Gemini North and South Laser Guide Star Systems
Requirements and Preliminary Designs

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ABSTRACT

In the near future, the Gemini Observatory will offer Laser Guide Star Adaptive Optics (LGS AO) observations on both Gemini North and South telescopes. The Gemini North AO system will use a 10W-class sodium laser to produce one laser guide star at Mauna Kea, Hawaii, whereas the Gemini South AO System will use up to five such lasers or a single 50W-class laser to produce one to five sodium beacons at Cerro Pachón, Chile. In this paper we discuss the similarities and differences between the Gemini North and South Laser Guide Star Systems. We give a brief overview of the Gemini facility Adaptive Optics systems and the on-going laser research and development program to procure efficient, affordable and reliable lasers. The main part of the paper presents the top-level requirements and preliminary designs for four of the Gemini North and South Laser Guide Star subsystems: the Laser Systems (LS), Beam Transfer Optics (BTO), Laser Launch Telescopes (LLT), and their associated Periscopes.

Keywords: Laser Guide Star Adaptive Optics (LGS AO), Sodium Lasers, Multi-Conjugate Adaptive Optics (MCAO)

1. INTRODUCTION

Gemini North and Gemini South, two IR-optimized 8-m telescopes respectively located at the summit of Mauna Kea, Hawaii, and Cerro Pachon, Chile, will soon be equipped with both Natural Guide Star (NGS) and Laser Guide Star Adaptive Optics (LGS AO) systems. A 10W-class laser will be associated with Altair[1, 2], the altitude conjugated- NGS AO system at Gemini North. The laser system will complete Altair's upgrade to a LGS AO facility instrument in late 2003. The Gemini South LGS AO system will follow two to three years later, potentially the Multi-Conjugated Adaptive Optics[3, 4, 5] (MCAO) system equipped with a 50W-class laser. For a range of criteria, MCAO mean performance over a one square arc minute field-of-view will be comparable to the on-axis performance of the Altair LGS mode at Gemini North. Useful levels of atmospheric turbulence compensation will be achieved over a full two arc minute diameter field-of-view, the maximum possible with the Gemini telescope design. Sky coverage will also be comparable with Altair or somewhat superior. To achieve this, the MCAO system will use 3 Deformable Mirrors (DM), 3 NGS and 5 LGS, hence the Gemini South laser system power five times as high as the Gemini North one.

Both Gemini LGS systems rely on the excitation of mesospheric sodium atoms to create the artificial wavefront reference required by Adaptive Optics systems where no NGS of sufficient brightness exist near the science target. The Gemini North and Gemini South Laser Guide Star systems are being designed and developed in parallel so that the southern system is regarded as an upgrade of the northern system. Whenever possible, systems will be identical and use the same hardware and software. Design, fabrication, integration and commissioning time scales are such that the simpler single beam system will serve as a test-bed for the second, more complex, five beam system. Integration and commissioning of the Gemini South facility AO system will be phased as well, beginning with a depopulated 1-DM, 1-NGS, 1-LGS system to be commissioned early 2005. Pending final approval to complete MCAO and status of the 50W-class laser system procurement at that time, the Gemini South facility AO could offer full MCAO capabilities for science observations as soon as 2006.

Each laser guide star system includes six subsystems, namely: the Laser System (LS), Beam Transfer Optics (BTO), Laser Launch Telescope (LLT) and its associated Periscope, the LGS Control System (CS) and the Safety Systems (SALSA). The Laser System, expected to mount on the side of the telescope, produces the laser beam(s) used for sodium excitation; the Beam Transfer Optics relay those beams to the top-end of the telescope, and the Laser Launch Telescope project them on the

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sky. The LGS Control System controls the LS, BTO, LLT and SALSA, as well as all system-level interactions with the AO module, the telescope and the observer. In the case of the Gemini South AO system, the LGS CS is designed as a subsystem of the MCAO Control System. The MCAO CS and SALSA systems are not described in this article, since a separate paper addresses their design elsewhere in these proceedings[6]. Section 2 of this paper presents the top-level requirements for the Gemini North and South Laser Systems, and review the status of the Gemini sodium laser research and development program to procure affordable fully-engineered high power solid-state lasers suitable for efficient and reliable LGS beacon generation at 4-10m class telescopes. Section 3 presents the top-level requirements and preliminary designs for the Gemini North and South BTO, LLT and periscopes. All requirements and designs presented in this paper reflect those developed for the MCAO Preliminary Design Review[7] that was held on May 24-25, 2001, in Hilo, Hawaii.

2. LASER SYSTEMS

2.1 Laser requirements

The Laser System includes all components, both hardware and software, necessary to produce and maintain one (Altair) or five (MCAO) laser beams at the sodium wavelength. These components are one or multiple laser heads and laser enclosures, the laser electronics, a control system, cooling systems, and all necessary diagnostics. An early version of all detailed requirements for the Gemini North Laser System was issued in October 1999 and is still currently available on the Gemini web site[8]. Those requirements, which will serve as the basis for the final Gemini North and South Laser System requirements, are to be reviewed and updated in the coming months.

The first requirement of interest is obviously the laser power requirement. Earlier Gemini papers[9, 10] describe the approach taken to derive the laser power requirement per laser beacon for both Gemini telescopes. An important result is that laser powers required to create sodium laser guide stars of sufficient magnitude for Altair and MCAO are approximately the same per laser beacon. The use of different sets of assumptions for average seeing values, atmospheric and optical transmissions, detector parameters, etc., partly accounts for the slight differences in power requirements per laser beacon for both Gemini AO systems. However, those differences are absorbed within system design margins that deal with more strongly varying parameters such as zenith angle, sodium abundance and seeing. Therefore the laser power requirement for Gemini South is about five times as much as the laser power requirement for Gemini North.

Zenith angle	θ = 0-45º (useful performance up to 60º)
Laser wavelength	λ = 589.0 nm
Projected laser beam quality	< 1.5 times diffraction-limited
BTO transmission	T_{BTO} = 0.8 (laser system head mounted on the telescope primary mirror cell)
LLT transmission (incl. vignetting)	T_{LLT} = 0.9
LLT pupil diameter	D_{LLT} = 450 mm
Beam diameter on LLT primary mirror	D_{laser} = 300 mm @$1/e^2$ intensity points
Atmospheric transmission (one-way) at zenith	T_{atmo} = 0.8
Poor-to-median (MK)/median (CP) seeing conditions (i.e. design point seeing conditions)	MK: r_0 = 17.2 cm @ 0.589 µm (corresponds to 0.70'' @ 0.55 µm) CP: r_0 = 18.0 cm @ 0.589 µm (corresponds to 0.65'' @ 0.55 µm)
Low-to-average sodium column density	$C_S = 2\ 10^9 - 3\ 10^9$ atoms/cm^2 (to be updated)
Sodium layer altitude and thickness	Z = 95 km +/- 5 km (to be updated)
Non-saturated slope efficiency of a 10-MHz CW laser	SE = 0.26 photons.m^2/ms/W/atom
Telescope + AO fold transmission	$T_{telesope + AO fold}$ = 0.8
AO Module transmission @ 589 nm	MK: T_{AOM} = 0.70 CP: T_{AOM} = 0.65
LGS WFS Detector quantum efficiency	MK: η = 0.85 CP: η = 0.95

Table 1: LGS system parameters used or to be used to derive laser power requirements for Mauna Kea (MK) and Cerro Pachón (CP). Most parameters will be updated in the near-term, as well as corresponding laser power requirements.

