# Beam Transfer Optics and Laser Launch Telescope Design Document

## MCAO Conceptual Design Review Material


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# Revision Control

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# 1. Introduction

The purpose of this document is to describe/discuss the design of two subsystems of the Cerro Pachon (CP) Laser Guide Star (LGS) system: the Beam Transfer Optics (BTO) and the Laser Launch telescope (LLT). The present document is a compilation of miscellaneous remarks and notes which does not intend to be exhaustive and have not always been strictly updated to the current BTO and LLT design. The following sections may instead investigate alternative solutions to the current design.

# 2. Acronyms

| | |
|---|---|
| AOM | Adaptive Optics Module |
| BTO | Beam Transfer Optics |
| CoDR | Conceptual Design Review |
| CP | Cerro Pachon |
| CTE | Coefficient of Thermal Expansion |
| e.e. | Encircled Energy |
| EPD | Entrance Pupil Diameter |
| FoV | Field of View |
| LGS | Laser Guide Star |
| LLT | Laser Launch Telescope |
| M2TS | Secondary Mirror Tip/Tilt System |
| MCAO | Multi-Conjugate Adaptive Optics |
| MCAO CS | MCAO Control System |
| MK | Mauna Kea |
| NGS | Natural Guide Star |
| OCDD | Operational Concepts Definition Document |
| PSD | Position Sensing Device |
| SSS | Secondary Support Structure |
| WFS | Wavefront Sensor |

# 3. BTO and LLT overview

## 3.1. General description

The BTO and LLT designs follow the Gemini requirement that there is a single design for both MK and CP. In the following, we described the BTO and LLT when used as part of the Multi-Conjugate Adaptive Optics (MCAO) system at Cerro Pachon (CP). It is assumed that the 5 Laser Guide Stars (LGS) for MCAO are produced by 5 independent laser heads.

The BTO receives the laser beams from the 5 laser heads of the laser system located either on the center section of the telescope or in the High Resolution Spectrograph room in the pier. The BTO propagates the beams along the telescope truss until they reach the top end ring, then sends them over the (-X, +Y) vanes towards the central frame, where they are directed to the LLT. The BTO has numerous pointing and centering loops to keep the beams aligned and correctly pointed at the sky, beam diagnostics and safety systems.

The LLT is basically a laser beam expander. The small diameter laser beams enter the LLT from the top and are sent through the sky with a bigger diameter. The LLT is positioned behind the secondary mirror of the telescope. It is composed of a primary mirror located at the bottom of the LLT and a refractive secondary at the top.

The BTO and LLT are controlled by the MCAO Control System.

## 3.2. MCAO CoDR drawings

The following AutoCAD drawings give an overview of the opto-mechanical conceptual design of the BTO and LLT. These drawings will be referenced to throughout this document. All drawings are appended to the main MCAO CoDR report.

- *Conceptual view of the BTO beam path* (HROSPATH.DWG)
- *Beam Transfer Optics along the –X +Y top end vane* (VANEPATH.DWG)
- *Beam Transfer Optics conceptual design for a single beam* (LLT1PLAN.DWG)
- *Beam Transfer Optics conceptual design for a five beam array* (LLT5PLAN.DWG)
- *Deployment concept for the LLT primary mirror* (DEPLOY.DWG)
- *Concept to optimize repeatability of LLT primary mirror deployment* (LLT_MC1.DWG and LLT_MC2.DWG)
- *Secondary Support Structure to LLT mounting interface* (SSS.DWG)

### 3.3. Operational concepts and requirements

A description of both the BTO and LLT operational concepts can be found in the MCAO Operational Concepts Definition Document. Requirements for the BTO and LLT are respectively described in the BTO Requirements Document and the LLT Requirements Document.

### 3.4. BTO and LLT components

Figure 1 (same as fig. 1 in the MCAO OCDD) gives an overview of the BTO and LLT elements. See also the BTO and LLT AutoCAD drawings for reference.

The LLT is composed of a retractable primary mirror M1, a fixed fold mirror FM, and a diverging lens assembly L1.

The BTO is composed of several flat mirrors Mi to propagate the beam from the laser system output to the LLT. M1 being the LLT primary mirror, and FM the Fold Mirror within the LLT, the BTO flat mirrors are numbered backwards from the LLT:

- M2 is a fast tip tilt mirror array made of 5 independent tip/tilt mirrors
- M3 is a slow tip tilt mirror array made of either 5 independent tip/tilt mirrors or 5 mirrors mounted on a single tip/tilt platform
- M4, M5, … are fixed mirrors
- M6, M7, … are slow tip tilt mirrors

The BTO also includes:

- a rotator so that the 5 LGS constellation remains steady on the sky (and on the AOM LGS WFS) while the telescope is tracking
- some various fixed optics:
  - a cube beam splitter (BS)
  - a corner cube (CC)
- a flip mirror (called shutter on fig.1) to divert the beam to a cooled dump/power meter mounted on the top-end ring

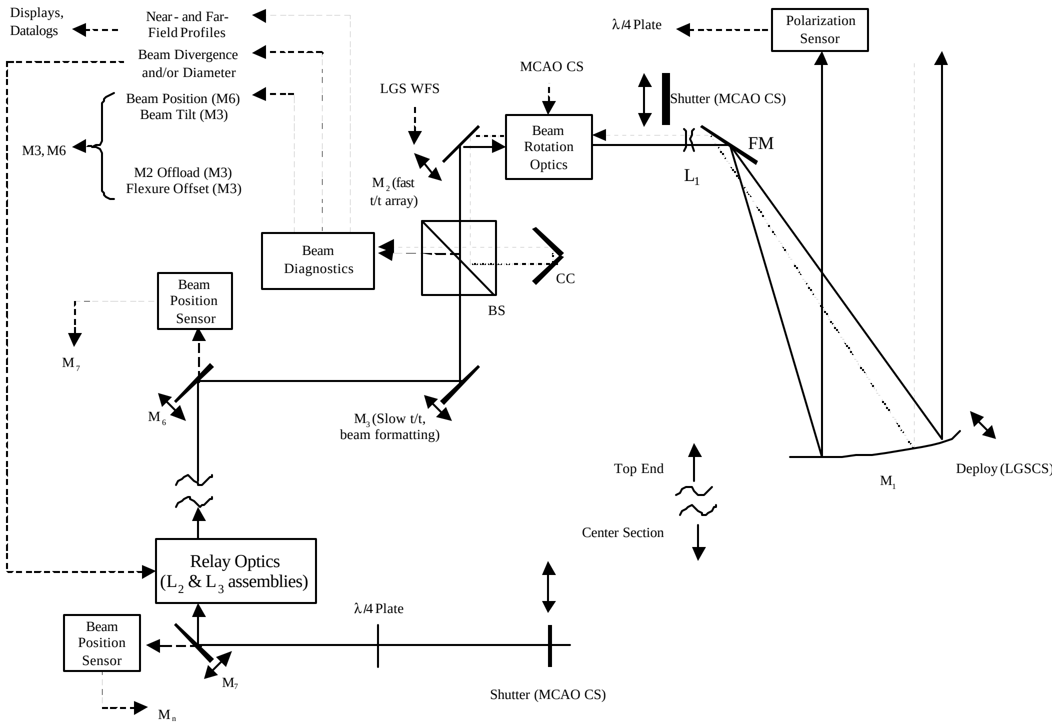



**Figure 1**: BTO and LLT schematic

- some relay optics (relay and /or zoom lenses):
  - L3 is the first lens assembly encountered by the propagating beam
  - L2 is the second one
- one or two laser shutters (power shutter and fast shutter) located at the output of the laser system
- a power shutter located before the LLT on the LLT structure
- some beam diagnostics:
  - beam position sensors (quad cell type)
  - beam profilers (near- and far-field)
  - beam power meter
- a quarter-wave plate to make the laser polarization circular
- a polarization meter

### *3.5. Laser propagation*

The laser beam diameters vary along the laser path.  At the output of the laser system, all beams are parallel and stacked in a line.  Due to free space diffraction, the beams naturally diverge (but remain parallel with respect to each other) so there is a need to re-collimate them along the laser path using the L3 and L2 lens assemblies.  The beams stay stacked in a line until they reach the slow tip-tilt array M3 where they are aimed and reformatted in an X-shape pattern.  From here, beams converge so that they overlap on M1 (see drawings VANEPATH.DWG and LLT5PLAN.DWG).

L2 and L3 form an afocal telescope which relay the output laser aperture on mirror M1.  In the current simplified design, L2 and L3 are the same so that the magnification ratio equals 1 between M7 and M6.  L3 and L2 are separated by about 10 m.  Between L2 and L1, the beams are collimated.  The diverging lens assembly L1 expands the beams before they reach M1.  A goal is to design L2 and L3 so that, during observations, they enable beam diameter changes on M1 to adapt the LGS spot size to the current seeing conditions.

All laser beam diameters stay smaller than 8-10 mm (99% energy) along the laser path.

## 4. The Beam Transfer Optics Design

### *4.1. Interfaces*

#### 4.1.1. BTO/Laser System interface

The Laser System output plane is the physical interface between the laser system and the BTO.

#### 4.1.2. BTO/LLT interface

The front face of the diverging lens assembly (L1) is the physical interface between the LLT and BTO.

### *4.2. Mirror Control*

#### 4.2.1. Fast tip-tilt mirrors

Each fast tip-tilt mirror is controlled by commands computed by the MCAO CS according to jitter measurements at the AOM LGS WFS level.  The differential jitter introduced on the up-link by the atmosphere is significant compared with the individual LGS spot stability requirement, then requiring separate correction for each LGS.

### 4.2.2. Slow tip-tilt mirrors

The tip/tilt loops are shown on figure 1. Using light leaking through the mirrors, position sensors (quad-cells or similar) are mounted behind the mirrors to measure the beam position. This signal is then sent to the MCAO CS to adjust the previous mirror position. If it were not possible to put a quad cell behind certain mirrors because of their tip/tilt actuators, a camera could be used to monitor the beam position on the front surface. However, the quad-cell solution is preferred for mirror control because camera images could be difficult to process due to large amounts of laser light scattering. Cheap cameras could still be used prior to observation to help as acquisition tools.

