KAON 659

Next Generation Adaptive Optics System

Laser Launch Facility Beam Generation System

Preliminary Design

May 10, 2010

VersionV1.3

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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 (659)
1.2	Nov 04, 2009	JC	Updated risk summary
1.3	May 10, 2010	TS	Updates for PDR

TABLE OF CONTENTS

REVISION HISTORY 2
TABLE OF CONTENTS 3
1 INTRODUCTION 5
2 REFERENCES 5
  2.1 REFERENCED DOCUMENTS 5
  2.2 ACRONYMS AND ABBREVIATIONS 5
3 OVERVIEW 7
4 REQUIREMENTS 8
5 DESIGN 8
  5.1 OPTO-MECHANICAL DESIGN 8
    5.1.1 Optical Design Choices 8
      5.1.1.1 Patrolling Asterism Generator 9
      5.1.1.2 Central Asterism Generator 12
      5.1.1.3 Image rotator 12
      5.1.1.4 Beam Expander 12
      5.1.1.5 Detailed System Design 13
      5.1.1.6 Optical Breadboard 16
    5.1.2 Zemax Model 16
      5.1.3 Mechanical Design 16
      5.1.3.1 Cover 16
      5.1.3.2 Pneumatic Purge 16
  5.2 ELECTRICAL DESIGN 17
  5.3 DIAGNOSTICS 19
  5.4 SAFETY 19
    5.4.1 Final Shutter 19
    5.4.2 Laser Containment 19
    5.4.3 Laser Status Indicators 19
    5.4.4 Laser Shutter Permissive Disable 20
  5.5 INTERFACES 20
    5.5.1 External Interfaces 20
      5.5.1.1 Infrastructure Interfaces such as Power, Pneumatic and Glycol (Ed) 20
    5.5.2 Internal Interfaces within the NGAO System 20
      5.5.2.1 Mechanical Interface to Launch Telescope 20
      5.5.2.2 BGS Interface to the BTO 20
      5.5.2.3 BGS Electrical Interface 21
6 SYSTEM PERFORMANCE 21
  6.1 OPTICAL 21
    6.1.1 Transmission 21
    6.1.2 Wavefront Error 22
    6.1.3 Pointing Errors 22
  6.2 MECHANICAL 22
    6.2.1 Mass on Telescope 22
    6.2.2 Heat Dissipation and Glycol requirements 23
  6.3 ELECTRICAL 23
7 OPERATIONS 24

7.1 MODES 24
7.2 PROCEDURES 24
7.2.1 ALIGNMENT ON TELESCOPE 24
7.2.2 Cleaning 24
7.3 CONFIGURATION MANAGEMENT 24
7.4 OPERATIONAL RESOURCES 25

8 DEVELOPMENT AND TESTING 25

8.1.1 INITIAL ALIGNMENT 25

9 REQUIREMENTS COMPLIANCE VERIFICATION 26

10 RISK AND RISK REDUCTION PLAN 26

10.1 POLARIZATION 27
10.2 ABILITY TO FIT COMPONENTS INTO THE ALLOWABLE VOLUME AND MASS CONSTRAINTS 27
10.3 AIR BREAKDOWN AT FOCUS 27
10.4 TELESCOPE VIBRATION 27
10.5 ASTERISM GENERATOR MOTION DEVICES 28

11 DELIVERABLES 28

12 MANAGEMENT 28

A. ZEMAX MODEL LISTING 29

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.

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	KAON 643	1.0	WMKO	NGAO Device Architecture

Table 1: Reference Document

2.2 Acronyms and Abbreviations

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

Acronym/Abbreviation	Definition
AG	Asterism Generator
BGS	Beam Generation System
BTOB	Beam Transport Optical Bench
BTOS	Beam Transport Optical System
CAG	Central Asterism Generator
CW	Continuous Wave
DDR	Detailed Design Review
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
PAG	Patrolling Asterism Generator
PDR	Preliminary Design Review
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).

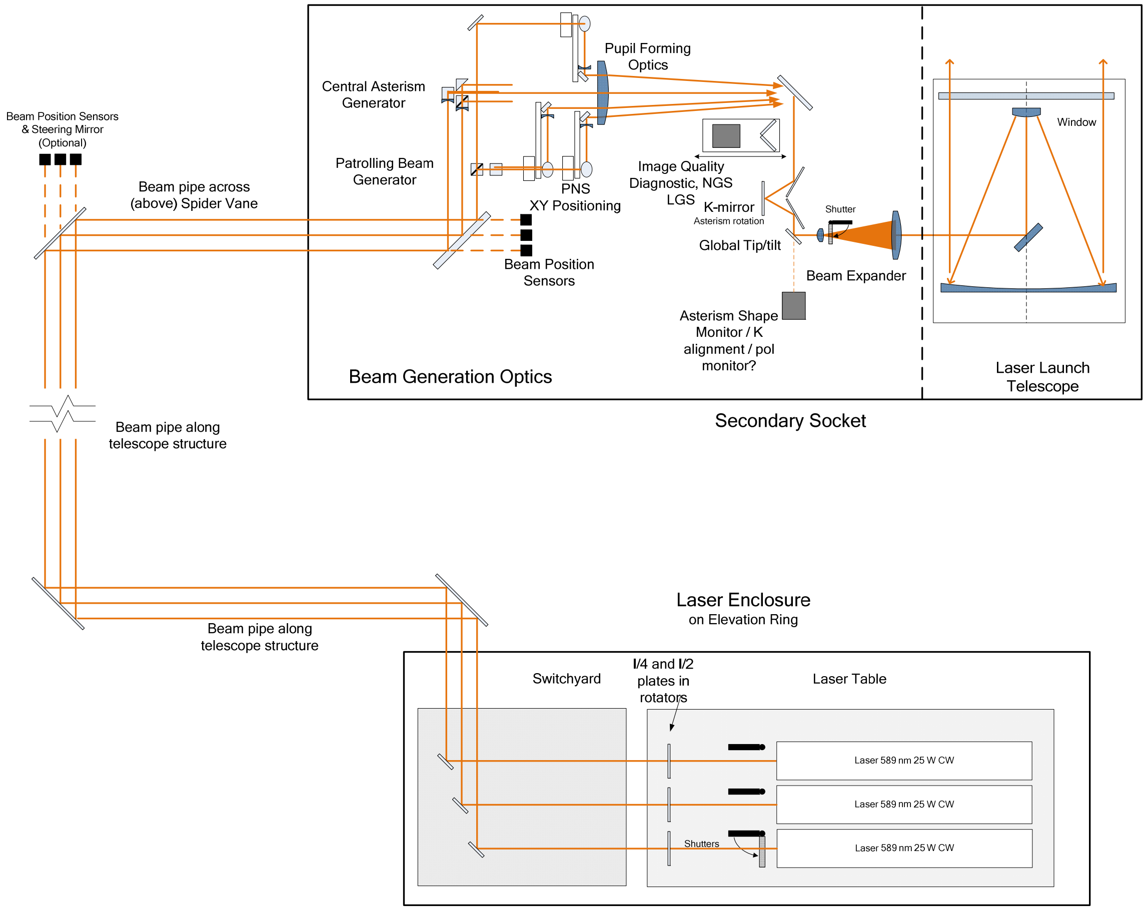

Figure 1: Laser Launch Facility Layout

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.

