGAO System Design Manual |
| 3 | | x.x | Web | Optical Characterization of the Laser-Induced Sparks in Air |
| 4 | TBD | 1.0 | WMKO | LLF Requirements Document |
| 5 | TBD | 1.0 | WMKO | LLF Requirements Compliance Matrix Document |

**Table 1: Reference Document**

### 2.2 Acronyms and Abbreviations

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

| Acronym/Abbreviation | Definition |
|---|---|
| BGS | Beam Generation System |
| BTOB | Beam Transport Optical Bench |
| BTOS | Beam Transport Optical System |
| CW | Continuous Wave |
| DDR | Detailed Design Review |
| K1 | Keck 1 |
| KAON | Keck Adaptive Optics Note |
| LGS | Laser Guide Star |
| LLF | Laser Launch Facility |
| LT | Launch Telescope |
| MCLS | Motion Control System |
| NGAO | Next Generation Adaptive Optics System |
| NGS | Natural Guide Star |
| OPD | Optical Path Difference |
| PDR | Preliminary Design Review |
| PNS | Point and Shoot |

| | |
|---|---|
| PNSAG | Point and Shoot Asterism Generator |
| TBD | To Be Determined |
| WMKO | W. M. Keck Observatory |

**Table 2: Acronyms and Abbreviations**

## 3 OVERVIEW

The Laser Launch Facility (LLF) includes all of the systems involved in forming a focused spot at the sodium layer from the output of the laser units. During the Preliminary Design phase this layout from KAON 511 has changed somewhat from the concept presented during the System Design phase. The new overall layout is shown in Figure 1. This document covers the Beam Generation System (BGS) which in located in the secondary socket along with the Laser launch telescope (LT).

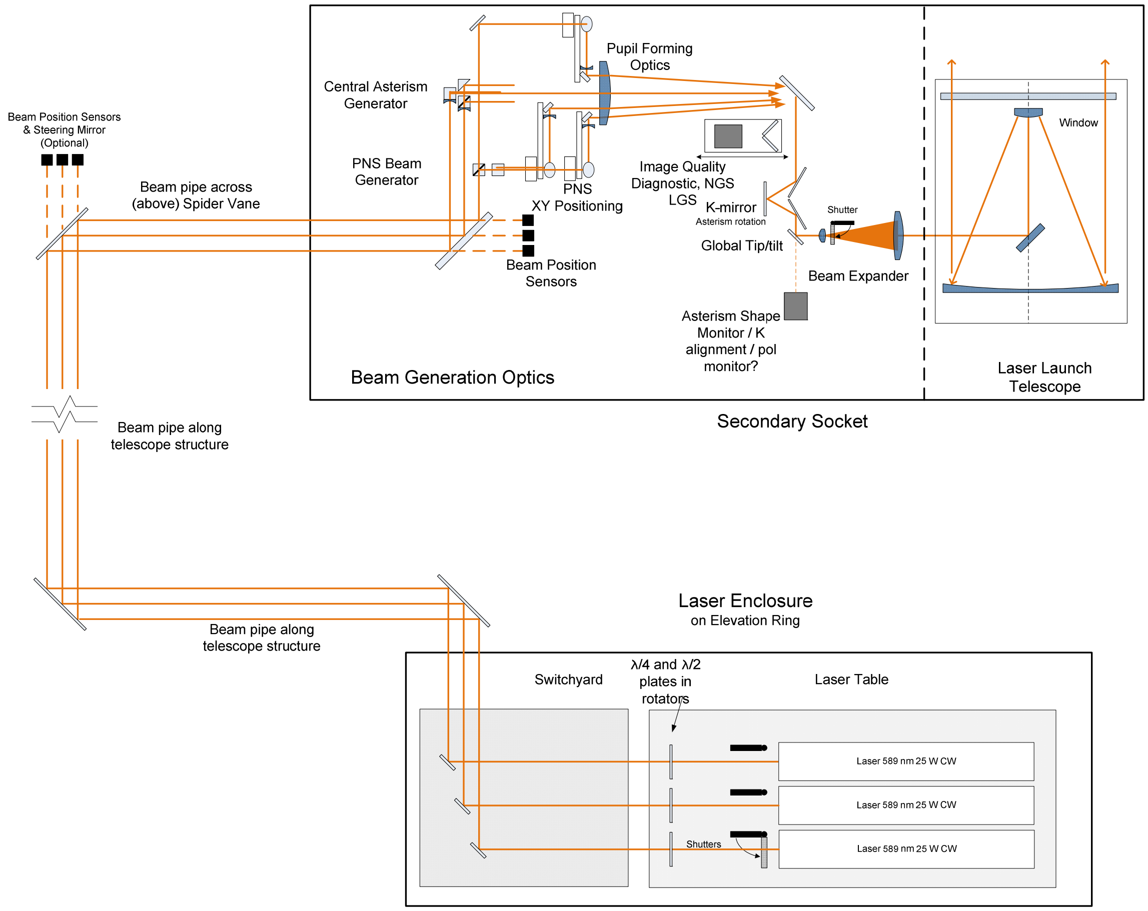


**Figure 1: Laser Launch Facility Layout**

The location of where the BGS system fits into the overall NGAO System is shown in Figure 2. The BGS will have a mechanical interface to the f/15 module or components within the f/15 module.

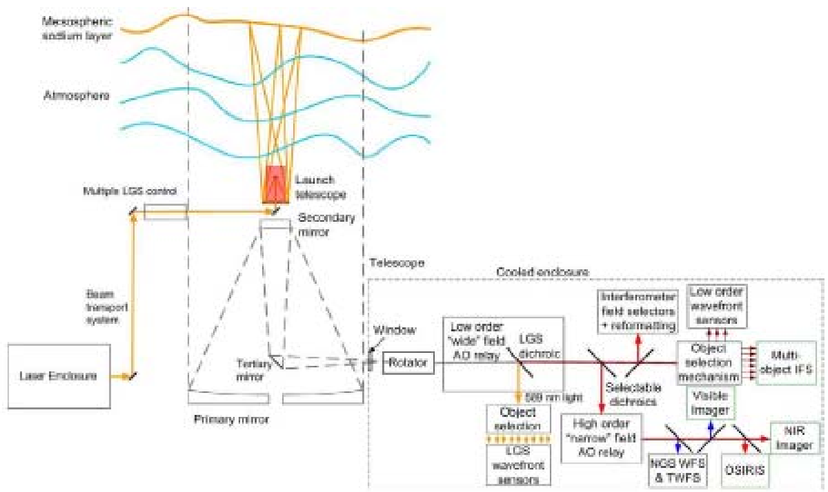


**Figure 2: Laser Launch Facility BGS (shaded in red) within the NGAO System**

# 4 REQUIREMENTS

A detailed list of all the requirements for the Beam Transport Optical System is presented in the LLF Requirements Document. The BGS is part of the BTOS and will apply the requirements as outlined by the BTOS.

The main function requirements for the BTOS are as follows:

- Relay the output of the laser units to the LT
- Divide the output of the three laser units into a total of seven beams
- Form the central asterism of one on-axis beam surrounded by three others in an equilateral triangle of inscribed radius 10 arcseconds on sky
- Position the remaining three beams at arbitrary locations in an annulus with an inner diameter of 15 arcseconds and outer diameter of 60 arcseconds on sky
- Reformat the 3 mm diameter beams output by the lasers into the 28.8 mm diameter beams required as input for the LT
- Adjust the polarization of the beams such that the output from the LT is circularly polarized
- Provide steering for the entire seven beam asterism on sky to allow for flexure correction and alignment
- Provide the set of diagnostic capabilities outlined in the requirements listed in the contour database

# 5 DESIGN

## 5.1 Opto-Mechanical Design

### 5.1.1 Optical Design Choices

The BGS design has three main components that drive the design choices: the PNS asterism generator, the central asterism generator, and the beam expander. Since the PNS asterism generator requires positioning three beams in arbitrary locations over a large field, its design influences much of the rest of the system and served as a good starting point. Based on the concepts developed for the PNS generator, the central asterism generator was designed next and finally the beam expander was created to fit the rest of the system. For this design, it was assumed that the LT would have the same input/output beam specifications as the one recently delivered for the Keck 1 LGS project.