### 4.2.3. Tip/tilt mirrors error budget

A tentative error budget for the BTO slow and fast tip/tilt mirrors is appended at the end of this document. This is an Excel sheet presenting the dynamic range and accuracy requirements for mirrors M2, M3, M6 and M7.

## *4.3. Beam diagnostics*

### 4.3.1. BTO alignment

The BTO includes Position Sensing Devices (PSD) and/or cameras to center the beam on particular mirrors. More details can be found in the following document, appended to the MCAO CoDR main document: *Conceptual Design Review Material –Electronics, Sensors & Actuators in the Beam Transfer Optics (Chris Carter, April 2000).*

### 4.3.2. LLT alignment

We need to make sure that the LLT is:

1/ bore-sighted with respect to the Gemini telescope.

2/ adequately focused (collimated) on the sky.

Proposed methods:

(i) position sensors to make sure that the LLT primary mirror is right in place

(ii) use the acquisition camera to look at the LGS spot size (need to focus the Gemini telescope on the sodium layer first – we have checked that spherical aberration remains small enough when the telescope is defocused at 90 km)

(iii) imaging a star with the BTO diagnostics by means of a beam splitter and corner cube arrangement presented in figure 1 (see section 4.3.3.)

### 4.3.3. BTO/LLT pointing and centering loops

The beams must be centered on the LLT primary mirror, and their global tilt out of the LLT must be controlled. This means controlling the tilt in the BTO before the LLT, and controlling the optical axis bore-sight with respect to the Gemini telescope. Therefore, we need pointing and centering diagnostics to drive adequate tip/tilt mirrors.

The baseline approach is to use two cameras: one imaging the beam near-fields (for centering information) and one imaging their far-fields (for pointing information). Reference targets in the focal plane of the cameras are given by looking at a NGS through the LLT using method (iii) above. Note that this also enables plate scale calibration on the sky. When the laser beams are propagated through the BTO, they are sent to the diagnostics box containing both cameras via a low reflectivity beam splitter. If the location of the central beam coincides with the reference targets on both cameras, then it is co-aligned with respect to the LLT optical axis. The difference between alignment and co-alignment actually depends on the accuracy with which the corner cube is mounted with respect to the LLT optical axis. The corner cube apex has to be centered on the LLT axis for the central laser beam to be perfectly aligned with the LTT axis. The 4 outside beam location is measured on the far-field camera and compared to their ideal location on the sky. The near-field and far-field central beam measurements drive tip/tilt mirrors M6 and M3 to correct for misalignment with respect to the reference targets. M6, which is about 5 meters away from the diagnostics box is used mostly for centering the outgoing beams on M1, whereas both M6 and M3 are used for pointing adjustments on the sky.

Depending on space envelopes, the diagnostics box could be located either between M3 and M2 or between M2 and the LLT. These locations are indicated as the “case I” and “case II” diagnostics box on the *Beam Transfer Optics Conceptual Design For a Five-Beam array* AutoCAD drawing. Preference is given to the first location (case I) because the beams are not smeared yet by the fast tip/tilt motion induced by M2.

### 4.3.4. Laser beam parameters

We need to measure:

- the total beam power and if possible individual beam powers: use of a leak behind a mirror or of another diagnostics which can additionally give power measurement by means of calibration

- the beam profiles in the near-field and in the far-field + encircled energy + beam quality

- the beam polarization (to drive the quarter-wave plate at the output of the laser and maximize photon return from the sodium layer)

## *4.4. Shutters*

The BTO includes two shutters.

1/ The first shutter is located after the laser system output. This is the fast shutter controlled by the safety systems via the MCAO CS. This shutter prevents the laser beams from propagating through the BTO (and subsequently the LLT and the sky). It must close down as fast as possible whenever an airplane is detected near the laser path to the sodium layer or in any other emergency. This shutter must also dump the full laser power of the laser system for any length of time. This so-called "power shutter" can optionally be a slower system, located between the laser system and the fast shutter. The power shutter starts shutting down at the same time as the fast shutter. Cooling is available at the laser system location and is not an issue here.

2/ The second shutter is located on the other end of the BTO. It is not a fast shutter but it must dump the laser full power too, whenever the laser is propagated through the BTO but not to the sky. This must be done without creating a significant heat source at the top-end of the telescope, which would go against the upper-limit requirements on heat dissipated to the air and emissivity. There are two possibilities:

(i) An unusually large beam dump (larger than 0.5 m in diameter) could be mounted on the dome ceiling, and the telescope pointed to this fixed location whenever the laser needs to be propagated through the BTO and LLT but not to the sky.

(ii) A smaller beam dump can be located at the end of the BTO before the LLT and block the beam whenever needed. The laser is not propagated through the LLT in this case.

Practical reasons make it easier to envision a small beam dump, so solution (ii) is preferred. However, since no cooling is available at the top of the secondary structure where the LLT sits, the shutter will actually be made of two elements. A flip mirror will intercept the laser beams before they are expanded by the LLT and will direct the beams to the actual beam dump located on the top-end ring of the telescope, where cooling is available. Since this shutter is only used for BTO system calibration purposes, there is no need to hide the beams behind a vane and the beam dump can be conveniently located close to existing cooling and power supply installations.

### 4.5. Optics coatings and mirror covers

All BTO mirrors are high reflectivity mirrors with dielectric coatings (R>99% @ 589 nm) and all refractive optics such as lenses and beam splitters have anti-reflection coatings @ 589 nm. All coatings must resist to high energy densities of the order of 300 W/cm$^2$ or above (300 W/cm$^2$ correpsonds to five 10-W, 5 mm diameter beams superimposed).

There is no other way to maintain such high reflection and anti-reflection properties than protecting the optics from dust. In order to lower the maintenance load due to optics cleaning, all mirrors and optics will be protected form dust by covers. On top of the LLT structure, there will be an overall dust cover to protect al the optics mounted there. Along the telescope truss down to the laser system location, BTO mirrors will be protected by covers whenever the laser is not propagated. These covers will be remotely controlled by the MCAO Control System.

### 4.6. MCAO special requirements

#### 4.6.1. 5 beams instead of one

Drawings LLT1PLAN.DWG and LLT5PLAN.DWG show the great similarity existing between the BTO design for one beam and the BTO design for 5 beams. Differences between those two designs are:

- the dither sensor required for dither operations with mono-LGS AO systems is suppressed in the 5 beam design.

- M2 and M3 are single tip/tilt mirrors in the single beam design, whereas they are tip/tilt mirror arrays in the 5 beam design.

#### 4.6.2. X-constellation shaper concept

The BTO must "arrange" the beams in a square pattern: 1 beam on-axis, 4 beams in the corner of the square. The baseline specification is that the square has a 85 arcsec diagonal on the sky.

2 possibilities:

(i) either the 5 beams are arranged in this square pattern at the very beginning of the BTO, on the center section

(ii) or they are aligned on top of each other until they have crossed over the vane, then are re-arranged in a square pattern.

Baseline is solution (ii).

On top of its slow tip/tilt functionality, M3 will also serve as an "X-constellation shaper" as described by Figure 2. See also drawings VANEPATH.DWG and LLT5PLAN.DWG.

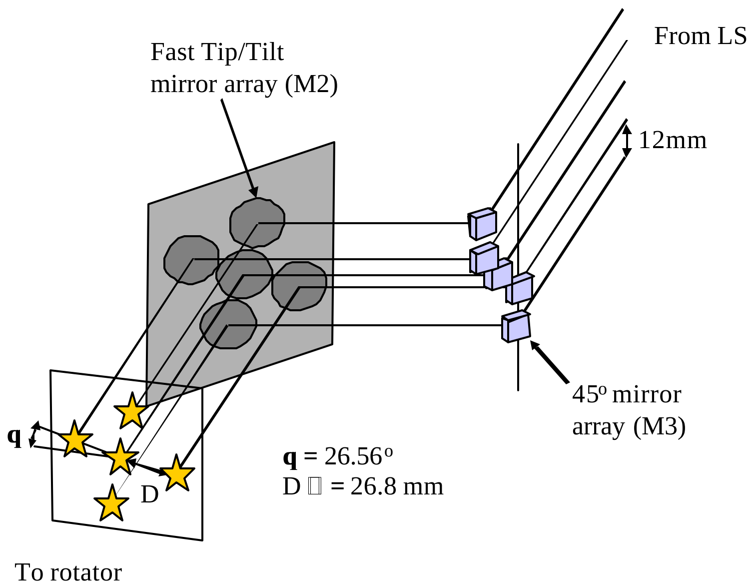



**Figure 2** “X-constellation shaper” concept

### 4.6.3. Field rotator

There must be a rotator along the BTO path to have the 4 off-axis LGS rotate around the on-axis LGS. This is a priori less difficult to do than having a field de-rotator inside the AOM package. The rotator could be a K prism, located in between M2 and the diverging lens L1, once the 5 beams have been arranged in the final square pattern and almost overlap.

### 4.6.4. Diagnostics

The baseline is to use the same type of diagnostics as for the MK LGS AO system.

Note that the use of a rotator somewhere along the BTO path before the diagnostics would imply that the 5-beam pattern is rotating at this point.

3 possibilities:

(i) either we have a permanent de-rotator before the diagnostics which keeps the pattern steady on the sensors

(ii) or we have a field stop which filters out the 4 off-axis beams and only look at the on-axis beam, and the diagnostics are configured to look at this one beam only (but then we never know about the other beams, profile, power, etc…)

(iii) or the diagnostics can monitor the 5 beams together each time the rotator is not working (before and after science observation), and they only monitor the one beam on-axis (thanks to a field stop) during MCAO closed loop operation.