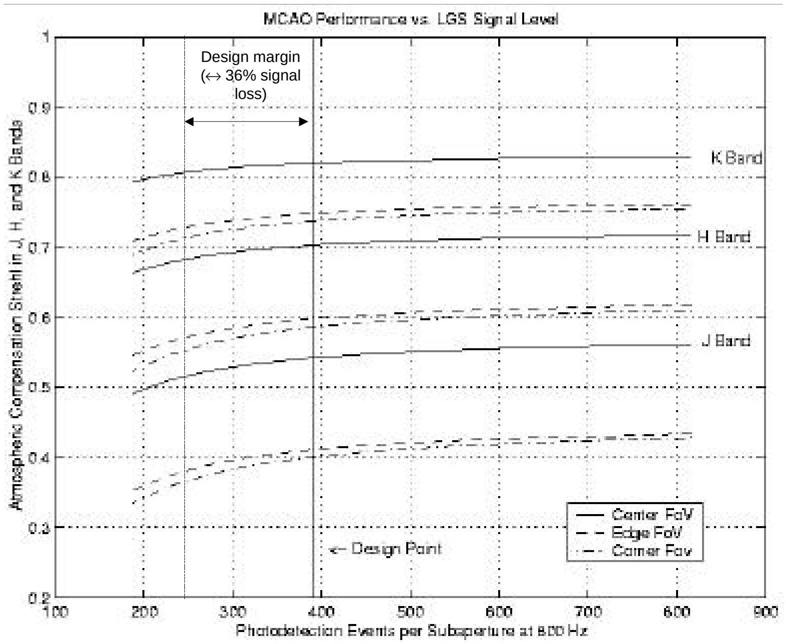

Figure 1: MCAO design margin in terms of photodetection events per subaperture per frame at the LGS wavefront sensor (WFS). The design point was used as a baseline to derive the laser power requirement per laser beacon for MCAO. The design margin allows for as much as a 36% signal loss. This corresponds to half a LGS magnitude and accounts for reasonable system performance degradation in case of low laser power, low sodium abundance, low atmospheric transmission, or any other cause of signal loss.

The exact laser power requirement also strongly depends on the temporal and spectral format of the laser used to excite mesospheric sodium atoms (for more details on the physics of laser/sodium interaction , see for instance references [11, 12, 13, 14, 15, 16]. Above all, the laser power requirement depends on a somewhat subjective choice for a design point that provides satisfactory system performance over zenith angles in the 0-45º range. Figure 1 presents the chosen design point in terms of photodetection events per subaperture per frame for simulated MCAO performance[7]. Together with the assumptions listed in Table 1, the required 390 PDE's/subap/frame yields laser power requirements per laser beacon in the 6-15W range for continuous-wave (CW), mode-locked and micro-macro-pulse lasers, whereas lasers with other pulse formats have higher power requirements[10]. All power requirements will be updated shortly to take into account new data relative to typical nightly and yearly variability of mesospheric sodium abundance above Mauna Kea and Cerro Pachón.

However, the laser power requirement range is not expected to change significantly. **That is the reason why Gemini refers to lasers for Altair and MCAO as 10W-class and 50W-class lasers respectively although the maximum power requirement for each type of lasers is actually higher than 10 and 50W.**

Beside total laser power, nearly all performance, functional and operational requirements are identical between the Gemini North and Gemini South laser systems. Major requirements are summarized below.

Performances requirements:

- Beam quality: < 1.2 times diffraction-limited
- Excellent pointing stability
- Laser tuned to the highest peak of the sodium D2 absorption line @ 589.0 nm (e.g. wavelength of the sodium D2 $3^2S_{1/2}$(F=2, M=2) → $3^2P_{3/2}$(F=3, M=3) hyperfine transition)
- Temporal and spectral formats optimized to ensure: (a) maximum photon return from the sodium layer, and (b) minimum background noise due to Rayleigh scattered light along the beam(s). In the case that (b) is identified as an essential driver for laser temporal format requirements, pulse repetition rates in the 650-800 Hz range (depending on exact pulse length possibly in the 200-500 µs range) will be necessary to time-gate the LGS signal.

Functional and operational requirements:

- Ability to tune laser wavelength off sodium transition if laser temporal format does not allow time-gating
- Laser head(s) located on the telescope center section
- All systems designed for typical Gemini telescope environment (temperature, altitude, dust, changing gravity vector, etc.)
- Mechanics, electronics, cooling, software, safety: design follows all appropriate standards, and is fully compatible with existing Gemini infrastructure
- Fully automated Laser System controlled by its own built-in control system which is interfaced with the Altair LGS/MCAO Control System[6]

- Laser System includes all diagnostics necessary to produce and maintain the laser beam(s) at required performance levels
- Easy maintenance and high reliability

2.2 Sodium laser technologies

Several laser technologies are able to produce 589 nm laser beams but they have various levels of scientific and technological maturity. Producing a 589 nm beam is not so much the difficulty as is extracting the power out of the laser system. The task is all the more challenging when high performance is required in terms of beam quality, wavelength purity and beam pointing stability. Until very recently, even the more advanced laser system concepts to date did not offer the high automation standards desirable at an astronomical observatory site, and so far fielded sodium lasers have been closer to laboratory prototypes than fully engineered systems.

Dye lasers
Studied and developed since the beginning of lasers some 35 years ago, dye lasers are by far the most mature option for sodium light generation. They can be either continuous-wave (CW) like the modified commercial ALFA dye laser[17] at Calar Alto observatory, Spain, or pulsed, like the pulsed dye lasers built by Lawrence Livermore National Lab (LLNL) for the Lick[18] and Keck[19] Observatories. However commercial CW dye lasers are limited in output power (up to 6 W with some level of effort), and pulsed dye lasers are rather complex systems that have proven difficult to operate. The dye laser pulse formats are amongst the least efficient formats in exciting sodium atoms so that they require even higher output power levels than other candidate lasers[10]. Moreover dye lasers are messy and present potential safety issues. Note that due to the relatively low output power of the ALFA dye laser, LGS AO observations at Calar Alto (Spain) are said to be "technically extremely difficult and very demanding on atmospheric conditions"[20] so the decision has been made to decommission the laser part of the ALFA AO system. On another hand, much work has been done during the past few years to bring the Lick laser system to its current satisfying level of performance[21]. It is planned that the Keck laser, which has benefited from similar upgrades, will be working at the Mauna Kea summit by the end of this year (2001). But in spite of progress made towards efficient use of sodium dye laser with LGS AO, the Lawrence Livermore National Lab and the Keck Observatory are already considering a solid-state replacement for their lasers in the mid-term future. For all these reasons, Gemini does not consider dye laser technology to be an option for its LGS program.

Solid-State and Fiber Lasers
In comparison with dye lasers, solid-state lasers and fiber lasers are relatively new in the field, but interest in them has been growing rapidly during the past 10 years. Solid-state lasers with bulk materials and fiber lasers certainly offer the most attractive option for short-term and near-term LGS projects. Solid-state lasers can be either flash-lamp- or diode pumped, with ever growing diode lifetimes and decreasing diode laser prices. There are many different ways to create 589 nm beams with solid-state and fiber technologies, and as many corresponding laser formats from CW to Q-switched, mode-locked or macro-micro pulses. Proposed 589 nm laser concepts include one or several of the following non-linear processes: Optical Parametric Oscillation (OPO), sum-frequency generation (SFG), second-harmonic-generation (SHG) and the Raman process. OPO-based lasers look attractive, although some prototyping is needed to ensure that existing OPO temporal formats and achievable beam quality can produce efficient sodium beacon generation (meaning reasonable power requirements). Raman/SHG-based lasers can either produce the 589 nm radiation from bulk materials, fibers, or a resonant cavity filled with gas. Among those possibilities, the Raman fiber scheme looks very promising but still necessitates non-straightforward R&D to prove the concept viable. Getting the power out of a Raman-based laser is an issue for any approach. The SFG-based laser, also called the "sum-frequency laser"[14, 22], is certainly the more advanced concept to date. The 589 nm radiation is created by combining 1.06 μm and 1.32 μm beams in a non-linear crystal. One of the major difficulties consists in building the 1.32 μm laser using a Nd:YAG crystal, which is also the crystal material routinely used to produce the 1.06 μm beam. Several sum-frequency laser prototypes have been built during the past 10 years with different temporal formats, and at least two of them have been implemented at a telescope site by the Starfire Optical Range and the University of Chicago[22]. However sum-frequency lasers still need some engineering to satisfy all automation and reliability requirements for LGS generation. 10-W class sum-frequency lasers are almost there, but the 50-W class still needs to be demonstrated.