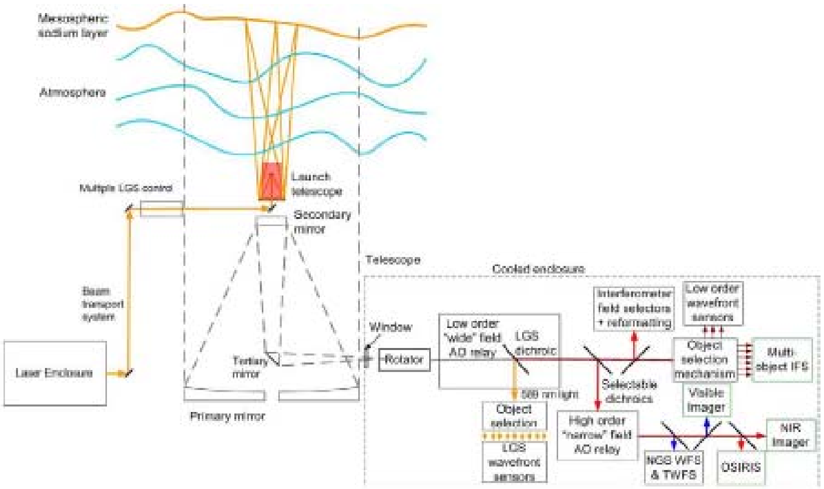

Figure 2: Laser Launch Facility BGS (shaded in red) within the NGAO System

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 from the flow down of requirements.

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 radius of 15 arcseconds and outer radius 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 patrolling asterism generator, the central asterism generator, and the beam expander. Since the patrolling 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 patrolling asterism 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 the LT input/output beam specifications were taken from the recently awarded contract for the Keck 2 center launch telescope, which are substantially similar to those for the recently deliver Keck 1 LT.

5.1.1.1 Patrolling Asterism Generator

The patrolling asterism generator (PAG) 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 PAG. The two possibilities are in the secondary socket or in the laser enclosure. If the PAG 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 $1/e^2$ 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 formed from these 16 mm diameter beams 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 PAG in the secondary socket.

Similar considerations of angular field size result in the conclusion that the beam expander must be between the PAG and the LT. At the input to the LT where the beams have a 28.8 $1/e^2$ diameter the full angular field is only 0.84 degrees, which means that even the outermost PAG beams overlap until after propagating almost two meters from the LT and the inner, fixed asterism beams must propagate much farther. Since this path length is impractical to contain in the secondary socket, the PAG must operate with the smaller beams directly from the BTO.

Since the laser beams are approximately collimated, the separation from the PAG 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 beams are well separated so 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.

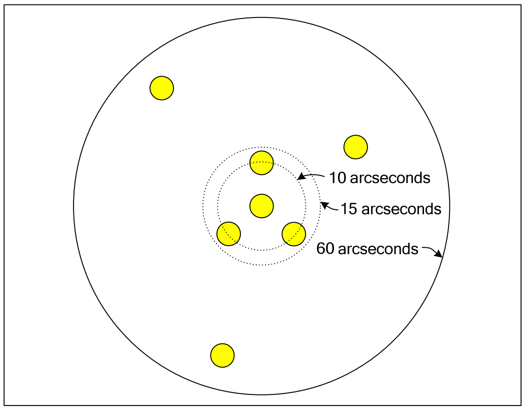

Figure 3: Asterism Generator Field Layout

The PAG 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.

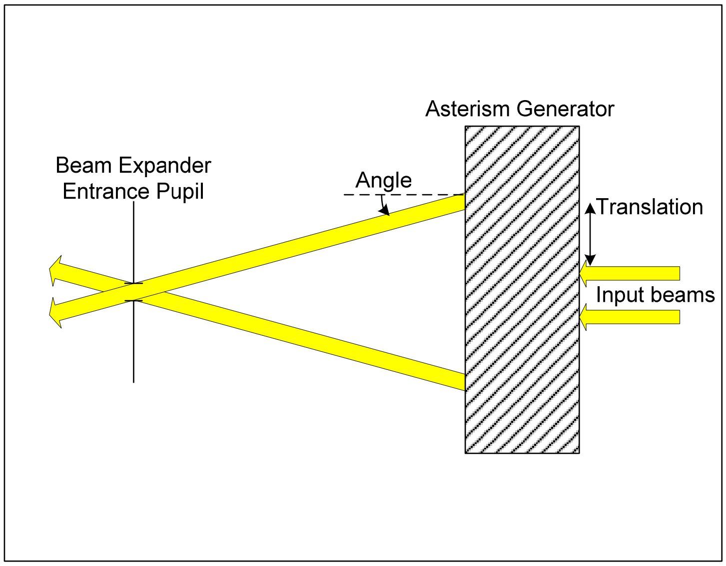

Figure 4: The PAG must set both the field position and angle to properly illuminate the pupil.

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 PAG 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 .

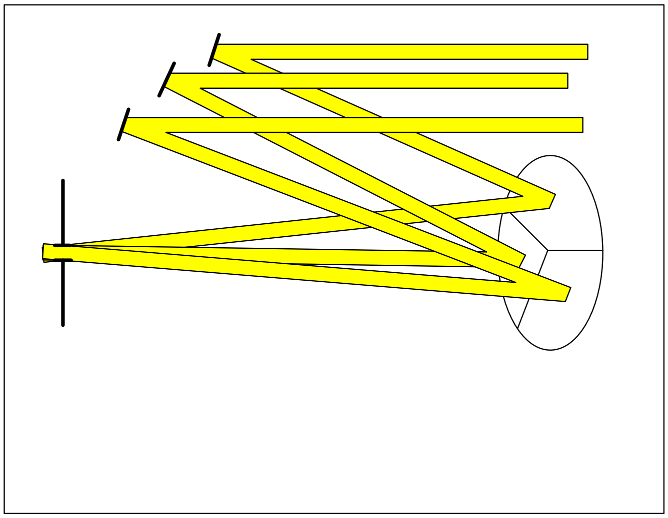

Figure 5: Split mirror concept

This concept has the advantage that all of the control is done by six tip/tilt mirrors. This results in a reasonably simple, compact system with a minimum number of surfaces that is also light weight. It does not allow arbitrary patrolling 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 a straightforward implementation of the setup shown previously in Figure 4. 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 patrolling 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 parallel input 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 7 for a model of the x-y stage arrangement.

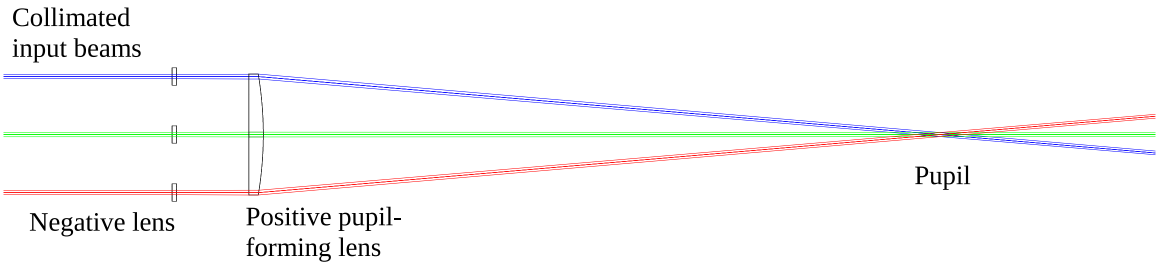

Figure 6: Pupil forming optics.