In the baseline design, the de-rotator actually stands after the diagnostics package and the remarks above do not apply any more. The diagnostics will effectively sense all beams at the same time.

## *4.7. Scattered light*

### 4.7.1. Prior experience at other observatories

This section gives a comparison of the status of the scattered laser light issue for the AO WFS and the instrument in various observatories.

#### *4.7.1.1. MMT*

In his Ph.D. dissertation (*Sodium Laser Guide Star Projection For Adaptive Optics*, University of Arizona, 1997), Jake Jacobsen makes a calculation based on Rayleigh scattering that a negligible amount of scattered light eventually enters the science path. MMT is so deeply convinced that scattered light is not an issue that their plan is to expand the laser beam to its maximum size (about 50 cm) while the beam is crossing over the primary mirror in direction of the secondary frame.

#### *4.7.1.2. ALFA*

The ALFA team reports (Sebastian Rabien’s e-mail, 11/4/99): “Before the beam relay was closed, we once did a measurement on the background we were introducing on the wfs. On the pictures we took, as far as I remember no additional background could be seen with laser on/off (…)”. Note that the laser beam path has been enclosed ever since, but for reasons of air turbulence and dust protection only.

#### *4.7.1.3. Lick*

Herb Friedman and his team from the LLNL did not want to take any risk of having scattered light in the science path. That is why the beam path is enclosed from end to end. The Lick team reports seeing a lot of scattered light in the dome when any of the covers is open. Herb Friedman’s concern is the following: calculations based on Rayleigh scattering are inadequate since scattering in the dome is due to dust and particules much bigger than those involved in standard Rayleigh scattering. Moreover, those calculations do not take the laser format into account and assume CW power. This may change results a lot for pulsed laser formats such as the Lick’s.

### 4.7.2. Gemini

Mark Chun did the same calculations as Jake Jacobsen and confirm them partly. It is difficult to make a better calculation by taking real parameters into account (type of scattering and laser format). We will know more once we get information on the amount of dust measured in the dome (experiments are under way).

The baseline plan is to cover the up-going part of the beam path with demi-tubes only. This will protect the science path from any subsequent direct scattered light while avoiding beam-path conditioning required by fully enclosed tubes. Air flow through the dome due to the Gemini vents will prevent turbulence from building up in the tubes due to chimney effects. When the beams are crossing over the primary mirror, they will be hidden behind a vane in order to reduce any direct scattering onto the primary mirror of the telescope. There should not be any problem with scattering within the dome from the expanded beams leaving the LLT since the distance between the LLT and the dome is shorter than 0.5 m.

Note: do the beams have to be precisely hidden behind the 1-cm vane?

The answer is not straightforward. According to calculations we have made, scattered light should not be an issue for the AOM WFS nor for the instrument. However results of these calculations are highly subject to the assumptions we made on dust particle densities and sizes at Cerro Pachon. Therefore it is wise to consider keeping the beams precisely hidden behind the vane just in case.

# 5. The Laser Launch Telescope Design

## *5.1. Optical design*

### 5.1.1. Overview

The LLT is composed of an off-axis parabolic primary mirror (M1) at the bottom, a flat fold mirror at the top (FM), and a diverging lens assembly (L1). We choose a diverging lens as the secondary element of the beam expander in order to avoid bringing the laser beams to sharp focus (discussed in section 5.1.4).

The baseline M1 has a clear aperture of **450mm** and a focal length of **1750mm** to be matched to off-the-shelf off-axis parabolas seen in catalogs. 450 mm is about the maximum diameter that can be inserted within the existing secondary frame.

The LLT magnification is set by the ratio between the entrance beam diameter and the beam size on the LLT primary mirror. We must choose both values before completing the LLT design. Note that the magnification ratio should be the same for the MK LLT and CP LLT. The entrance beam diameter should not be too small in order to limit the energy density onto the BTO and LLT entrance optics, and also to avoid large magnification ratio LLT designs. On the opposite, the entrance beam diameter should not be too large for the beam to avoid turbulence-induced jitter. The maximum beam diameter is finally set by the necessity to hide the beams over a telescope vane. The baseline exit beam diameter is chosen equal to 300 mm at the $1/e^2$ intensity point, corresponding to a 471 mm beam diameter at 99% encircled energy. Section 5.1.2 gives a brief discussion of the 300 mm choice.

(1) If the beams were arranged in an X-shape at the start of the BTO, we would choose:

- input beam $1/e^2$ diameter = 2.0 mm (for 5 beams to be arranged in a cross pattern, separated by there 99% encircled energy diameter, and being hidden behind the top-end vane, whatever their position in rotation – calculation: $3*(\pi*2/2) = 9.4$ mm / vane is 10 mm wide)
- output beam $1/e^2$ diameter = 300 mm
- which gives a magnification ratio equal to 300/2.0 = 150

(2) Baseline is actually to stack the beams in a line when crossing over the vane, so that the beam diameter can be larger:

- input beam $1/e^2$ diameter = 5.0 mm
- output beam $1/e^2$ diameter = 300 mm
- which gives **a magnification ratio equal to 300/5.0= 60**

### 5.1.2. Alignment tolerances and derived requirements

A tolerance analysis is being conducted to derive the following requirements for the LLT and BTO:

#### *5.1.2.1. LLT focus*

The distance variations between the primary mirror and the secondary mirror of the LLT shall be no longer than **± 5 mm** maximum.

Note: A defocus of 5 µm produces a LGS spot size enlargement smaller than 0.1 arcsec on the sky at 90 km. Note that the 0.1 arcsec criteria is also used to set the laser system pointing stability requirement.

#### *5.1.2.2. LLT structure alignment*

We must determine:

(a) the static mechanical positioning error of the LLT axis relative to the secondary support structure (SSS) in angle and in translation

(b) the LLT primary mirror deployment repeatability

From there, we will work out what the BTO tip/tilt mirrors dynamic ranges have to be in order to keep the BTO/LLT system aligned (M3 and M6 especially) and the LGSs in their intended position on the sky. This will also define all optics minimum clear aperture diameters to avoid vignetting.

Notes:

(1) According to Dave Montgomery:

- The secondary module tilts up to 2 arcsec depending on zenith angle.
- There is a 2.4 mm sag for the top-end module (<-> 200 mrad over 12 m)

(2) Will the look up table used to correct for the secondary frame tilt vs. telescope elevation angle be adequate to correct for the LLT structure tilt vs. elevation angle?

The LLT focus stability and the LLT structure alignment are discussed in the LLT Mechanical Design section (section 5.3).

### 5.1.3. Preliminary LLT optical design and tolerance analysis with ZEMAX

#### *5.1.3.1. LLT optical design*

##### 5.1.3.1.1. Baseline

The baseline design was created by Jim Oschmann, using an off-axis parabola and a diverging lens assembly found in the ZEMAX lens catalog (Spindler & Hoyer). At that time, Jim used a FoV smaller than required by MCAO. The entrance pupil diameter (EPD) was 8 mm, and the magnification ratio 32.5, smaller than our present baseline choice for MCAO. With the FoV scaled to +/- 1 arcmin on the sky, the performance is not nearly as good any more.

A drawing of Jim's design can be found in appendix at the end of the present document together with spot diagrams and encircled energy plots (figure 6). We have used a paraxial lens to focus the collimated beams in order to assess the design optical performance. The paraxial focal length is chosen equal to 206.27 mm so that one micron in the focal plane is equivalent to one arcsecond on the sky. The LGS spot radii are in the range of 0.6 arcsec RMS.

##### 5.1.3.1.2. Comments on LLT magnification ratio

In the following we assume that the laser beam diameter on the LLT primary mirror is fixed and equal 300 mm @ $1/e^2$ intensity points.

A 5.6 mm $1/e^2$ diameter laser beam, corresponding to a 8.9 mm 99% e.e. diameter beam is the maximum beam diameter to be hidden behind the vane without being seen in the acquisition camera square 2*2 arcmin FoV. This corresponds to a minimum magnification ratio of 55. Hiding the 5 laser beams behind the vane is not an issue providing that the magnification ratio is greater than 55. We can allow the magnification ratio to vary if it help to improve the optical design performance.

If we assume:

- parabola focal length = 1750 mm
- LGS separation on the sky = +/- 42.5 arcsec

We can derive the LLT input FoV for any magnification ratio above 55 (see table below).

| Input beam diameter (99% e.e.) in mm | Input diameter (@ 1/e2 intensity points) in mm | Magnif. Ratio | DV lens focal length in mm | LLT Input 1/2 FoV in degree |
|---|---|---|---|---|
| 8.6 | 5.5 | 55.0 | 32.4 | 0.6 |
| 7.9 | 5.0 | 60.0 | 29.7 | 0.7 |
| 6.7 | 4.3 | 70.0 | 25.4 | 0.8 |
| 5.9 | 3.8 | 80.0 | 22.2 | 0.9 |
| 5.2 | 3.3 | 90.0 | 19.7 | 1.1 |
| 4.7 | 3.0 | 100.0 | 17.7 | 1.2 |
| 4.3 | 2.7 | 110.0 | 16.1 | 1.3 |
| 3.9 | 2.5 | 120.0 | 14.7 | 1.4 |
| 3.6 | 2.3 | 130.0 | 13.6 | 1.5 |
| 3.4 | 2.1 | 140.0 | 12.6 | 1.7 |
| 3.1 | 2.0 | 150.0 | 11.7 | 1.8 |

##### 5.1.3.1.3. Alternative designs

Other designs have been proposed in order to correct the aberrations introduced by the off-axis parabola. Those designs are currently under study.

