GEMINI

8-M Telescopes Project

Laser Launch Telescope Requirements Document

Exhibit B to Schedule C, Contract Form, RFP No. N210158

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1. Introduction

1.1. Acronyms and notations

The following acronyms will be used throughout the text.

A&G	Acquisition and Guiding
AO	Adaptive Optics
BTO	Beam Transfer Optics
BTOOB	Beam Transfer Optics Optical Bench
CDR	Critical Design Review
CoG	Center of Gravity
CP	Cerro Pachón
d_{1/e^2}	Input laser beam diameter at $1/e^2$ intensity points
$d_{99\%e.e.}$	Input laser beam diameter at 99% encircled energy
D_{1/e^2}	Output laser beam diameter at $1/e^2$ intensity points
$D_{99\%e.e.}$	Output laser beam diameter at 99% encircled energy
FoV	Field of View
FWHM	Full Width at Half Maximum
GNAO	Gemini North Adaptive Optics
GSAO	Gemini South Adaptive Optics
LGS	Laser Guide Star
LGS CS	Laser Guide Star Control System
LLT	Laser Launch Telescope
MCAO	Multi-Conjugate Adaptive Optics
MK	Mauna Kea
NIC	Not in Contract (Indicates items that are not part of the Work)
NGS	Natural Guide Star
OAP	Off-Axis Parabola
PDE	Photo-Detection Event
PDR	Preliminary Design Review
PF WFS	Prime Focus Wavefront Sensor
r_0	Seeing parameter (Fried's parameter)
RMS	Root Mean Square
SNR	Signal to Noise Ratio
SSS	Secondary Support Structure
WFS	Wavefront Sensor

Note that in the following, the Laser Launch Telescope will always be called by its full name or by its acronym (LLT) in order not to be confused with the Gemini 8-m telescopes (the "telescopes" or "telescope" in the text).

1.2. General

1.2.1. Mauna Kea and Cerro Pachón LLTs

There will be **two Laser Launch Telescopes** (LLTs): one for Gemini North, Mauna Kea, Hawaii, and the other one for Gemini South, Cerro Pachón, Chile.

The **Gemini North LLT** will be a subsystem of the Mauna Kea Laser Guide Star (LGS) system for the Gemini North Adaptive Optics (GNAO) system, Altair. This LGS AO system will use a **10-15W laser** to produce a **single LGS**. The LLT will expand the single gaussian laser beam and project it to the sky to produce a single LGS.

The **Gemini South LLT** will be a subsystem of the Cerro Pachón Laser Guide Star (LGS) system for the Gemini South Adaptive Optics (GSAO) system. This LGS AO system will use a **10-50W laser** to produce **either 1 or 5 LGSs**. In the latter case, the LLT would expand the five gaussian laser beams simultaneously and project them to the sky to produce a constellation of 5 LGSs. The 5 beams would be arranged as an X-shaped constellation, continuously rotating around its central axis (center of the X). There would be one beam at the center of the X, and one beam at each of the four corners.

1.2.2. LLT requirements document

This document describes the LLT subsystem performance specifications and requirements for both Gemini North and Gemini South. The specifications and requirements are the same for both LLTs. <u>The Gemini North and Gemini South LLTs must be identical and interchangeable</u>. In the following, it is implicit that requirements are given for both sites.

Sometimes goals are specified at the same time as requirements. Whereas all requirements must be met by the proposed LLT, goals do not have to. Those are extra-features of interest to AURA but Vendors should not try to meet some goals when they either lead to missing other requirements or increasing the system cost significantly.

1.2.3. LLT overview

The Laser Launch Telescope will basically be a laser beam expander. The LLT system must include all optics, mechanics and electronics that are necessary for the LLT to meet the performance, functional, and interface requirements described in this document. The LLT is envisioned as a standalone instrument, with specific interfaces with the existing Gemini telescope Secondary Support Structure (SSS). It will be integrated and bench-tested before mounting on the telescope.

1.2.4. LLT conceptual, preliminary and final designs

The Gemini AO team prepared a conceptual LLT design for the GSAO Conceptual Design Review (CoDR) in May 2000. The design has been somewhat modified since then. This design is included in section 5 of this document as an example of a possible

LLT optical design and opto-mechanical structure. All the optical and mechanical designs presented in the following sections are only conceptual and as such may fall short of some of the requirements presented in this document.

In their proposals, Vendors are expected to produce a preliminary design for the LLT. Vendors are welcome to take inspiration from the conceptual designs provided in this document, but they must exercise their own independent design judgment in preparing their proposed LLT designs rather than assuming the AURA conceptual design is correct. In particular, Vendors should make sure that the proposed preliminary designs will meet all requirements. After a contract is awarded, the preliminary designs will be further developed and turned into final designs to meet all Laser Launch Telescope specifications and requirements.

1.2.5. LLT interfaces with other systems

1.2.5.1. Interface with Secondary Support Structure (SSS)

The Laser Launch Telescopes will be mounted behind the secondary mirrors of the Mauna Kea and Cerro Pachón telescopes. The LLT structure will be mounted inside the existing Secondary Support Structure (SSS) and interface with it. See drawing telescope1.dwg in section 5.2.2. The LLT mechanical interface requirements with the SSS are given in section 3.3 of this document and corresponding interface drawings are given in section 5.2.1.

The LLT will be installed in the Secondary Support Structure (SSS) while the telescope is in a quasi- horizontal position, without disassembly of the secondary support structure or the telescope top end. The space between the dome and the top-end for inserting the LLT being limited to **1830 mm**, it is desirable that the LLT integration procedure be carefully investigated ahead of time. The specifications for integration with the telescope are presented in section 3.3.10.1.

1.2.5.2. Interface with Beam Transfer Optics (BTO)

The laser beams to be projected on the sky will be relayed from the laser system located on the telescope center section up to the Laser Launch Telescope mounted in the SSS by the Beam Transfer Optics (BTO). The BTO is another subsystem of the GNAO and GSAO systems and is not a part of the Work. The BTO is independent of the LLT subsystem and interfaces both optically and mechanically with it. The BTO Optical Bench (BTOOB) relays the beams from the (–X, +Y) vane of the telescope to the input of the LLT. The BTOOB is also not a part of the Work. See drawings in section 5.2.1.

The LLT top mounting plate is sandwiched between the SSS top plate and the BTO Optical Bench. The optical interface consists of the beams' locations and height above the SSS, their range of angles of incidence at the LLT entrance pupil, and the LLT entrance pupil location and diameter. These optical requirements are presented in section 2. Mechanical interface requirements are presented in section 3.3.

2. Laser Launch Telescope Performance Specifications

Most of the following sections are divided in two subsections (e.g section 2.2 is divided into subsections 2.2.1 and 2.2.2). The purpose of the first subsection ("rationale") is to describe how the Gemini AO design team came up with the requirement provided in the second subsection ("requirement"). Vendors are only really concerned by the second subsection. The first subsection ("rationale") is provided as a reminder for the AO design team as well as a courtesy for Vendors should questions on the requirement section arise.

2.1. Beam propagation direction

In the following, the LLT input is taken at the LLT interface with the BTO. The LLT output beams are the magnified beams projected to the sky.

2.2. Magnification ratio

2.2.1. Rationale

At the entrance of the LLT the chosen input laser beam diameter is the result of a compromise between:

(i) the need to keep the beams small enough to be hidden from the telescope Acquisition and Guiding (A&G) Wavefront Sensors (WFS) and from the telescope instruments when crossing the primary mirror behind the (-X, +Y) vane
- 1cm-wide vane
- +/- 6 arcmin max FoV for the telescope peripheral WFSs
- beam crossing the telescope primary mirror ~ 60 cm above the vane
  → max beam diameter at 99% encircled energy $d_{99\%e.e.}$ = 7.9mm
  → max diameter at $1/e^2$ intensity points $\mathbf{d_{1/e^2} = 5mm}$

(ii) the need to keep the beams hidden behind the vane in spite of possible beam jitter (due to telescope flexures, thermal distortions, laser jitter and beam pointing and centering control loops adjustments)

(iii) the desire to lower the laser power density on BTO and LLT optics by increasing the beam diameter.

The choice for the output beam diameter is driven by the need to create the smallest LGS spot in the sky, considering the effects of:
- diffraction (the larger the aperture, the smaller the diffraction pattern)
- atmospheric turbulence (the LLT aperture must not exceed 2-3 r_0, where r_0 is Fried's parameter)
- optical throughput (we must limit the loss of laser power caused by aperture clipping of the gaussian beams)

The baseline laser beam diameter at $1/e^2$ intensity points is $\mathbf{d_{1/e^2} = 5\ mm}$. The baseline output diameter at $1/e^2$ intensity points is $\mathbf{D_{1/e^2} = 300\ mm.}$

2.2.2. Requirement

The LLT magnification ratio shall be equal to $\mathbf{D_{1/e^2} / d_{1/e^2} = 60}$, within a **1%** tolerance.

2.3. Field of View

2.3.1. Rationale

The FoV requirement is derived from the following considerations:

- The BTO includes 1 (GNAO) or 5 (GSAO) beam pointing and centering control loops whose purpose is to keep the central beam aligned with the telescope axis and, in the GSAO case, have the 5 beams overlap on the LLT optical stop (in the conceptual design, on the LLT off-axis parabola). The BTO pointing and centering loops correct for laser beam jitter, telescope flexures and thermal distortions. They will introduce non normal incidence angles at the LLT entrance pupil, equivalent to up to 30 arcsec deviation on the sky.
- The GNAO system, which uses a single laser beam, must comply with the telescope dithering requirements of +/- 30 arcsec on the sky.
- The GSAO may use up to 5 laser guide stars arranged in an X-shaped constellation with 42.5 arcsec on the sky from center to corner (fig.1). The constellation will be rotating on the sky to accommodate telescope tracking and de-rotation by the cassegrain rotator so that the LGS constellation will appear fixed on the AO LGS Wavefront Sensor (WFS).