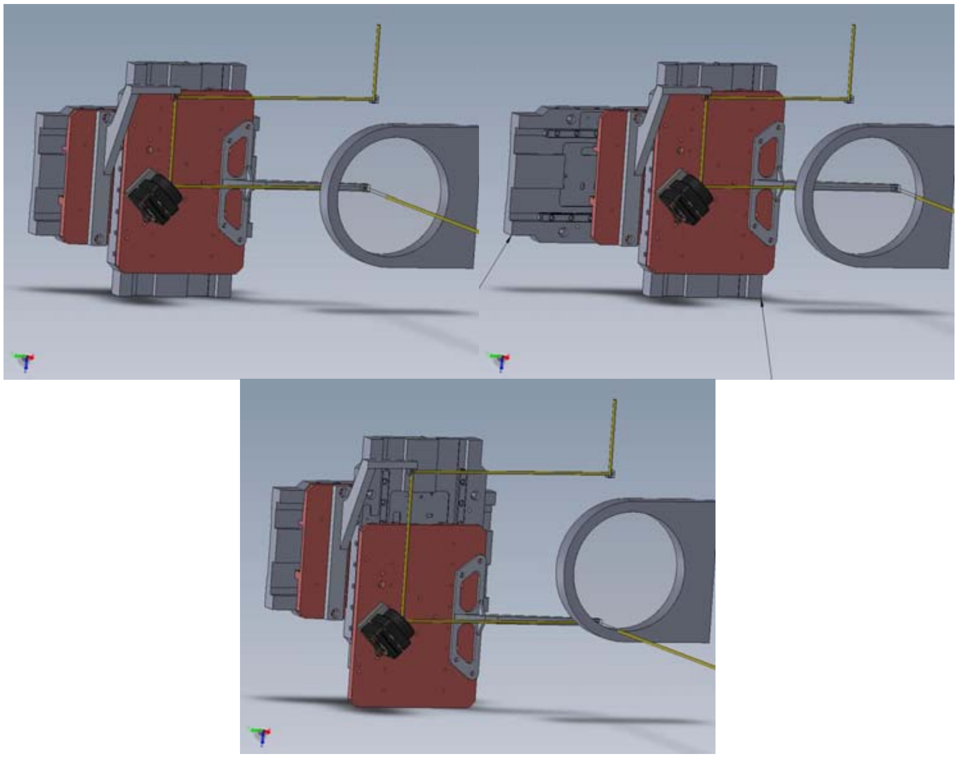

Figure 7: Layout for x-y stages.

A single input beam is split into three parts to generate the three patrolling 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 patrolling 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 three on 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 8.

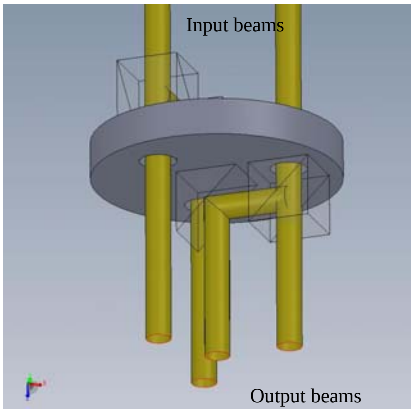

Figure 8: Central asterism generation using beam splitters. (Each side of the mounting plate has a beam splitter and mirror pair.)

5.1.1.3 Image rotator

The BGS must have an image rotator to keep the whole asterism aligned with the wavefront sensors on the AO bench that are after the AO rotator. 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 9 shows a conceptual model of the K mirror assembly mounted on a Newport rotation stage.

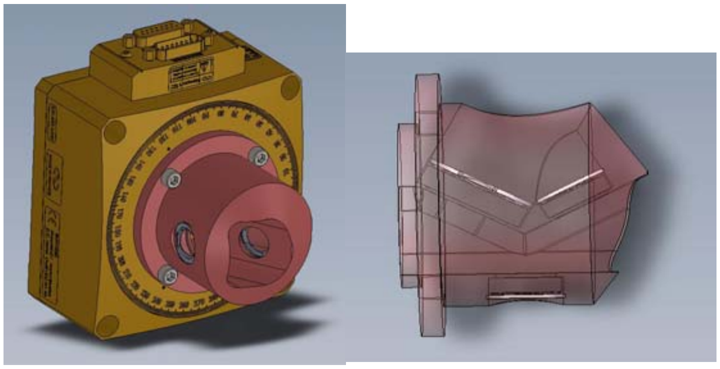

Figure 9: Image rotator

5.1.1.4 Beam Expander

The beam expander accepts the small diameter beams from the AG output and expands them to form a 28.8 mm $1/e^2$ 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 while steering the asterism. This steering capability is used to correct for both flexure and alignment errors.

To produce a compact system, a refractive design was used. 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 2.1×10^8 W/cm^2, which is approximately two orders of magnitude lower than where air breakdown effects are expected to start[1] at 1×10^{10} W/cm^2. If possible, a risk reduction using a comparable CW laser during the detailed design phase to confirm the absence of air breakdown would be beneficial.

The finished preliminary design for the beam expander results in an rms wavefront error that varies from 19.0 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 AG and the beam expander was a critical choice. The main constraint for this is that the minimum radius for the PAG 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 10.

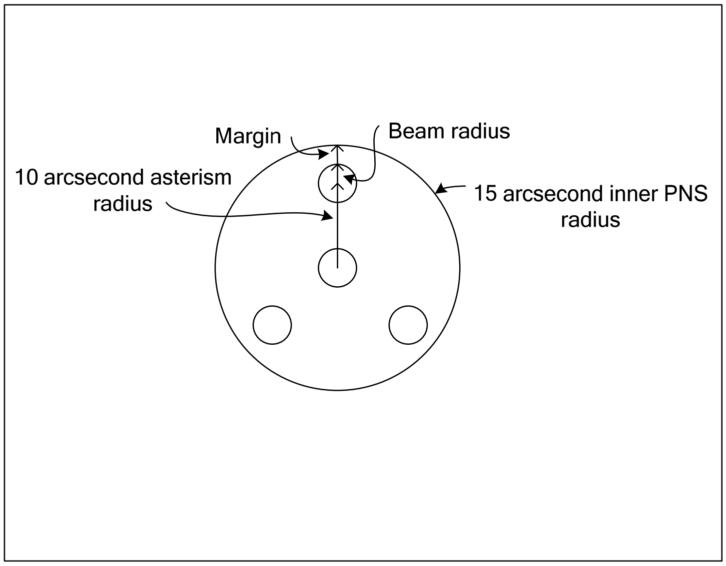

Figure 10: Central asterism dimensions

The physical scale of the central asterism as shown in Figure 10 is related to both the beam size and the distance from the AG 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 AG to the tip/tilt mirror

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[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

coupled with the angular scale of the pattern determines the AG platescale in mm/arcsecond. Therefore, for a given beam size there will be a minimum distance between the AG and the beam expander that will allow the 15 arcsecond minimum patrolling beacon radius.

After some iteration with component layout and beam sizes, the layout shown in Figure 11 was chosen.