#### 5.1.1.1 PNS Asterism Generator

The PNS asterism generator (PNSAG) has the task of positioning three laser beams into an array with the correct spacing and angles required to produce a correctly formatted input to the LT. The LT then refocuses this pattern on the sodium layer. This requires positioning the three beams in space and angling them such that they overlap at the entrance pupil to the LT.

The first decision to be made is where to put the PNSAG. The two possibilities are in the secondary socket or in the laser enclosure. If the PNSAG is in the laser enclosure, the asterism it generates must be relayed to the secondary socket. This would be difficult due to the requirement to enclose the laser beam path in a 25mm wide tube over the spider that supports the secondary socket on the telescope. The angular size of the pattern is inversely proportional to the beam size, and is set by the desired output configuration of a 360 mm diameter beam with a ±60 arcsecond field. A 16 mm $1/e^2$ diameter Gaussian beam is the largest that would fit with minimal truncation losses in a 25mm tube. Even if a pupil was placed at the halfway point, the asterism would have a 65 mm diameter at either end of the spider tube. Relay lenses could be placed in the tube to correct this, but since this would add many surfaces and be sensitive to alignment errors it was decided to place the PNSAG in the secondary socket.

Similar considerations of angular field size result in the conclusion that the beam expander must be between the PNSAG and the LT. At the input to the LT the full angular field is only 0.84 degrees, which means that even the outermost PNS beams overlap until after propagating almost two meters from the LT. Since this path length is impractical to contain in the secondary socket, the PNSAG must operate with the smaller beams from the lasers.

Since the laser beams are approximately collimated, the separation from the PNSAG to the LT input pupil and thus the associated platescale is somewhat arbitrary. It needs to be small enough that the overall system is easy to package, but must be large enough such that the mechanisms for the different beams do not vignette each other. There must also be a mechanism to incorporate the central asterism into the field. See Figure 3 for the field layout.

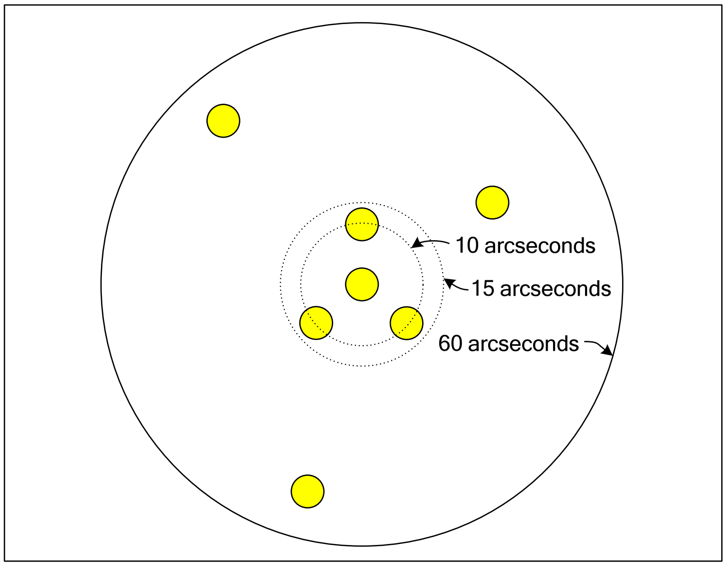


**Figure 3: PNS Field Layout**

The PNSAG must not only position the beam at the desired location in the field shown in Figure 3, but it must also adjust the angle of the beam such that it is centered on the entrance pupil of the LT. This is shown in Figure 4.

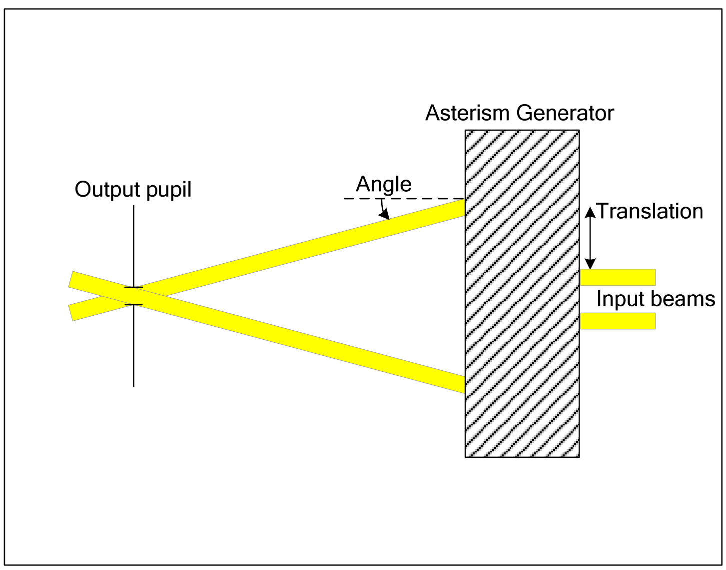


**Figure 4: The PNSAG must set both the field position and angle**

There were a few different methods considered to achieve the required position and angle control. An early concept was to use an actuated tip/tilt mirror at the input to the PNSAG to steer each input beam to the desired point in the output plane. A mirror split into three segments with independent tip/tilt control would then steer that beam onto the LT input pupil. This concept is shown in Figure 5 .

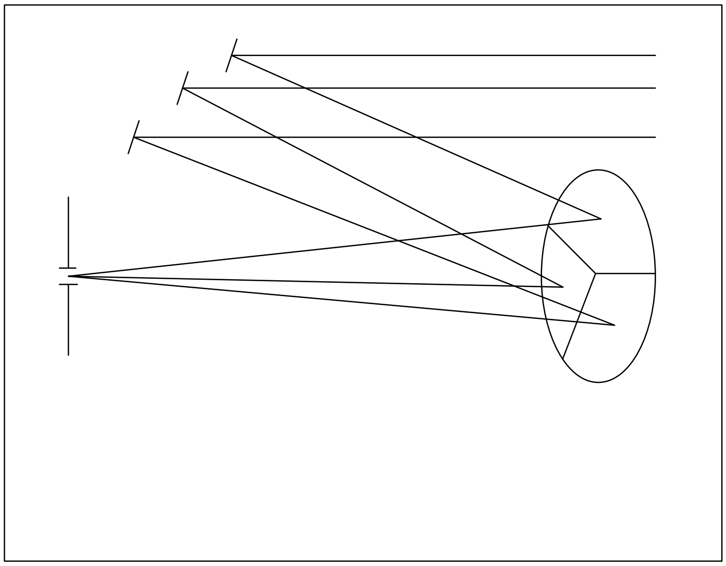

**Figure 5: Split mirror concept**

This concept has the major advantage that all of the control is done by six tip/tilt mirrors. This results in a reasonably simple system with a minimum number of surfaces that is also light weight. It does not allow arbitrary PNS beacon placement, however, as there can only be one beam on each segment. One alternative would be to use more segments, for instance dividing the field into 60 degree wedges. This would allow slightly more flexibility at the cost of adding three more tip/tilt mechanisms. It would also double the areas of the field lost to the boundaries between segments.

It was felt that the limitations of one beam per segment would reduce the chance of finding an appropriate set of NGS guide stars in the field, so an alternative that allowed beacon placement anywhere in the field was sought. Two small mirrors controlled by an x-y stage would allow placement anywhere in the field, but would also require tip/tilt actuation to steer the beam to the LT entrance pupil. This is the direct implementation of the setup shown previously in Figure 4, and could also be seen as a version of the split mirror concept if the segments are reduced in size and allowed to move around the field. The tip/tilt stage would require a tilt range of a few degrees which would be difficult to do in a small package. Using a relatively bulky tip/tilt mount on the pickoff would result in either vignetting or interference issues between the three separate PNS beams. After some thought, it was realized that a lens that has a focal length equal to the distance to the beam expander input pupil would serve to overlap input parallel beams. This lens would also produce a focus at the beam expander input pupil, however, so a small negative lens is required in each of the incoming beams to produce no net power for the system. See Figure 6.

Get image of current system from Drew's Model

**Figure 6: Pupil generator optics and x-y stage layout**

A single input beam is split into three parts to generate the three PNS beacons by using two beam splitters. The first beam splitter has a 33/66 ratio, while the following unit has a 50/50 split. This results in three equal intensity beams. If there are fewer than three PNS targets, mounting the beam splitters on stages allows sending the unused laser power to the remaining targets.