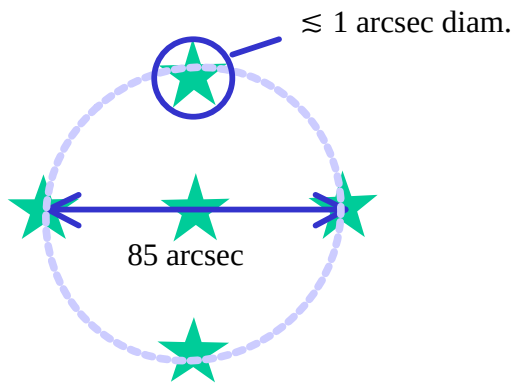

Figure 1: X-shaped LGS constellation for Gemini South AO.

2.3.2. Requirement

The minimum LLT unvignetted output field of view (FoV) shall be equal to ± **1.2 arcmin on the sky**. For a magnification ration of 60, this corresponds to an unvignetted input FoV of ± **1.2 degree**.

Note that the image quality requirements are specified over a reduced FoV of ± 1.0 arcmin only. Those requirements are presented in section 2.5.

2.4. Optical design specifications

2.4.1. Conceptual design

A conceptual design for the LLT is presented in section 5.1. It is an afocal telescope design with no intermediate focus. The conceptual LLT design includes a toroidal fold mirror, an aspheric diverging lens and an off-axis parabolic mirror. The following requirements are described with respect to the conceptual design. Vendors shall transpose them to whatever design they propose so that the following properties are preserved.

2.4.2. No central obscuration

The laser beams to be expanded by the LLT are gaussian beams in the TEM_{00} mode and as such most of the laser power is concentrated on axis. In order not to clip the central portion of the beams, the LLT shall have no central obscuration. That is why the conceptual LLT design uses an off-axis parabola (OAP).

2.4.3. No internal focus

The LLT shall have no sharp intermediate focus where the laser beam power density may be significantly higher than reasonable in a dusty environment like the telescope domes on the Mauna Kea and Cerro Pachón summits. It is feared that dust particles flying through a sharp focus may significantly degrade the outgoing laser beam quality. That is why the conceptual LLT uses a diverging lens to expand the beam.

2.4.4. Optical stop

The optical stop of the LLT shall be located on the off-axis parabola (OAP) or equivalent. The OAP clear aperture diameter shall be close to **450 mm** and be compatible with other requirements such as space envelope.

Note that the gaussian laser beam(s) diameter at the $1/e^2$ intensity points on the STOP will be on the order of 5mm times the magnification ratio of 60 equal 300mm. The corresponding beam diameter at the 99% encircled energy intensity points being 471mm, the AO design team is aware that a 450mm diameter STOP will partially clip the edges of the gaussian beam. The STOP clear aperture shall be as large as possible when considering the relatively tight space envelope requirements presented in section 3.3.2.3.

All other LLT optical elements shall be oversized in order not to vignette the gaussian laser beam(s) prior to the stop at more than the 99% encircled energy diameter, over the full field-of-view specified in section 2.3.2 above.

2.4.5. Entrance pupil

2.4.5.1. Rationale

The LLT entrance pupil is the main optical interface between the LLT and Beam Transfer Optics (BTO). The BTO includes beam pointing and centering control loops that aim at

(i) centering the 1 (GNAO) or 5 (GSAO) beams on the LLT entrance pupil, conjugated to the LLT off-axis parabola or equivalent, and (ii) keep the central beam angle of incidence at the LLT entrance pupil close to zero. In the GSAO case, the X-shaped 5 beam pattern is converging with a center to corner separation angle of 42.5 armin (42.5 arcsec on the sky times the LLT magnification ratio of 60) onto the LLT entrance pupil location where the beams finally overlap. Note that the laser beams are collimated at this point. See drawing LLT5Sep.dwg in section 5.2.2.

In the GSAO case, the appropriate incidence angles on the LLT entrance pupil (normal incidence for the center beam, 42.5 arcmin for the corner beams) will be created by the array of 5 fixed mirrors called the "X-Shaping Mirrors" in drawing LLT5Sep.dwg The center and corner beams must be separated enough at this location to enable using half-inch diameter mirrors. There is therefore a minimum distance required between the X-Shaping Mirrors and the LLT entrance pupil. For instance, if we require that the beams must be separated by at least 13mm at the X-Shaping Mirror location, the minimum required distance along the beam path is 13mm/tan(42.5 arcmin) = 1051mm.

Because the minimum required distance is taken along the beam path on the BTO Optical Bench, it depends on the BTOOB design which may vary slightly in the future. That is the reason why the requirement regarding the LLT entrance pupil location is given with respect to the LLT central axis instead. The so-called "LLT central axis" is the optical axis of the LLT in output space. The central laser beam is propagating along the input optical axis indicated in green on drawing ICR10.DWG. Assuming that the beam path is not folded by the fold mirror seen in ICR10.DWG, the optical axis would remain horizontal and propagate in direction of the LLT central axis as defined above. The requirement on the LLT entrance pupil location is defined with respect to the corresponding "unfolded" entrance pupil along the unfolded horizontal optical axis.

2.4.5.2. Requirement

The "unfolded" LLT entrance pupil shall be located within a **235mm** distance of the LLT central axis (see drawing ICR10.dwg in section 5.2.1).

Specification for the entrance pupil diameter shall be derived from the magnification ratio, the STOP diameter specification (see section 2.4.4), and the specifics of the optical design proposed by the vendor. The height of the entrance pupil along the axis shall match the beam height specification in section 3.3.2.1.

2.5. Wavefront errors

2.5.1. Rationale

The LLT image quality requirements are presented in terms of wavefront aberrations over a reduced field of view equal to ± **1.0 arcmin** on the sky. Note that this FoV is smaller than the LLT unvignetted FoV of ± 1.2 arcmin specified in section 2.3. The largest FoV (± 1.2 arcmin) shall be considered a goal for the LLT design image quality.

The LLT must not significantly increase the beam wavefront aberrations when compared to the input laser beam quality and the wavefront distortions created by atmospheric turbulence. Neither must the LLT introduce significant beam pointing jitter on the sky at frequencies which could not be corrected by the BTO pointing and centering loops.

2.5.2. Tip/tilt errors

We consider two categories of tip/tilt error: static and dynamic.

2.5.2.1. Static tip/tilt errors

The **static tip/tilt error** has to do with the overall misalignment of the LLT with respect to the Gemini telescope optical axis when the telescope is pointing to zenith. This tip/tilt error may to some extent be corrected by the pointing and centering mirrors of the Beam Transfer Optics Optical Bench (BTOOB) (see drawing LLT5Sep.dwg), however the correction must not be so large that the beams separated by 42.5 arcsec from the central beam in the Gemini South configuration enter at larger than the ± 1.2 arcmin unvignetted field of view of the LLT. It is AURA's intent to correct for this tip/tilt at the mechanical interfaces between the Secondary Support Structure (SSS) and the Laser Launch Telescope (LLT), and between the LLT and the Beam Transfer Optics (BTO) by introducing shims at both interfaces. This will be AURA's responsibility. In this matter, Vendors are therefore only required to **meet the tolerance requirements** presented in drawings ICR20.dwg, ICR21.dwg and ICR22.dwg (see section 5.2.1).

2.5.2.2. Dynamic tip/tilt errors

The **dynamic tip/tilt error** has to do with tip and tilt introduced by flexures, vibrations, temperature change, wind buffeting, etc. during normal telescope operation. These tip and tilt can be either internal to the LLT, caused by motion of the optics mounts with respect to each other, or they can be of a global nature more like static tip/tilt errors. The BTO pointing and centering loops will be able to correct for most of the low-frequency part of the dynamic tip/tilt error and some of the high frequency part. The following requirements on the LLT dynamic tip/tilt allowable errors are derived from the overall error budget of the GNAO and GSAO beam pointing error budget:

Frequency range	Dynamic tip/tilt introduced by LLT on the sky
< 0.1 Hz	< 10 arcsec (peak)
0.1-1 Hz	< 1 arcsec (peak)
1-30 Hz	< 0.2 arcsec (peak)
> 30 Hz	< 0.03 arcsec RMS

2.5.3. Other wavefront errors

The following requirements deal with low and high order wavefront aberrations. We will consider "low order aberrations" all aberrations of second and third order. The requirements are derived from the overall error budget for the MK and CP LGS systems

in terms of required laser power vs. LGS spot size on the LGS WFS. The error budget was obtained from a simulation including:

- 30 cm $1/e^2$ laser beam diameter
- 45 cm diameter LLT aperture
- laser beam quality
- wavefront aberrations introduced by an optically-aberrated LLT
- atmospheric turbulence (uplink and downlink)
- LGS WFS pixel blurring

To derive the LLT optical error budget, we require that the LLT optical aberrations do not contribute to increase the error in AO WFS subaperture centroiding due to noise by more than **20%**, with a goal of **10 %**. The penalty splits evenly between a 10% (resp. 5%) increase in LGS spot size on the subaperture and a 10% (resp. 5%) decrease in signal to noise ratio (SNR). Low order aberrations (focus, astigmatism, coma, trefoil, spherical) mostly impact the LGS spot size, whereas high order aberrations mostly impact the number of photo-detection events (PDE's) in the core of the LGS spot, and therefore degrade the SNR.

2.5.3.1. Low order aberrations

Simulations show that the following independent aberrations can separately introduce a 10% increase in LGS spot size:

DEFOCUS	0.1 wave RMS @ λ = 589 nm
ASTIGMATISM	0.18 wave RMS @ λ = 589 nm
COMA	0.1 wave RMS @ λ = 589 nm
TREFOIL	0.25 wave RMS @ λ = 589 nm
SPHERICAL	0.1 wave RMS @ λ = 589 nm

On this basis, we require that the LLT does not introduce more than **0.15 wave RMS** of low order aberrations @ λ = 589 nm, with a goal of **0.1 wave RMS**. These errors are defined with respect to uniformly illuminated, 45 cm diameter aperture.