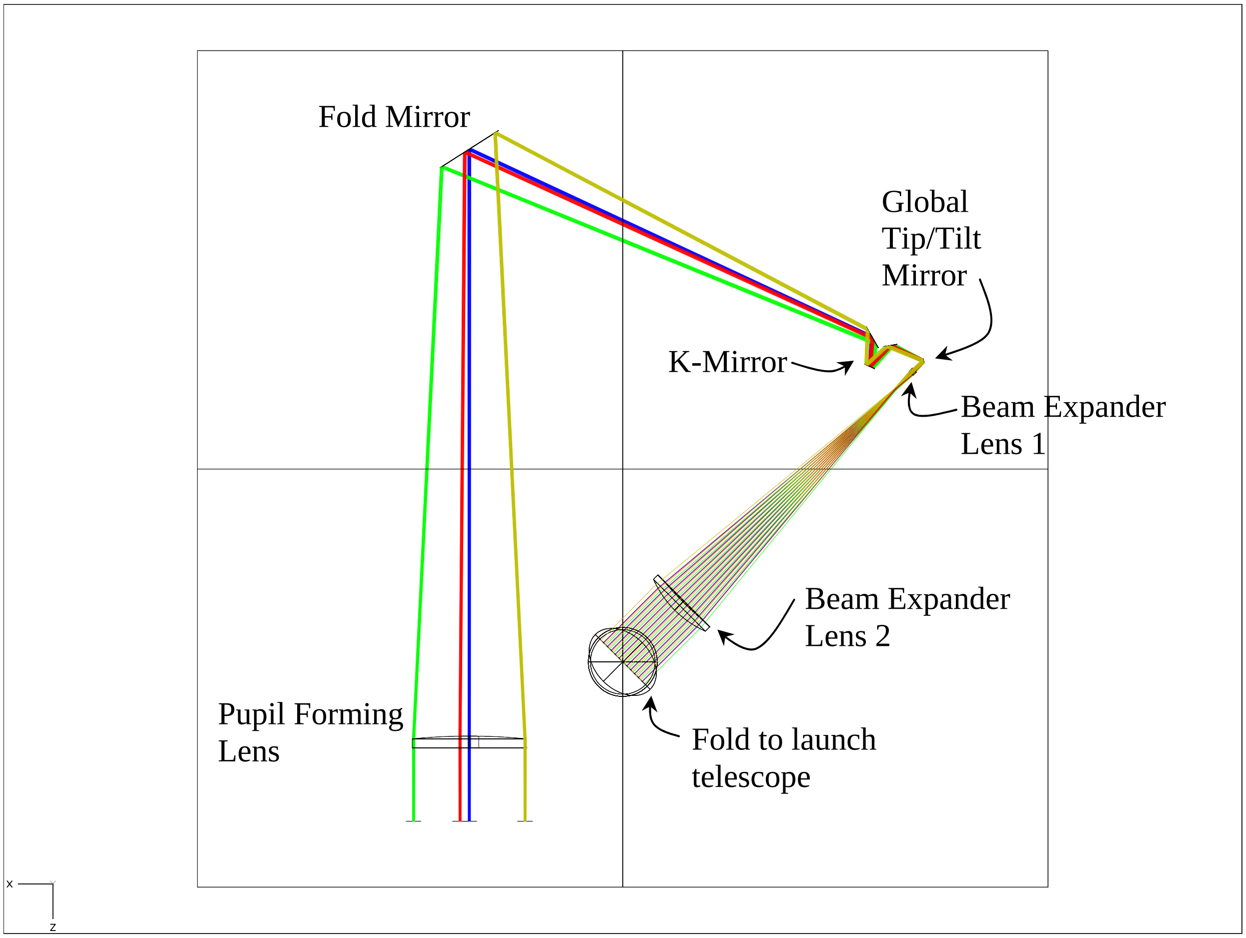


Figure 11: BGS optical layout.

The total distance from the AG to the tip/tilt mirror is 765 mm, and the required beam size at the AG 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 AG of 0.633 mm/arcsecond and meets the 15 arcsecond minimum patrolling 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 one aspheric surface on each element. It images the pupil formed by the AG onto the secondary of the LT with the correct magnification. The on-axis wavefront error is 19.0 nm rms while the wavefront error at the edge of the field is 33.5 nm rms. The layout is shown in Figure 12and the OPD curves are in Figure 13. A complete listing of the Zemax model is in Appendix A

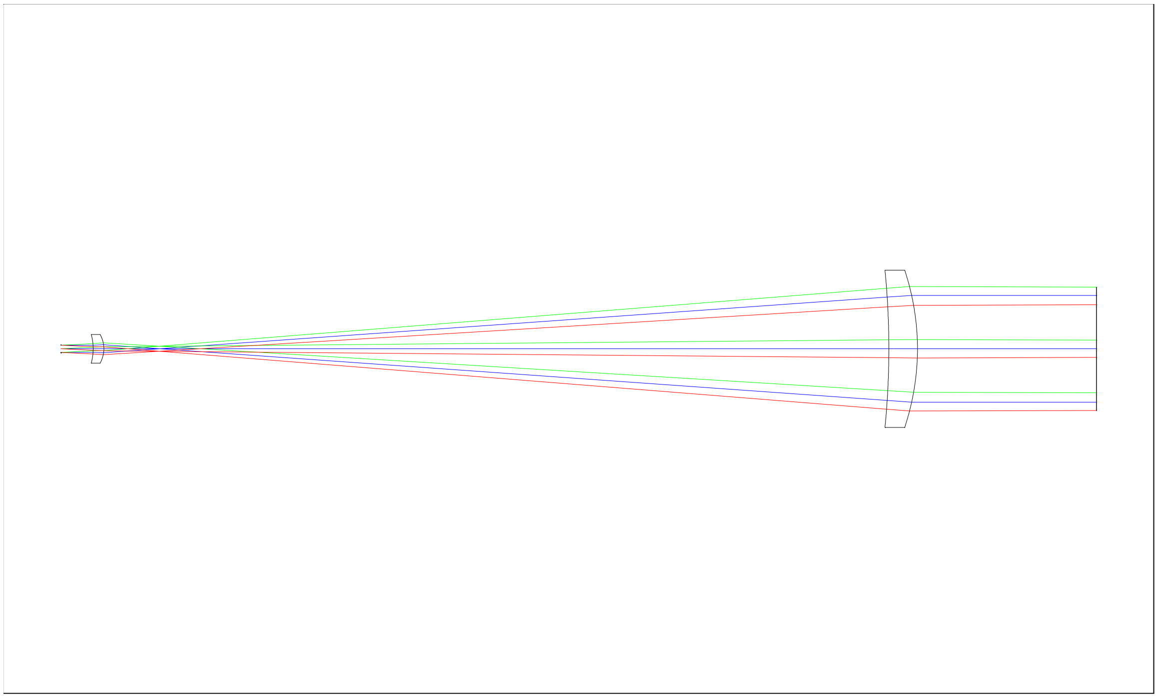


Figure 12: Beam expander layout.

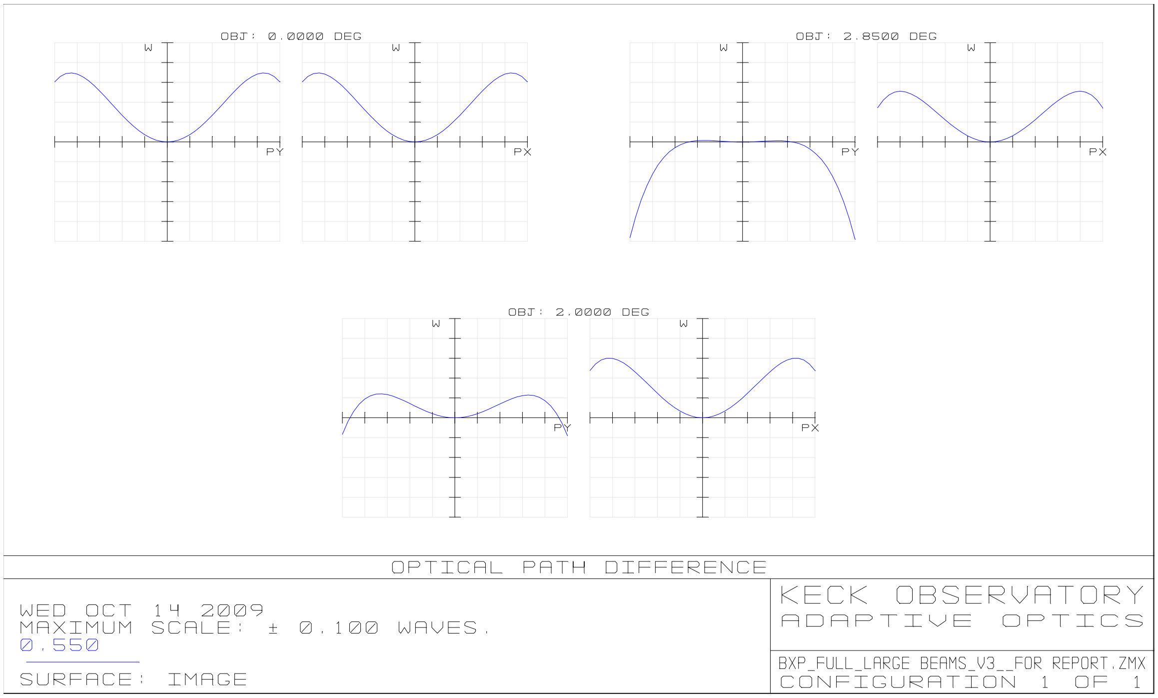


Figure 13: Beam expander wavefront error.