#### 5.1.1.2 Central Asterism Generator

The central asterism is a fixed pattern of four beams, arranged with one central spot surrounded by an equilateral triangle inscribed on a 10 arcsecond diameter circle as shown in the center of Figure 3. These four beams are produced by dividing each of the two incoming laser beams using a beam splitter and a mirror as shown in Figure 7.

Get image from Drew's model

**Figure 7: Central asterism generation using beam splitters.**

#### 5.1.1.3 Image rotator

The BGS must have an image rotator to keep the PNS beacons aligned with the target NGS guide stars. A conventional K-mirror in a rotation mount will provide the necessary field rotation. It will be placed as close as practical to the pupil formed on the global tip/tilt mirror to minimize its physical size. Due to the small size of the beam pattern at this location, the K mirror can be machined from one solid block of metal. Figure 8 shows a conceptual model of the K mirror assembly mounted on a Newport rotation stage.

Drew's Model

**Figure 8: Image rotator**

#### 5.1.1.4 Beam Expander

The beam expander accepts the small diameter beams from the PNSAG output and expands them to form a 28.8mm diameter beam at the input to the LT. To simplify the steering mirror requirements, a Keplerian telescope was used to form a real pupil. The real pupil image allows steering the entire laser constellation with a single tip/tilt mirror without causing pupil misalignment. Without the real pupil image, two coordinated tip/tilt mirrors would be required to maintain proper pupil alignment. This steering capability is used to correct for flexure and alignment errors.

To produce a compact system, a refractive design was considered. Ideally the design would have only two elements to maximize throughput, and would be arranged as a Keplerian telescope so that it will form a real image of the pupil at the LT secondary. This topology, however, does create a real focus inside the beam expander which is a concern with high power laser systems. The lasers used for the NGAO system, however, are CW which significantly reduces the peak power. The expected peak power density is $2.1 \times 10^8$ $W/cm^2$, which is approximately two orders of magnitude lower than where air breakdown effects are expected to start[1] at $1 \times 10^{10}$ $W/cm^2$.

The finished preliminary design for the beam results in an rms wavefront error that varies from 20.6 nm on-axis to 33.5 nm at the edge of the 60 arcsecond field.

#### 5.1.1.5 Detailed System Design

After the general system layout was decided, detailed calculations were made to determine the Gaussian beam sizes at various points in the system. The beam size and separation between the PNSAG and the beam expander was a critical choice. The main constraint for this is that the minimum radius for the PNS beams must be 15 arcseconds on the sky. Inside this circle must fit the central asterism of four beams along with some margin to allow for small amounts of misalignment. The relationship of these dimensions is shown in Figure 9.

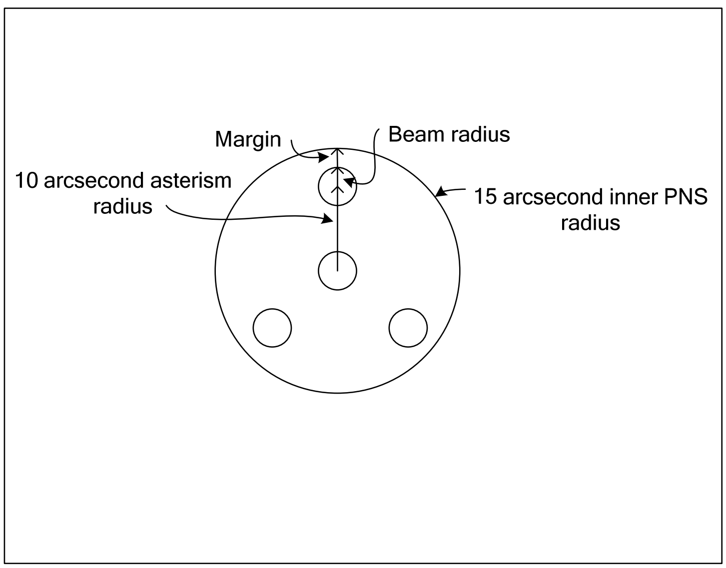


**Figure 9: Central asterism dimensions**

The physical scale of the central asterism as shown in Figure 9 is related to both the beam size and the distance from the PNSAG to the tip/tilt mirror. The beam size determines the magnification required in the beam expander and so also determines the angular scale. The distance from the PNSAG to the tip/tilt mirror coupled with the angular scale of the pattern determines the PNSAG platescale in mm/arcsecond.

[1] P.X. Tran and C.M. White. Optical Characterization of the Laser-Induced Spark in Air. U.S. Department of Energy Memorandum, retrieved 10/18/2009 from http://www.igrant.demon.co.uk/PAPERS/Tran2.pdf

Therefore, for a given beam size there will be a minimum distance between the PNSAG and the beam expander that will allow the 15 arcsecond minimum PNS radius.

After some iteration with component layout and beam sizes, the layout shown in Figure 10 was chosen.

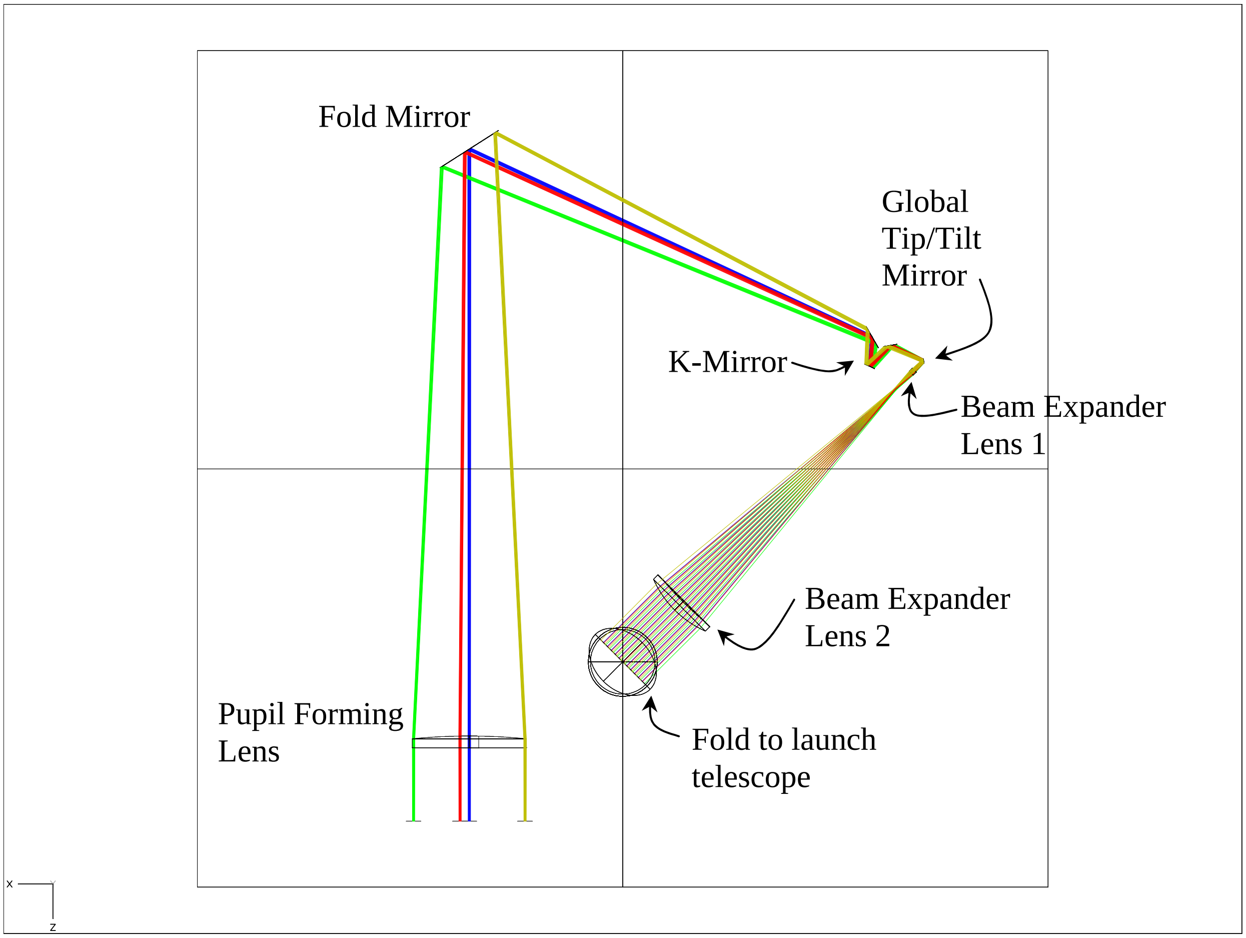


**Figure 10. BGS optical layout.**

The total distance from the PNSAG to the tip/tilt mirror is 765 mm, and the beam size at the PNSAG is 1.3 mm diameter. This results in a full field angle of 5.7 degrees and requires a beam expander magnification of 13.68. This produces in a plate scale at the PNSAG of 0.633 mm/arcsecond and meets the 15 arcsecond minimum PNS radius.