2.5.3.2. High order aberrations

We assumed a WFS with 6 electrons of read-out noise and a required working range for the GNAO and GSAO of 250-390 PDE's/subaperture/frame. Within that range, a 10% penalty on the SNR corresponds to a 15% reduction in photo-detection events. Assuming that the laser beams do not saturate the sodium atoms, this means that the laser power would have to be increased by 15% to compensate for that penalty.

High order aberrations can produce a 15% decrease in the number of photo-detection events by lowering the Strehl ratio of the LGS spot image of the WFS subaperture by 15%. We can derive the corresponding wavefront aberration by using the formula:
Strehl ratio = $\exp(-\sigma_\Phi^2)$

On this basis, we require that the LLT does not introduce more than **0.06 waves RMS** of high order aberrations @ λ = 589 nm, with a goal of **0.04 waves RMS**. These errors are defined with respect to a uniformly illuminated, 45 cm diameter aperture.

2.5.4. Requirements

Error budget breakdown for the LLT design aberrations in terms of wavefront aberrations:

Wavefront aberrations	Requirement	Goal
Tip/Tilt – static (mounting)	See ICR20.dwg, ICR21.dwg and ICR22.dwg	
Tip/Tilt – dynamic (during operation) < 0.1 Hz 0.1-1 Hz 1-30 Hz > 30 Hz	 < 10 arcsec (peak) on the sky < 1 arcsec (peak) on the sky < 0.2 arcsec (peak) on the sky < 0.03 arcsec RMS on the sky	
Low order aberrations incl. focus	<0.15 wave RMS	<0.1 wave RMS
High order aberrations	<0.06 wave RMS	<0.04 wave RMS

These requirements/goals include all sources of wavefront error, including fabrication, initial alignment, vibration, and thermal/gravitational effects (see section 3.2). Note that, as explained later in the section 3.3.8, passive compensation methods will be strongly preferred if at all possible.

2.5.5. LLT focus adjustment

2.5.5.1. Rationale

The projected laser beams must be focused on the sodium layer, whose altitude above sea-level varies between 80km and 110km, with an average around 90-95km. The Gemini North (resp. Gemini South) altitude of 4200m (resp. 2700m) must be subtracted from these values to get the distance between the LLT and the sodium layer. Also note that as the telescope points from 0 degree (zenith) up to 60 degree zenith angle, the range to the sodium layer varies as $1/\cos(\theta)$ where θ is the telescope zenith angle. However, if the LLT focus is fixed so that the output beams are basically collimated, the changes in the distance to the sodium layer are expected to produce changes in spot size which are small compared to the distortion effect of atmospheric turbulence.

2.5.5.2. Requirements

The LLT will be **afocal** so its output beam will be nominally collimated. The LLT focus will be fixed over the whole range of temperature, gravity components, vibrations and other disturbances described in section 3.2.

2.5.5.3. Goal

It is only a goal for the LLT that its focus be remotely adjustable when the telescope zenith angle varies from 0 (zenith) to 60 degree. Simple schemes for remote focus adjustment will be considered provided that this does not increase the LLT cost significantly.

2.6. Optical transmission

2.6.1. Rationale

The laser beam power transmission at 589nm must be equal or superior to **95%** including the power loss due to aperture clipping of the gaussian beam. For a gaussian beam centered within the LLT exit pupil with a 300 mm diameter @ $1/e^2$ intensity points, the transmitted energy through a 450 mm diameter aperture is 98.9%.

The LLT will sometimes be used to image a natural guide star for alignment and calibration purposes of the BTO subsystem. Therefore, the LLT optical transmission must be high enough in the visible that enough light emitted by a star is transmitted from the sky back to the BTO.

2.6.2. Requirements

The LLT optical transmission shall be **> 97% @ 589 nm**. This requirement must be met not only at the LLT delivery but also during normal operation after the LLT optics have been cleaned.

The average transmission in the visible (450-700nm) shall be on the order of **50 %**.

2.7. Optical substrates and Coatings

2.7.1. Rationale

The optics located at the entrance of the LLT will see up to five 10-W class laser beams almost overlapping each other. This corresponds approximately to an average single 50-W class gaussian beam, which for a 5mm beam diameter @ $1/e^2$ intensity points will produce a peak intensity of about 500 W/cm^2 (continuous wave).

It is worth noting that the LLT will be operated in a very dusty environment, with no easy way to monitor dust depositing on the optical surfaces out of scheduled cleaning maintenance periods.

2.7.2. Requirements

The LLT reflective optics will be coated with highly reflective, high-damage threshold coatings compatible with the safe use of continuous-wave power densities in the 500-1000 W/cm^2 range @ 589nm.

The LLT refractive elements will be made of laser-grade low absorbing materials and they will have anti-reflection coatings @ 589nm.

All materials and coatings will be chosen bearing in mind the peculiar environmental conditions at both Gemini sites. Those environmental conditions are described in section 3.1.

3. Laser Launch Telescope Functional Requirements

3.1. Lifetime

Assuming that the LLT optics are re-coated at the frequency recommended by Vendor, the MK and CP LLT must be designed so that they meet their performance specifications and functional requirements for a period of **10 years** or longer.

3.2. Environmental requirements

The following requirements are based on the *Gemini Environmental requirements* ICD-G0013, Revision B, dated Oct. 8, 1996.

Two separate environmental conditions are specified. The first is involved with general site operations and the second with operating the LLT while mounted on the telescope. It is recognized that it may be difficult or prohibitively expensive to actually test the LLT under all of these conditions. Where this is the case, these specifications can be used as a guide for the design and verified by analysis or experience with previous systems. This section is little more than a description of the conditions experienced by existing instruments in transit or operating at Mauna Kea and Cerro Pachón.

3.2.1. Handling Environment

The handling environment is those conditions experienced under normal telescope operations including:

- Storage at the base and mountain facilities
- Transportation and shipping to and from the base and mountain facilities
- Assembly/disassembly onto the telescope
- Storage and operation on the telescope.

The LLT is not expected to meet all its performances requirements during those conditions which are harsher than the operating environment conditions described in the following section. However, after repeated cycles of the conditions listed below the LLT must meet its operating performance requirements with no intervention from the operations staff other than routine tasks (handling, connecting services, etc.).

Transportation / Shipping / Handling / Survival Environment	
Condition	**Requirement**
Altitude	Sea level to13, 000 m

Ambient air temp	–25 °C to +71 °C
Ambient air temp step	±35 °C
Relative humidity[2]	0% to 100% with condensation
Wind speed	0 to 67 m/sec
Gravity orientation	All orientations
Vibration (minimum integrity)[1, 3]	PSD 0.015 g^2/Hz 10 to 40 Hz 0.00015 g^2/Hz @ 500Hz
Shock[0, 3]	Peak acceleration 15.0g, 0.015 second half-sine
Seismic acceleration[0,3]	12 g X, Y and Z directions
Mechanical Interface	Handling cart or facility cranes, Shipping Crate
Cleanliness	Occasional wind blown dust, sand & insects

[0] Specification differs from ICD-G0013, Revision B
[1] IAW MIL-STD-810F, January `00, section 514.5
[2] Frequent low humidity levels increase the risk of electrostatic discharge damage to sensitive electronic devices.
[3] It shall be demonstrated by analysis that the LLT meets those requirements (no vibration testing experiment required).

3.2.2. Operating Environment

The operating environment is the conditions experienced under normal telescope operations during adaptive optics observations. The LLT performance requirements must be met under these conditions. These conditions also include the testing of the instrument on its handling cart at the telescope and at the base facilities.

Operating environment	
Condition	Requirement
Altitude	Sea level to 4300m
Ambient air temp	-5°C to +20°C
Median air temp[4]	0°C Mauna Kea 9°C Cerro Pachón
Ambient air temp rate of change during the night	±0.2°C/hour Mauna Kea ±0.8°C/hour Cerro Pachón
Relative humidity[1]	0% to 90%
Wind speed[0]	0 to 11 m/sec
Gravity component limits[0, 2]	X axis 0g Y axis 0 to -1g Z axis -1g to 0g

Vibration[3]	PSD $1x10^{-5}$ g^2/Hz, 20-1000Hz, 6db/oct drop- off to 2000Hz
Cleanliness	Occasional wind blown dust, sand & insects

[0] Specification differs from ICD-G0013, Revision B
[1] Frequent low humidity levels increase the risk of electrostatic discharge damage to sensitive electronic devices.
[2] The coordinate system is the Optical Support Structure coordinate system (see drawing 90-GP-0001-0023, Rev. B).
[3] It shall be demonstrated by analysis that the LLT meets those requirements (no vibration testing experiment required).
[4] The Mauna Kea and Cerro Pachón median temperatures are significantly different. The design for the LLT, however, must be identical for both sites. If this temperature difference is significant in the design of the LLT, it must be accounted for in some form of adjustment or alignment internal to the LLT and not affect any of the space envelopes or interfaces defined in this document.

3.3. Mechanical requirements

3.3.1. Laser Launch Telescope location

The LLT structure must fit within and be rigidly mounted to the Secondary Support Structure (SSS) of the Gemini 8M Telescope's top end assembly. Because the LLT is situated within the SSS, access to its components will be limited. Any maintenance or adjustments performed after installation of the LLT must be possible given only access either through the SSS and LLT frames or from the top of the LLT.

Due to the airborne debris in the environment, certain components of the LLT, such as the primary OAP mirror, must be covered when not in use and the cover opened when observing (see section 3.3.7). Since the LLT location will be close to the dome shutter, the LLT and its components will be subjected to wind buffeting during observation. Any LLT component that might be caught by the wind, such as the LLT primary mirror cover, must be sufficiently restrained or shielded so that beams are not vignetted and no vibrations are propagated through the LLT system.

3.3.2. Space envelope

3.3.2.1. Input beam height above Secondary Support Structure top plate

The optical axis of the Beam Transfer Optics Optical Bench (BTOOB) is **2273 mm** above the SSS Reference Plane. Therefore the LLT optical axis at its optical interface with the BTO is **2273 mm** high above the SSS Reference Plane, oriented as shown in drawing ICR10.DWG.