Gemini sodium laser research and development (R&D) program
In October 1999, Gemini issued a Request For Proposal (RFP) to procure a 10W-class laser for the Mauna Kea LGS system. The procurement process failed because the proposals received were beyond the current AO budget for Mauna Kea and also included significant technical risks. Although procuring 5 identical lasers for MCAO (actually 6 including the laser for Mauna Kea) could attract proposals for a future RFP, it was thought that Gemini should review its options and strategy if any

10-50W-class lasers were to be implemented at Mauna Kea and Cerro Pachón, both in a reasonable time-scale and for an affordable total price. A second RFP was issued in January 2000 that sought laser Research and Development (R&D) proposals in the field of sodium Laser Guide Star AO. Laser R&D proposals had to propose 9-12 month risk-reduction experiments on key components for producing high power 589 nm beams. Gemini received more than a dozen proposals, spanning across virtually all possible laser technologies. In particular, R&D work on OPO's, fiber lasers and Raman lasers looked promising but was thought to imply longer-range efforts than the three selected proposals, all of which suggested R&D work on sum-frequency laser variants. Gemini therefore initiated two R&D contracts to develop the sum-frequency technique: one with Coherent Technologies Incorporated (CTI)[23], a laser company based in Boulder, Colorado, and a second with the University of Chicago teamed with Lite Cycles[24], another laser company based in Tucson, Arizona. The University of Chicago/Lite Cycles laser R&D work was jointly funded with NSF and the Center for Adaptive Optics (CfAO). We also signed a Cooperative Research and Development Agreement (CRDA) with the Air Force Research Lab for joint funding of on-going laser developments at the Starfire Optical Range at Albuquerque, New Mexico.

The power limitations and other sources of concern of previous sum-frequency laser prototypes are now well understood and problems to be solved are more engineering issues than physics issues. Gemini and its partners chose to diversify the approaches to the sum-frequency laser so that different technologies could be compared. All three lasers under development are diode-pumped, but involve different techniques. CW, macro-micro-pulse and mode-locked temporal formats are being addressed. Side-pumped Nd:YAG zig-zag slabs are being investigated for the production of 1.32 and 1.06 micron lasers as well as end-pumped Nd:YAG rods. At least three non-linear crystals are considered to combine the 1.32 and 1.06 micron beams and produce the 589nm beam. But all efforts focus on improving gain module designs by managing the Nd:YAG crystal thermal load and pumping uniformity.

The intent of the Gemini sodium laser R&D program is three fold: (a) reduce technology risks, (b) foster competition in order to reduce laser unit cost, and (c) pave the way to the successful procurement of a 10W-class laser system for Mauna Kea and a 50W-class laser system for Cerro Pachón. Although not all three programs are complete yet at this time (June 2001), very encouraging results have been obtained towards engineering a 10W-class for Altair, and interesting growth paths have been developed for higher power sum-frequency lasers. Success of the Gemini risk-reduction program will therefore enable to resume the Altair laser procurement shortly. The MCAO laser procurement must begin by mid-2002 to support the current project schedule with commissioning in early 2005, but significant uncertainties still exist in the approach that will be taken. Several possible options are envisioned as this is written (June 2001), all of which will enable commissioning a depopulated MCAO system with a single 10-W laser guide star in early 2005 at the very least. The basic questions that will need to be resolved before adopting a procurement strategy for Gemini South include (i) pulsed vs. CW lasers, (ii) one vs. multiple lasers, (iii) what level of risk is acceptable when beginning the procurement, and (iv) the possibility and role of additional risk-reduction activities. Gemini began addressing points (iii) and (iv) some 9 months ago by submitting a comprehensive proposal for sodium laser R&D to the National Science Foundation (NSF) in collaboration with three other leading institutions in the sodium laser guide star adaptive optics field, namely the Center for Adaptive Optics, Keck Observatory and Air Force Research Lab. The NSF response is not known at this point.

3. BEAM RELAY AND PROJECTION SYSTEMS

3.1 Requirements

The Beam Transfer Optics (BTO) is the LGS subsystem that relays the single (Altair) or five (MCAO) laser beam(s) from the Laser System located on the telescope center section up to the top-end ring, then propagates the beam(s) in the shadow of one of the spider vanes and feed the Laser Launch Telescope (LLT) mounted behind the secondary mirror. The Laser Launch Telescope is basically a beam expander that projects the beam(s) on the sky and focus laser light on the mesospheric sodium layer. The top-level requirements for the BTO and LLT are driven by the necessity not to waste laser photons and to create the smallest LGS spot size(s) on the sky. Major BTO and LLT requirements are presented in Table 2. The following paragraphs explain how we came up with the BTO and LLT detailed wavefront error budget.

LLT location	On-axis, behind the secondary mirror
	Do not obstruct secondary mirror central hole when Altair LGS/MCAO is not used ($\rightarrow$ Periscope)
LGS constellation	1 beam on-axis (both LLT) + 4 beams off-axis at the corner of a 42.5 arcsec center-to-corner X-pattern for Gemini South
Transmission coefficients @ 589 nm	$T_{BTO} > 0.8$ (laser system mounted on the telescope center section)

	$T_{LLT} > 0.9$ (including vignetting)	
LLT focus	Fixed, ~ 105 km	
Transmitted wavefront quality (defined with respect to uniformly illuminated, 450mm diameter aperture)	Low order aberrations BTO < 47 nm RMS LLT < 88 nm RMS (defocus removed)	High order aberrations BTO < 21 nm RMS LLT < 35 nm RMS
1-axis blind positioning accuracy on the sky	< 1 arcsec (peak)	
1-axis pointing accuracy @ 800 Hz on the sky	< 0.05 arcsec RMS	
Optics and coatings	Can sustain power densities in the 500-1000 W/cm^2 range	
Heat dissipation	< 10 W for beam dump on top-end < 10 W for all BTO Optical Bench and LLT elements combined < 10 W for all other BTO elements combined < 0.5 W for periscope assembly	
Additionnal mass on Secondary Support Structure	< 125±25 kg	
Functionalities	All motions remotely controlled by the MCAO Control System	
	Low maintenance (because of difficult access)	
	Preserve laser circular polarization (to optimize LGS photon return from the sodium layer)	
	Minimizes light scattered into science path	

Table 2: BTO and LLT top-level requirements.

Wavefront error budget

The low-order and higher order aberration requirements presented in Table 2 are derived from an overall analysis of LGS wavefront sensor (WFS) measurement accuracy as a function of LGS signal level and spot size on the LGS WFS. The error budget for these aberrations was obtained from the results of a wave propagation simulation[4] including: (i) a diffraction limited gaussian beam magnified to a 300 mm diameter at $1/e^2$ intensity points and projected by a 450mm LLT, (ii) wave front aberrations introduced by optically-aberrated BTO and LLT, (iii) atmospheric turbulence (uplink and downlink), and (iv) LGS WFS lenslet and pixel blurring. Wavefront errors introduced by the three subsystems (LS, BTO and LLT) are split between low order (LO) and high order (HO) aberrations. Low order aberrations are mostly responsible for spot broadening on the LGS WFS while high order aberrations are responsible for Strehl ratio decrease, equivalent to signal level decrease. No assumption was made yet as to the contribution of low order vs. high order aberrations in the assumed 1.2 times diffraction limited laser beam, so we simply considered the aberrated laser beam width to be equal to 1.2 times the non-aberrated beam width on the sky. We first determined the LLT error budget as explained in the following paragraph, then derived the corresponding error budget for the BTO, to ensure that the overall wavefront quality error budget was compatible with the 1.5 times diffraction limited projected beam quality used in all Altair and MCAO performance simulations.