After determining the required magnification for the beam expander a design was produced. The design uses high index glass to minimize aberrations and incorporates two aspheric surfaces. The on-axis wavefront error is 11.8 nm rms while the wavefront error at the edge of the field is 17 nm rms. The layout is shown in Figure 11and the OPD curves are in Figure 12.

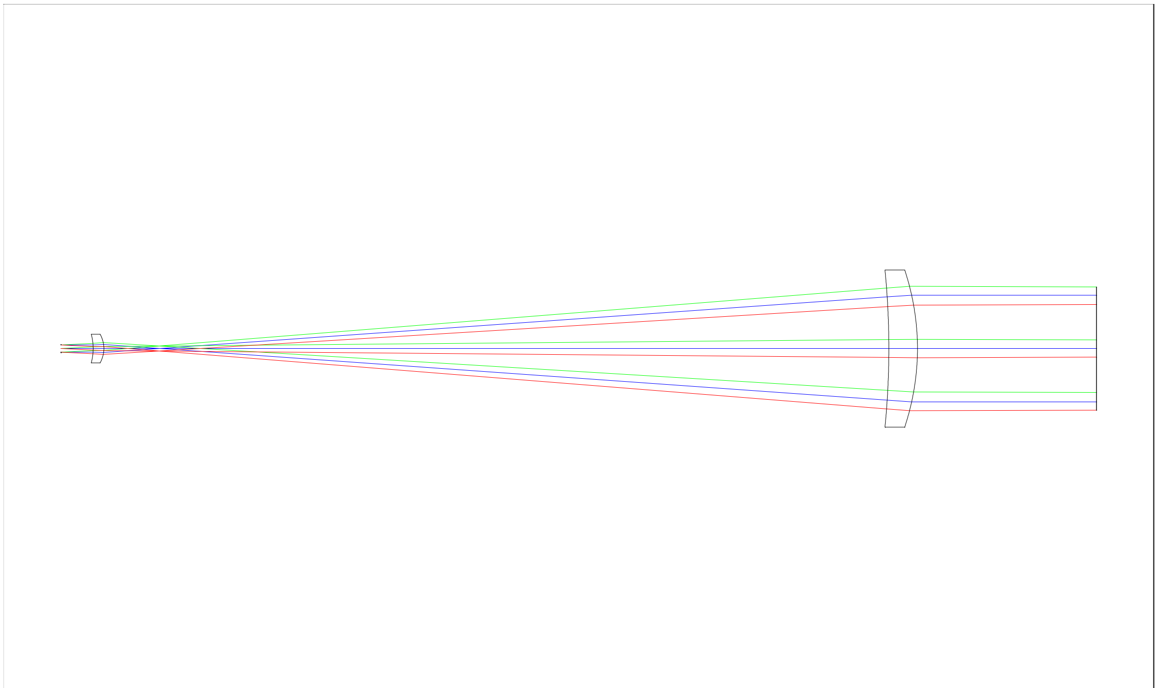

**Figure 11. Beam expander layout.**

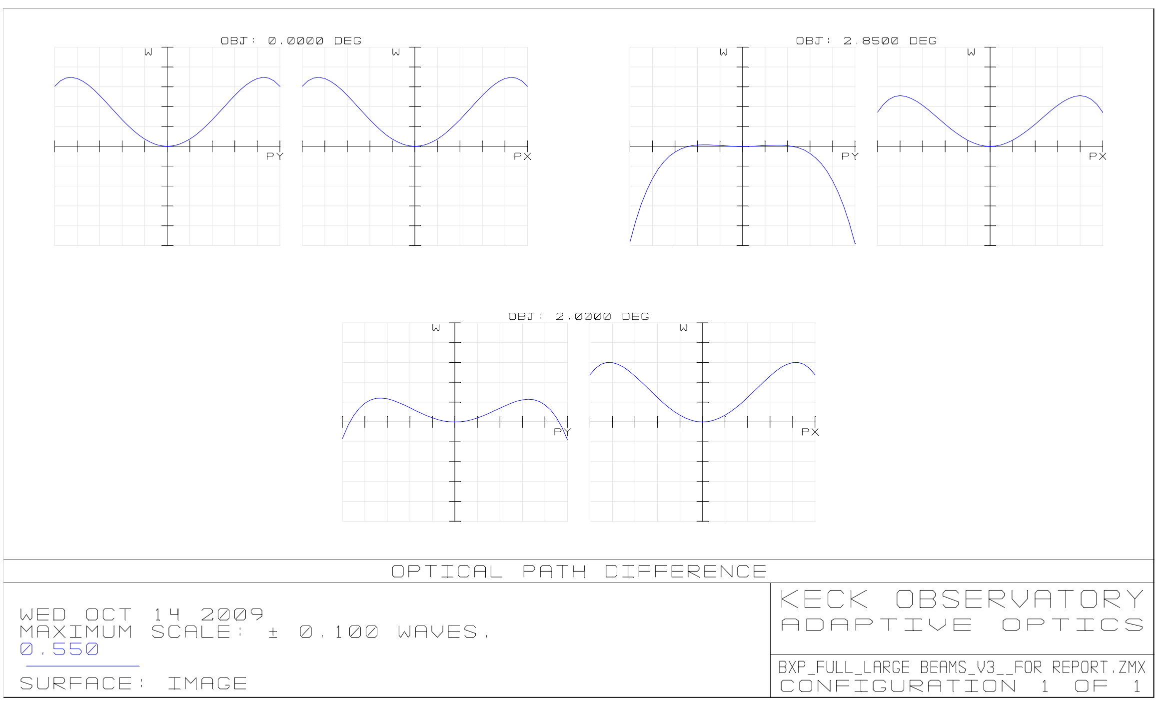


**Figure 12. Beam expander wavefront error.**

#### 5.1.1.6 Optical Breadboard

The breadboard design is still TBD and will depend on the results of a tolerance analysis for the BGS optics. The only portion of the BGS optical design where close tolerances are expected is between the two elements of the beam expander. If this is an issue, one solution might be to combine the mount for these two optics into a subassembly. This could allow meeting the tolerance requirements between these two elements without increasing the size, weight, or complexity of the whole BGS support structure.

### 5.1.2 Zemax Model

### 5.1.3 Mechanical Design

#### 5.1.3.1 Cover

The BGS will include a cover similar to what is shown in Figure 13. The cover shown is the cover for the K1 BTOB. The cover is a clam shell style that is designed for only one side to be removed during servicing. The cover is made to be removed while it is in-situ in the f/15 module. The actual mounting of the cover is made to attach to the LT and not the BGS. A pliable seal is on the cover to allow for a light tight and air tight seal. A bulkhead will have to be developed for the cable access to the BGS.