3.3.2.2. Max distance to dome ceiling

The space available for elements mounted above the SSS top plate is limited in height because of the short distance from the SSS Top Plate to the inside of the dome. This distance has been measured in-situ in different places and shows a minimum distance of 300 mm from the SSS Top Plate or **2448 mm** from the Reference Plane. In order to insure sufficient clearance for all components of the LLT/BTOOB assembly, this allowable envelope has been limited to **2348 mm** from the Reference Plane. The BTOOB (not a part of the Work) will include a fixed cover to eliminate dust and stray light. In order for the BTOOB cover (not a part of the Work) to encompass the LLT components mounted on the LLT top plate, no LLT component shall extend more than 50 mm above the LLT/BTOOB optical interface or **2323 mm** from the Reference Plane as shown in drawing ICR02.DWG.

3.3.2.3. LLT diameter

The Gemini Telescopes secondary mirror support assembly is attached to the bottom plate of the SSS. The LLT must have the ability to be installed and removed without removal or disturbance of the secondary mirror assembly. Therefore the diameter of the LLT is constrained by the geometry of the secondary frame as shown in drawing ICR02.DWG. The inside diameter of the SSS frame is **610mm**. Due to welds on the inside of the SSS, any portion of the LLT that must be inserted through the SSS top plate may have a maximum diameter of **590 mm**. The Gemini telescope Prime Focus WFS (PF WFS) mounting brackets inside the SSS frame limit the diameter to **500 mm** for any portion of the LLT that inserts beyond them. The inside diameter of the LLT and its components is limited by the vignetting of the outgoing beam(s) reflecting off the LLT's OAP primary mirror.

3.3.2.4. LLT depth

The vertical depth of the LLT is limited by the depth of the secondary frame as shown in drawing ICR02.DWG. The depth of the SSS ranges from **2148 mm** above the SSS Reference Plane, down to the Reference Plane itself. However, due to the presence of a 2-mirror periscope located at the bottom of the SSS, the length available for the LLT inside the frame is limited. The LLT space envelope bottom boundary is a plane located **475 mm** above the SSS Reference Plane.

3.3.3. LLT/BTOOB interface

The Beam Transfer Optics Optical Bench (BTOOB) will be mounted to the top of the LLT via three- **60 mm** diameter raised pads as shown in drawing ICR20.DWG. As mentioned earlier in section 3.3.2.1, the central beam height above the Reference Plane is **2273 mm**. Because the central beam height and its direction of propagation define the BTOOB optical axis which must be bore-sighted to the LLT optical axis (see section 3.7.2), the 2273mm distance shall be accurate to better than **0.5 mm**.

The maximum height of the LLT components is **2323 mm** above the Reference Plane. Any LLT component extending beyond the LLT/BTOOB interface (**2178 mm** above the Reference Plane) must be within a **315 mm** radius of the SSS central axis. The inner

radius is limited by the vignetting of the outgoing beam(s) reflecting off the OAP primary mirror or equivalent. The inner radius must be calculated according to the OAP clear aperture diameter and the LLT unvignetted field of view. A safety margin of 10mm on top of the calculate radius is desirable to derive the minimum inner radius. The sides of the remaining footprint must lie within **40 mm** of the Y-axis as shown in drawing ICR20.DWG. Unless agreed to by AURA, all components must be placed along the $^{-}$Y-axis.

3.3.4. Weight

The total mass of the LLT should not exceed **120kg max.** This includes all components of the LLT that must be mounted on either its own frame or the SSS frame, including the primary OAP mirror or equivalent, the LLT mirror cover, the fold mirror/diverging lens assembly or equivalent, and any positioning/alignment components that will remain with the LLT.

3.3.5. Orientation

The laser beam(s) entering the LLT at the first optical surface will be propagated parallel to the SSS top plate, in the $^{-}Y \rightarrow {}^{+}Y$ direction as shown in drawing ICR02.DWG. The orientation will be as stated above unless the Vendor can show that it would increase the LLT mechanical stability if the LLT is oriented otherwise and AURA agrees.

3.3.6. LLT structure

The frame for the LLT shall be fabricated from **6061-T6 Aluminum**. This will eliminate thermal mismatching between the LLT and the SSS. All welding to be performed on the structure must be full penetration type welds using the latest materials and techniques specified by the American Welding Society for aluminum welding. All weld testing must be non-destructive. After welding and prior to final machining, the LLT frame must be completely heat treated, straightened and aged back to a T6 condition.

3.3.7. Dust cover

The large optics of the LLT must remain free from dust and other airborne debris. To reduce the accumulation of contaminants, a dust cover must be integrated into the LLT design. The cover will remain closed when the LLT is not used. It is a strong goal that the cover be remotely operated when required. If so, sensors will be provided by Vendor to report the two critical positions of the cover, open and closed, to the controlling software (see section 3.4.1).

Dust accumulated on the cover must not fall either on the 8m telescope primary mirror or on the LLT large optics itself when the cover is deployed and when the telescope is not pointed at zenith.

3.3.8. Mounting points and mechanical alignment accuracy

The existing mounting points on the SSS frame consist of three central mounting brackets within the SSS (oriented as shown in drawing ICR02.DWG) and the SSS Top Plate. The central mounting brackets were welded to the inside of the SSS and vary in their vertical

locations by ±7 mm. The SSS Top Plate was not machined after the structure was welded; hence the surface is not guaranteed to be flat or perpendicular to the central axis. Therefore, all vertical dimensions will be referenced from the SSS Bottom Plate/Reference Plane. The most appropriate interface point between the LLT and the SSS is the intersection of the SSS Reference Plane and the SSS Central Axis as shown in drawing ICR02.DWG.

The optical axis of the LLT must be aligned with the optical axis of the Gemini 8M telescope. The mechanical interface between the LLT and the SSS will be at 2153 mm above the Reference Plane, 5 mm above the SSS top plate, as shown in drawing ICR02.DWG. AURA will supply 5 mm thick shims, 60 mm in diameter which will allow for this alignment. Note that the LLT/SSS alignment on the telescope will be AURA's responsibility. It may happen that the LLT has to be dismounted from the SSS. In order to simplify realignment of the LLT with respect to the Gemini 8M telescope during reinstallation, two alignment pins will be placed through the LLT, LLT shims, and SSS top plate. To guarantee correct placement of the alignment pins, the fabricator must drill two pilot holes through the LLT top plate on the machined pads as shown in drawing ICR21.DWG.

The SSS top plate has an existing bolt circle pattern of Ø **26 mm** holes going through the **25 mm** thick plate as shown in drawing ICR02.DWG. AURA will take advantage of this existing hole pattern in mounting the LLT. The connection between the LLT and the SSS top plate will be made via four- **60 mm** diameter raised pads with protruding M20 studs as shown in drawing ICR21.DWG. These pads constitute an interrupted surface and must be perpendicular to the SSS central axis and parallel to the LLT/BTOOB interface as shown in drawing ICR22.DWG.

The Central Mounting Brackets are not situated within the SSS with a high degree of accuracy. One option is to remove the Central Mounting Brackets and use the entire diametral space envelope along the full depth of the LLT. However, the LLT mechanical design should avoid cutting those brackets if at all possible. If this option is exercised, (a) new hard point(s) must be defined at or near the bottom of the LLT in order to meet all performance requirements. Any modification of the SSS or implementation of new hard points must be approved by AURA.

3.3.9. Relative Alignment of LLT Components

3.3.9.1. LLT Primary Mirror

The LLT Off-Axis Parabola or equivalent must be held in position with respect to the LLT Central Axis (output optical axis) and centered on it. All components required for alignment and locking the mirror in place must be contained within the space envelope mention in section 3.3.2.

3.3.9.2. Thermal Compensation

In the CoDR LLT optical design presented in section 5.1, the linear distance from the diverging lens to the OAP primary mirror must be held to tight tolerances (approximately **+/- 5 microns**). Likewise with any other optical design that Vendors may propose, a mechanical system must be proposed which can compensate for thermal variations in the ambient temperature of **+/- 15°C**. This may be accomplished using either active or passive compensation schemes. Due to the mass and heat dissipation requirements, **a passive system is preferred**.

3.3.10. Handling fixtures

3.3.10.1. Mounting/dismounting on the telescope

The LLT will be installed in the secondary frame while the telescope is in a quasi-horizontal position, without disassembly of the top end, secondary support structure, or the secondary mirror support assembly. The presence of the LLT must not in any way prevent removal of the Secondary Mirror Tip/tilt System (located below the SSS Reference Plane) or its associated components.

The space between the dome and the top-end for inserting the LLT is **1830 mm**. Due to shipping crates, BTOOB integration in the lab and subsequent installation on the Gemini Telescope, the LLT must have the ability to be lifted, supported and manipulated anywhere from a horizontal position to a vertical position. The LLT integration procedure must be defined and the LLT delivered with the adequate handling equipment. The Vendor is responsible for defining lifting points that can be attached to use Gemini's facility crane or a similar method.

3.3.10.2. Large optics handling

The LLT OAP mirror or its equivalent will need to be periodically removed and recoated in order to maintain its optical performance. A method for removing the mirror from the LLT without removing the LLT from the Gemini telescope must be developed and documented by the Vendor (see section 3.6). This may require a separate handling fixture, be part of another fixture, or be integrated into the LLT frame itself. AURA must approve the handling procedure and all fixtures.

3.3.10.3. Shipping and Storage

The Vendor must construct a shipping crate that can handle not only transportation and shipping, but storage as well. All conditions for the various environments are specified in section 3.2.

3.3.10.4. Handling Procedure Documentation

All handling procedures must be clearly defined and documented by the Vendor for each fixture produced. There may be separate documents for each fixture, or all documents may be combined into one. If combined, each fixture must have a separate section, with a clear and distinct division between each.

3.3.10.5. Delivery

All crates, fixtures and associated documentation must be part of the Vendors' proposal and will become AURA property upon completion of the contract.

