The Laser Guide Star Facility for the Thirty Meter Telescope

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The Laser Guide Star Facility for the Thirty Meter Telescope

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ABSTRACT

The Thirty Meter Telescope (TMT) will utilize adaptive optics to achieve near diffraction-limited images in the near-infrared using both natural and laser guide stars. The Laser Guide Star Facility (LGSF) will project up to eight Na laser beacons to generate guide stars in the Earth's Na layer at 90 – 110 km altitude. The LGSF will generate at least four distinct laser guide star patterns (asterisms) of different geometry and angular diameter to meet the requirements of the specific adaptive optics modules for the TMT instruments. We describe the baseline concept for this facility, which draws on the heritage from the systems being installed at the Gemini telescopes. Major subsystems include the laser itself and its enclosure, the optics for transferring the laser beams up the telescope structure and the asterism generator and launch telescope, both mounted behind the TMT secondary mirror. We also discuss operational issues, particularly the required safety interlocks, and potential future upgrades to higher laser powers and precompensation of the projected laser beacons using an uplink adaptive optics system.

Keywords: adaptive optics, laser guide star, TMT

1. INTRODUCTION

The TMT will be a 30 m class telescope equipped with instrumentation for both imaging and spectroscopy over the entire 0.3 – 28 µm wavelength region accessible from a ground-based facility. Maximizing the scientific capability will require the TMT to achieve as close to diffraction-limited performance as possible through the use of adaptive optics (AO) systems specifically optimized for the instrumental capabilities. In the infrared, where one is generally limited by sky and telescope background and AO is most effective, the sensitivity is enhanced by both the increase in telescope aperture D and the consequent reduction in the background through a diffraction-limited focal plane aperture, and can approach a D^4 scaling law. Laser Guide Star (LGS) systems have been demonstrated to work effectively with AO and are being instituted at several major observatories[1-4]. Achieving the ambitious scientific goals of TMT requires that the LGSF and AO systems operate reliably and effectively as part of an integrated observatory system.

Eight first- and second-generation instrumental capabilities were defined for the first decade of TMT operation, including a wide-field optical spectrograph, mid- and high-resolution infrared spectrographs, and a multiple-IFU spectrograph. Up to seven of these instruments will work with AO systems which provide either partial AO correction at visible wavelengths or diffraction-limited images at wavelengths beyond 1 µm. Because the AO requirements of some of these instruments overlap, it was possible to define four separate AO systems, some of which will serve multiple instruments. Each of these AO systems has specific requirements for the number and geometry of the LGS beacons.

The strategy of the effort presented here is to design a concept for the TMT LGSF which meets the AO LGS requirements and includes the necessary interfaces to the observatory and telescope control, computer, and safety systems. Whenever possible, the design utilizes heritage from other LGS systems which are in operation or under construction and relies on currently available technology. The design is sufficiently modular so that changes in the AO LGS requirements, anticipated AO upgrades, and technology advances, particularly in the field of laser development, can be incorporated at the scheduled start of the preliminary design phase.

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2. TOP-LEVEL REQUIREMENTS

The top-level requirements are summarized below. The four AO systems NFIRAOS (Narrow-field Infrared AO System), MOAO (Multi-object AO), MIRAO (Mid-infrared AO), and GLAO (Ground-level AO) have specific power and geometry requirements for the LGS asterisms[5]. Since TMT is likely to be used in queue observing mode, where instruments (and AO systems) can be changed during the night in response to science program requirements or observing conditions, the LGSF must be capable of rapid switching from one asterism to another. Also, guidestar elongation becomes a serious issue for a 30-meter class telescope[6], and separate laser power requirements must be specified for either continuous wave (CW) laser systems, or pulsed laser systems used with "dynamically refocused" wavefront sensors that track microsecond-length laser pulses through the sodium layer[7].