To derive the LLT wavefront error budget, we consider the well-known expression for the noise-equivalent angle σ_θ (e.g. the LGS WFS subaperture tilt measurement error due to noise):

$$(0) \qquad \sigma_\theta = \theta \,/\, SNR$$

and require that σ_θ does not increase by more than 20%. The penalty splits evenly between a 10% increase in θ, the LGS spot size on the LGS WFS subaperture, and a 10% 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 (e.g. the Strehl ratio), and therefore degrade the SNR. Figure 2 shows typical results obtained for a perfect laser beam with either focus, coma, or spherical aberration. Combined results from all low order aberrations command 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.

To derive the image quality requirement for the higher order aberrations, we assume a WFS with σ_e=6 electrons of read-out noise and an operating signal range of N=250-390 PDEs/subaperture/frame. We have:

$$(1) \qquad SNR = N \,/\, \mathrm{sqrt}(N + 4\sigma_e^2)$$

so that:

$$(2) \qquad \Delta N \,/\, N = [2\,(N + 4\sigma_e^2) \,/\, (N + 8\sigma_e^2)]\; \Delta SNR \,/\, SNR$$

Within that signal range, a 10% penalty on the SNR corresponds roughly to a 15% reduction in photo-detection events. Assuming that laser beams do not saturate sodium atoms, this means that the laser power would have to be increased by 15% to compensate the SNR penalty. To first order, high order aberrations produce a 15% decrease in the number of photo-detection events by lowering the Strehl ratio of the LGS spot image by 15%. We can derive the corresponding wave front aberration by using the formula:

$$\text{(3)} \qquad \text{Strehl ratio} = \exp(-\sigma_\Phi^2)$$

where σ_Φ is the high order phase error contribution. On this basis, the LLT must not introduce more than 0.06 wave RMS of high order aberrations @ λ = 589 nm, with a goal of 0.04 wave RMS. Note that for the sake of simplicity, all errors are defined with respect to a uniformly illuminated, 450 mm diameter aperture.

To derive the BTO contribution, we make the additional assumptions that: (a) the beam delivered by the laser system is 1.2 times diffraction limited, (b) low and high order aberration requirements for the LLT are compatible with the values given above, and (c) the overall projected beam quality is close to 1.5 times the diffraction limit. Figure 2 shows that combined BTO and LLT low order contribution increase the spot size diameter on the LGS WFS by a factor of 1.1 for 0.17 wave RMS of defocus, yielding a BTO contribution equal to sqrt(0.17^2-0.15^2) = 0.08 wave RMS. Times diffraction-limit beam quality parameters are multiplicative so that the total LS + BTO + LLT spot size increase is on the order of 1.1 times 1.2 equals 1.32. In other words, we have:

$$\text{(4)} \qquad \theta_{\text{aberrated}} = 1.32\ \theta_{\text{non aberrated}}$$

where $\theta_{\text{non aberrated}}$ is the spot size obtained for unity Strehl ratio. We make the approximation that the 1.5 times diffraction limited projected beam satisfies:

$$\text{(5)} \qquad \sigma_{\theta\ \text{aberrated}} = 1.5\ \sigma_{\theta\ \text{non aberrated}}$$

Equations (0), (4) and (5) yield:

$$\text{(6)} \qquad \text{SNR}_{\text{aberrated}} = (1.32/1.5)\ \text{SNR}_{\text{non aberrated}}$$

Substituting $N = N_0 \exp(-\sigma_\Phi^2)$ in equations (1) and (6) with N_0=250-390 PDEs/subaperture/frame the initial signal range under consideration produces a second order equation in $\exp(-\sigma_\Phi^2)$. Solving the equation finally yields a BTO + LLT high order contribution of 0.07 wave RMS, so that the BTO high order contribution alone equals sqrt(0.07^2-0.06^2) = 0.04 wave RMS.

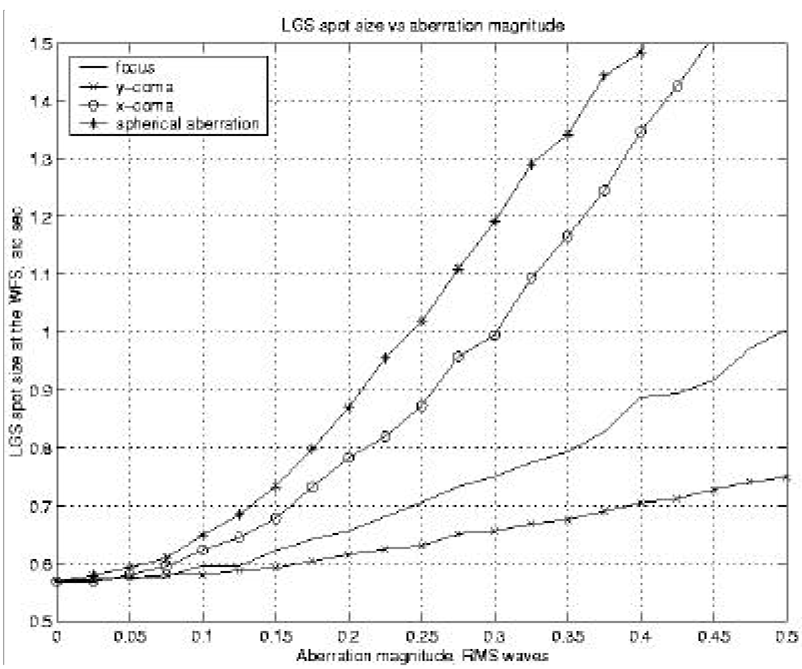

Figure 2: Spot size variation on LGS WFS subaperture vs. amount of focus, coma or spherical aberration introduced in the beam. The simulation assumes a diffraction-limited laser beam to start with, a 0.65 arcsec seeing @ 0.55 µm, 1 arcsec squared pixels and a gaussian pixel blurring distribution with variance of ¼ the pixel size. In this simulation, the spot size is defined as the inverse of the tilt measurement gain of the quadcell across the subaperture. With 0.65 arcsec seeing, this spot size metric typically corresponds to about 60% of the spot FWHM on the LGS WFS. The graph yields $\theta_{\text{non aberrated}}$ = 0.57 arcsec and $\theta_{\text{aberrated}} \cong 1.1 \times \theta_{\text{non aberrated}}$ = 0.63 arcsec for 0.17 wave RMS of defocus, corresponding to a 1.05 arcsec spot at FWHM on the LGS WFS.

3.2 Beam Transfer Optics design

The BTO optical train from the output of the laser source to the entrance pupil of the LLT is conceptually presented in Figure 3. In the following, the text may tend to refer to the 5-beam LGS configuration and corresponding hardware. In general, the 1-beam configuration can be considered to be the same, except that the corner beams of the constellation are deleted, as are the corresponding optics of any mirror array. The BTO can be thought of in two sections: the first section delivers the 5 beams from the laser source to the BTO Optical Bench (BTOOB) above the telescope secondary without letting scattered light contaminate the WFS's; the second section formats the beams into the 5-beam constellation and aligns the beams into the LLT. Separate control systems guide the control surfaces of each BTO section. Starting from the laser source, the key BTO components are:

- Two actively-controlled mirrors/mirror arrays to point and center the beam across the secondary vane (CA and PA)
- A relay telescope to relay the pupil of the laser source to the entrance pupil of the LLT; this relay is located on the side of the main telescope
- Fast steering array/mirror (FSA/M) for active tip/tilt control of each of the LGS's
- An array of static mirrors that reformats the incoming beams into the 5-beam X-shaped constellation seen on the sky
- A diagnostic package that provides feedback for the alignment of the beam over the secondary vane and provides boresighting information between the main telescope and the LLT
- Two actively-controlled mirrors that point and center into the LLT, thus compensating flexure or other common-mode pointing errors (CM and PM)
- An actively-controlled, rotating K-mirror that keeps the orientation of the LGS constellation constant with respect to the WFS.