3.3.11. Gemini Standards

3.3.11.1. Factor of safety for structural component design

A minimum safety factor of 4 on Yield strength must be used for all structural elements.

3.3.11.2. Component finish and protection from corrosion

Non critical surfaces must have a minimum surface finish quality of 3 microns or better unless function dictates otherwise.

All components must be finished by removing sharp edges and burrs, unless required by the parts' function. All mild steel components must be cleaned, de-greased, primed and painted with a high performance paint such as epoxy, or polyurethane. Aluminum component must be anodized unless function dictates painting (for example for anti-reflection or to lower emissivity).

Mild steel surfaces that cannot be painted for functional reasons (accurate interface surfaces) must be protected by a non-tracking anti-corrosion dry film lubricant.

3.3.11.3. Mechanical drawings

All drawings and geometric tolerances must comply with ANSI standards, latest revisions.

3.4. Electrical / electronics / control requirements

3.4.1. Remote controls

Remote controls must be implemented through the GNAO and GSAO Control Systems. The GNAO and GSAO CS control various tasks using an EPICS interface. However no software would need to be developed with the LLT. The electronics would receive power and control signals for motor driving. The power supply would also be turned on and off from the GNAO and GSAO CS. With these signals, the LLT could drive possible motors. It could send limit switch or encoder signals back to the GNAO and GSAO CS to indicate the motor positions. The limit switch signals should also be used within the LLT electronics for internal protection. The LLT shall be delivered with the adequate testing capability to check that all remotely controlled functions are indeed working ('Self–test' features).

3.4.2. Electronics and cables

All necessary electronics should be mounted on the telescope, preferably not on the secondary frame, but possibly on the top-end ring and/or the telescope center section. The use of long cables should be foreseen, with a maximum length of about 50 m.

Appropriate signal–transmission techniques must be employed over long cable–runs (for example, differential transmission and reception, shielding, use of current loop schemes, etc.) as required to ensure reliable operation with minimum interference with other adjacent systems. If absolutely necessary, some electronics boxes can be mounted on the secondary frame. The volume allocated to the boxes is 100x225x880 mm as shown in drawing ICR03.DWG. Due to the tight thermal constraint applied to equipment mounted on the SSS, and the lack of coolant to this structure, the electronics mounted in this location must use a rigorous low–power design and, if practicable, have the ability to be either powered off entirely or placed in a low–dissipation state when not in use.

If LLT electronics are located on the telescope top-end ring or on the telescope center section, cables will be run along one of the secondary vanes so that the telescope primary mirror cannot see them. The vane is only 10mm wide and cables MUST be hidden behind the vane. Such cables shall have connectors at the top-end ring so that the top-end can be removed without dismounting the LLT first. This is a requirement for all systems mounted in this location.

The cabling used on the top–end ring is not subject to size restrictions, but that which passes across the vanes is. In that case, the cabling must fit within the vane cable–tray space envelope of 7 mm X 30 mm. In general this means a loose bunch of twisted–pair cables rather than a large single cable containing multiple pairs (as the latter is almost invariably of too great a diameter).

3.4.3. Gemini standards

This section provides as a list of guidelines in the event that Vendors propose a LLT design requiring some of the following elements.

3.4.3.1. Standardization

The following standards shall be applied to ensure compatibility with existing telescope systems.

3.4.3.1.1. Connectors

Where possible (for example, when connecting power and data signals between units) an appropriate ITT-Cannon MIL-C-26482 Series 1 KPT or KPSE connector shall be employed. Use of keyed connectors to lower the risk of accidental connector-swapping is strongly encouraged. Crimp connectors are preferred over solder types.

3.4.3.1.2. Cable and signal identification

All external cables shall be uniquely identified and labeled. The labeling and identification shall strictly adhere to the appropriate Gemini standard (Gemini Electronic Design Specification SPE-ASA-G0008 provided upon request) and shall be in a clearly visible and non-removable form. This identification scheme shall be identical to that used in the system documentation. Identification of cables by color-coding is appropriate and encouraged but not a substitute for clear labeling.

3.4.3.1.3. Electronic system documentation

All electronic circuit schematics and printed-circuit board (PCB) designs must be supplied in both printed and electronic form. The electronic form shall be OrCAD V9.0 native format or 100% compatible with it. The vendor must demonstrate, if non–OrCAD design files are supplied, that they are capable of being unambiguously and correctly imported into the current version of OrCAD. AURA will then use the converted OrCAD file as the official design file document(s).

3.4.3.1.4. Environmental rating

All electrical and electronic components shall be rated for operation below zero degree Celsius (rating to minus twenty degrees Celsius is sufficient). The ambient temperature in the telescope dome frequently falls below zero degree Celsius for extended periods. The Vendor will ensure that electronic equipment supplied by third parties – for example, as part of a sensor package – meets this requirement. In particular, tolerances on electronic devices such as sensors, etc., must be such as to allow correct operation of the mechanism in which they are located over the entire temperature range without recalibration or adjustment. In other words, the component specifications must be such that the *system* meets the operating requirements over the full temperature range.

3.4.3.1.5. Electrical components

All commercially available electrical components have to be UL listed. Items which do not meet this requirement will have to be approved by AURA prior of being incorporated into the system.

3.4.3.2. Signal Transmission

To minimize the risk of spurious operation of the LLT and other systems, adherence to the following guidelines are required. Low-level signals, for example those from analogue sensors, that are routed outside of a screened enclosure, over extended distances, through or near areas of high electromagnetic interference, must be transmitted by an appropriate method. Examples of such methods include, but are not limited to, differential voltage transmission via shielded, twisted–pair cable, 4–20mA current–loop systems, etc. Appropriate design measures shall be taken to minimize the coupling, generation and radiation of interfering electromagnetic signals shall be taken wherever necessary. As indicated above, these measures shall include, but not be limited to, the provision of adequate grounding and shielding and the use of appropriate robust signal transmission techniques.

3.4.3.3. Fail-safe Systems

The following provisions shall be followed in regard to fail-safe systems in the LLT electronics.

3.4.3.3.1. Limit switches

Electromechanical or electronic limit switches, where used, shall be wired such that a break in the connecting cable to them shall cause a fault condition to exist. This

precludes the use of switches wired such that the 'normally open' state indicates a 'no fault' condition. Limit switches used for safety interlocks should be equipped with positive opening safety contacts, as well as monitoring contacts.

3.4.3.3.2. Others

Fail-safe, self checking circuits have to be incorporated in the design wherever control malfunctions or improper sequencing may create a hazard to personnel, cause personal injury or damage to equipment or parts. This circuitry should give a protection against:

- Failure of one or more devices to function properly
- Improper sequencing in manual or automatic operation

Control circuits incorporating position sensors, movement sensors, push buttons and similar devices should be designed in such a manner that a device must be released or otherwise returned to its reset state before it can be used to initiate a control action. The design should prevent continuous operation or cycling due to a device that has been tied down, jammed or otherwise defeated.

3.5. Heat dissipation

No more than **2 W** of heat must be dissipated into the air from all the LLT elements which are located behind the telescope secondary mirror (i.e. on the Secondary Support Structure). This requirement includes all heat dissipated by the optics when up to 50W of laser power is used.

3.6. Optical cleaning and coating

All efforts shall be made to protect the LLT optics from dust. It must be possible to access and clean small LLT optics without removing them from the LLT or removing the LLT from the SSS. Section 3.3.10.2 also requires that it must be possible to remove the LLT large optics to re-coat them without removing the LLT from the SSS. All LLT optical mounts shall be designed so that there is no need for more than a minor and well documented re-alignment procedure of the LLT after the optics is returned to its mount, or the mount is returned to the LLT structure.

3.7. Optical alignment

3.7.1. LLT internal alignment off telescope

3.7.1.1. Before delivery

Vendors shall prepare a **preliminary alignment plan** to be included in their response to this Request for Proposal. The alignment plan will be further detailed and presented at the Preliminary Design Review for discussion and approval with AURA. This is to make sure that there will not be any flaws in the global BTO/LLT/SSS alignment plan to be prepared by AURA with relevant help from Vendors.

3.7.1.2. At delivery

Vendors shall prepare a complete and fully **detailed alignment plan** to be delivered along with other LLT documentation. Acceptance tests which will be held (i) at Vendors' facility before shipping, and (ii) at the Gemini delivery site after shipping, shall include a test on the ability to align/realign the LLT by following the alignment plan provided by Vendor.

It is expected that the alignment procedure or the optical performance testing will necessitate the use of a **large reference flat mirror** (autocollimation procedure). This large flat mirror and/or any other special equipment used to test the LLT alignment and optical performance shall be made available to AURA for acceptance tests at the Gemini delivery site after shipping. If the large flat or other special equipment were to be rented for a limited amount of time by Vendors in order to save the cost of purchasing expensive specialty items, AURA may request to arrange for a time extension of the rental in order to use this equipment for subsequent mounting and alignment of the BTOOB on the LLT. This issue will be discussed ahead of time at the Preliminary Design Review.

Note also that in the event that Vendors would indeed plan to use a large flat mirror to perform an autocollimation alignment procedure, they must not overlook the need to machine some fixed reference points to support the large flat mirror. Similarly, all light sources or sensors reference points and mounts designed by Vendors to enable the LLT alignment procedure must be delivered to AURA with the LLT. All light sources and sensors purchased by Vendors under this contract will become AURA's property after delivery. If special items like light sources and sensors that are necessary for the LLT alignment were the Vendors' property and remain so after delivery, Vendors shall fully document their use and propose solutions to buy or rent them, were the necessity to fully realign the LLT arise in the future.

3.7.1.3. After delivery

The necessity to re-align the LLT entirely is considered a major re-alignment task and this must not occur. It is a requirement that a first order LLT optical alignment be maintained during storage, handling, installation, and after re-assembly following cleaning, re-coating or replacement of the LLT optics. However, should the re-alignment of the whole LLT become necessary after the LLT structure had to be removed from the telescope top-end for instance, the alignment procedure provided by Vendor should enable the LLT complete re-alignment.