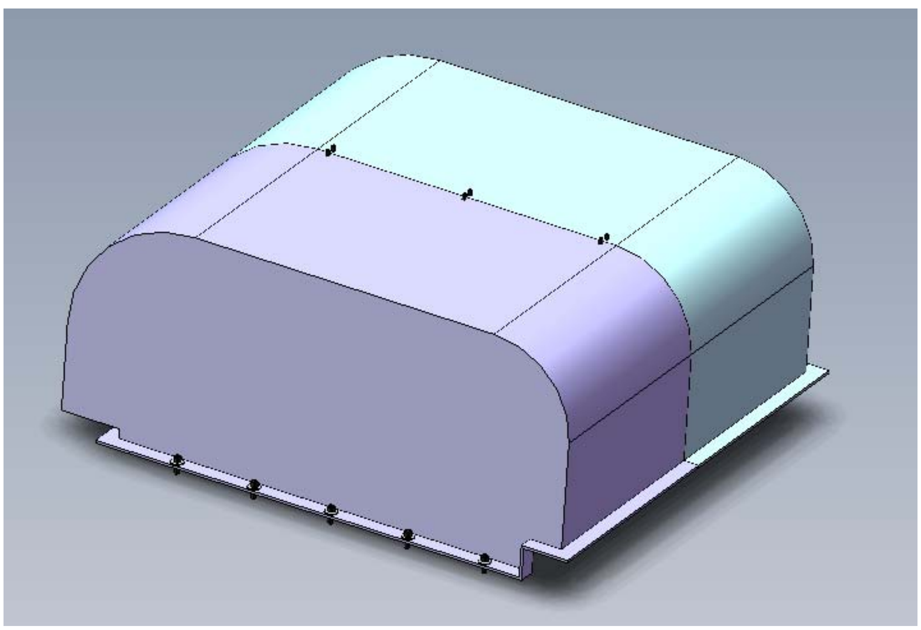

**Figure 13: BGS Cover**

#### 5.1.3.2 Pneumatic Purge

A pneumatic purge will be provided at 1 to 2 SCFM to maintain cleanliness in the BGS. Purge air is already available at the top socket of the telescope.

## 5.2 Electrical Design

### 5.2.1 Motion Control System

Table 3 shows the devices in the BGS and their characteristics. These devices will be controlled by the NGAO Motion Control System (MCLS); this should not be confused with the Multi-System Command Sequencer (MCS). The MCLS will not be reviewed in this document; however, the devices chosen will be in a format that can be controlled by the MCS as part of the NGAO Device Architecture Document (KAON 643).

| | Device | DOF per stage | No Each | TL DOF | Type | Axes | Range | Accuracy / Repeatability | Tracking Device? | Tracking Rate | Slew Rate | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Point-n-shoot beam splitter | 1 | 2 | 2 | Linear | x | 12.5 mm | 60 um | No | | 1 mm/s | |
| 2 | Star imager pickoff | 1 | 1 | 1 | Linear | x | in/out, 50mm | 30 um | No | | 5 mm/s | |
| 3 | Laser Point-n-shoot steering | 2 | 3 | 6 | Linear | x,y | 100mm | 30um | Yes | Slow (UTT offload) | 10 mm/s | linear piezo (PI M-683 + PI controller or driver). Tracking refers to UTT offload. |
| 4 | Laser Asterism rotator | 1 | 1 | 1 | Rotational | θ | 360 deg | 0.05 deg | Yes | Sideral | 10 deg/s min, 30 deg/s preferable | |
| 5 | Laser Asterism Tip/Tilt | 2 | 1 | 2 | Tip/tilt | x,y | 3 mrad | 3 urad | Yes | Slow (Flexure) | | Possible alternative for BTO vibration contr |
| 6 | Fast Shutter | 1 | 1 | 1 | Solenoid | x | | | | | 0.1s | |
| 7 | Beam Expander Focus | 1 | 1 | 1 | Linear | x | 5mm | 10 um | Yes | Elevation (100um from 90 to 20 el) | 100 um/s | |
| 8 | Laser Beam dump | 1 | 0 | 0 | Linear | x | | Low precision | No | | | If not built into fast shutter |
| 9 | LTO Cover* | 1 | 1 | 1 | Rotational | x | | Low precision | No | | | This will be a slow devices to provide a so cover for the LT. |
| 10 | LTO Polarization sensor* | 2 | 1 | 2 | Rotational | θ | 360 deg | 0.1 deg | No | | 20 deg/s min, 50 deg/s or more preferred | Rotating waveplates in polarization analyze |

**Table 3: BGS Motion Devices**

*The Launch Telescope devices are being addressed as part of the BGS Motion Devices.

### 5.3 Diagnostics (Ed)

Table 4 shows the diagnostics for the BGS and LT.

| Ref # | Item Name | Component Description | Real Time | Accuracy |
|---|---|---|---|---|
| 1 | Beam Dump | Beam Dump for laser when not propagation | Yes | 0.1 Watts |
| 2 | Position Sensing Diode | Diode for measuring laser power and position while propagating | Yes | 0.1 Watt, 1um |
| 3 | Camera 1 | Laser WFS | No | TBD |
| 4 | Camera 2 | Asterism Imager | Yes | TBD |
| 5 | Camera 3 | Beam polarization*2 | TBD | TBD |
| 6 | Camera 4 | NGS WFS error or NGS alignments | No | TBD |
| 7 | Temperature Sensors* | Measurement of temperature impacting focus | Yes | 0.5 degrees C |
| 8 | Relative Humidity* | Measurement of Relative Humidity to ensure the LT does not have condensation. Dew point can be substituted if necessary. | Yes | 5% RH |

**Table 4: BGS Diagnostics**

*These diagnostics are defined for the Launch Telescope.

### 5.4 Safety

The BGS will be considered a Class IV laser facility since the power at this location is above 500mW. The ANSI Standard Z136.1 will be used to ensure proper precautions are followed. Since the BGS is only one segment of the LLF, the entire LLF should be examined as a whole for safety concerns and mitigation. The discussion in this document will address the mitigations that are part of the BGS.

#### 5.4.1 Final Shutter

The BGS will include a final shutter prior at its output. The shutter will operate in conjunction with a glycol cooled beam dump to dissipate the laser power. The preferred location will allow all diagnostics to function even though the lasers are not propagating onto the sky.

#### 5.4.2 Laser Containment

The BGS will include a cover as shown in Figure 13 to contain the light during normal operations. For alignment purposes, this cover will be removed and the laser power turned down where it does not become a hazard. The cover will include limit switches that will use as part of the Laser Safety System interlock chain.

#### 5.4.3 Laser Status Indicators

Laser status indicators shall be provided at entry point to the BGS by the safety system. The status shall be based on the status of the laser and its shutter. The indicators will be represented in the following tables. The indicators will be momentary to minimize light contamination in the dome.

| | Status Level | Status Description |
|---|---|---|
| 1 | Green | Acceptable to enter, no hazardous radiation in the system |

| | | |
|---|---|---|
| 2 | Yellow | Acceptable to enter, hazardous radiation contained within the laser system |
| 3 | Red | Do not enter, hazardous radiation at the BGS |

**Table 5: Laser Status Indicator Definition**

#### 5.4.4 Laser Shutter Permissive Disable

Either for service or in case of emergency, a switch shall be located at the BGS to disable the laser shutters. This will prevent any laser beams from entering the BGS. The switch output will be fed into the safety system to disable the shutter permissive via a hardwire connection to the lasers.

### 5.5 Interfaces

The interfaces are separated into two sections. External interfaces are considered those with equipment outside of the NGAO System, such as the telescope. Internal interfaces are considered those within the NGAO System, such as interfaces with the BTO and LT.

#### 5.5.1 External Interfaces

##### 5.5.1.1 Infrastructure Interfaces such as Power, Pneumatic and Glycol (Ed)

#### 5.5.2 Internal Interfaces within the NGAO System

##### 5.5.2.1 Mechanical Interface to Launch Telescope

The BGS is expected mount onto the LT similar to what is currently done on K1 LGS. The BGS shall be an optical breadboard with kinematic mounts. Figure 14 shows the Keck I BTOB on the 3-point kinematic interface with the LT. A similar or identical interface shall be used for the Keck II BGS.