5.1.1.6 Optical Breadboard

The breadboard design will depend on the results of a detailed tolerance analysis of the BGS optics during the detailed design phase. The only portion of the BGS optical design with close tolerances, however, is between the two elements of the beam expander. Ideally these two elements will be combined into a common, dust-tight mount. This would reduce alignment-based wavefront error and also prevent dust accumulation on the inner two surfaces.

The BGS will use a repeatable kinematic mount to attach to the LT so that it may be easily removed for servicing. This will allow servicing in a clean environment to minimize contamination of the optical surfaces.

5.1.2 Zemax Model

5.1.3 Mechanical Design

5.1.3.1 Cover

The BGS will include a dust-tight cover similar to what is shown in Figure 14. The cover shown is the cover for the Keck I BTOB, but the version for K2 would be very similar. The cover is a clam shell style that is designed for only one side to be removed during servicing. To minimize contamination of optics the cover will be made such that it can be mounted to the BGS during assembly in a clean environment and remain in place while mounting the BGS on the LT. It shall also be possible to remove the cover for servicing in-situ in the f/15 module, although in this case it is preferable to use a tent and air filters to provide a clean environment to reduce optical contamination. Any major service work should be done with the BGS dismounted from the telescope and placed in a clean environment. A pliable seal will be used 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.

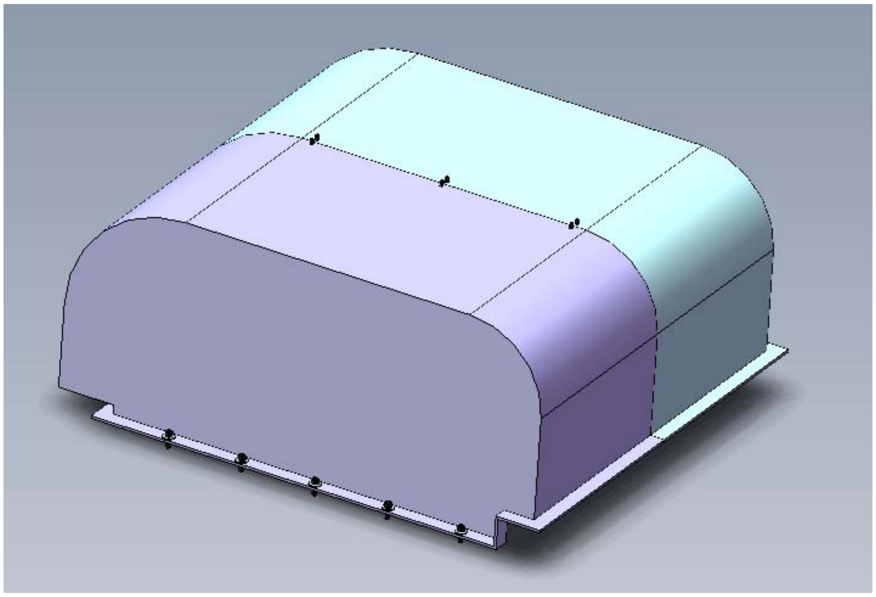


Figure 14: BGS Cover

5.1.3.2 Pneumatic Purge

A pneumatic purge of dry, highly filtered air will be provided at 1 to 2 SCFM to maintain cleanliness in the BGS. This air will be introduced into the BGS and will flow down the BTO to a relief port located at the laser enclosure. This relief port will create a slight positive pressure in the optical system to prevent dust infiltration. Purge air is already available at the top socket of the telescope.

5.2 Electrical Design

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	Patrolling beacon 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	Patrolling Laser steering	2	3	6	Linear	x,y	100mm	30um	No	Slow (UTT offload)	10 mm/s	linear piezo (PI M-683 + PI controller or driver). – OR – smarAct SLC-24120
4	Laser Asterism rotator	1	1	1	Rotational	θ	360 deg	0.05 deg	Yes	Sidereal	10 deg/s min, 30 deg/s preferable	Newport RGV100BL, brushless, 30mm aperture, sin/cos encoder
5	Laser Asterism Tip/Tilt	2	1	2	Tip/tilt	x,y	3 mrad	3 urad	Yes	Slow (Flexure)		Possible location for vibration control
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 soft cover for the LT.

Table 3: BGS Motion Devices

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

5.3 Diagnostics

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, one per laser (3 total)	Yes	0.1 Watt, 1um
3	Camera 1	Asterism Imager	Yes	TBD
4	Camera 2	NGS WFS error or NGS alignments	No	TBD
5	Temperature Sensors*	Measurement of temperature impacting focus	Yes	0.5 degrees C
6	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 14 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 Keck I LGS. The BGS shall be an optical breadboard with kinematic mounts. Figure 15 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.

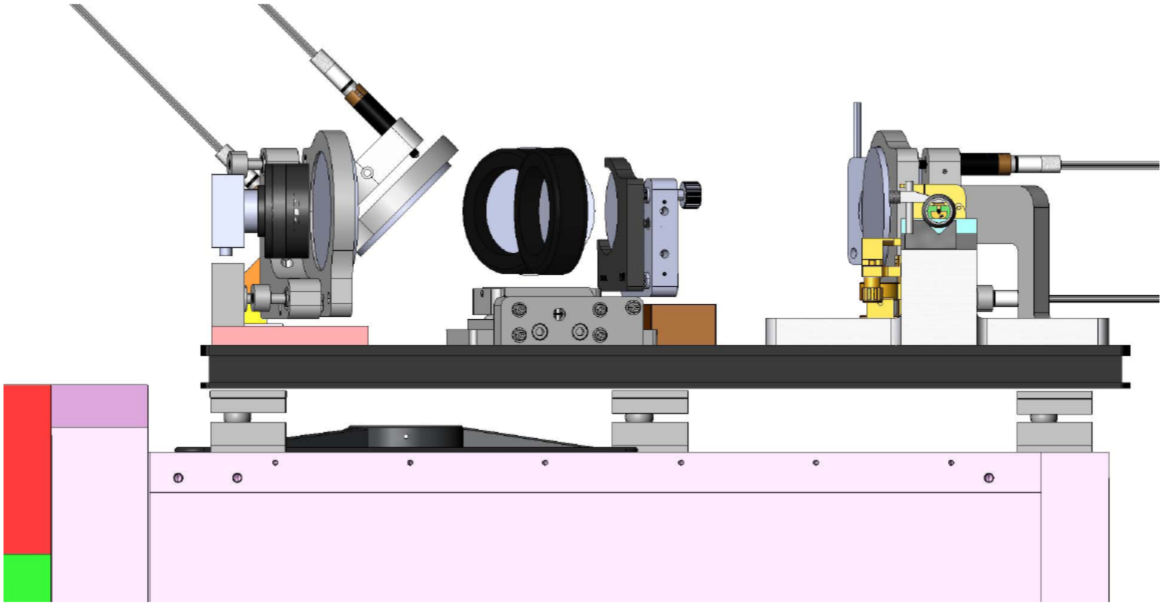


Figure 15: Keck I BGS Interface with launch telescope

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 a minimum of 1 kHz rate for all three beams. The BTO will use this information to properly steer the beam into the BGS.