#### *5.1.3.2. BTO/LLT misalignment tolerance analysis*

##### 5.1.3.2.1. LLT5PLAN.DWG vs. LLT5PLAN.ZMX

We have started to analyze the effects of beam wander on the LLT primary mirror due to the BTO tip/tilt mirrors motion (see figure 7 in appendix). We have used a paraxial design to reproduce the opto-mechanical design presented in the AutoCAD drawing LLT5PLAN.ZMX. Distances are identical between the AutoCAD and ZEMAX drawings. The 5 laser beams are represented by the following FoV with:

a = 0.71 * sin(26.568 deg) and b = 0.71 * cos(26.568 deg)

(FoV = 42.5 arcsec on the sky corresponds to +/- 0.71 degree):

| | FoV 0 | FoV 1 | FoV 2 | FoV 3 | FoV 4 |
|---|---|---|---|---|---|
| X angle | 0 | a | -b | -a | b |
| Y angle | 0 | b | a | -b | a |

#### 5.1.3.2.2. Preliminary results

This preliminary study shows some level of vignetting of the beams (see plots in appendix). Here are some preliminary results.

Assumptions:

- Paraxial lens for DV lens (f = -29 mm) and M1 (f = 1750 mm)
- Magnification coefficient. = 60
- All optics dimensions are fixed using the parabola 450 mm diameter as a stop to determine them
- STOP = beam 7.8 mm 99% e.e. diam ( corresponding to 5.0 mm @ $1/e^2$ intensity points)
- FoV = 0 (beam on axis)
- Use paraxial lens of focal length = 206.27 mm to visualize far-field so that 1 micron in the image plane <--> 1 arcsec on the sky

(a) Single beam design

DITHER: A tilt of 0.25 deg of dither mirror create a 30 arcsec dither on the sky.

Footprint diagrams are used to visualize the beam wander on the primary mirror and DV lens:

- for dist(Dither mirror-DV lens)=105 mm, the 1/e2 diam. remains included in the 450 mm diam. parabola, but not the 99% ee diam.

- for dist(Dither mirror-DV lens)= 50 mm, it looks much better overall

Conclusion: the dither mirror should be located as close as possible to the diverging lens (closer than 50 mm if possible).

(b) 5 beam design

FAST TT: A tilt of 0.0083 deg of fast TT mirror create a 1 arcsec tilt on the sky.

Footprint diagrams are used to visualize the beam wander on the primary mirror and DV lens:

- for 1 arcsec tilt: not bad

- for 7 arcsec tilt (corresponds to the 1 mrad 1/2 tilt supported by PI fast TT platform): beam much off the parabola

Conclusion: the fast TT mirror should be located as close as possible to the diverging lens AND its tilt amplitude should be limited.

### 5.1.4. Optimized spot size at the LLT primary mirror

This section describes how to choose the optimized spot size on the LLT primary mirror when its diameter is fixed by practical constraints to 450mm.

(a) *Ideal gaussian beam, no turbulence*

Compromise between:

- smallest spot size on sodium layer
- max power transmitted
- less far field intensity reduction due to aperture clipping (if the sodium layer is in the far field)
- less near field ripples due to aperture clipping (if the sodium layer is in the near field)

A complete theoretical description is given by A. E. Siegman in *Lasers*, University Science Book, 1986, pp 731-734

(b) *Non-ideal gaussian beam, no turbulence*

A real beam has a $M^2 > 1$ which means that the beam expands $M^2$ times more than an ideal gaussian beam does. This does not affect the choice of the optimized beam size providing there is a zoom adjustment prior to the LLT in order to resize the beam spot on the LLT primary mirror.

(c) *Non-ideal gaussian beam with turbulence*

Compromise between:

- optimized beam size for ideal or real gaussian beam described by its $M^2$ value
- seeing

  → beam size between 2 to 3 $r_0$ should be the best choice

- MCAO system optimization for bad seeing (we want to increase the signal to noise ratio for bad seeing where the SNR is low rather than increase it for good seeing conditions where the SNR is already large)

Cf Jake Jacobsen's PhD thesis, *Sodium Laser Guide Star Projection for Adaptive Optics*, U. of Arizona, 1997

<u>Conclusion</u>: the optimized spot size is chosen to be **300 mm @ 1/e$^2$ intensity points**.

### 5.1.5. LLT focusability

This section discusses whether the LLT focus should be adjustable or not.

(a) *Ideal gaussian beam, no turbulence*

A calculation of the LGS spot size at the sodium layer for an ideal gaussian beam show that **there should be no need to change the LLT focus** once it has been adjusted for a nominal focal length in the range of 90-180 km (e.g. 100 km). Distances other than the nominal LLT focal length will be in the Rayleigh range of the gaussian beam, which means that the spot size will not increase by more than 2 times its nominal value along that range.

Table 1 gives the theoretical spot size of the LGS for various elevation angles along with the corresponding Rayleigh range. The sodium layer altitude is assumed to be 90 km above sea level, which is 86 km above Mauna Kea (MK) and 87.3 km above Cerro Pachon (CP). Results are given for MK only, as they would be fairly similar for CP. The 1/e2 spot size at the LLT primary mirror is 30 cm. We used the following formulas:

$$w_1 = \frac{\lambda f}{D}$$

$$Z_R = \frac{\pi w_1^2}{\lambda}$$

where $2*w_0$ = 30 cm is the 1/e$^2$ intensity diameter at the LLT primary mirror

$2*w_1$ is the 1/e$^2$ intensity diameter at the sodium layer

$Z_R$ is the Rayleigh range of the gaussian beam at the sky

D = 45 cm is the diameter of the LLT primary mirror (Note: one usually uses D = $\pi w_0$ but here $\pi w_0$ = 47 cm > D = 45 cm so we use the actual value of D – anyway results are very close)

f is the focal length of the LLT

| Elevation angle | 0 (zenith) | 30 degree | 45 degree | 60 degree |
|---|---|---|---|---|
| Distance to average sodium layer | 86 km | 100 km | 122 km | 172 km |

| | | | | |
|---|---|---|---|---|
| Spot size if focused at the corresponding distance ($1/e^2$ diameter) | 22.5 cm | 26.2 cm | 31.9 cm | 45.0 cm |
| Corresponding Rayleigh range | 18-154 km | 9-191 km | 0-263 km | 0-450 km |

Table 1: LGS spot size and Rayleigh range versus elevation angle for a LLT focused at the sodium layer (ideal laser beam, no turbulence)

If we assume that the LLT is focused at 100 km, we can calculate what the theoretical LGS angular diameters seen from the ground would be for all other elevation angles than 30 degree. The gaussian beam propagation laws give:

$$w(z) = w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}$$

$$FWHM_r = w(z) * \sqrt{2\ln 2}$$

$$FWHM_a = \frac{FWHM_r}{l}$$

where z=0 gives the beam waist location (at 100 km on the LLT optical axis)

z is the distance between the sodium layer and the beam waist

w(z) is the $1/e^2$ intensity radius at the sodium layer (seen perpendicular to the LLT optical axis)

$FWHM_r$ is the radial FWHM of the spot

$FWHM_\alpha$ is the angular FWHM of the spot seen from the ground

l is the on-axis distance to the sodium layer

Results are presented in table 2.

| Elevation angle | 0 (zenith) | 30 degree | 45 degree | 60 degree |
|---|---|---|---|---|
| On-axis distance to sodium layer | 86 km | 100 km | 122 km | 172 km |
| Spot size at the sodium layer ($1/e^2$ diameter) | 26.2 cm | 26.2 cm | 26.9 cm | 33.4 cm |
| $FWHM_\alpha$ seen from the ground | 0.37 arcsec | 0.32 arcsec | 0.27 arcsec | 0.24 arcsec |

Table 2: LGS angular spot size versus elevation angle for a LLT focused at 100 km (ideal laser beam, no turbulence)

(b) *Non-ideal gaussian beam, no turbulence*

The laser beam quality can be partially described by an $M^2$ number or "times diffraction limited" number which, to some extent, allows to scale the gaussian beam propagation laws to a non-ideal laser beam. According to these laws, if we keep the spot size fixed on the LLT primary mirror (i.e. the non-ideal gaussian beam has the same spot size as the ideal one), the LGS spot size at the sodium layer will increase proportionally to $M^2$ but the focus location (the waist location) will not change.

The MK LGS Laser System Requirements document specifies a laser beam about 1.5 times diffraction limited. For such a laser system, Table 2 results in terms of spot size at the sky translates into the results given in Table 3.

| Elevation angle | 0 (zenith) | 30 degree | 45 degree | 60 degree |
|---|---|---|---|---|
| On-axis distance to sodium layer | 86 km | 100 km | 122 km | 172 km |
| Spot size at the sodium layer ($1/e^2$ diameter) | 39.3 cm | 39.3 cm | 40.4 cm | 50.1 cm |
| $FWHM_\alpha$ seen from the ground | 0.56 arcsec | 0.48 arcsec | 0.41 arcsec | 0.36 arcsec |

Table 3: LGS angular spot size versus elevation angle for a LLT focused at 100 km (1.5 times diffraction-limited laser beam, no turbulence)

(c) *Non-ideal gaussian beam with turbulence*

Whatever the theoretical out of focus spot size increase (or decrease), the change is either of the same order of magnitude or negligible in comparison with the LGS spot size increase due to turbulence distortion (cf Francois Rigaut's simulations)

<u>Conclusion</u>: there is no need to change the LLT focus (assuming the LLT mechanical design ensures a perfect stability)

### 5.1.6. Power density at sharp focus

Should we avoid bringing the laser beam to too sharp a focus?

For reference:

(a) The maximum average power density that LLNL allows at the dye/glass interfaces in the Keck and Lick lasers is 10 $kW/cm^2$.

(b) Typical damage thresholds on coated optics (Coherent, Melles Griot): 10-500 $MW/cm^2$ for pulsed lasers (10 ns pulses usually), 1-1000 $kW/cm^2$ for CW lasers.

If we focus a sum-frequency laser, 10W average power, 5mm diameter, with a 10 mm focal length lens, the power density at focus will be close to 300 MW/cm2. If we focus a LLNL laser, 25 W average power, 5mm diameter beam, with a 10mm focal length lens, the power density at focus will be close to 800 MW/cm2. Those numbers are close to or above typical damage thesholds in terms of average power densities, they are definitely above in terms of PEAK power densities. Of course, we would not use any optics in the focal plane of the 10 mm converging lens, but any dust particle that would stand at focus could deteriorate the laser beam quality a lot.