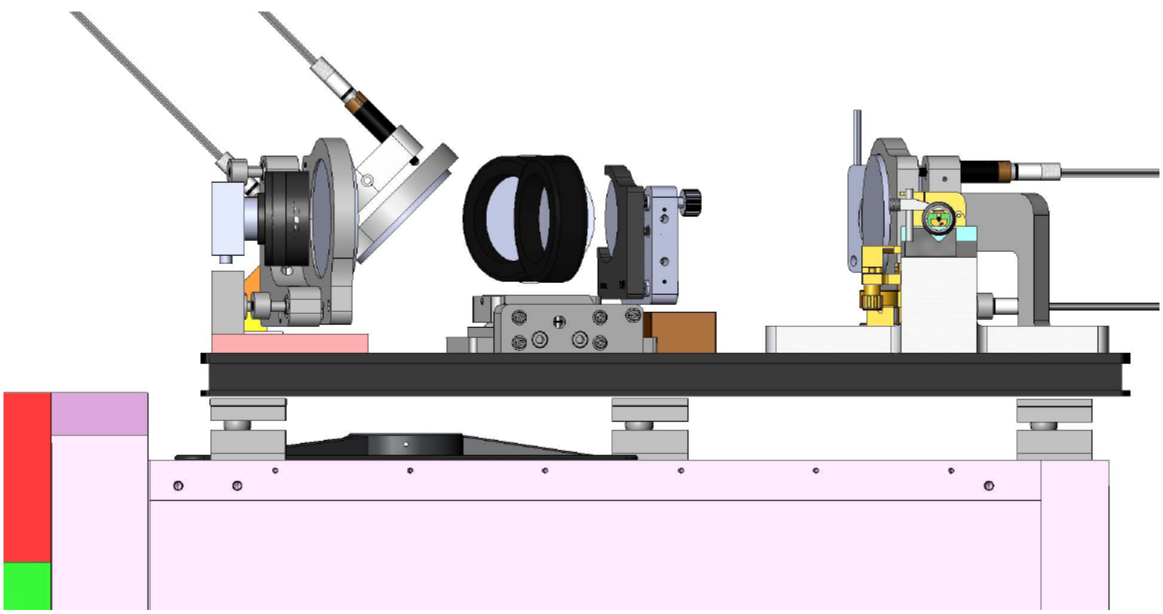

**Figure 14: Keck I BGS Interface with launch telescope**

##### 5.5.2.2 BGS Interface to the BTO

The BTO shall provide a stabilized set of three laser beams to the BGS. These beams will be arranged in a single line with a spacing of 25 mm. The BGS will provide a continuous position feedback signal at TBD

Hz rate for all three beams. The BTO will use this information to properly steer the beam into the BGS. The BGS is expected to have a mechanical interface with the BTO shown in Figure 15.

From Drew's Model

**Figure 15: BGS to BTO interface**

#### 5.5.2.3 BGS Electrical Interface

The BGS shall have an electrical interface with the MCS for motion control as well as diagnostics.

| Ref # | Device Types | Cabling | Connection | Quantity | From | Description | Format |
|---|---|---|---|---|---|---|---|
| 1 | DC Servo Motion | 25 wire | TBD | 8 | MCS | DC Servo System; drive, encoder, limits | Low DC Voltage Analog |
| 2 | Piezo Motion | 6 wire | Mil-Circular, LEMO | 8 | MCS | High voltage piezo control; feedback | High DC Voltage Analog |
| 3 | Solenoid | 2 wire | Mil-Circular, DB | 1 | Safety System | Shutter | High Current Analog |
| 4 | Position Sensors | 2 wire | | XA | MCS | PSDs | Low DC Voltage Analog |
| 5 | Calorimeter | 2 wire | Mil-Circular, DB | 1 | MCS | Beam Dump | Low Voltage Analog |
| 6 | Camera | RG59 | BNC | TBD | Diagnostic System | Low Resolution Cameras | NTSC Analog |
| 7 | Camera | TBD | TBD | TBD | Diagnostic System | High Resolution Camera | Digital such as camera link |
| 8 | Network | CAT5 | RJ-45 | TBD | Network Switch | Ethernet | CAT5 |

| Ref # | Device Types | Cabling | Connection | Quantity | From | Description | Format |
|---|---|---|---|---|---|---|---|
| 9 | Digital I/O | TBD | Mil-Circular, DB | TBD | Safety System | Switches and feedback | Digital 24VDC |

**Table 6: BGS Electrical Interface**

# 6 System Performance

## 6.1 Optical

### 6.1.1 Transmission

Based on the accepted NGAO guidelines, a base reflectivity of 0.994 is assumed for mirror coatings and a transmissivity of 0.996 for AR coated surfaces. An additional factor of 0.995 is added to account for dust or other surface imperfections.

With these guidelines, the overall throughput of the BGS is 81.20% for the PNS beams and 84.52% for the central asterism. Table 7 shows a listing of the surfaces in the path for the PNS beams, while Table 8 is the same data for the central asterism.

The 0.5% contribution from dust and dirt on the optics is a significant factor in a system with this many surfaces, and is also difficult to estimate if this is a reasonable value. Even though the BGS enclosure is purged with filtered air, some dust infiltration is to be expected during maintenance with the cover open and also when the system is disconnected to remove the secondary module from the socket. Access for cleaning will be included in the mechanical design whenever possible, but some elements may be difficult or impossible to access for thorough which would result in an increase in the dirt loss over the life of the instrument. Conversely, the dirt loss for some elements could be plausibly reduced by careful mechanical design. For example, if the mount for the beam expander lenses L1 and L2 includes a sealed shroud between the two elements, the only dust that should accumulate would be on the outer two surface. The two surfaces inside the shroud should see an extrememly small amount of dust.

Please refer to the system level document for a complete throughput budget for the entire LLF and a comparison to the system requirements.

| Element Name | Number of Surfaces | Trans. per Surface | Dirt/scatter | Total Element Transmission |
|---|---|---|---|---|
| Astr. Gen. B.S. 1 | 2 | 99.60% | 0.50% | 98.20% |
| Astr. Gen. B.S. 2 | 2 | 99.60% | 0.50% | 98.20% |
| Astr. Gen. Mirror 1 | 1 | 99.40% | 0.50% | 98.90% |
| Astr. Gen. Mirror 2 | 1 | 99.40% | 0.50% | 98.90% |
| Astr. Gen. Mirror 3 | 1 | 99.40% | 0.50% | 98.90% |
| Astr. Gen. Negative lens | 2 | 99.60% | 0.50% | 98.20% |
| Astr. Gen. Pupil Imaging lens | 2 | 99.60% | 0.50% | 98.20% |
| Fold | 1 | 99.40% | 0.50% | 98.90% |
| K Mirror assembly | 3 | 99.40% | 0.50% | 96.74% |
| Global TT mirror | 1 | 99.40% | 0.50% | 98.90% |

| | | | | |
|---|---|---|---|---|
| Beam Expander Telescope Lens 1 | 2 | 99.60% | 0.50% | 98.20% |
| Beam Expander Telescope Lens 2 | 2 | 99.60% | 0.50% | 98.20% |
| BTOB fold | 1 | 99.40% | 0.50% | 98.90% |
| | | | | |
| **TOTAL Transmission Throughput** | | | | **81.20%** |

**Table 7: BGS PNS Transmission**

| **Element Name** | **Number of Surfaces** | **Reflec./Trans. per Surface** | **Dirt/scatter** | **Total Element Transmission** |
|---|---|---|---|---|
| Astr. Gen. B.S. 1 | 2 | 99.60% | 0.50% | 98.20% |
| Astr. Gen. Mirror 1 | 1 | 99.40% | 0.50% | 98.90% |
| Asterism fold mirror | 1 | 99.40% | 0.50% | 98.90% |
| Negative lens | 2 | 99.60% | 0.50% | 98.20% |
| Pupil imaging lens | 2 | 99.60% | 0.50% | 98.20% |
| | | | | |
| Fold | 1 | 99.40% | 0.50% | 98.90% |
| K Mirror assembly | 3 | 99.40% | 0.50% | 96.74% |
| Global TT mirror | 1 | 99.40% | 0.50% | 98.90% |
| | | | | |
| Beam Expander Telescope Lens 1 | 2 | 99.60% | 0.50% | 98.20% |
| Beam Expander Telescope Lens 2 | 2 | 99.60% | 0.50% | 98.20% |
| | | | | |
| **TOTAL Transmission Throughput** | | | | **84.52%** |

**Table 8: BGS central asterism transmission**

### 6.1.2 Wavefront Error

Most catalog optics are specified by peak to valley wavefront error, however it is actually the RMS wavefront error that is used in calculating system performance. All custom elements will use an RMS wavefront specification directly. For the stock catalog items used in the system a conversion factor can be applied to convert the PV error into RMS, however this is not exact and varies with the nature of the surface errors. Generally accepted conversion factors range from 1/3 to 1/5 depending on what assumptions are made about the surface. This analysis will adopt a conservative approach that RMS = PV/3.