Parameter	Requirement
Asterisms	Four separate LGS asterisms as follows: NFIRAOS: 1 on-axis and 5 equally spaced at 35 arcsec radius MOAO: 3 equally spaced at 70 arcsec radius and 5 equally spaced at 150 arcsec radius MIRAO: 3 equally spaced at 70 arcsec radius GLAO: 4 equally spaced at 510 arcsec radius
LGS Power	26W per beacon, first light system with CW lasers; 17W minimum 9.2W per beacon, first light system with pulsed lasers and dynamic refocusing
Total Laser Power	150W, first light system with CW lasers (may be more than one laser)
LGS Image Quality	Far-field $1/e^2$ diameter 0.6 arcsec
LGS Tip/tilt Jitter	50 mas
Polarization	98 % circularly polarized (TBR)
Projected Beam Profile	Gaussian with $1/e^2$ diameter of 300 mm
LLT Diameter	500 mm
Transmittance	0.75 from the laser system to the laser launch telescope
Operation	Downtime < 5%. Operability may be met using reduced number of lasers as long as a minimum power of 17W per beacon is maintained Switch from one AO asterism to another in 2 min
Safety	Must meet safety requirements for Class 4 lasers with respect to damage to personnel or observatory, illumination of aircraft or satellites, and interference with neighboring telescope operation
Calibration	Must include calibration and diagnostic systems
Observatory	Must support hardware and software interfaces to observatory
General	Must meet TMT requirements for mass, volume, power consumption, heat dissipation, and ease of servicing
Power Upgrade	Include plan for eventual upgrade in laser power by factor of 4 to 5, and allow for higher laser power in materials/coating specifications: 140W per beacon, upgraded system with CW lasers 50W per beacon, upgraded system with pulsed lasers and dynamic refocusing
ULAO Upgrade	Include plan for eventual incorporation of uplink AO (ULAO) and reserve sufficient space in optomechanical layout for this upgrade

The two upgrades listed at the end of the requirements table are not intended as first-light requirements, but the LGSF must be designed to accommodate them when and if they are eventually implemented. The power upgrade accommodates a planned upgrade of the NFIRAOS to utilize 0.25 m WFS subapertures in place of the 0.5 m subapertures in the first-light system. The ULAO upgrade effectively incorporates low-order AO into the LGSF to compensate for the impact of atmospheric turbulence on the projected laser beacons; this is unlikely to be considered seriously as an upgrade option until the costs and technical limits of pulsed lasers and dynamic refocusing are better understood.

3. DESIGN OVERVIEW

The basic concept for the opto-mechanical layout of the TMT LGSF is based upon the LGS systems employed on the Gemini North (Altair) and Gemini South (MCAO) telescopes. The two Gemini systems are virtually identical, except that Altair projects a single LGS beacon, whereas MCAO projects a fixed 5-beacon asterism. Like the Gemini systems, the TMT LGSF consists of three primary subsystems. The Laser System includes the sodium lasers and the enclosure housing them, mounted on the telescope structure. The Beam Transport Optics/Laser Launch Telescope System (BTO/LLT) transports the laser beams up the telescope truss to a position behind the secondary mirror where the BTO Optical Bench (BTOOB) and LLT are located. The BTOOB consists of the optics which generate the asterisms, feed the beams to the LLT, maintain the asterism orientation on the sky, and evaluate the beam quality and pointing. The LLT itself is located behind the secondary on the optical axis of the telescope. Finally, the Laser Safety System is responsible for preventing any risk to the observatory or personnel, avoiding illumination of aircraft or satellites, and avoiding beam interference with any neighboring telescopes. Figure 1 illustrates these subsystems on the TMT and the beam path up the telescope structure.

Although the functional layout of the TMT LGSF is similar to the Gemini systems, the TMT LGSF must project four different AO asterisms with the ability to switch quickly from one to another, and output a total laser power of 150W. The design must also incorporate the goal of 95% operability once the TMT is established in a mode where AO correction is required for most of the observing programs, and consider the likelihood that the sodium laser itself is likely to be the critical factor in determining whether the LGSF is operable. We utilized the following guidelines in the development of the current LGSF concept:

- The use of separate subsystems to address the asterism generation and operating efficiency issues.
- The use of more than one sodium laser to permit continued operation, at least in some AO modes, should one laser be nonfunctional.
- The baseline design should utilize a sodium laser which exists.

The baseline LGSF uses three 50W, CW sodium lasers to achieve a total power of 150W and address the operating flexibility issue in a fairly straightforward manner. A 50W CW laser has been demonstrated by the USAF Research Laboratory at the Starfire Optical Range, and a somewhat similar system is now under development by Lockheed Martin Coherent Technologies (LMCT) for delivery to Gemini in early 2007. The 150W total power requirement is driven by the goal of operating the six-beacon NFIRAOS asterism at 25W per beacon. However, the minimum power requirement per beacon (17W) can be achieved with a total power of 100W, so it is possible to maintain NFIRAOS operation with one of the three lasers inoperable. Likewise, the MIRAO three-beacon asterism can be generated with any single laser, and the four-beacon GLAO asterism with any two lasers. There are thus a total of 11 configurations (four for NFIRAOS, three each for MIRAO and GLAO, one for MOAO) supported by the LGSF.