Conclusion: we should avoid focussing the beam if we can.

## *5.2. Miscellaneous on LLT alignment procedures*

### 5.2.1. In the lab

We could use, for instance, a "star simulator" similar to the one built by Space Optics Research Labs. Specifications are the following:

Clear aperture: 38.1 cm

Central obscuration: 0.5% area

System wavefront: lambda/6 Peak to Peak @ 633 nm

Source diameter: 8 arcsec

Star brightness range: -2 t0 +6 magnitude in ½ mag. Increments

Angular adjustments: +- 5 deg in azimuth, +- 5 deg in elevation

Dimensions: 152x51x97 cm

Price???

Contact: SORL, 7 Stuart road, Chelmsford, MA 01824 USA, Phone: 978 250 8640

Other possibility: Use a point source located on axis before the beam splitter (which samples the beam and send it to the diagnostics), send the light through the LLT, retro-reflect onto a large flat mirror, then sense the light back (double pass) in the diagnostics.

### 5.2.2. On the telescope

One possibility is to point the Gemini telescope at a bright NGS, and look at the light coming from this star through the LLT, sent into the diagnostics package through the beam splitter placed in front of it. This gives an idea of how well the LLT itself is aligned (see aberrations). Then you can compare the NGS light on the diagnostics with the laser beam and get the feeling of how well the BTO and LLT are aligned with respect to each other. If the beams are superimposed both in the near field (beam centering) and in the far field (beam pointing), then the BTO optical axis is coincident with the LLT optical axis. If not, the NGS values become the new targets for the BTO beam alignment loops.

### 5.2.3. Spot size in the sky

We can acquire and estimate the LGS spot size in the sky by using the Gemini acquisition camera with the 8-m telescope refocused at 90 km. The spherical aberration using the telescope at this conjugate is smaller than the nominal seeing, so the acquisition camera can also be used to detect focus errors.

## *5.3. Mechanical Design*

There are several criteria that influence the design of the Laser Launch Telescope (LLT). The LLT must allow the Gemini telescope to have a clear line-of-sight through the entire Secondary Support Structure (SSS). Another consideration is the alignment between the Diverging Lens (L1), Fold Mirror (FM), and the LLT Primary Mirror (M1). These three components must be held to tight tolerances with respect to each other in order to retain the correct focus. Even small changes in temperature can affect focus. Therefore, some form of thermal compensation must be utilized. The LLT cannot interfere with any of the existing functions of the Secondary Tip/Tilt System (M2TS). This includes the amount of mass being added as well as any geometric interference. Geometric considerations include allowing the Gemini telescope to have a clear line-of-sight through the entire SSS. The LLT must also be able to mount to the existing SSS. The following sections show how these issues are addressed.

### 5.3.1. Retractable Mirror

It is an uncompromising science requirement that the primary mirror of the LLT does not obstruct the secondary hole when MCAO is not in use. M1 MUST therefore be retractable. This will be accomplished by allowing the M1 mirror and mirror cell to pivot from 0° (the deployed position when in use) to 90° (the retracted position when not in use). See drawing DEPLOY.DWG for reference. The mirror cell will have pivot brackets on the +X and -X sides, offset from the central axis of the LLT. This will allow the cell to retract against the -Y side of the LLT frame, allowing the CP telescope to have a clear viewing path through the LLT.

The pivoting motion of the mirror cell will be performed by a small electric motor, either connected directly to the pivot bracket, or connected through linkages to the side of the cell. The MCAO Control System will control the motor. The limits of motion (0° and 90°) will be set by limit switches, which feed their signal back to the MCAO Control System.

### 5.3.2. Repeatability of the LLT Primary Mirror Position

The current design of the LLT primary mirror cell (drawings LLT_MC1.DWG and LLT_MC2.DWG) holds the mirror using a spring retainer system. This allows the mirror to "float" with respect to the mirror cell. Thus, when the primary mirror is deployed, the mirror will land on a positioning platform, separating it from the mirror cell. This will eliminate any contribution to a repeatability error from the deployment mechanism.

### 5.3.3. Focus Compensation

The distance between the diverging lens and the primary mirror is the parameter that controls the LLT correct focus. This distance has to be controlled at better than **+/- 5 microns.** This length change gives a 0.1 arcsec enlargement of the spot size at the sky. (Note: 0.1 arcsec is the number we used to set the Laser System pointing stability requirement).

The off-axis focal length of the off-axis parabola is 1761.2 mm. For a magnification ratio of 60, the diverging lens assembly focal length will be of the order of 29.3 mm, so that the distance between the LLT primary mirror and the diverging lens is on the order of **1731.9 mm** along the LLT optical axis. This distance will be held by the aluminum LLT frame and supporting brackets. Because the thermal expansion of aluminum is relatively high compared to other materials, thermal compensation is required.

The LLT frame will be fabricated out of 6061-T6 aluminum. This will eliminate any thermal variation stresses in the LLT frame with respect to the secondary frame (also fabricated out of 6061-T6 aluminum). Because of this, all thermal variations will be considered with respect to aluminum. The coefficient of thermal expansion (CTE) for 6061-T6 aluminum is 23.6 µm/m-°C. This is the value rated at 20.0°C and will be assumed to be constant throughout the temperature ranges being considered here. The 1731.9 mm focal distance and a 1 °C temperature rise, produces an expansion of:

$$DL = C_T LDT$$

$$DL = 23.6 * 10^{-6} \text{ m/m-°C} * 1731.9 \text{ mm} * 1.0 \text{ °C} = 0.0416 \text{ mm} = \mathbf{40.8\ microns}$$

In order to compensate for this, the diverging lens and supporting bracket will be placed on a translation table. Two 150.0 mm zero-expansion, carbon composite rods will be pinned on either side of the table, and bracketed off the base of the table. The rods will be offset at an angle from the translation direction as shown in Figure 3.

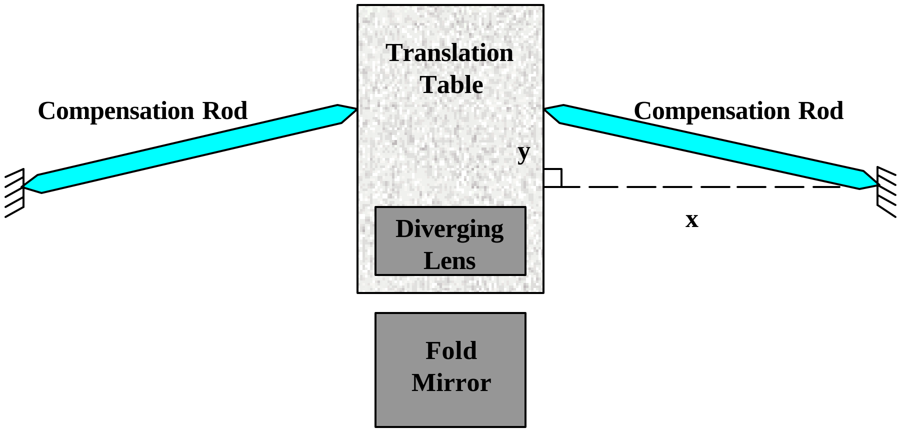



**Figure 3:** Radial Alignment Concept For Thermal Compensation

If we let:

$C_T$ equal the Coefficient of Thermal Expansion for aluminum

DT equal the temperature change (here a 1 °C temperature change will be used)

d equal the required thermal compensation

x equal the rod offset from the translation table

Dx (= $C_T$*DT*x = $C_T$ * x) equal the thermal expansion of the x axis

x' [= x + Dx = (1 + $C_T$)x] equal the rod offset in the expanded state

= (1 + $C_T$) x for a 1 °C temperature rise

y equal the initial translational offset of the pinned rod

Dy (= -d) equal the required thermal compensation

y' (= y + Dy = y - d) be the initial position plus required compensation

L equal the constant rod length

And we know that:

$x^2 + y^2 = L^2$ Equation A

$x'^2 + y'^2 = L^2$ Equation B

$= (1 + C_T)^2 x^2 + (y - d)^2 = (1 + C_T)^2 x^2 + y^2 - 2dy + d^2 = x^2 + y^2$

Bringing all quadratic terms to the left side of the equation and canceling:

$[(1+C_T)^2 - 1]\, x^2 = 2dy - d^2$

$C_T\,(2 + C_T)\, x^2 = 2dy - d^2$

or

$$x^2 = \frac{2d}{C_T(2+C_T)}\,y - \frac{d^2}{C_T(2+C_T)}$$

Plugging this in to Equation A to eliminate the $x^2$ term, and bringing all terms to the left produces:

$$y^2 + \frac{2d}{C_T(2+C_T)}y - \left(\frac{d^2}{C_T(2+C_T)} + L^2\right) = 0$$

We calculate y by solving the quadratic equation for a 300 mm zero-expansion rod, then derive x. This gives the amount of thermal compensation required.

#### *5.3.3.1. Focal Compensation Error*

Passive compensation of this nature produces a non-linear response to thermal variations within the compensation assembly. The following comparative graphs show the compensation error as a function of temperature change for a 200 mm and 300 mm rod respectively.