The BTO Optical Bench (BTOOB) supports all of the BTO components from the FSA/M to the LLT. Its detailed opto-mechanical layout is presented in Figure 4. Additionally, auxiliary cameras aid in the coarse alignment of the BTO. The control systems/active mirrors are described in the following paragraphs, as well as a few other optical and mechanical parts with specific functionalities.

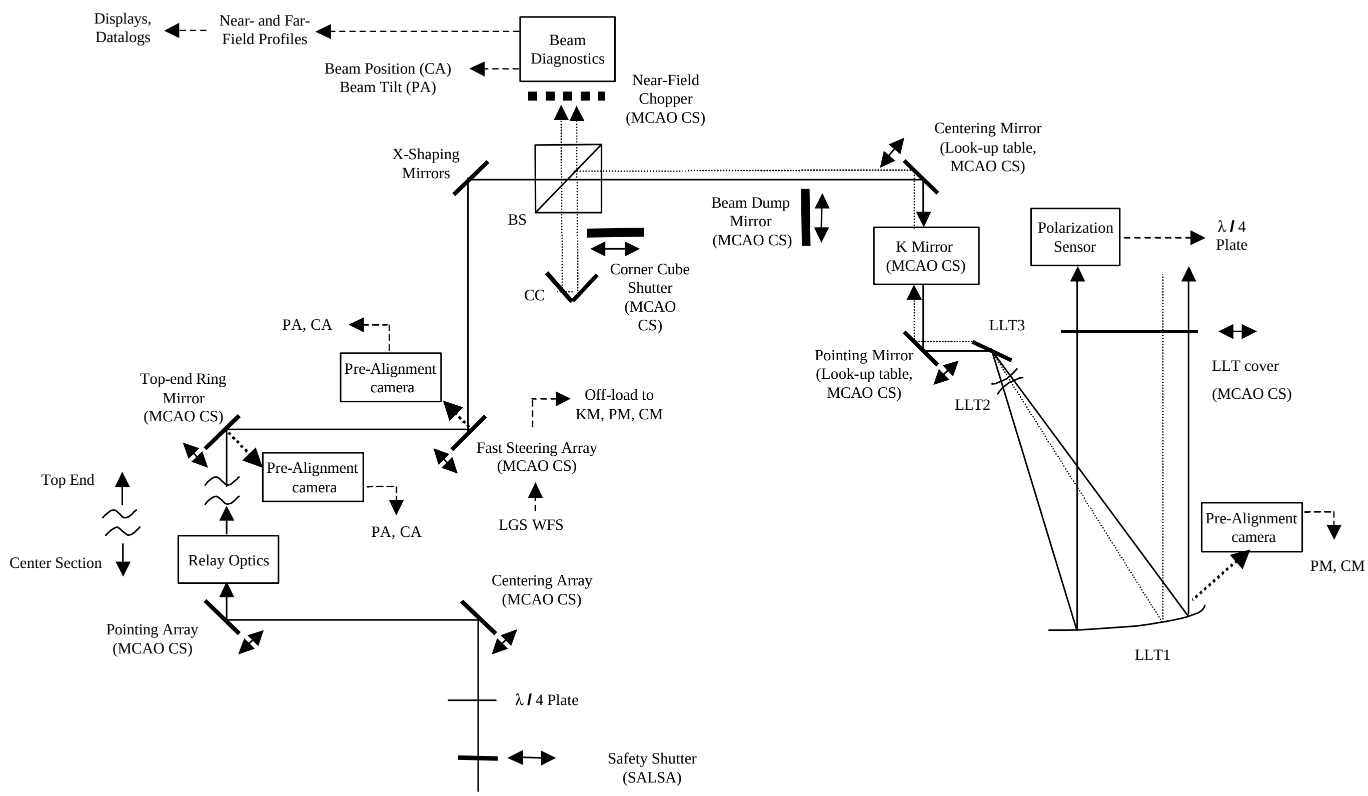

Figure 3: BTO and LLT schematic. The MCAO Control System (MCAO CS) which controls all actuated components in the BTO is described in reference[6].

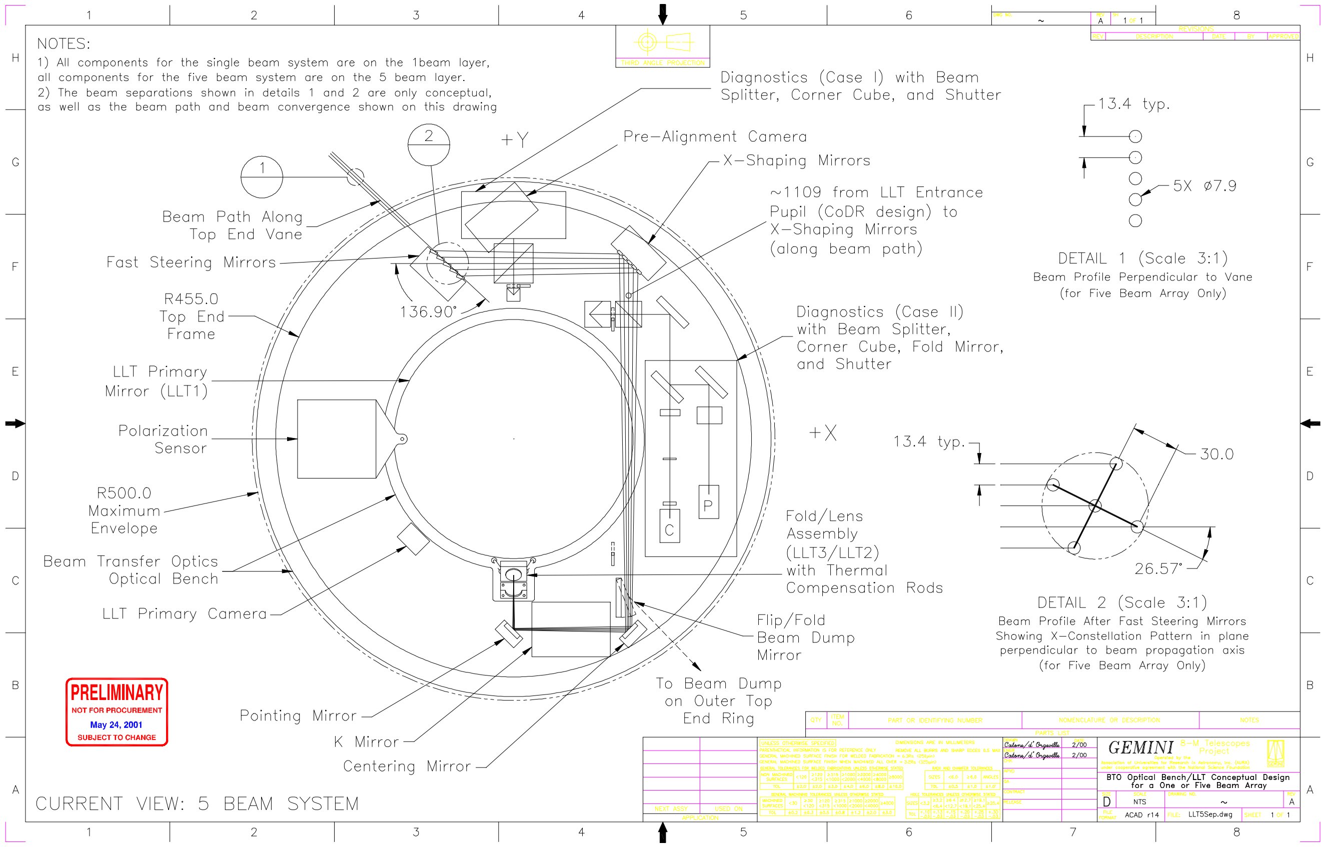

Figure 4: Top view of the BTO Optical Bench located on top of the LLT and Secondary Support Structure top plate. This view presents the 5-beam design for MCAO. The single beam design is generally identical to this one except for: (i) the absence of K-Mirror, (ii) all mirror arrays replaced by single mirrors, and (iii) the presence of a beam splitter in the beam between the pointing mirror PM and the LLT entrance pupil sending light to a camera that will monitor +/- 1 arcmin dithers during telescope dithering supported by Altair.