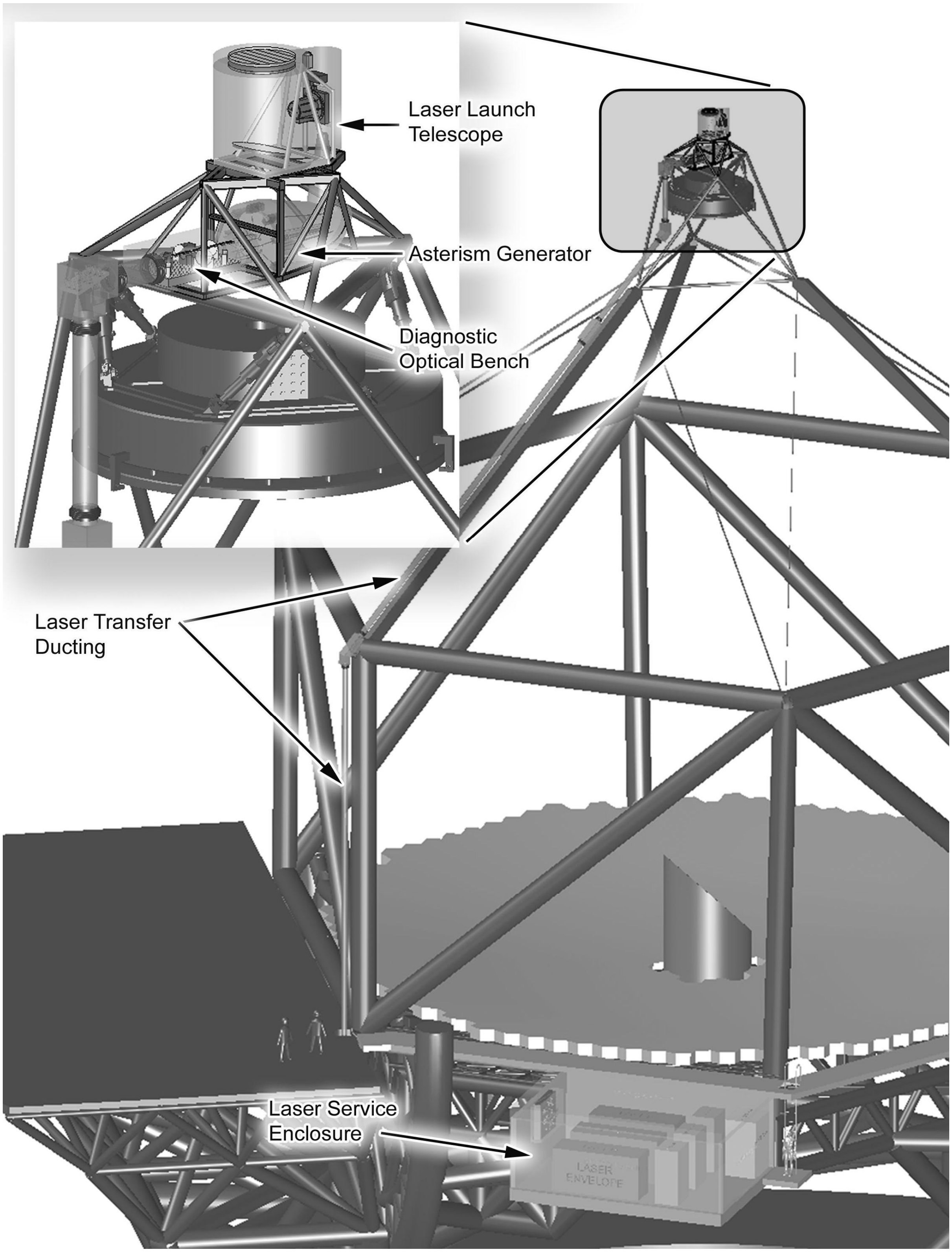

Figure 1: Schematic layout of the major LGSF subsystems on the TMT

Figure 2 is a functional block diagram of the LGSF. The novel aspects of this layout are the two subsystems which effectively separate the asterism generation and operation contingency functions. The Laser Switchyard accepts the input beams from the operating laser systems and, utilizing controllable beamsplitters and mirrors, delivers the proper number of beams at the desired power level. The Asterism Generator accepts these beams and directs them, at the proper location and convergence angle, to the input pupil of the LLT for projection on the sky. For this reason, it must be located on the BTOOB, near the LLT. The Laser Switchyard has no such requirement and, for reasons of size, weight, and maintenance, is located within the Laser Enclosure.