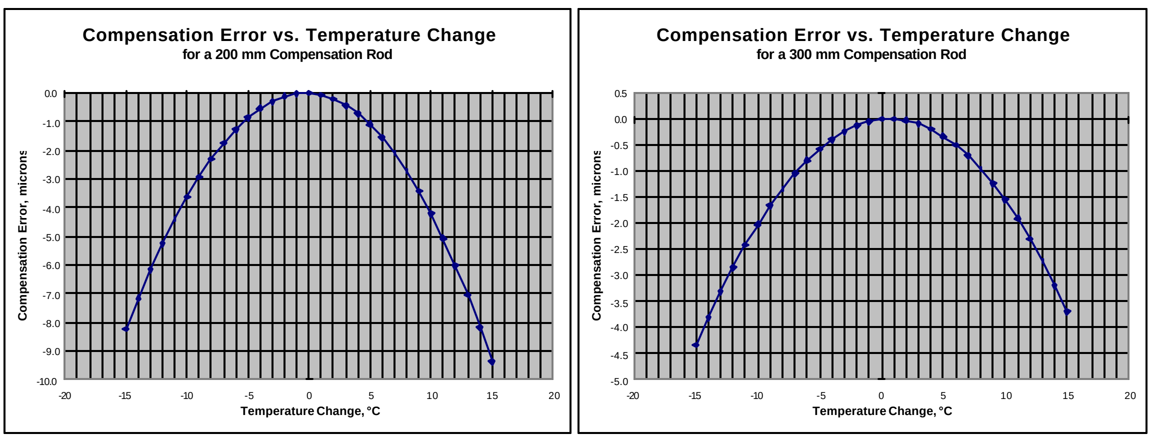



**Figure 4:** Compensation Error vs. Temperature Change

In order to reduce the compensation error to within the acceptable limit of 5 microns across the maximum designed temperature change of 15 °C for the Gemini Telescope; a compensation rod of **300 mm** minimum length will be required.

### 5.3.4. Weight Estimates

The addition of the LLT will increase the mass of the Secondary Support Structure (SSS). The addition of mass will reduce the resonant frequency of the Gemini Telescope's Secondary Mirror Tip/Tilt System (M2TS) supporting structure. Therefore, it is a Gemini requirement that any additional mass being added to the top end must be limited to **125 ± 25 kg**. This will include the LLT and all Beam Transfer Optics (BTO) components to be mounted on the SSS. The following table shows the mass estimates for the LLT/BTO components supported by the SSS for the MCAO system.

| ITEM | INCLUDED ITEMS | MASS (kg) |
|---|---|---|
| LLT Frame | Aluminum Structure | 56.456 |
| | Mounting Hardware | 5.000 |
| Slow Tip/Tilt Array | 5X STT Mirrors | 3.500 |
| | 5X Alignment Sensors | 0.010 |
| | STT Mounting Bracket | 3.000 |
| | Mounting Hardware | 0.500 |
| | Electronics | 1.000 |
| Fast Tip/Tilt Array | 5X FTT Mirrors | 1.000 |
| | 5X Alignment Sensors | 0.010 |
| | FTT Mounting Bracket | 1.500 |
| | Mounting Hardware | 0.500 |
| | Electronics | 1.000 |
| Diagnostics (Case I) | Beam Splitter | 0.781 |
| | Corner Cube | 0.781 |
| | Folding Mirror | 0.001 |
| | Folding Mirror Bracket | 0.844 |
| | CCD camera | 1.000 |
| | 3XLenses | 0.500 |
| | Electronics | 1.000 |
| | Mounting Hardware | 0.500 |
| Rotator | 2X Folding Mirror | 0.002 |
| | Rotator | 1.500 |
| | Mounting Hardware | 0.500 |

| | | |
|---|---|---|
| Lens/Fold Assembly | Diverging Lens | 0.001 |
| | Lens Bracket | 0.046 |
| | Lens Bracket Adjustment Rods | 1.000 |
| | 4X Adjustment Rod Retainer Brackets | 1.000 |
| | Lens Bracket Hardware | 0.500 |
| | Folding Mirror | 0.001 |
| | Folding Mirror Bracket | 0.844 |
| | Folding Mirror Bracket Hardware | 0.500 |
| LM1 Mirror Assembly | LM1 Mirror | 14.393 |
| | LM1 Mounting Bracket | 12.035 |
| | LM1 Mirror Mounting Hardware | 2.000 |
| | 2X Mounting Bracket Pivot Bracket | 0.100 |
| | Pivot Bracket Hardware | 1.000 |
| | 3X Mounting Bracket Location Pins | 0.091 |
| | Location Pin Hardware | 1.000 |
| | Pivot Motor | 2.500 |
| | Pivot Motor Mounting Hardware | 0.500 |
| | Pivot Motor Mounting Bracket | 1.000 |
| | Pivot Motor Bracket Hardware | 0.500 |
| | Pivot Motor Linkage | 1.000 |
| | Pivot Motor Linkage Hardware | 0.500 |
| | LM1 Storage "Cubby" | 1.000 |
| | Storage "Cubby" Hardware | 1.000 |
| Polarization Sensor | Folding Mirror | 0.001 |
| | Polarization Sensor | 1.000 |
| | Electronics | 1.000 |

| | | |
|---|---|---|
| | Mounting Hardware | 1.000 |
| | **TOTAL** | **126.397** |

**Table 4:** Weight estimates for BTO/LLT elements mounted on the SSS.

#### 5.3.5. Secondary Support Structure Interface

The LLT will be mounted to the SSS by means of the existing Prime Focus Wave Front Sensor (PFWFS) mounts located within the central hole of the SSS and the top plate of the SSS (drawing SSS_INTERFACE.DWG). The PFWFS mounts are not accurately located with respect to the top plate due to the welded construction of the SSS. Therefore, shims will be required to align the LLT with respect to the SSS.

All other LLT/SSS interface considerations are described in the document: *Gemini Laser Guide Star Program – CoDR Material – Secondary Support Structure Interface (Chris Carter, April 2000)*

# 6. Appendix

### *6.1. BTO tip/tilt mirrors error-budget*

The error budget for the required dynamic ranges and accuracies of the tip/tilt mirrors, PSDs and diagnostics in the BTO is presented in the following Excel spreadsheets.

### *6.2. ZEMAX results*

The results discussed in section 5.1.3 are presented after the Excel spreadsheet.

***Assumptions:***

The laser system is mounted on the telescope center section.

The BTO mirror train is described in the "MCAO BTO and LLT design document" and in the MCAO OCDD.

Tip-tilt mirrors are:

M7 :on center section, slow tip-tilt mirror for centering on M6, controlled by MCAO CS

M6: on top end ring, slow tip-tilt mirror for centering on M3, controlled by MCAO CS

M3: on LLT structure - slow tip-tilt mirror array controlled by MCAO CS

M2: on LLT structure - fast tip/tilt mirror array controlled by the AO Module

The 5 laser beams are arranged in a line over the vane, then they are re-shaped in an X pattern by M3.

From M3 to M2, the beams are collimated and parallel.

M2 introduces the final beam tilt between the 5 beams so that they are separated by **42.5 arcsec from center to corner** on the sky.

From M2 to the DV lens assembly, the 5 beams converge towards M1, however each of them is still collimated.

Each **beam diameter** (99% encircled energy) at the entrance of the LLT is about **8 mm** (corresponds to a LLT magnification ratio equal to ~60)

All angles are full-angles or peak to peak angles (+- half-angle)

The **LLT magnification** is assumed to be **60** (5.0 mm magnified to 300 mm @ 1/e2 intensity points)

***Votes:***

**[0]** The mirror open-loop dynamic ranges for the tip/tilt mirrors and the PSDs or diagnostics dynamic range requirements are derived from the following considerations:

(a) laser beam jitter < 34 µrad over 1 ms, 0.6 mrad over 1s (MK LGS Laser System Req. Doc.)

(b) initial alignment tolerance = about 3 mrad - according to Dave Montgomery (this is a 3 mm surface error over 1 m of telescope truss, center section, etc.) for each mirror, which can combine into a peak error of 6 mrad between two mirrors

(c) telescope flexures and thermal variations:

2.4 mm sag for the top-end module --> 200 µrad over 12 m

2 arcsec = 10 mrad tilt for the top-end optical axis vs. Gemini telescope optical axis

(d) ability to move the beam from one side to the other side of the next mirror Mi-1

(e) special dynamic range requirement (MCAO: LGS pattern on the sky = +/- 42.5 arcsec across)

**[1]** M3 and M6 open-loop dynamic range requirements are derived from the BTO/LLT alignment tolernce analysis

**[2]** MCAO: during dithering, the LGSs pattern will move with the telescope, there will be no need (actually not even the possibility) to move the LGSs pattern in the opposite direction as required in the ALTAIR case

**[3]** The LGS system must have a blind pointing accuracy of 1.0 arcsec on the sky so that the LGS spot falls within the WFS subaperture FoV (a subaperture has a 1 arcsec FoV with a field stop of 1.5 arsec and a dead pixel between two adjacent subapertures)

**[4]** For the sake of simplicity, each mirror tip/tilt accuracy requirement is chosen identical to the other mirrors, so that the RMS sum equals the BTO accuracy equirement on the sky (after magnification by the LLT). TBDiscussed

5] The fast tip/tilt mirror must keep the LGS position stable by better than 0.05 arcsec on the sky. The slow tip/tilt mirrors must keep the alignment stable by better than 0.05 arcsec on the sky. TBDiscussed

6] The laser jitter and turbulence along the BTO path are negligible in comparison to the jitter due to the atmospheric turbulence on the way up.

A seeing r0 = 17.2 cm @ 589 nm (MK bad seeing) creates 1.2 µrad rms = 0.25 arcsec rms of jitter on a 45 cm beam in the sky.

With a mgnification ratio of 60, this corresponds to 0.07 mrad rms in the BTO.

The fast tipt tilt mirror dynamic range is chosen to be at least 4 times the rms value. Being conservative, we choose 1 mrad.