A value of 21 nm RMS was used for the lens and beamsplitter surfaces, while a better value of 11 nm was used for the flat mirror surfaces. Another source of wavefront error is the beam expander design, which introduces 34 nm RMS at the edge of the field and 19 nm RMS at the central asterism radius. The resulting values are 86.4 nm RMS for the PNS beams and 74.8 nm RMS for the central asterism, shown in Table 9 and Table 10.

Please refer to the system level document for a complete wavefront error budget for the entire LLF and a comparison to the system requirements.

| **Element Name** | **Number of Surfaces** | **PV error (waves @ 632.8 nm)** | **RMS WFE (nm, per surface)** | **RMS WFE (nm, per element)** |
|---|---|---|---|---|
| Astr. Gen. B.S. 1 | 2 | 0.100 | 21.1 | 29.8 |
| Astr. Gen. B.S. 2 | 2 | 0.100 | 21.1 | 29.8 |
| Astr. Gen. Mirror 1 | 1 | 0.050 | 10.5 | 10.5 |
| Astr. Gen. Mirror 2 | 1 | 0.050 | 10.5 | 10.5 |
| Astr. Gen. Mirror 3 | 1 | 0.050 | 10.5 | 10.5 |
| Astr. Gen. Negative lens | 2 | 0.100 | 21.1 | 29.8 |
| Astr. Gen. Pupil Imaging lens | 2 | 0.100 | 21.1 | 29.8 |
| | | | | |
| Fold | 1 | 0.050 | 10.5 | 10.5 |
| K Mirror assembly | 3 | 0.050 | 10.5 | 18.3 |
| Global TT mirror | 1 | 0.050 | 10.5 | 10.5 |
| | | | | |
| Beam Expander Telescope Lens 1 | 2 | 0.100 | 21.1 | 29.8 |
| Beam Expander Telescope Lens 2 | 2 | 0.100 | 21.1 | 29.8 |
| Beam Expander Telescope Design | 1 | | 33.5 | 33.5 |
| | | | | |
| BTOB fold | 1 | 0.050 | 10.5 | 10.5 |
| | | | | |
| **Total RMS WFE** | | | **86.4** | **nm** |

**Table 9. BGS PNS wavefront error.**

| **Element Name** | **Number of Surfaces** | **PV error (waves @ 632.8 nm)** | **RMS WFE (nm, per surface)** | **RMS WFE (nm, per element)** |
|---|---|---|---|---|
| Astr. Gen. B.S. 1 | 2 | 0.100 | 21.1 | 29.8 |
| Astr. Gen. Mirror 1 | 1 | 0.050 | 10.5 | 10.5 |

| | | | | |
|---|---|---|---|---|
| Asterism fold mirror | 1 | 0.050 | 10.5 | 10.5 |
| Astr. Gen. Negative lens | 2 | 0.050 | 21.1 | 29.8 |
| Astr. Gen. Pupil Imaging lens | 2 | 0.050 | 21.1 | 29.8 |
| | | | | |
| Fold | 1 | 0.050 | 10.5 | 10.5 |
| K Mirror assembly | 3 | 0.050 | 10.5 | 18.3 |
| Global TT mirror | 1 | 0.050 | 10.5 | 10.5 |
| | | | | |
| Beam Expander Telescope Lens 1 | 2 | 0.050 | 21.1 | 29.8 |
| Beam Expander Telescope Lens 2 | 2 | 0.050 | 21.1 | 29.8 |
| Beam Expander Telescope Design | 1 | | 20.6 | 20.6 |
| | | | | |
| BTOB fold | | | | |
| | | | | |
| Total RMS WFE | | | 74.8 | nm |

**Table 10. BGS central asterism wavefront error.**

### 6.1.3 Pointing Errors

There are a few sources of pointing errors in this system. The contribution from mechanical flexure will be determined after the detailed mechanical design, and will be a major consideration during that design. The other major sources of pointing error will be

- K-mirror misalignment
- Positioning error for the PNSAG stages
- Position error for the global tip/tilt mirror

The K-mirror alignment is made easier by the demagnification present in the rest of the system. Any angular error in the K-mirror is reduced by a factor of 171 on sky. This means that even an arcminute of angular error in the K-mirror would only produce an error of 0.35 arcseconds on-sky. This also holds true for the global tip/tilt mirror.

The plate scale for the PNSAG stages is 0.633 mm/arcsecond which determines the relationship between the position error of the stage and on-sky error. Any quality translation stage should be accurate to at least 10 microns which translates into a 0.016 arcsecond error on-sky. After the exact stage model for the PNSAG is chosen this estimate can be refined, although there is little risk that it will be a significant error.

## 6.2 Mechanical

### 6.2.1 Mass on Telescope

Table 11 shows the total mass of the BGS. As a comparison, the K1LGS Beam Transport Optical Bench was 28 Kg. The added weight is offset within the f/15 module by removing mass from the counterweight to balance the module. The removed mass is expected to be approximately ½ of the BGS due to the longer moment arm. If no mass is removed from the top end, the appropriate mass or 1.8x the cumulative f/15 additions must be added to the Cassegrain location. Since the BGS is a small portion of the weight that will be added to the telescope as part of the LLF, it will not have any significant impact. Similar weights were balanced on the Keck 1 telescope. It is also important to note the mass at the Keck II Cass location is larger than that of Keck I due to the heavier ESI instrument as compared to LRIS. This will assist in maintaining the balance on the telescope.

| | Item | Mass (Kg) |
|---|---|---|
| 1 | Breadboard including kinematic mounts | 10.0* |
| 2 | PNSAS Opto-Mechanics | 25.0 |
| 3 | Image Rotator | 2.0 |
| 4 | Beam Expander | 3.0 |
| 5 | Cover | 7.0* |
| 6 | Diagnostics | 2.0 |
| | Total | 49.0 |

**Table 11: BGS Mass**

Note: * Based on estimates for the K1 BTOB

### 6.2.2 Heat Dissipation and Glycol requirements

The seven laser beams from the PNSAG will require a shutter and beam dump for terminating the lasers at the BGS. The total power (75W) of the lasers exceeds the allowed power dissipation at the top end. The shutter and beam dump will require instrument glycol cooling to remove the heat from the laser beams. Instrument glycol is already available at the top end of the telescope for the Infrared Fast Steering Mechanism at much higher capacity than the BGS. All other diagnostics are expected to generate minimal amount of heat. Since instrument glycol will already be available at the BGS, any generation of heat can be cooled by instrument glycol. Since the BGS resides above the primary mirror of the telescope, all lines shall be either hard lines or braided Teflon to minimize any chance of breakage.

It is possible the terminating shutter and beam dump can be located at the switchyard location. However, terminating at the switchyard location does not allow the three laser beams to be tracked along the Beam Transport Optics to the BGS in between laser propagations.

| | Item | Power (W) |
|---|---|---|
| 1 | Seven lasers | 75 |
| 2 | Motor Control (6 DoF) | 10 |
| 3 | Camera Electronics | 20 |
| 4 | Diagnostics | 15 |
| | Total | 120 |

**Table 12: BGS Heat Dissipation**

## 6.3 Electrical (Ed)

Both commercial and clean power is available at the top end of the telescope. The expected power is expected to be significantly less than the 120VAC 20 amp circuit available in the telescope.

| | Item | Power (W) |
|---|---|---|
| 1 | Camera Electronics AC converters | 30 |
| 2 | Diagnostics AC Converters | 22 |
| | Total | 52 |

**Table 13: BGS Power Consumption**

# 7 OPERATIONS

## 7.1 Modes

### 7.1.1 Alignment

The BGS will have 2 modes of operation. For initial rough alignment, an alignment mode will be available to ensure the laser beams are within the tolerances of the position sensor devices. This rough alignment mode is expected to be completed under low power, possibly with the BGS cover off. The lower power will likely be generated by a filter or polarizer at the switchyard. The BGS diagnostic must have the dynamic range to operate with lower power alignment beams as well as nominal power beams.