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
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 a quote from Advanced Thin Films who has supplied similar mirrors for the Keck I and Gemini laser projects, a base reflectivity of 0.998 is assumed for mirror coatings and a transmissivity of 0.998 for AR coated surfaces. Depending on the environment, an additional transmission factor of 0.99 or 0.995 is added to account for dust or other surface imperfections.

The 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. 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 surfaces. The two surfaces inside the shroud should see an extremely small amount of dust.

With these guidelines, the overall initial throughput of the BGS is 96.1% for the fixed asterism beams and 95.9% for the patrolling asterism. After the allowance for contamination is added, these numbers drop to 80.2% for the fixed asterism and 79.2% for the patrolling asterism.

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

6.1.2 Wavefront Error

Due to the tight tolerances required for the launch optics, all surface specifications will be made as wavefront nanometers rms. Most catalog optics are specified by peak to valley wavefront error, however, so to allow some comparison of specifications a rule of thumb is that the peak to valley error is 3 to 5 times the rms error may be used.

A value of 7 nm RMS was used for the lens and mirror surfaces, while a slightly looser value of 10 nm was used for the beamsplitter surfaces. Another source of wavefront error is the beam expander design, which introduces 33.5 nm RMS at the edge of the field and 19 nm RMS at the central asterism radius. The resulting values are 52.6 nm RMS for the patrolling asterism at the edge of the field and 38 nm RMS for the central asterism.

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

6.1.3 Pointing Errors

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

- K-mirror misalignment
- Positioning error for the PAG 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 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 PAG 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. The exact stage model for the PAG will be chosen during the detailed design phase, but currently the choice is a stage from SmarAct that will easily exceed this estimate.

6.2 Mechanical

6.2.1 Mass on Telescope

Table 7 shows the total mass of the BGS. As a comparison, the Keck ILGS 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	AG 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 7: BGS Mass

Note: * Based on estimates for the Keck I BTOB

6.2.2 Heat Dissipation and Glycol requirements

The seven laser beams from the AG 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)	6
3	Camera Electronics	30
4	Diagnostics	22
	Total	133

Table 8: BGS Heat Dissipation

6.3 Electrical

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 9: BGS Power Consumption

7 OPERATIONS

7.1 Modes

The BGS will have an alignment mode. During this mode, the power will be reduced significantly by the use of a beam splitter at the SYD. The

7.2 Procedures

7.2.1 Alignment on Telescope

Initial alignment of the BGS on the telescope will be done in the low power mode available from the laser enclosure. This will ensure the laser beams are within the capture range of the position sensor devices. The BGS position sensors must have the dynamic range to operate with lower power alignment beams as well as nominal power beams.

1. Install the BGS on the LT.
2. Adjust the BTO system to place the laser beams on the position sensors and close the positioning loop.
3. Verify the output beam performance, including centration in the exit aperture, beam size, focus, and lack of vignetting over the full field.

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 1% results in a loss of about 16%.

The power per beam will be monitored using the asterism alignment camera and a beam dump power meter. 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 16% cleaning will be required to restore the system performance to the expected level. 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 or misalignment.

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

8.1.1 Initial Alignment

The BGS assembly will be initially aligned in the lab in a clean environment using simulated input beams. The performance will be monitored using the asterism camera and also by monitoring the output beams that would normally enter the LT. Rough locations for all parts will be determined from Solidworks models, possibly by either printing various full size diagrams or other metrology methods.

1. Properly format the test input beams. A single 589 nm laser will be divided into three beams to simulate the three laser beams from the BTO. The waist size and location will be adjusted using a beam expander to match the interface specification between the BTO and the BGS.
2. The mirrors mounted on each of the stages in the PAG will be aligned with the direction of motion. The pairs of stages for each PAG arm will then be assembled and adjusted to ensure orthogonality.
3. The three PAG arms will be mounted to the BGS assembly and adjusted to act in parallel planes.
4. The beam splitters that create the patrolling asterism will be installed and aligned along with the first fold mirrors. The result of this is a beam that enters the PAG arms parallel to the motion of the mirrors on the input stage.
5. The CAG will be aligned as a monolithic unit and then mounted in the BGS. The fold mirrors for the two input CAG laser beams will be adjusted such that the two input beams to the CAG are properly centred on their beamsplitters and parallel. This will be checked by measuring the geometry of the output asterism as a function of distance.
6. The pupil forming lens will be then be installed. Its plano surface will be adjusted to be parallel to the planes of motion of the PAG arms. The PAG beams should form a pupil at the design distance.
7. The CAG pointing will be adjusted such that the pupil formed by the CAG beams is coincident with that formed by the PAG beams, while at the same time the on-axis CAG beam is centered on the pupil-forming lens. It will likely be necessary to iterate between the positioning of the CAG and the input fold mirrors to achieve this.
8. The K-mirror will be aligned separately as a unit and then mounted on the BGS in the correct position along with the global tip/tilt mirror.
9. The intermediate fold between the pupil-forming lens and the K-mirror will be installed and adjusted to place the pupil on the global tip/tilt mirror. The fold should be adjusted in tilt and decenter until the on-axis beam of the central asterism is centered on the K-mirror rotation axis at the same time the pupil is centered on the global tip/tilt mirror. The on-axis beam should also be checked for wobble at a point several meters after the k-mirror to ensure the k-mirror axis is truly aligned with the central asterism.

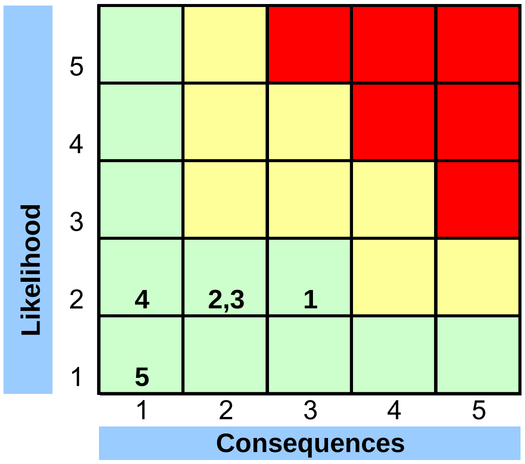
10. The beam expander will be aligned as a unit and then placed on the BGS. It will be adjusted in position along with the tip/tilt of the global tip/tilt mirror so that the on-axis laser beam is centered on both beam expander lenses and also passes over the center of the exit aperture.
11. The LT fold mirror will be installed such that the on-axis laser exits the BGS at the proper location and direction.
12. The asterism camera fold mirror, beam reducer, and asterism camera will then be installed in the leakage beam from the LT fold, and adjusted such that the entire field is visible on the camera.
13. The position sensors will be adjusted to produce a zero reading with the properly aligned input beams.
14. As a final check the output pupil position, beam waist size and location will be verified against the specified design.
15. The completed BGS assembly will then be mounted to the LT for alignment checks using the LT alignment fiducial assembly that is specified in its documentation.

9 REQUIREMENTS COMPLIANCE VERIFICATION

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

10 RISK AND RISK REDUCTION PLAN

Table 10 and Table 11 show individual risks within BGS in accordance with KAON 510.



Likelihood					
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟨	🟨	🟨	🟥
2	🟩 **4**	🟩 **2,3**	🟩 **1**	🟨	🟨
1	🟩 **5**	🟩	🟩	🟩	🟩
	1	2	3	4	5
	Consequences				

Table 10: Risk Matrix

#	Trend	Consequence	Like-lihood	Description	Status	Mitigation
1		3	2	Polarization problems, change as K-mirror rotates	Each beam's angle will vary by several degrees that may impact the polarization.	Further examination of the coatings is necessary.