***Acronyms:***

PSD = Position Sensor Detector

EPD = Entrance Pupil Diameter

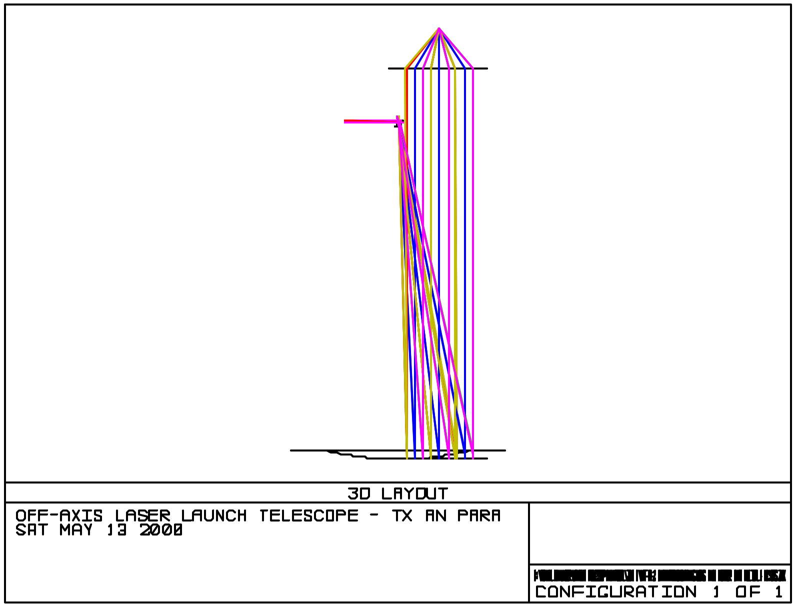
| | BTO spec. | M7 | M6 | M3 | M2 |
|---|---|---|---|---|---|

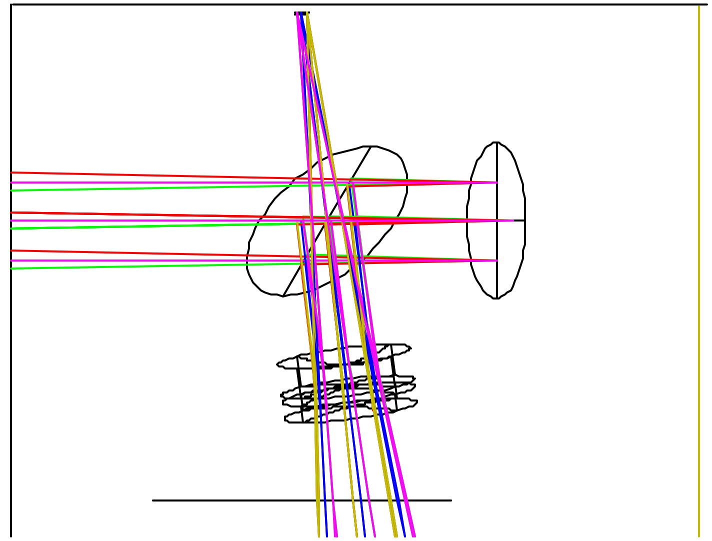
| | BTO spec. | PSD behind M7 | PSD behind M6 | Pointing and centering diagnostics | |
|---|---|---|---|---|---|
| ndividual beam size on the mirror (99% energy) | _ | ~ 8 mm | ~ 8 mm | ~ 8 mm | ~ 8 mm |
| Mirror clear aperture diameter | _ | 25 or 50 mm | 50 mm | 25 mm or smaller | 25 mm or smaller |
| Distance to next mirror | _ | (M7-M6)~12 m | (M6-M3)~5 m | (M6-M3)~0.12 m | _ |
| Max. 1-axis tilt angle **on the sky** | **Fast tip/tilt spec. is 1 arcsec** | _ | _ | _ | 3.3 arcsec **[6]** |
| Mirror open-loop 1-axis tilt dynamic range | _ | 2 x 4 mrad **[0(d)]** | TBD **[1]** | TBD **[1]** | 1 mrad **[6]** |
| Open-loop 1-axis tilt accuracy **on the sky [3]** | **1.0 arcsec** | 0.5 arcsec | 0.5 arcsec | 0.5 arcsec | 0.5 arcsec |
| Mirror open-loop 1-axis tilt accuracy **[0], [4]** | _ | 150 µrad | 150 µrad | 150 µrad | 150 µrad |
| Mirror closed-loop sampling rate | **Fast tip/tilt @ 1 kHz** | 10-20 Hz | 10-20 Hz | 10-20 Hz | 1 kHz |
| Closed-loop 1-axis tilt accuracy **on the sky [5]** | **0.05 arcsec @ 1 kHz [5]** | _ | _ | _ | 0.05 arcsec @ 1 kHz |
| | **0.05 arcsec @ 10-20 Hz** | 0.03 arcsec @ 10-20 Hz | 0.03 arcsec @ 10-20 Hz | 0.03 arcsec @ 10-20 Hz | _ |
| Mirror closed-loop 1-axis tilt accuracy | _ | _ | _ | _ | 15 µrad @ 1 kHz |
| | _ | 9 µrad @ 10-20 Hz | 9 µrad @ 10-20 Hz | 9 µrad @ 10-20 Hz | _ |

**Table 5**: Tip/tilt mirrors error budget

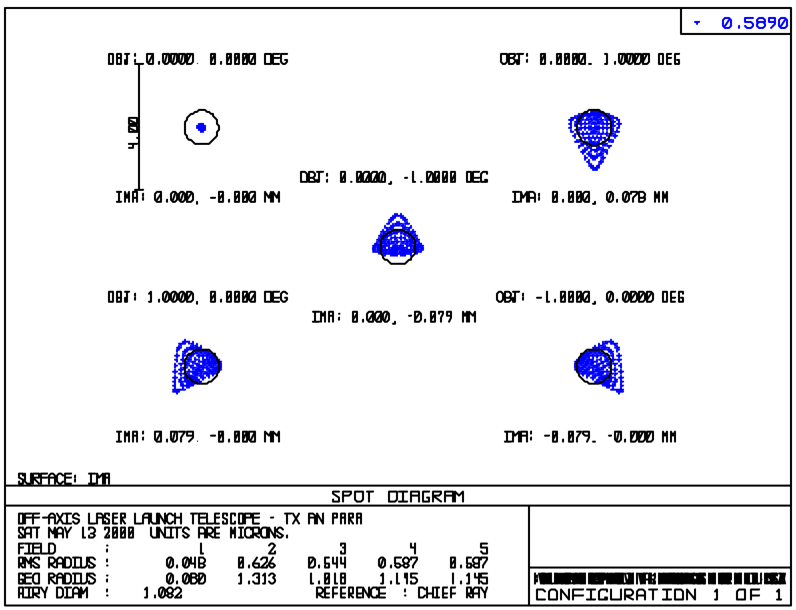
| | | | | |
|---|---|---|---|---|
| Position sensor (located behind mirror Mi) dynamic range | | | | |
| Position measurement (= PSD diameter) | – | – | 50 mm | Must image LLT M1 |
| 1-axis tilt | **2 x 42.5 arcsec on the sky** | – | – | 2 x 13mrad |
| Position sensor (located behind mirror Mi) accuracy | | | | |
| Position measurement | – | – | 1.8 mm (150 μrad @ 12 m) | TBD (cf LLT optical design ~-1 mm ?) |
| 1-axis tilt | **1.0 arcsec on the sky** | – | – | 300 μrad |

**Table 6**: PSDs and BTO diagnostics error budget



LLT diverging lens assembly (with 2 fold mirrors ahead)



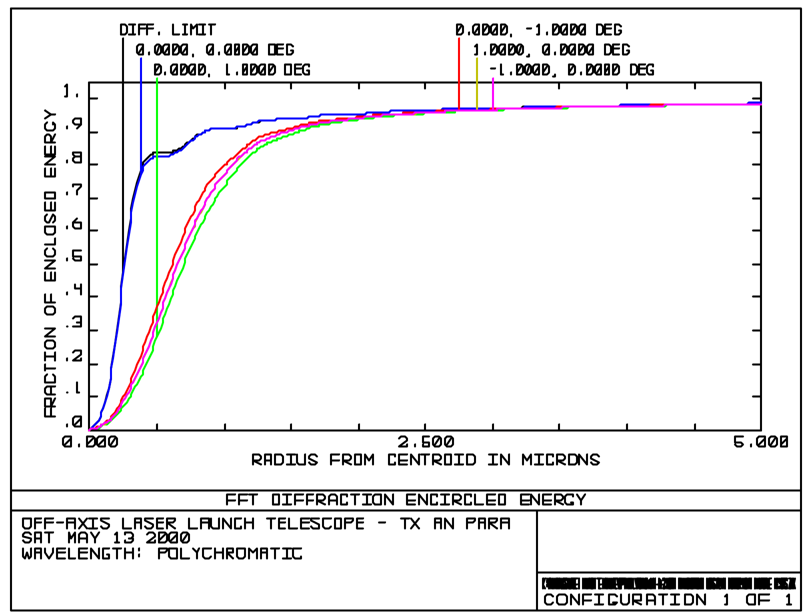
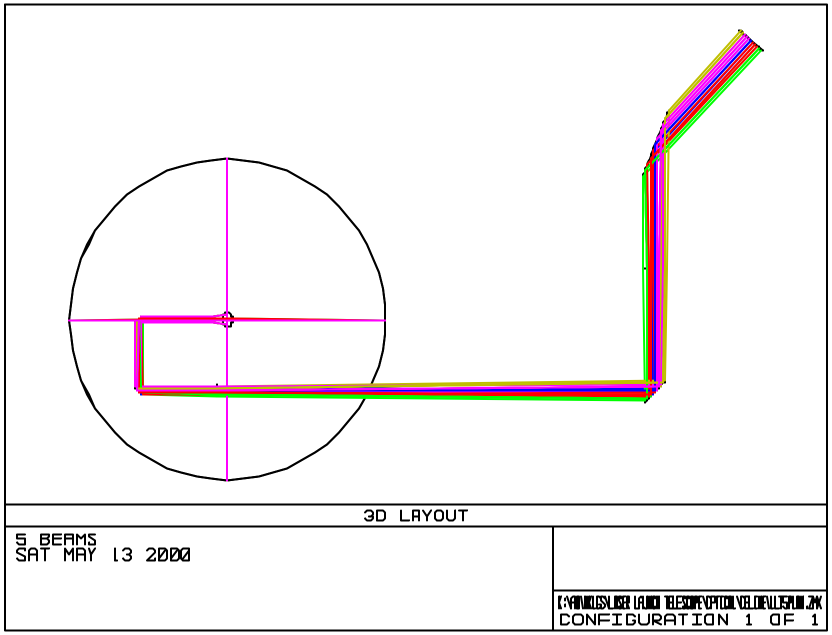
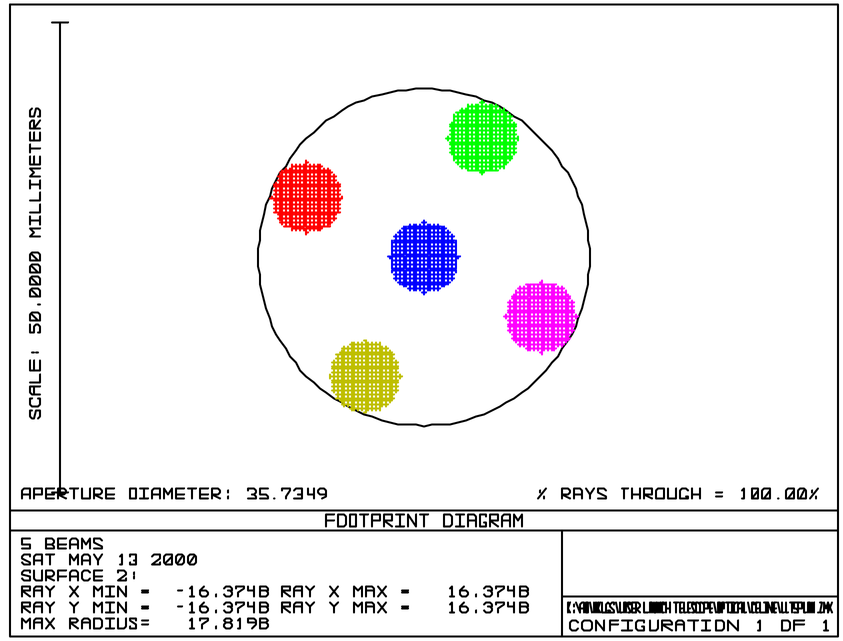