Active mirror description

Pointing Array (PA) and Centering Array (CA) - Since each of the 5 beams must be aligned over the secondary vane, each beam must have two control mirrors upstream of the vane to point and center the beam correctly. These control mirrors take the form of a 5-mirror PA and a 5-mirror CA. These mirrors are sized large enough so that the beams will not "walk off" mirrors as the telescope flexes.

Fast Steering Array (FSA) - The Fast Steering Array consists of 5 high-bandwidth, 25 mm diameter tip-tilt mirrors (for instance Physik Instrumente model # S-330). The +/-1 mrad surface tilt range provides +/- 3.5 arcsec range on the sky with the 60x LLT. The resonance frequency of the unloaded t/t platform is 3.5kHz. The resonance frequency is reduced by the addition of mass on the platform, but does not degrade performance as long as the resonance frequency is sufficiently far from the frequency of correction (800 Hz). A 25 mm diameter, 6 mm thick mirror has a moment of inertia 550 g mm^2 with respect to the tip/tilt mirror pivot point (cf. 650 g mm^2 for the platform itself). This reduces the resonance frequency to 2.6kHz, still well above the frequencies of interest.

Pointing Mirror (PM) and Centering Mirror (CM) - The PM and CM are located just before the entrance pupil of the LLT, and so steer the 5 beams bodily into the LLT and onto the sky. The PM and CM are steered in a coordinated manner to compensate for telescope flexure and other common-mode pointing errors of the LGSs. The flexure correction is derived from a lookup table, with residual errors corrected in closed-loop using LGS WFS measurements (via an offload from the FSA). In addition, the PM and CM can be steered in a coordinated, open-loop manner to adjust the centering of the beams into the LLT; the input for this is taken from a lookup table generated using the pre-alignment camera mounted just at the top edge of the LLT (looking down at the LLT primary).

K-mirror - The K-mirror is a 3-mirror configuration that rotates about an axis parallel to the incoming beam; this rotates the constellation. The K-mirror is controlled via a look-up table that is keyed to the orientation of the main telescope.

Diagnostic sensors and alignment cameras

The purpose of the BTO diagnostics package is two-fold. First, the diagnostics provide feedback for the MCAO control system to steer the 5 beams behind the –X,+Y secondary vane, via the CA and PA control mirrors. Second, the BTO diagnostics package assures that the 5 beams are properly co-registered at the LLT pupil and pointed correctly with respect to each other before delivery to the LLT. These two goals are consistent with each other, and in fact, the second requirement is subsumed within the requirement of the first, given appropriate boresighting and calibration of the BTO diagnostics.

Scattered light analysis indicates that the 5 beams propagating over the 10 mm secondary vane should be aligned within 0.5 mm of the center of the vane at either end to avoid excess scattered light into the WFSs. The 0.5 mm centering requirement represents 10% of the $1/e^2$ diameter of the beam; this is the same as the alignment requirement into the LLT. The pointing requirement at the vane is on the order of 0.5 mm/4.8 m = 0.1 mrad, whereas the requirement for the LLT is looser—the beam must remain within the FOV of the WFS (2 arc seconds on the sky, which is 2 arc minutes, or 0.6 mrad on the BTO; finer control is provided by the closed-loop FSA/M at the direction of the WFS), and within the correction range of the fast tip/tilt mirrors (approx 1 mrad). Thus, the pointing and centering requirements to keep the beams behind the vane are more stringent than those for alignment into the LLT. We consider only the vane requirements in the diagnostics design.

The BTO diagnostics package sits on the BTOOB, "downstream" of the secondary vane and FSA, and before the final pointing and centering mirrors PM and CM into the LLT. The diagnostics therefore indicate the far-field pattern on the sky and the co-registration of the beams into the LLT. A small sample of light is sent to the diagnostics package via a dichroic beamsplitter cube. In addition, the diagnostics package may view a star through the LLT via the beamsplitter cube and a retroreflector; remotely actuated shutters allow the selection of one path or the other or both. The purpose of looking at the sky is to aid boresighting the LLT and main telescope. Note that it may be possible to use a plate beamsplitter rather than a beamsplitter cube. An antireflective "V-coat" centered near 589 nm (easily applied to a plate; harder with beamsplitter cubes) will yield a small "leak" to the diagnostics package and non-negligible reflection in the rest of the visible. This will allow some throughput from the sky to the diagnostics. If a plate is used, it should be wedged to "kick out" ghosts. A subsequent wedge oppositely oriented to the first can re-steer the beam back along its original path.

The diagnostics consist of a "centering" camera and a "pointing" camera. A small telescope images the FSA plane onto the centering camera (a small CCD); a lens images the far-field of the beam(s) onto the pointing camera. The "aligned" positions of these cameras are set so that the beam is centered over the secondary vane. A 7-position rotating chopper wheel isolates each of the 5 beams for the two cameras; there is also a "dark" position, and an open, "all-beams" position. In addition to the diagnostics package that is used closed-loop, there are a few auxiliary cameras that are used as alignment aids and system "health" monitors. Mounted cameras looking at the top-end ring mirror (TRM) and the FSA aid in coarse alignment; these cameras allow the system to be aligned to the point where the control loops can take over. These cameras are turned off after alignment is complete. There is also a camera perched near the edge of the LLT looking down at the LLT primary. The scattered light off this surface allows direct evaluation of the centering of the beam(s) on the LLT.

Relay telescope

The relay telescope relays the 5 LGS beams from a plane near the laser source to the Fast Steering Array (FSA). When the beams emerge from their source packages, they are nominally collimated with a $1/e^2$ diameter of 5 mm. Without any optics, the beams would diverge to about a 6 mm $1/e^2$ diameter. While this is not an enormous increase, the difference does basically consume the budget for aligning over the secondary vane (+/-0.5mm). Just as importantly, the long throw between the control mirrors near the bottom of the telescope and the FSA "target" at the top end means that the resolution of the control mirror tilts would have to be very fine (< 0.5 mm/20 m/2=12 μrad; this would imply < 0.5μm motions of the actuator, given a 50 mm lever arm). This is not a trivial requirement. Further, since the CA and PA would both be approximately 20 m away (perhaps 20m and 21m), the cross-coupling between the two control mirrors would be very strong. Use of a relay telescope can ease these concerns by relaying a convenient surface, such as the centering array, to the fast tip/tilt mirror; the pointing array would be a short distance (perhaps 1m) away. Thus, the throw distances are much smaller (and much less strongly cross-coupled)—the PA operates solely as a pointing mirror, and the CA is mostly a centering mirror. In addition, the actuator movements are much larger and easier to control.

While the necessity of the relay telescope is not cut-and-dried, it appears to be desirable. A preliminary design of an afocal relay telescope consists in a "4f" design. The telescope would be mounted on the side of the telescope and provide a 1:1 pupil relay from the PA to the FSA. Since the mounting location of the laser systems is not known, this design is not final. The PA-FSA distance was assumed to be 20 m; thus it uses 5 m focal length optics. An assumption that the vertical interbeam spacing at the FSA was 27 mm (slightly more than the 25 mm diameter of the fast tip/tilt stages) resulted in lens diameters that are not particularly small: 125-150 mm diameter lenses would be appropriate. However, mounting moderate-sized lenses such as these is not difficult.