2		2	2	The ability to fit all components to meet the size and weight requirements	Need to complete the mechanical modelling to ensure compliance.	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	1	AG Motion Devices	The ability of these devices in a changing gravity vector is a concern	Testing during DDR phase to alleviate concern

Table 11: 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 generation 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 verify that air breakdown due to high laser power will not be an issue. This should be investigated as early as possible in the detailed design phase by focusing a high power CW laser to comparable intensities and observing the results. Consideration should be made for different ambient pressure if this is not done at the Mauna Kea summit. If this proves to be a problem the beam expander will be changed to a Galilean type to remove the internal focus. The system will then need two steering mirrors to keep the exit pupil in the correct place while steering the asterism on the sky.

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. If this proves to be the case, the global tip/tilt mirror can be used as a fast correction element to correct for vibrations. It would likely use an accelerometer to sense the vibrations to correct.

10.5 Asterism Generator Motion Devices

There is a general concern about the SmarAct linear piezomotor devices for the AG stages. The concern is that the stages may not be able to develop the required force to operate properly under the changing gravity vector that these devices will experience. To alleviate the concerns, the project will test this device under different gravity vectors to determine their performance during the detailed design phase.

11 DELIVERABLES

Figure 16 shows the deliverables for the BGS.

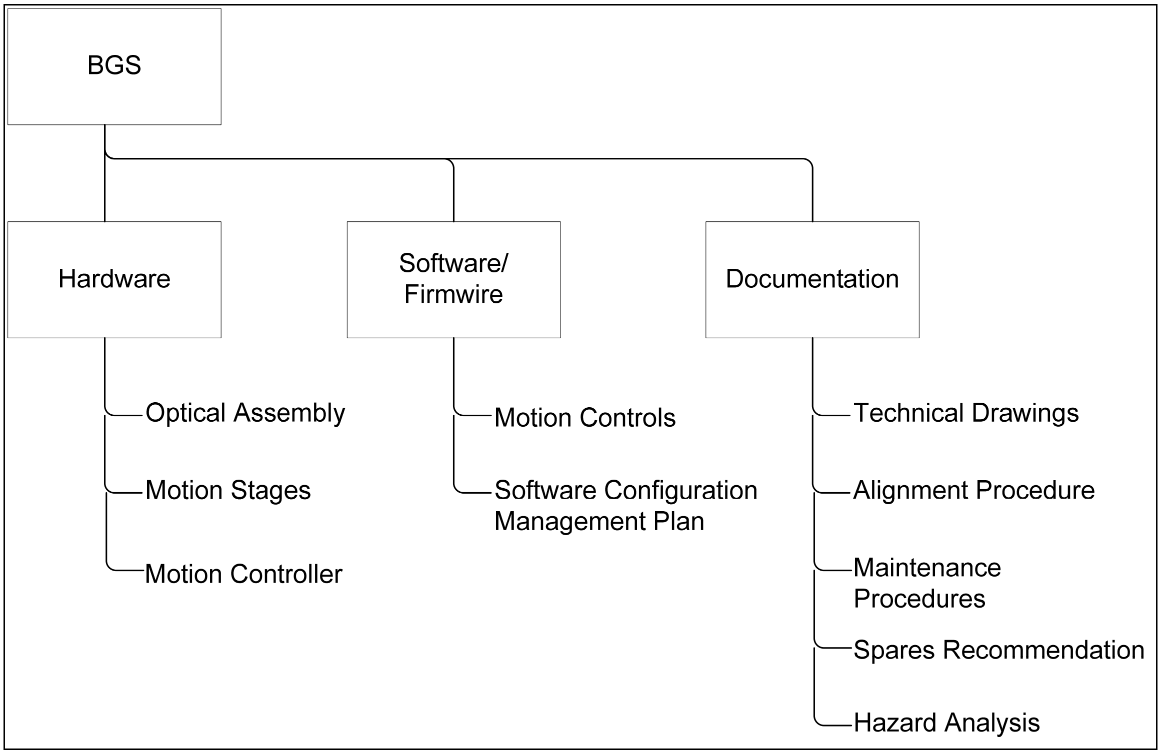


Figure 16: BGS Deliverables

12 MANAGEMENT

Management issues will be dealt with separately in the PDR.