## 7.2 Procedures

### 7.2.1 Alignment

### 7.2.2 Cleaning

The need for cleaning the optics should be minimized by the sealed enclosure design. With the relatively large number of surfaces, however, maintaining clean optical surfaces is critically important to keep the system throughput high. If each surface gathers enough dust or other contaminants to scatter just 0.25% of the light the overall throughput for the BGS drops by 4%. The design value of 0.5% results in a loss of about 8%.

The power per beam will be monitored by the asterism alignment camera. When this is combined with power measurements in the laser enclosure the total system throughput can be monitored. When the total throughput drops by more than 8% cleaning will be required to restore the system performance. Cleaning based on performance metrics versus scheduled intervals is desirable for a number of reasons. Since the enclosure is sealed and purged with filtered air, opening the enclosure for unnecessary optical cleaning may actually introduce more dust into the system. Also, cleaning only when necessary reduces manpower requirements and the possibility for damage to the optics.

## 7.3 Configuration Management

The BGS drawings will be under configuration management. The BGS will be a sub-branch of the NGAO Laser Guide Star Facility drawing set. Both mechanical and electronics drawings will be branches off this BGS branch.

## 7.4 Operational Resources

The BGS shall be designed to require minimal maintenance. To ensure the throughput requirement is met, the BGS will be positively pressured to keep out contaminants. The baseline maintenance effort will be a cleaning of the optical surfaces quarterly to ensure optimal throughput. The cleaning will be completed with the unit in the f/15 module. It is recommended the cleaning be conducted with the module on the

Nasmyth Deck. This effort will result in a telescope restriction at horizon for ½ day every quarter. The effort shall be 1% of an FTE per year.

## 8 Development and Testing

This section will be presented at the DDR.

## 9 Requirements Compliance Verification

The compliance matrix will be presented as a whole for the entire LLF in the LLF Requirements Compliance Matrix document.

## 10 Risk and Risk Reduction Plan

Table 14 and Table 15 show individual risks within BGS in accordance with KAON 510.

| Likelihood \ Consequences | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 5 | | | | | |
| 4 | | | | | |
| 3 | | | 1 | | |
| 2 | 4,5 | 2,3 | | | |
| 1 | 6 | | | | |

**Table 14: Risk Matrix**

| # | Trend | Conse-quence | Like-lihood | Description | Status | Mitigation |
|---|---|---|---|---|---|---|
| 1 | | 3 | 3 | Polarization problems, change as K-mirror rotates | Each beam's angle will vary by several degrees that may impact the polarization. | Further examination is required |
| 2 | | 2 | 2 | The ability to fit all components to meet the size and weight requirements | Need to complete the model and design. | Further examination is required |
| 3 | | 2 | 2 | Air breakdown in internal BXP focus | Need to understand the issue better | Further examination is required |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 | | 1 | 2 | Telescope vibration | The Switchyard stages can support vibration cancellation in the system | Further examination is required |
| 5 | | 1 | 2 | Diagnostics | Determine if all requested diagnostics can fit into the allowable volume as well as meeting the mass constraints | Further examination is required |
| 6 | | 1 | 1 | PNS Motion Devices | The ability of these devices in a changing gravity vector is a concern | Testing during DDR phase to alleviate concern |

**Table 15: Risk Analysis**

### 10.1 Polarization

The polarization will vary due to the angle of incidence of the seven beams into the rotator. The changes are not large but in the order of 3 degrees. The coatings will need to be verified to ensure this slight change in angle will not impact the polarization from beam to beam. Currently, polarization correction is done for each of the three laser beams in the Switchyard. If the individual beams are impacted, additional waveplates will be needed at the BGS to compensate for each beam individually. This will be resolved by PDR.

### 10.2 Ability to fit components into the allowable volume and mass constraints

The current design of the BGS is considerably tight to meet the asterism and PNS requirements, as well as the diagnostics that must be included in the BGS. Until the design is more mature, it is not known whether all the components can fit in the volume above the LT. One remedy as mentioned earlier is to use smaller motion stages which will eliminate weight as well as providing additional space for diagnostics. Once the design is more mature, this risk should be eliminated. This will be resolved by PDR.

### 10.3 Air Breakdown at Focus

Further examination is needed to determine if the air breakdown due to high laser power will be an issue. If so, the design of the optics in the BGS will be modified to increase the size of the beam. This will put tighter requirements on the motion control devices. This will be resolved by PDR.

### 10.4 Telescope Vibration

The telescope has known vibration modes at the top end based on accelerometer readings from the interferometer. The accelerometer data needs further examination to determine if it will be an issue for the BGS. This will be resolved by PDR.

### 10.5 Diagnostics

The required diagnostics are currently not all included in the design; although they have been considered as to their locations. Further design choices must be made to ensure they can be included in the BGS and meet the requirements. This will be resolved by PDR.

### 10.6 PNS Motion Devices

There is a general concern about the SmarAct ultrasonic devices for the PNS stages. The concern is the changing gravity vector that these devices must function under. To alleviate the concerns, the project will test this device under different gravity vectors to determine their performance.

## 11 DELIVERABLES

Figure 16 shows the deliverables for the BGS.

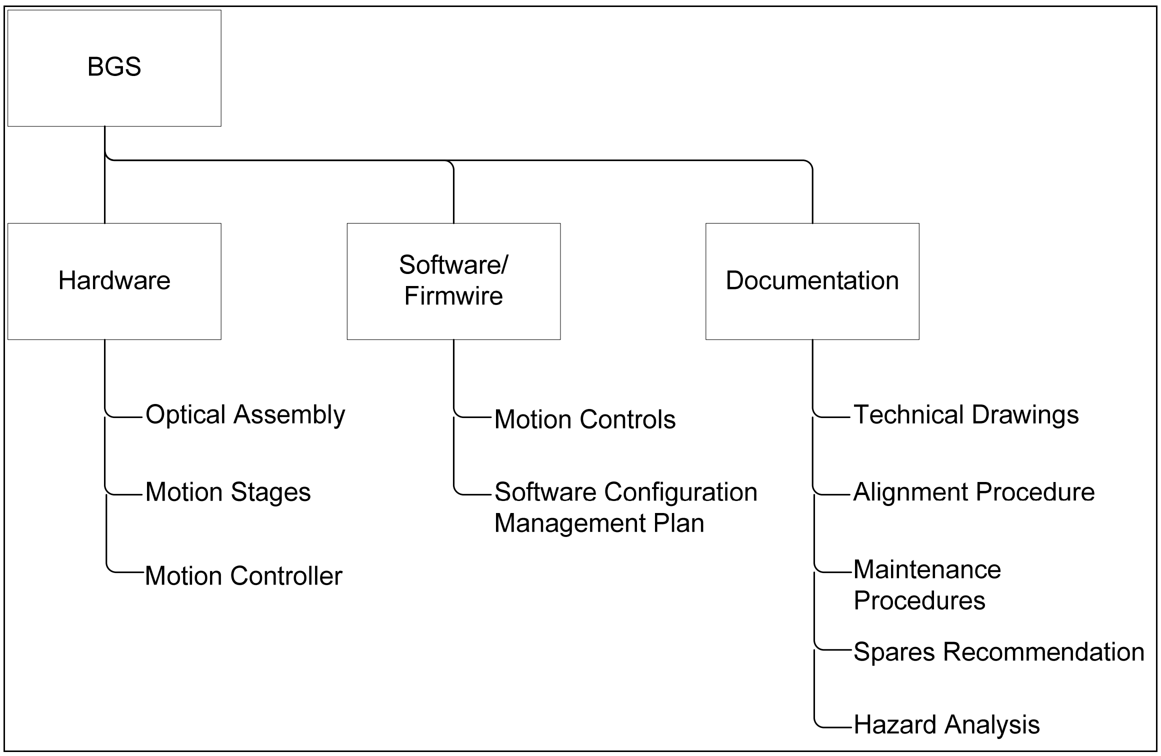


**Figure 16: BGS Deliverables**

## 12 MANAGEMENT

### 12.1 Budget

This section will be presented at the PDR.

### 12.2 Schedule

This section will be presented at the PDR.

## 13 PLANS FOR THE NEXT PHASE

This section will be presented at the PDR.