Error budgets

Detailed error budgets were developed and back-of-the-envelope calculations were made to confirm that the BTO preliminary design meets all the top-level requirements presented in section 3.1. The BTO alignment error budget, which also encompasses flexure and windshake, enables the use of standard commercial slow and fast tip/tilt platforms. The BTO transmission error budget assumes the use of high reflectivity narrowband dielectric coatings and high surface quality optics that are compatible with demonstrated performance. Analysis of scattering by dust particles on optics is more an issue and suggests that optics will have to be cleaned on a regular basis, perhaps as often as once a day, unless optics are protected by tubes and/or covers. The need for tubing is reinforced by the necessity to keep insects out of the dome, especially at the Gemini South site low altitude (Cerro Pachón is only 2700m high compared to the 4200m of Mauna Kea), and by the desire to keep light scattering as low as possible in the dome. Finally, the use of high quality optics in the $\lambda/20$ surface quality range is compatible with the wavefront error budget presented in section 3.1. It is our intention to refine this error budget by using more detailed simulations including typical wavefront aberration aberrations found in 1.2 times diffraction-limited laser beams. The budget will also be updated whenever measured wavefront error values for the LLT and BTO components become available. Note that thermal effects (such as temperature-induced stresses) were appropriately left for the detailed design phase, since the thermal analysis will make sense only in the context of a detailed and final design.

3.3 Laser Launch Telescope design

The laser beam(s) must be launched on-axis to minimize the perspective elongation of the LGS images. The LLT optical design is therefore constrained by two considerations: (1) the LLT structure must be hidden from the Gemini telescope field of view and fit inside the telescope secondary frame, and (2) the LLT clear aperture must be as large as possible (on the order of 50 cm) in order to create the smallest LGS spot size on the sky when seeing is good. Additionally, if the laser beam(s) is (are) to be hidden behind one of the secondary vanes, then the beam(s) must be fed into the LLT from the top of the structure, with a maximum beam full diameter (99 % encircled energy criteria) smaller than 10 mm. An analysis[25] of the optimized gaussian beam diameter to be launched to the sky for bad seeing conditions shows an optimum close to a 300 mm diameter at $1/e^2$ intensity points, which corresponds to a 99% encircled energy diameter of 471 mm. Ideally, the LLT pupil should not clip the gaussian beam, both to transmit the full laser power and to avoid large diffraction ripples in the beam far field. We choose the largest reasonable input beam diameter at $1/e^2$ intensity points to be 5.0 mm, corresponding to a 99% encircled energy diameter of 7.9 mm, so that the laser power density is as low as possible on the BTO and LLT optics. The corresponding LLT magnification is 300/5 = 60.

The maximum total laser power is expected to be around 50 W, and the laser peak power will be even higher if the laser system is pulsed. A quick calculation using available pulsed laser characteristics shows that the design should avoid bringing the beams to sharp focus if we want to avoid producing high power densities locally that could challenge beam quality. The baseline design uses a fold mirror/diverging lens assembly to send an expanding beam down onto an off-axis parabola that finally reflects the beams towards the sky. The beams are arranged in an X-shaped constellation with one on-axis beam and four off-axis beams separated by 42.5 arcsec from the on-axis beam on the sky. The FoV is +/- 1.2 arc minute on the sky to allow for the beam pointing corrections that will be introduced by the BTO to compensate for the Gemini telescope top-end flexures. The LLT boresight with the Gemini telescope will be adjusted 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. Residual errors may be corrected by the pointing and centering mirrors of BTO Optical Bench but the correction must not be so large that the four off-axis beams separated by 42.5 arcsec from the central beam in the MCAO configuration are aligned outside of the ± 1.2 arc minute LLT field of view.

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 range to the sodium layer varies as $1/\cos(\theta)$ where θ is the zenith angle. However, if the LLT focus is fixed at a distance of about 105km, defocus errors remain smaller than 0.02 wave RMS over the whole 0-45º range. For the sake of simplicity, the LLT focus will be fixed at about 105km, and passive compensation will be used to maintain focus over large temperature variations at the telescope site.

The LLT design concept is a true afocal telescope with a 60:1 magnification ratio that projects a 450mm collimated output beam to the sky. The real input beams will be gaussian beams with a diameter of 5 mm at the $1/e^2$ intensity points corresponding to a projected 300 mm diameter at the $1/e^2$ intensity points. The telescope consists of an off-axis parabolic primary mirror and an aspheric negative eyepiece lens, supplemented with a field-correcting convex toroidal mirror. Because of high laser power density at the small eyepiece lens in the 500-1000 W/cm^2 range, attention must be given to resistance of the glass itself, and to adhesion of the antireflection coatings. The candidate design is made from fused silica, but since the lens is monochromatic, it makes no optical difference what material is chosen. To further enhance durability, we chose to use a single aspheric lens, rather than two spherical elements in a traditional doublet. The combination of a simple eyepiece with an off-axis paraboloid produces a telescope seriously afflicted with linear astigmatism in the principal meridian of the OAP. We find that this can be corrected with a tipped convex toroidal folding mirror preceding the eyepiece lens. If the mirror/lens order is reversed, correction is not achieved.

Provided that optical alignment is maintained within the tolerances presented in Table 3, performance of this initial design is well above the diffraction limit. There are three sets of alignment tolerances corresponding to (1) the LLT internal optical alignment, (2) the LLT optical alignment with respect to the BTO, and (3) the LLT alignment with respect to the Gemini telescope. The first set is comparatively tighter than the second and third ones. The reason is that it is, for instance, possible to compensate for a relatively small LLT boresight error by moving the pointing and centering mirrors PM and CM to adjust the LGS positioning on the sky. On the opposite, it is not possible to use any BTO elements to compensate for a focus error of the LLT.

Alignment parameter		**Tolerance range description**	**Static correction**	**Dynamic correction**
Within LLT	Focus	On-axis distance between LLT secondary assembly and LLT M1 must be stable by +/- 5 μm	Passive stabilization scheme to correct for thermal expansion	Optional if static correction not good enough
	Primary-to-secondary tilt and decenter	Depends on LLT final design	Accurate pre-alignment in the lab and fixed optical mounts locations	Correct small misalignment with BTO PM and CM
BTO to LLT optical axis	Decenter	Tolerance ~ 0.5 mm (TBR)	Use alignment pins → Mounting error < 5 μm	Adjust line of sights with BTO pointing and centering loops
	Tilt	Tolerance ~ 20-30 arcsec	Use shims → Mounting error < 10 arcsec	
LLT to Gemini telescope optical axis	Decenter	Tolerance ~ 0.5mm	Use alignment pins → Mounting error < 10 μm	Adjust line of sight with BTO pointing and centering loops
	Top-end sag	Max top-end sag < 2mm	None	
	Tilt	Tolerance ~ 10 arcsec	Use shims → Mounting error < 10 arcsec	Adjust line-of-sight with BTO PM and CM and use LLT slightly off-axis
		Max top-end tilt < 30 arcsec	None	

Table 3: LLT opto-mechanical alignment tolerances

LLT assembly with BTO Optical Bench and Secondary Support Structure

The LLT module will be aligned in the lab in autocollimation, with removable apertures and targets, an alignment telescope, and an interferometer. The BTO Optical Bench (BTOOB) will also be integrated with the LLT in the lab, and mounted to the top of the LLT via three raised pads. These pads constitute an interrupted surface and will be perpendicular to the Secondary Support Structure (SSS) central axis and parallel to the LLT/SSS interface. In order to simplify the removal and replacement of the BTOOB on the LLT, locating pin/liner sets will be installed on two of the LLT/BTOOB interface pads to provide extremely good alignment repeatability. Once the BTOOB ad LLT have been aligned in the lab, they will be disassembled and the LLT mounted alone 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 SSS top plate being neither precisely flat nor perpendicular to the Gemini telescope optical axis, a static alignment scheme is required to ensure that the LGS fall within the LGS WFS FoV. There must be sufficient clearance between the LLT structure and the SSS to allow for angular pre-alignment. To this effect, shims with 5.0 mm nominal thickness will be used at the LLT /SSS top plate interface. Once the LLT is crudely aligned with the Gemini telescope optical axis, the BTOOB will be placed back on top of it, and the telescope pointed to a bright star. Using the BTO diagnostics sensors as explained in section 3.2, shims will be adjusted and the BTOOB/LLT assembly precisely boresighted to the telescope. One last time, the BTOOB will be removed for the LLT to be pinned down, then reinstalled. Later on, there should be no need for additional adjustment each time either the BTOOB or LLT or both are subsequently removed for service and reinstalled.