A. ZEMAX MODEL LISTING

```
System/Prescription Data

File : H:\docs\NGAO\LGSF\optical_design\zemax\Full launch optics large beam v3.zmx
Title:
Date : WED MAY 5 2010
Configuration 1 of 4

GENERAL LENS DATA:

Surfaces                :               46
Stop                    :               2
System Aperture         : Float By Stop Size = 0.178
Glass Catalogs          : SCHOTT INFRARED
Ray Aiming              : Real Reference, Cache On
 X Pupil shift          :               0
 Y Pupil shift          :               0
 Z Pupil shift          :               0
 X Pupil compress       :               0
 Y Pupil compress       :               0
Apodization             : Uniform, factor =   0.00000E+000
Temperature (C)         :    2.00000E+001
Pressure (ATM)          :    1.00000E+000
 Adjust Index Data To Environment  : Off
Effective Focal Length  :        -3433307 (in air at system temperature and pressure)
Effective Focal Length  :        -3433307 (in image space)
Back Focal Length       :   3.478909e+008
Total Track             :   8.600065e+007
Image Space F/#         :         9644122
Paraxial Working F/#    :           10000
Working F/#             :           10000
Image Space NA          :   2.149076e-006
Object Space NA         :        0.000178
Stop Radius             :           0.178
Paraxial Image Height   :               0
Paraxial Magnification  :               0
Entrance Pupil Diameter :           0.356
Entrance Pupil Position :            1000
Exit Pupil Diameter     :        1205.271
Exit Pupil Position     :   2.949604e+008
Field Type              : Angle in degrees
Maximum Radial Field    :               0
Primary Wavelength      :           0.589 µm
Lens Units              :   Millimeters
Angular Magnification   :               0

Fields          : 1
Field Type: Angle in degrees
#       X-Value       Y-Value        Weight
 1      0.000000      0.000000       1.000000

Vignetting Factors
#      VDX       VDY       VCX       VCY       VAN
1  0.000000  0.000000  0.000000  0.000000  0.000000

Wavelengths     : 1
Units: µm
#         Value        Weight
 1      0.589000       1.000000

SURFACE DATA SUMMARY:

Surf     Type         Radius      Thickness              Glass      Diameter          Conic   Comment
 OBJ STANDARD       Infinity             0                                 0              0   laser head
```

```
  1 STANDARD     Infinity        1000                          0           0
 STO PARAXIAL          -           0                      0.356           -   Laser BXP L2
  3 STANDARD     Infinity         300                      0.356           0
  4 PARAXIAL          -           0                   1.853749           -   Laser BXP L1
  5 STANDARD     Infinity       17000                   1.853749           0   laser enclosure
  6 STANDARD     Infinity        6000                   28.47147           0   spider start
  7 STANDARD     Infinity           0                   1.880416           0
  8 PARAXIAL          -           0                         10           -   Compensator lens
  9 COORDBRK          -          50                          -           -
 10 STANDARD     Infinity           8            BK7    1.805221           0
 11 STANDARD    -396.7683           0                   1.822486   -2.264799   pupil forming lens
 12 STANDARD     Infinity         400                   1.880416           0
 13 COORDBRK          -           0                          -           -
 14 STANDARD     Infinity           0         MIRROR    2.588627           0   Fold
 15 COORDBRK          -        -303                          -           -
 16 COORDBRK          -           0                          -           -
 17 STANDARD     Infinity           0         MIRROR    4.283588           0   KM3
 18 COORDBRK          -          20                          -           -
 19 COORDBRK          -           0                          -           -
 20 STANDARD     Infinity           0         MIRROR    2.632559           0   KM2
 21 COORDBRK          -         -20                          -           -
 22 COORDBRK          -           0                          -           -
 23 STANDARD     Infinity           0         MIRROR    4.346412           0   KM1
 24 COORDBRK          -          25                          -           -
 25 COORDBRK          -           0                          -           -
 26 STANDARD     Infinity           0         MIRROR    3.085553           0   TT pupil
 27 COORDBRK          -      -9.004                          -           -
 28 STANDARD     15.35619          -3         N-SF66     3.09379           0
 29 STANDARD     7.750997        -220                   3.471254   -0.824009   BXP L2
 30 STANDARD     225.6938          -8       F_SILICA    39.59746           0
 31 STANDARD     68.69392         -50                         50  -0.5038749   BXP L1
 32 COORDBRK          -           0                          -           -   90 deg fold
 33 STANDARD     Infinity           0         MIRROR    57.13182           0   fold to LT
 34 COORDBRK          -           0                          -           -
 35 COORDBRK          -          45                          -           -   rotate BTO wrt LT
 36 STANDARD     Infinity           5                   540095.1           0   LT envelope (650)
 37 STANDARD     Infinity        9.52            BK7    40.23733           0   En W
 38 STANDARD     Infinity      276.78                   40.21046           0   EnW ends
 39 COORDBRK          -           0                          -           -
 40 STANDARD     Infinity           0         MIRROR    56.60775           0   Tertiary
 41 COORDBRK          -        -359                          -           -
 42 STANDARD      -80.696         464         MIRROR          40          -1   Secondary
 43 STANDARD    -1008.696     -490.57         MIRROR    466.4573          -1   Primary
 44 TILTSURF          -        -30.47            BK7         508           -   ExW 3' tilt
 45 STANDARD     Infinity    -8.6e+007                        508           0   ExW end
 IMA STANDARD    Infinity                               30851.61           0   90km

SURFACE DATA DETAIL:

Surface OBJ     : STANDARD laser head
Surface   1     : STANDARD
Surface STO     : PARAXIAL Laser BXP L2
 Focal length   :       -76.782121
 OPD Mode       :                1
Surface   3     : STANDARD
Surface   4     : PARAXIAL Laser BXP L1
 Focal length   :        370.62205
 OPD Mode       :                1
Surface   5     : STANDARD laser enclosure
Surface   6     : STANDARD spider start
Surface   7     : STANDARD
Surface   8     : PARAXIAL Compensator lens
 Focal length   :             -500
 OPD Mode       :                1
Surface   9     : COORDBRK
 Decenter X     :               -0
```

```
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :              0
 Tilt About Z  :              0
 Order         : Decenter then tilt
Surface  10    : STANDARD
Surface  11    : STANDARD pupil forming lens
Surface  12    : STANDARD
Surface  13    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :           32.5
 Tilt About Z  :              0
 Order         : Decenter then tilt
Surface  14    : STANDARD Fold
 Mirror Substrate : Curved, Thickness = 5.17725E-002
Surface  15    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :           32.5
 Tilt About Z  :              0
 Order         : Decenter then tilt
Surface  16    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :             55
 Tilt About Z  :              0
 Order         : Decenter then tilt
Surface  17    : STANDARD KM3
 Mirror Substrate : Curved, Thickness = 8.56718E-002
Surface  18    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :             55
 Tilt About Z  :              0
 Order         : Decenter then tilt
Surface  19    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :            -20
 Tilt About Z  :              0
 Order         : Decenter then tilt
Surface  20    : STANDARD KM2
 Mirror Substrate : Curved, Thickness = 5.26512E-002
Surface  21    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :            -20
 Tilt About Z  :              0
 Order         : Decenter then tilt
Surface  22    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :             55
 Tilt About Z  :              0
 Order         : Decenter then tilt
Surface  23    : STANDARD KM1
 Mirror Substrate : Curved, Thickness = 8.69282E-002
Surface  24    : COORDBRK
```

```
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :             55
 Tilt About Z  :              0
 Order        : Decenter then tilt
Surface  25    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :             10
 Tilt About Y  :             35
 Tilt About Z  :              0
 Order        : Decenter then tilt
Surface  26    : STANDARD TT pupil
 Mirror Substrate : Curved, Thickness = 6.17111E-002
Surface  27    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :             10
 Tilt About Y  :             35
 Tilt About Z  :              0
 Order        : Decenter then tilt
Surface  28    : STANDARD
Surface  29    : STANDARD BXP L2
Surface  30    : STANDARD
Surface  31    : STANDARD BXP L1
 Aperture      : Floating Aperture
 Maximum Radius :          25
Surface  32    : COORDBRK 90 deg fold
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :             45
 Tilt About Y  :              0
 Tilt About Z  :              0
 Order        : Decenter then tilt
Surface  33    : STANDARD fold to LT
 Mirror Substrate : None
Surface  34    : COORDBRK
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :             45
 Tilt About Y  :              0
 Tilt About Z  :              0
 Order        : Decenter then tilt
Surface  35    : COORDBRK rotate BTO wrt LT
 Decenter X    :              0
 Decenter Y    :              0
 Tilt About X  :              0
 Tilt About Y  :              0
 Tilt About Z  :            -45
 Order        : Decenter then tilt
Surface  36    : STANDARD LT envelope (650)
 Aperture      : Rectangular Aperture
 X Half Width   :          290
 Y Half Width   :          285
 X- Decenter    :            0
 Y- Decenter    :          131.5
Surface  37    : STANDARD En W
 Aperture      : Circular Aperture
 Minimum Radius :            0
 Maximum Radius :         23.5
Surface  38    : STANDARD EnW ends
 Aperture      : Circular Aperture
 Minimum Radius :            0
 Maximum Radius :         23.5
Surface  39    : COORDBRK
```

```
 Decenter X     :              0
 Decenter Y     :              0
 Tilt About X   :             45
 Tilt About Y   :              0
 Tilt About Z   :              0
 Order          : Decenter then tilt
Surface  40     : STANDARD Tertiary
 Mirror Substrate : None
 Aperture       : Elliptical Aperture
 X Half Width   :          22
 Y Half Width   :        31.1
Surface  41     : COORDBRK
 Decenter X     :              0
 Decenter Y     :              0
 Tilt About X   :             45
 Tilt About Y   :              0
 Tilt About Z   :              0
 Order          : Decenter then tilt
Surface  42     : STANDARD Secondary
 Mirror Substrate : None
 Aperture       : Circular Aperture
 Minimum Radius :            0
 Maximum Radius :         20.5
Surface  43     : STANDARD Primary
 Mirror Substrate : None
 Aperture       : Circular Aperture
 Minimum Radius :            0
 Maximum Radius :        253.5
Surface  44     : TILTSURF ExW 3' tilt
 X Tangent      :              0
 Y Tangent      :              0
 Aperture       : Circular Aperture
 Minimum Radius :            0
 Maximum Radius :          254
Surface  45     : STANDARD ExW end
 Aperture       : Floating Aperture
 Maximum Radius :          254
Surface IMA     : STANDARD 90km

COATING DEFINITIONS:


MULTI-CONFIGURATION DATA:

Configuration   1:
  1 Comment      :              ON AXIS
  2 Y-field     1 :           0
  3 Param 1     9 :          -0

Configuration   2:
  1 Comment      :            60 ARCSEC
  2 Y-field     1 :           0
  3 Param 1     9 :    -37.98143

Configuration   3:
  1 Comment      :            10 ARCSEC
  2 Y-field     1 :           0
  3 Param 1     9 :    -6.330238 Pickup from configuration 2, operand 3, scale 0.166667, offset 0

Configuration   4:
  1 Comment      :            10 ARCSEC
  2 Y-field     1 :           0
  3 Param 1     9 :     37.98143 Pickup from configuration 2, operand 3, scale -1, offset 0
```