3.7.2. LLT alignment vs. BTOOB

3.7.2.1. AURA's responsibility for the task

Once the LLT has been delivered to the Gemini North or South facility and acceptance tests have been performed successfully, AURA will mount the Beam Transfer Optics Optical Bench (BTOOB) on the LLT top plate as described by drawing LLT5Sep.dwg and with the mechanical interface specified in drawings ICR20.dwg, ICR22.dwg. Note that this task is not part of the RFP and that it will be AURA's responsibility to align the

BTOOB with respect to the LLT. The purpose of this section is to help Vendors understand the overall BTO/LLT/SSS alignment philosophy. This should make it easier for AURA and Vendors to discuss the LLT alignment plan and its implications on the overall alignment strategy.

3.7.2.2. BTOOB diagnostics

As shown in drawing LLT5Sep.dwg (section 5.2.2), the BTOOB includes diagnostics to measure the far-field and near-field alignment of the laser beam(s) propagation axis with respect to the common optical axis of the BTOOB and LLT. During LGS AO observations, a far-field camera monitors the laser beam(s) propagation direction(s) with respect to the common optical axis of the BTOOB and LLT, and the near-field camera monitors the beam(s) position(s) on the LLT entrance pupil. A beam splitter and corner cube arrangement in front of the diagnostics makes it possible for the near-field and far-field cameras to image a bright star whose light is collected by the LLT and sent backwards to the diagnostics.

3.7.2.3. LLT/BTO alignment procedure

AURA must align the BTOOB optical axis with respect to the LLT optical axis both in centering and pointing. This will be done in the lab using shims at the interface between the LLT and BTOOB described in section 3.3.3. The detailed alignment procedure may make use of the BTO diagnostics described in the previous section, but has yet to be determined. Once the BTOOB has been aligned with respect to the LLT, pins will be drilled for the BTO/LLT alignment to be repeatable after the BTOOB is disassembled from the LLT top plate.

AURA may take advantage of the Vendors' proposed alignment plan for the LLT, and the light sources, sensors and/or special tools necessary to perform the BTO/LLT alignment. For instance, if Vendors plan to align the LLT by autocollimation using a large retro flat mirror to adjust the tip/tilts and centering of individual LLT elements, AURA may discuss with Vendors the possibility to use that same reference flat to co-align the BTOOB axis with the LLT axis.

Vendors are encouraged to suggest ideas to AURA about alignment procedures for the BTOOB boresight, pointing and centering with respect to the LLT.

3.7.2.4. LLT/BTO assembly alignment procedure with respect to SSS

This task is also AURA's responsibility. After the BTOOB and LLT have been co-aligned in the lab, the two systems will be disassembled before they are mounted on the Gemini telescope. To start with, the LLT will be mounted alone on the telescope and the LLT pointing axis will be centered on the Gemini telescope axis. This will probably involve the use of a survey instrument looking at a target centered on the back of the OAP mirror cell (or equivalent). The survey instrument placed at the Gemini Cassegrain focus will be looking up through the 180mm hole in the Gemini telescope secondary mirror. The LLT center axis will also be bore-sighted with the Gemini telescope pointing axis. The bore-sight procedure will most probably involve an accurate horizontality

measurement with a level or a plumb line when the Gemini telescope is pointing to zenith. Horizontality of the LLT top plate will be adjusted with 5mm thick shims.

Once the LLT is bore-sighted and centered correctly, the BTOOB will be mounted on the LLT again and locked back into place. The Gemini telescope will be pointed at a bright natural guide star and the star will be imaged both by the Gemini telescope acquisition camera and the BTO diagnostics. Provided that previous alignment steps were performed accurately enough, the star should fall in the field of view of the near field and far field cameras. Fine adjustments of the LLT and BTO assembly optical axis pointing and centering will be done by comparing the position of the star on the acquisition camera and the BTO far-field and near-field cameras. The final alignment should see the star imaged at the center of all cameras. Note that later on, the final star positions on the BTO cameras will serve as reference positions for the laser beam(s). Finally, pins will be drilled to lock the LLT into place. The static BTO/LLT/SSS alignment procedure will be complete at this point.

3.7.2.5. Use of BTOOB diagnostics to assess LLT performance on telescope

It is foreseen that some minor re-alignment of the LLT will be needed from time to time, for instance after large optics such as the OAP or equivalent have been removed, re-coated, and put back into place. Assuming that the LLT and BTOOB have been co-aligned within Gemini's specifications, it will be possible to assess the LLT image quality by pointing the telescope to a bright star and imaging this star through the LLT with the BTOOB near-field and far-field cameras and adequate software. The preliminary design of the BTOOB diagnostics includes the possibility to measure the low order aberrations introduced by the LLT. Vendors shall use this capability to derive a re-alignment procedure of the LLT in situ, i.e. without removing the LLT from the SSS. This procedure for minor realignments can be iterative in that it may require that a technician access LLT mounts or parts after the LLT aberrations have been measured on the sky. There may be a need to point the telescope back and forth between the star and the position where the technician can access the LLT several times in a row. All efforts will be made for the procedure to converge quickly. The alignment procedure will be well documented. Tables of recognizable aberration patterns specific to certain types of misalignments that are internal to LLT(defocus, decenters, tip/tilt of individual elements) or external to it (bore-sight error, vignetting, etc.) will be provided too.

4. Contract schedule and specifics

See the Main Document of the Contract and the Statement of Work.

5. Appendices

5.1. Conceptual optical design

5.1.1. Philosophy

The CoDR Laser Launch Telescope is an afocal telescope with no intermediate focus. The conceptual LLT design includes a toroidal fold mirror, an aspheric diverging lens and an off-axis parabola (OAP).

The OAP diameter, focal length and off-axis angle reasonably comply with the LLT system tight space envelope requirements. Those values were also tentatively chosen close to OAP specifications advertised by large optics Vendors in order to decrease fabrication cost.

The use of an aspheric diverging lens alone could not enable a significant balancing of asymmetric aberrations introduced by the OAP, that is the reason why the initially flat fold mirror was made toroidal. Since during adaptive optics observations at the Gemini South telescope the X-shaped laser guide star pattern will be rotating along the central beam axis, effort was made for the (Hx=±1, Hy=0) and (Hx=0, Hy=±1) fields to produce spots of similar RMS radii (say within ±0.03 arcsec on the sky).

The CoDR design was produced using ZEMAX. The design is presented in section 5.1.2 below. Note that the light propagation direction is reversed because it made it easier to handle the off-axis parabola element and make it the STOP this way. Also, the CoDR field of view was ± 1.0 arcmin, different from the ± 1.2 arcmin unvignetted FoV specified in this document. Spot diagrams presented in figure 4 are given for a ± 1.0 arcmin FoV, corresponding to the LLT CoDR design and similar to the LLT image quality specification in this document.

5.1.2. ZEMAX prescription and drawings

```
System/Prescription Data

File : K:\AO\MKlgs_(&CPlgs)\Laser Launch Telescope\optical\Celine\Celine
LLT 03-13-01 for RFP drawings.ZMX
Title: CoDR LLT design
Date : TUE MAR 13 2001

LENS NOTES:

       STOP = off-axis parabola, 450mm diam
        +/- 1 arcmin FoV


GENERAL LENS DATA:

Surfaces                :                16
```

```
Stop                     :                2
System Aperture          : Entrance Pupil Diameter = 450
Glass Catalogs           : schott MISC
Ray Aiming               : Paraxial Reference, Cache On
 X Pupil shift           :               0
 Y Pupil shift           :               0
 Z Pupil shift           :               0
Apodization              :Uniform, factor =   2.25000E+000
Effective Focal Length   :        17421.18 (in air)
Effective Focal Length   :        17421.18 (in image space)
Back Focal Length        :        391.6168
Total Track              :        1758.055
Image Space F/#          :        38.71373
Paraxial Working F/#     :        46.47258
Working F/#              :        45.72277
Image Space NA           :      0.01291424
Object Space NA          :       2.25e-008
Stop Radius              :             225
Paraxial Image Height    :         5.07775
Paraxial Magnification   :               0
Entrance Pupil Diameter  :             450
Entrance Pupil Position  :            1700
Exit Pupil Diameter      :        19.11694
Exit Pupil Position      :       -821.9922
Field Type               : Angle in degrees
Maximum Field            :          0.0167
Primary Wave             :           0.589
Lens Units               :   Millimeters
Angular Magnification    :        23.53933

Fields          : 5
Field Type: Angle in degrees
#        X-Value        Y-Value         Weight
 1       0.000000       0.000000       1.000000
 2       0.000000       0.016700       1.000000
 3       0.000000      -0.016700       1.000000
 4       0.016700       0.000000       1.000000
 5      -0.016700       0.000000       1.000000

Vignetting Factors
#       VDX       VDY       VCX       VCY
1  0.000000  0.000000  0.000000  0.000000
2  0.000000  0.000000  0.000000  0.000000
3  0.000000  0.000000  0.000000  0.000000
4  0.000000  0.000000  0.000000  0.000000
5  0.000000  0.000000  0.000000  0.000000

Wavelengths     : 1
Units: Microns
#          Value         Weight
 1       0.589000       1.000000
```

SURFACE DATA SUMMARY:

Surf	Type	Comment	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD		Infinity	Infinity		0	0
1	STANDARD	-	Infinity	1700		450.991	0
STO	STANDARD	STOP	Infinity	35		450	0
3	COORDBRK		-	0		-	-
4	STANDARD	OAP	-3344.6	0	MIRROR	966.0001	-1
5	STANDARD		Infinity	-1672.3		986.5968	0
6	COORDBRK		-	0		-	-
7	STANDARD	-	Infinity	32.194		1.004121	0
8	STANDARD		72.6	-2	SILICA	9.678982	0
9	STANDARD	ASPHERIC	-19.5	-45.7		9.297626	-1.14
10	COORDBRK		-	0		-	-
11	TOROIDAL	TOROIDAL	-1316.2	0	MIRROR	15.24893	0
12	COORDBRK		-	0		-	-
13	STANDARD		Infinity	-70.24922		9.901186	0
14	STANDARD	PARAX EXIT PUPIL	Infinity	200		7.673161	0
15	PARAXIAL	1MICRON <-> 0.01'	-	343.77		14.44857	-
IMA	STANDARD		Infinity			12.04812	0

```
SURFACE DATA DETAIL:

Surface OBJ     : STANDARD
 Scattering     : None
Surface   1     : STANDARD
 Comment        : -
 Scattering     : None
Surface STO     : STANDARD
 Comment        : STOP
 Scattering     : None
Surface   3     : COORDBRK
 Decenter X     :                0
 Decenter Y     :             -258
 Tilt About X   :                0
 Tilt About Y   :                0
 Tilt About Z   :                0
 Order          : Decenter then tilt
 Scattering     : None
Surface   4     : STANDARD
 Comment        : OAP
 Scattering     : None
Surface   5     : STANDARD
 Scattering     : None
Surface   6     : COORDBRK
 Decenter X     :                0
 Decenter Y     :                0
 Tilt About X   :             -8.8
 Tilt About Y   :                0
 Tilt About Z   :                0
 Order          : Decenter then tilt
 Scattering     : None
Surface   7     : STANDARD
 Comment        : -
 Scattering     : None
Surface   8     : STANDARD
 Scattering     : None
Surface   9     : STANDARD
 Comment        : ASPHERIC
 Scattering     : None
Surface  10     : COORDBRK
 Decenter X     :                0
 Decenter Y     :                0
 Tilt About X   :             49.4
 Tilt About Y   :                0
 Tilt About Z   :                0
 Order          : Decenter then tilt
 Scattering     : None
Surface  11     : TOROIDAL
 Comment        : TOROIDAL
 Rad of rev.    :           -557.3
 Coeff on y^2   :                0
 Coeff on y^4   :                0
 Coeff on y^6   :                0
 Coeff on y^8   :                0
 Coeff on y^10  :                0
```

```
 Coeff on y^12  :                0
 Coeff on y^14  :                0
 Scattering     : None
Surface  12     : COORDBRK
 Decenter X     :                0
 Decenter Y     :                0
 Tilt About X   :             49.4
 Tilt About Y   :                0
 Tilt About Z   :                0
 Order          : Decenter then tilt
 Scattering     : None
Surface  13     : STANDARD
 Scattering     : None
Surface  14     : STANDARD
 Comment        : PARAX EXIT PUPIL
 Scattering     : None
Surface  15     : PARAXIAL
 Comment        : 1MICRON <-> 0.01'
 Focal length   :           343.77
 OPD Mode       :                0
 Scattering     : None
Surface IMA     : STANDARD
 Scattering     : None
```

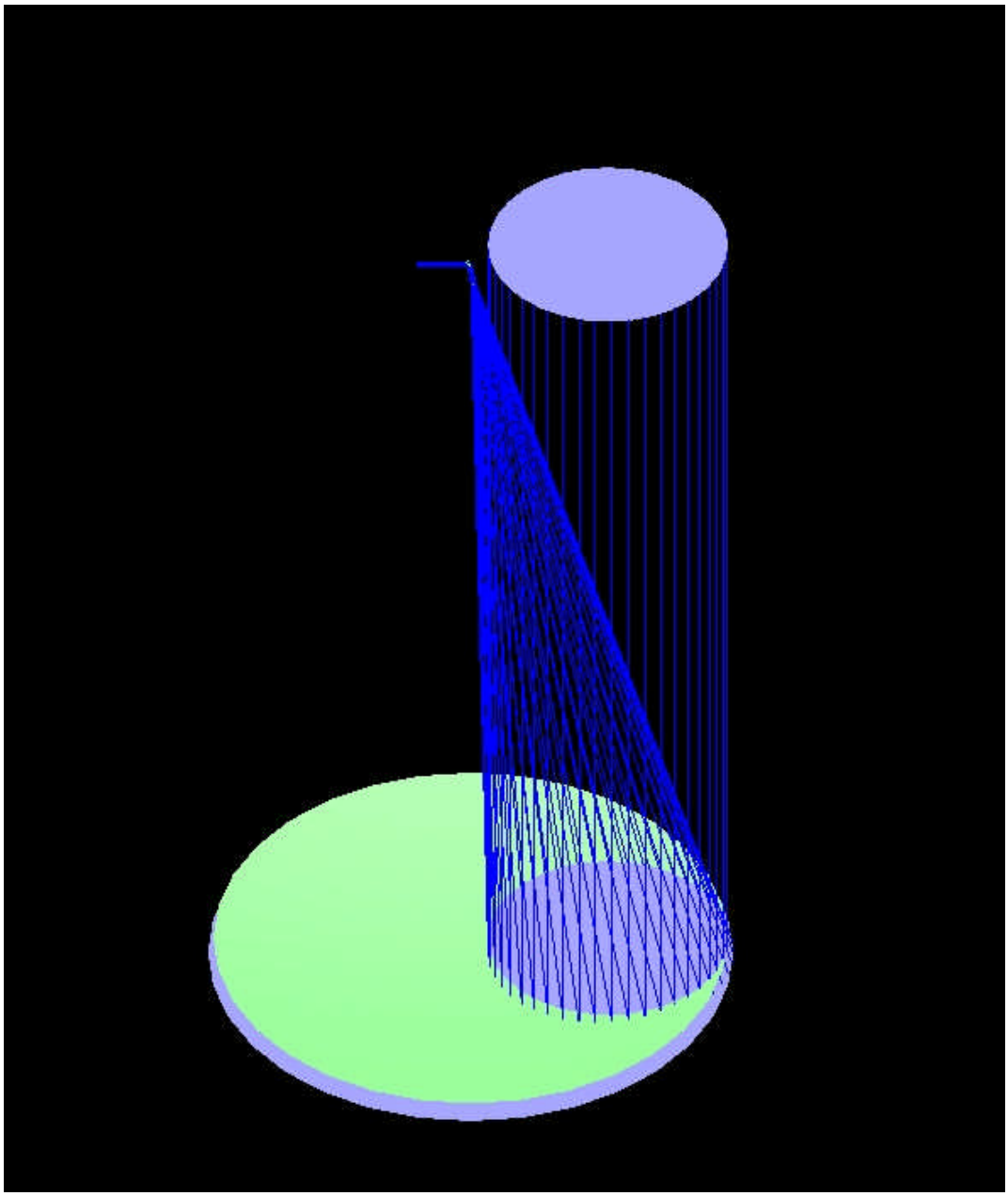

Figure 2: ZEMAX shaded model of the LLT CoDR design.
Shows the central beam only (Hx=0, Hy=0).

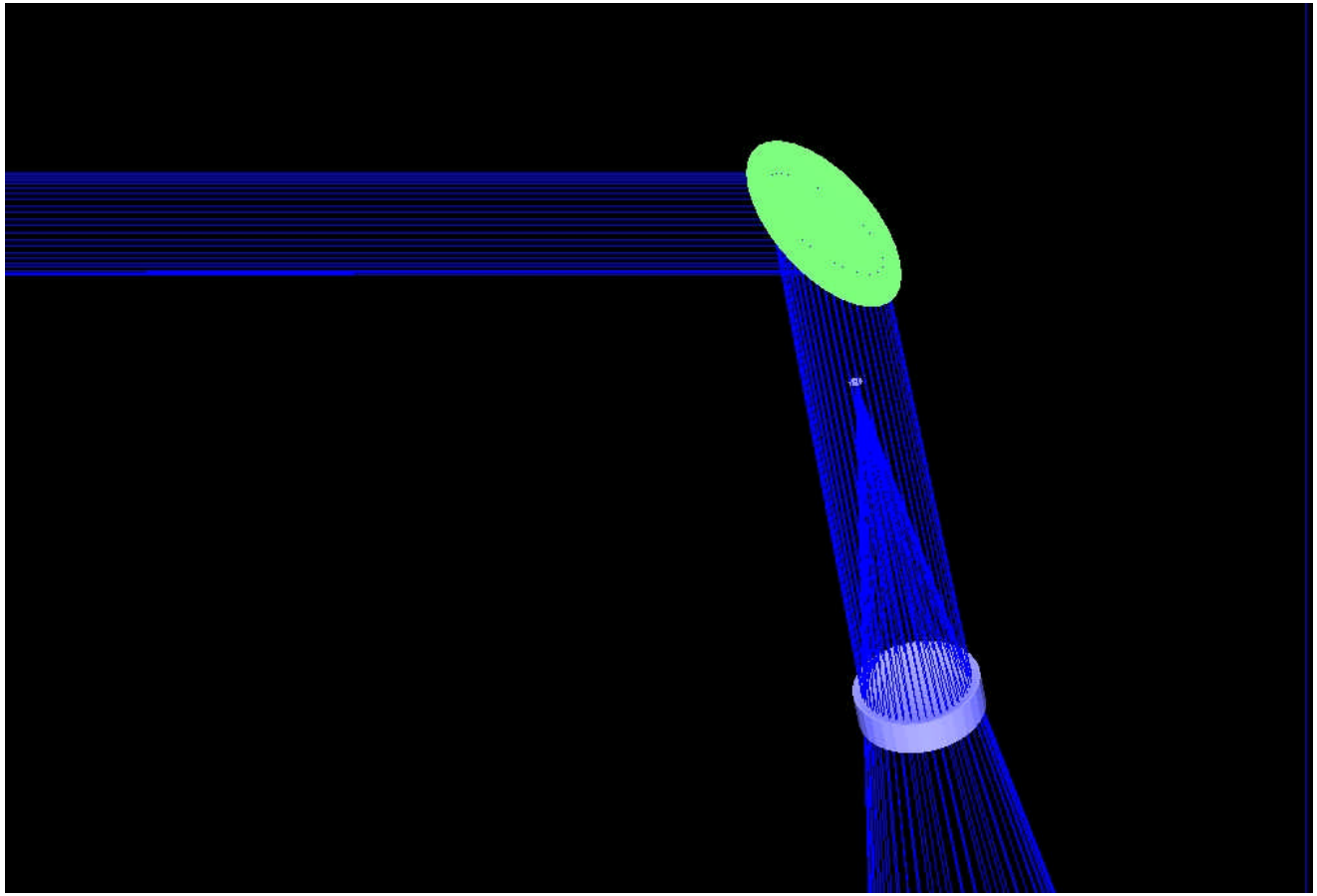

Figure 3: Close-up view on the aspheric diverging lens and toroidal fold mirror.
This view shows the intermediate OAP focal plane.