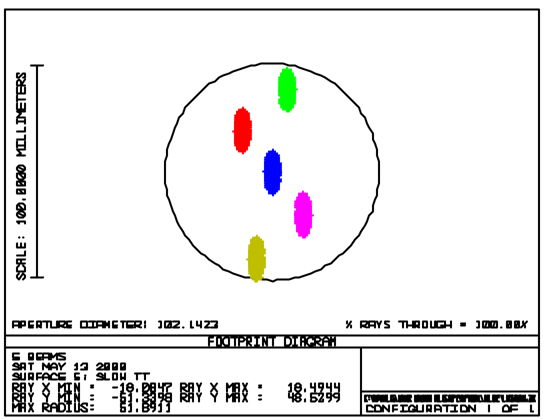

**Figure 5 Jim Oschmann's design (baseline design)**



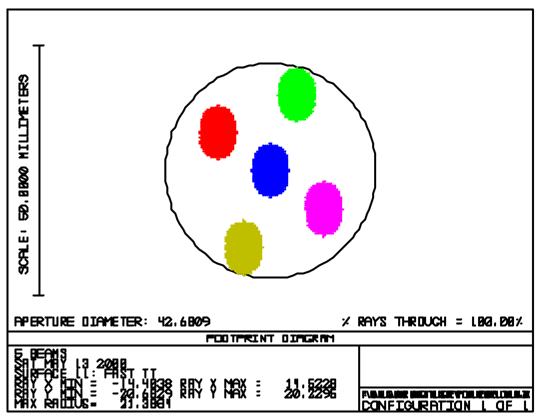

**LLT5PLAN.ZMX** (the beams overlap on M1)



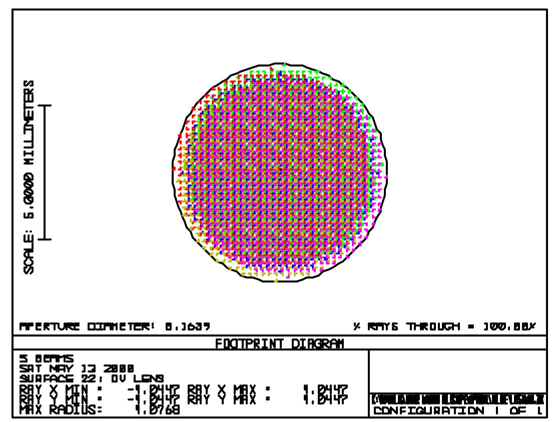

Beam prints in plane perpendicular to propagation axis after reflection on M3.




Beam prints on slow TT mirror array M3

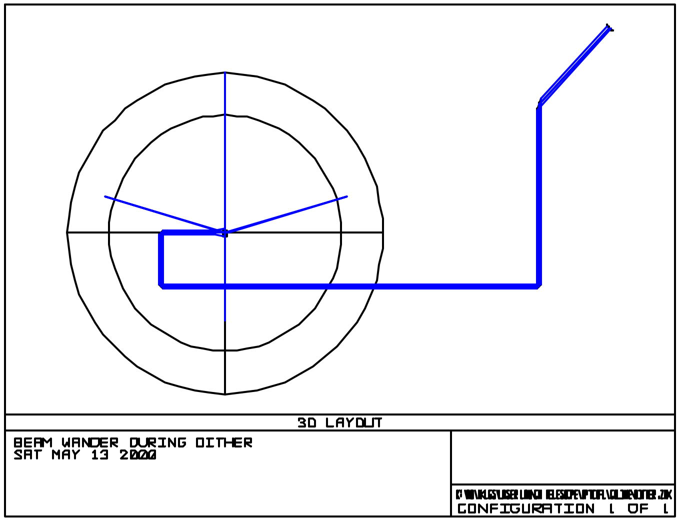



Beam prints on fast TT mirror array M2

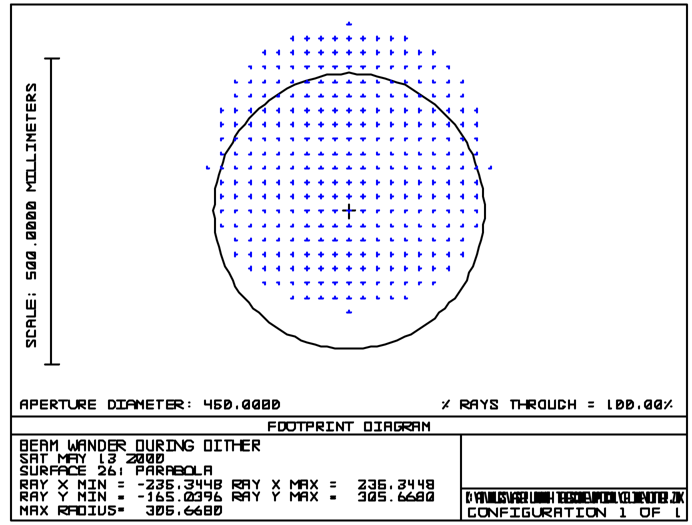



Beam prints on diverging lens L1

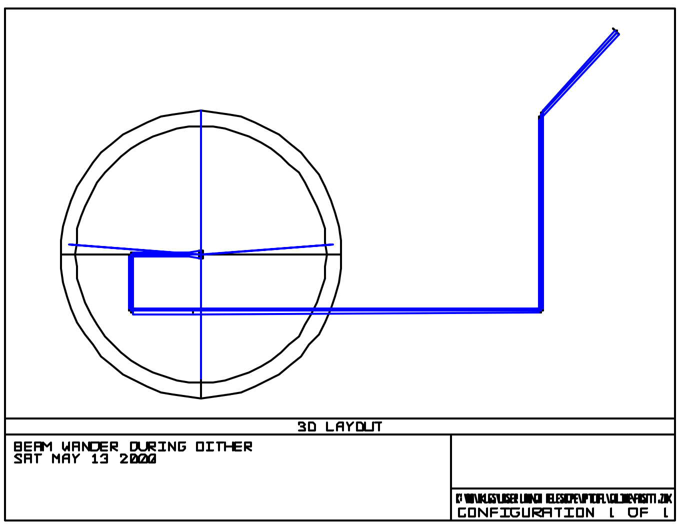
**Figure 7 LLT5PLAN.ZMX**



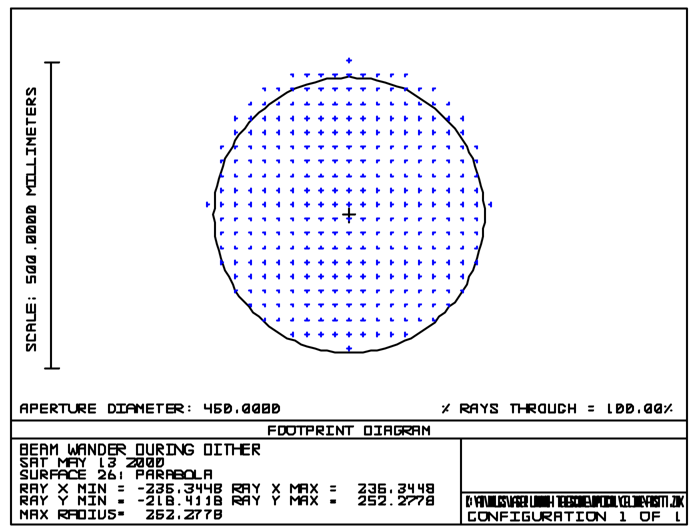

Dither mirror introduces 30 arcsec dither on the sky




Beam wander on LLT M1 for a 30 arcsec dither




Fast TT mirror introduces 1 arcsec tilt on the sky




Beam wander on LLT M1 for 1 arcsec tilt on the sky

**Figure 8 Preliminary results of tolerance analysis**