3.4 Periscope

Each science instrument package “looks at” the secondary mirror of the telescope, and in some cases re-images the secondary mirror, which is the aperture stop of the Gemini telescope. If the secondary mirror were not perforated, the instrument would “see” its own reflection, an effect known as “narcissus.” The secondary mirror therefore has a 168mm diameter central hole, which if unobstructed would let the instruments look directly into space, producing a background similar to that of an entirely unobstructed telescope, but with marginally greater transmission and without focused light. The Laser Launch Telescope will be located directly above the secondary mirror and will therefore block the secondary mirror hole. To restore a view of space, two mirrors will be used to deflect light around the LLT and again allow the instrument package to see the sky. Those two mirrors form the so-called “periscope.” The periscope will be mounted at the bottom of the Secondary Support Structure (SSS), below the LLT.

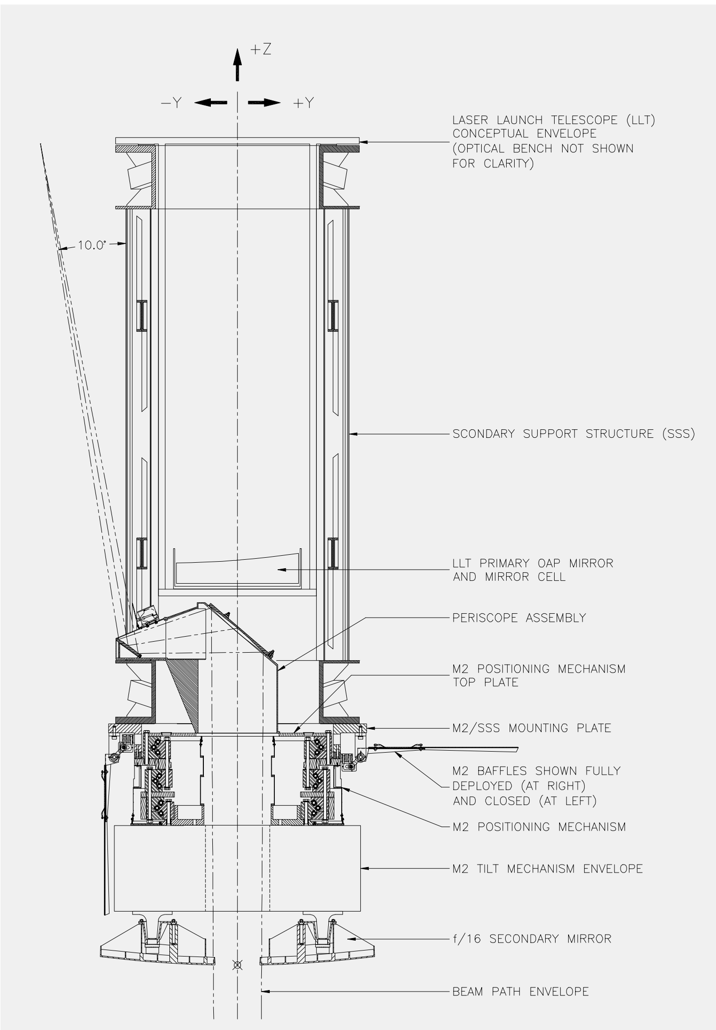

Figure 5: Periscope opto-mechanical design and location within Secondary Support Structure

Design

Owing to the limited apertures through the side of the SSS, simple flat mirrors do not work, and we have designed a quasi-Schwarzschild periscope to restrain the beam size within the secondary support structure, and to minimize its profile as it runs along the outside of that structure. Note that the periscope must NOT focus stars on the instrument focal plane, otherwise out of field objects could be confused with true telescope targets. Similarly, it is important that the periscope's field of regard be as small as possible, so that the keep-out region around the moon is minimized. The resulting design consists of two “off axis” aspheric metal mirrors, made as thin as possible to reduce weight and take up minimum volume. The periscope will be attached to one part of the Secondary Support Structure, while the Secondary mirror itself is attached to another part that both tips and decenters during fast guiding. Consequently, we have designed oversized Periscope optics to ensure the focal plane sees nothing but mirrors through the hole in the secondary mirror, regardless of secondary mirror position.

Packaging constraints dictate the size and shape of the beam path, from the instrument focal plane up to the end of the secondary support structure (SSS). The beams over the whole field of view are contained within a straight circular cylinder that extends from the front of the SSS down to the periscope convex mirror, PM2, which has the least possible inclination to the side of the SSS. This is not a collimated beam in space, however, and it diverges to form a cone of 3.7 degrees diameter, which is approximately half as large an angle as would occur if the optics were designed for collimated light in star space. If the parent system is made perfectly, the field of regard will be 3.7 degrees in diameter. The image of a star is defocused severely, to a focal plane irradiance less than if the instrument were simply peering through a hole in the secondary mirror directly at the star itself. Extended objects, like moon and clouds, affect the focal plane as though an f/98 camera lens were imaging an object within the 3.7 degree field onto the focal plane. If the optics were perfectly made, the exclusion angle would still be 3.7 degrees in diameter. The cost to produce substantially perfect optics is prohibitive, and for the purposes intended, unnecessary. We experimented with parameter tolerances, and found that if the allowable exclusion angle is increased to 4.5 degrees, component fabrication and assembly tolerances corresponding to many hundreds of wavelength of light are permissible. While optical methods may still be used to facilitate testing, ordinary mechanical tolerances are in fact sufficient. Pin registration of a precisely made module will ensure that the optics can be returned to the telescope after servicing, without need to align the optics ON the telescope. An alignment scheme to adjust the optics within the module will likely involve the use of an alignment telescope and both internal and external targets. Owing to the lax tolerances, measured in many minutes of arc, the periscope is not a precision mechanism and is virtually invulnerable to malfunction.

Mirror fabrication

An aluminum substrate will be preferred over a glass substrate due to the limited access to the periscope primary mirror, simplicity in mounting, and mass constraints. The accuracy for fabrication of the periscope mirrors resembles that found in the making of steel dies for automobile body parts. Therefore, numerically controlled machinery is suitable to the pre-polishing stage of mirror fabrication. Loose tolerances permit unusually thin metal sections on the mirrors. The final surfaces will be polished with appropriate, possibly but not necessarily, optical machinery. The aluminum substrates will be electroless nickel plated, stress-relieved, and measured to confirm satisfaction of component specifications.

4. CONCLUSION

The top-level requirements associated with the Laser Systems, Beam Transfer Optics, Laser Launch Telescopes and Periscopes for the Gemini North and South Laser Guide Star Systems have been refined since they were last presented in our 1999 and 2000 papers[9, 10]. The BTO, LLT and Periscope designs presented in this paper are at Preliminary Design level, and reflect the designs presented at the MCAO Preliminary Design Review that was held on May 24-25, 2001 at the Gemini Hilo Base Facility. Gemini will gain experience with a single beam LGS system for Altair at Gemini North for about two years before a similar (5-beam compatible but depopulated) LGS system is also implemented at Gemini South. We expect to upgrade this system to 5 beams for MCAO about a year later. In parallel to these beam relay and projection systems design activities, Gemini has been pursuing an active research and development program on sodium lasers to develop affordable, fully engineered, efficient and reliable, 10W-class lasers on time for the Altair LGS upgrade in late 2003. The risk-reduction activities showed enough progress with the sum-frequency technology that we now feel confident to proceed with the Altair laser procurement in about a couple of months. Early 2006, the LGS system for MCAO is planned to show full capability with five laser beacons and a required total laser power about five times that of the Altair laser. Provided funding is available, Gemini plans to renew the risk-reduction program to develop higher power lasers for MCAO and, if most reasonable, finally procure a single 50W-class laser instead of five 10W-class lasers or any other combination of 10, 20 and 30W lasers.

5. ACKNOWLEDGMENTS

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