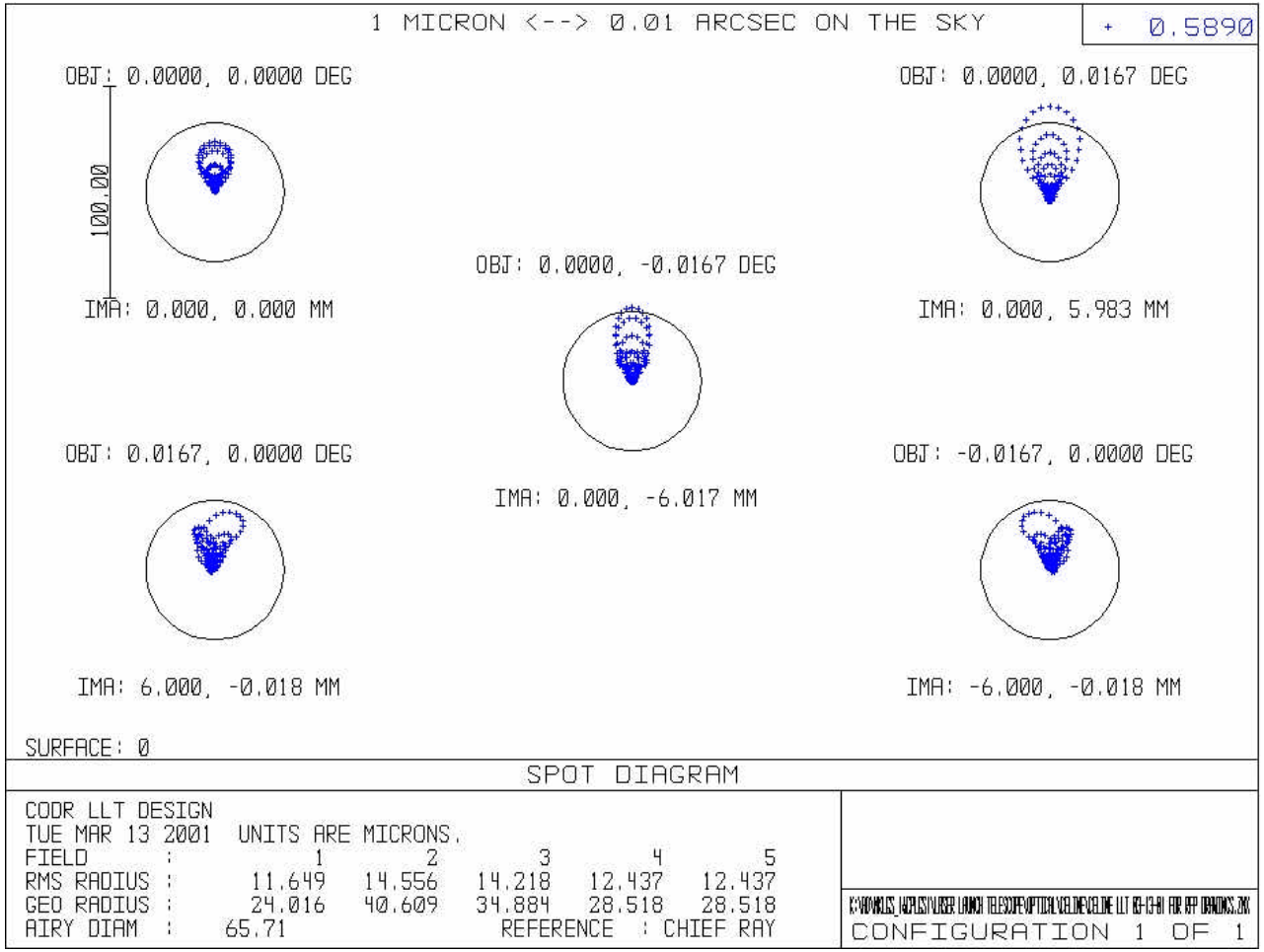

Figure 4: CoDR LLT design spot diagram for the central beam (Hx=0, Hy=0) and the four corner beams (Hx=0, Hy=1), (Hx=0, Hy=-1), (Hx=1, Hy=0) and (Hx=-1, Hy=0). In this representation, the scale is chosen so that 1micron corresponds to 0.01 arcsec on the sky if the light propagation was reversed.

5.1.3. Entrance pupil location

In the conceptual design, the paraxial entrance pupil is located about 25mm after the diverging lens (i.e. about 70mm after the toroidal fold mirror) along the principle ray in the laser beam propagation direction. This corresponds to a difference of z-height between the input beams parallel to the BTO Optical Bench and the location of the center of the LLT paraxial entrance pupil of about 69mm. Another way to look at this distance is to unfold the beam at the toroidal fold mirror and let the beams propagate horizontally until the "unfolded" paraxial entrance pupil. Then the horizontal distance between the center of the toroidal fold mirror and the "unfolded" paraxial entrance pupil is about 70mm. The horizontal distance of the center of the toroidal fold mirror to the LLT central vertical axis (axis going though the center of the STOP in the CoDR optical design) being about 260mm, then the horizontal distance between the "unfolded" LLT paraxial entrance pupil and this axis is about 190mm. See figure 5 below.

Note that this distance is well within the 235mm distance defining the LLT entrance pupil space envelope in section 2.4.5.2.

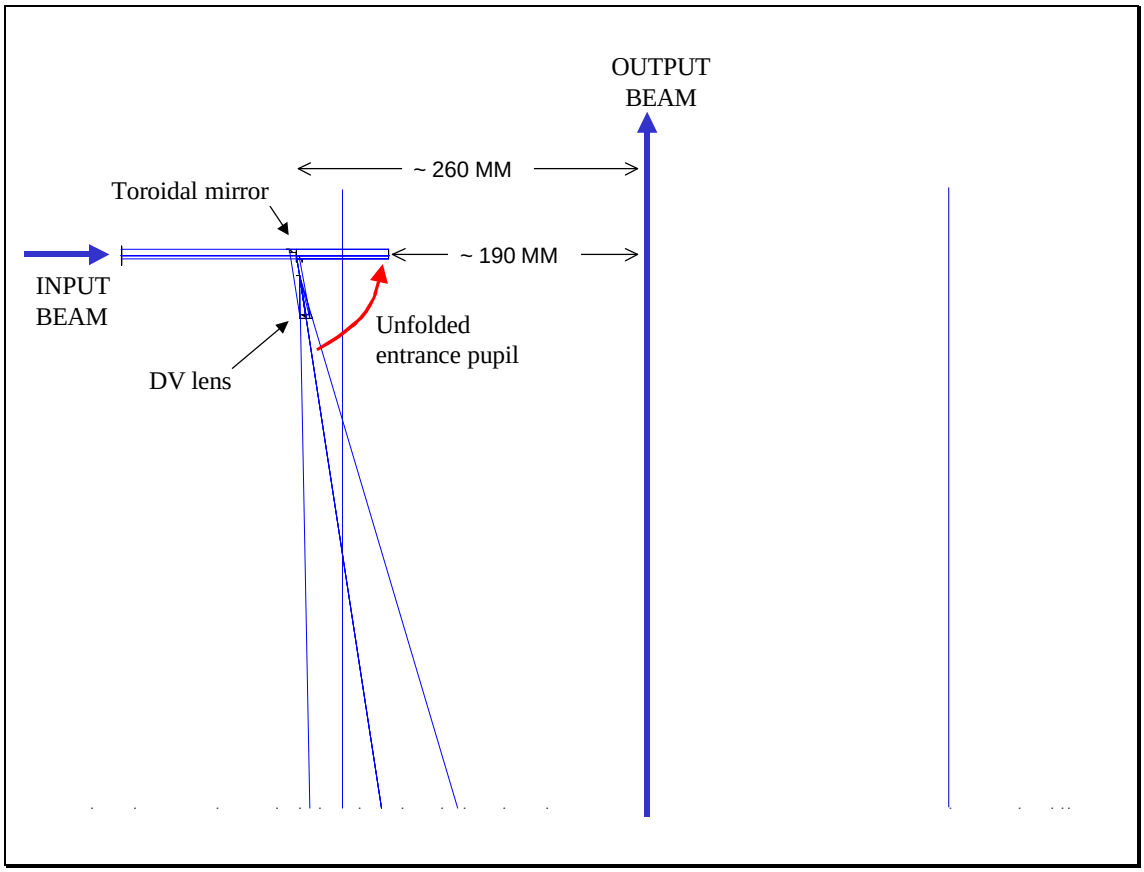

Figure 5: CoDR design entrance pupil location

5.2. Interface drawings

5.2.1. Interface with SSS and BTO

ICR01.dwg LLT interface control requirements for the secondary support structure

ICR02.dwg LLT interface control requirements for the secondary support structure

ICR03.dwg Electronics box interface for the secondary support structure

ICR10.dwg Orientation of components for the laser launch telescope

ICR20.dwg Required LLT/BTOOB interface for the laser launch telescope

ICR21.dwg Required LLT/SSS interface for the laser launch telescope

ICR22.dwg Required BTOOB/LLT/SSS interface for the laser launch telescope

5.2.2. Other applicable drawings

Telescope1.dwg 3D view of the Gemini 8-m telescope

LLT5Sep.dwg BTO Optical Bench/LLT Conceptual Design for a one or five beam array

Note: drawing LLT5Sep.dwg includes two views: (i) 1 beam system, and (ii) 5 beam system