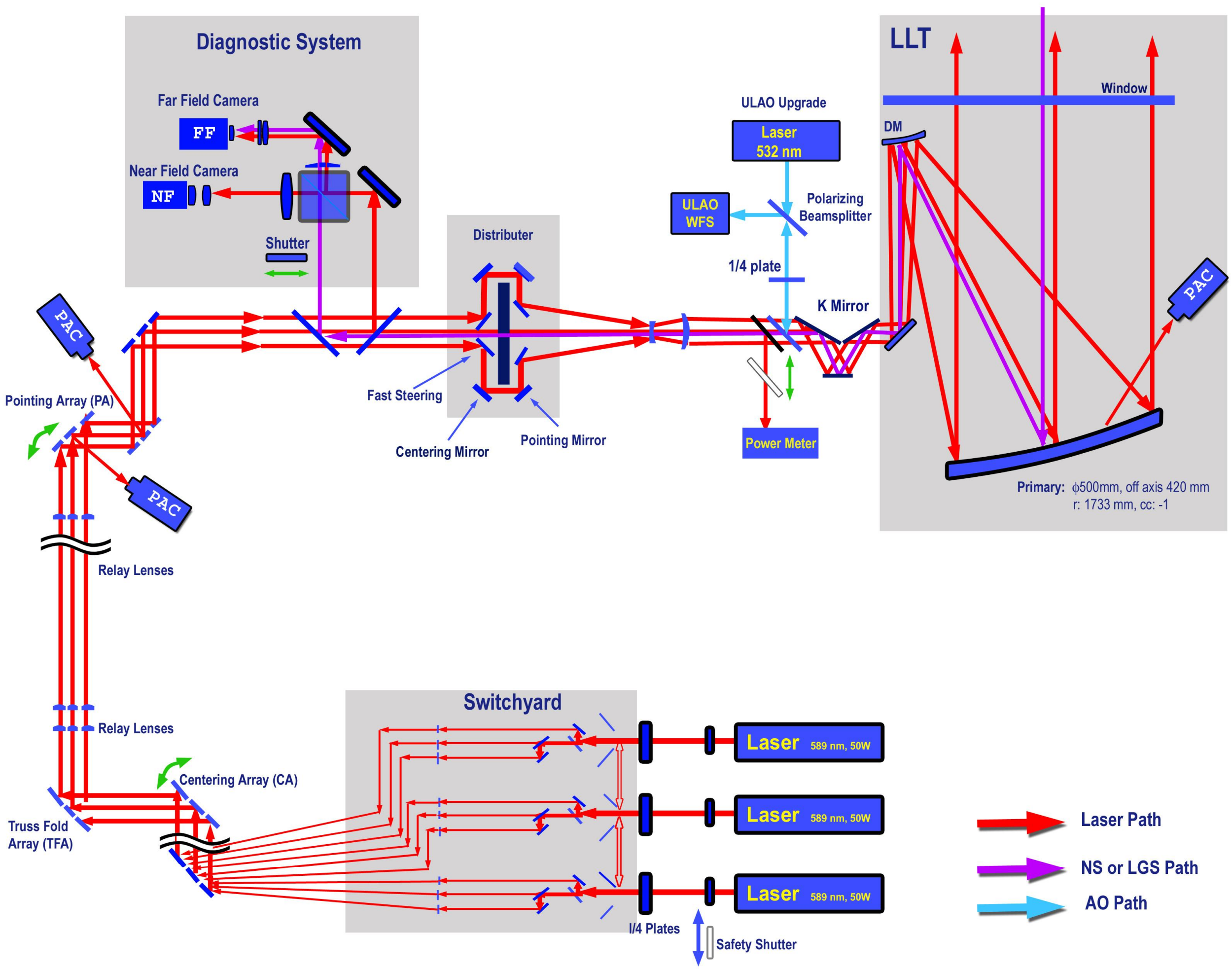

Figure 2: Functional block diagram of the LGSF, showing the major subsystems. For clarity only three of the nine beams are shown after the output of the Laser Switchyard. The Diagnostics, Asterism Generator and LLT are all installed at the TMT top end, behind the secondary mirror. The cameras labeled "PAC" are for remote verification of the laser beam positions at critical points within the optical path, as well as for monitoring critical safety components such as shutters.

4. LASER SYSTEM ENCLOSURE

The LGSF lasers require an enclosure that provides a clean, dry, temperature-controlled environment. The enclosure is specified as a class 10,000 clean room. In addition to the lasers and associated electronics, the enclosures must include HEPA filters, fans, cooling coils, ductwork, and a gown room for personnel entering or exiting the enclosure. Both vertical and horizontal orientations of the enclosure were investigated to allow the eventual selection of the concept that best fits the telescope requirements. Figure 3 shows the scale of the enclosures mounted on the telescope structure.

Maintenance personnel would reach the laser enclosure from a catwalk accessible from the Nasmyth platform when the telescope is at zenith.

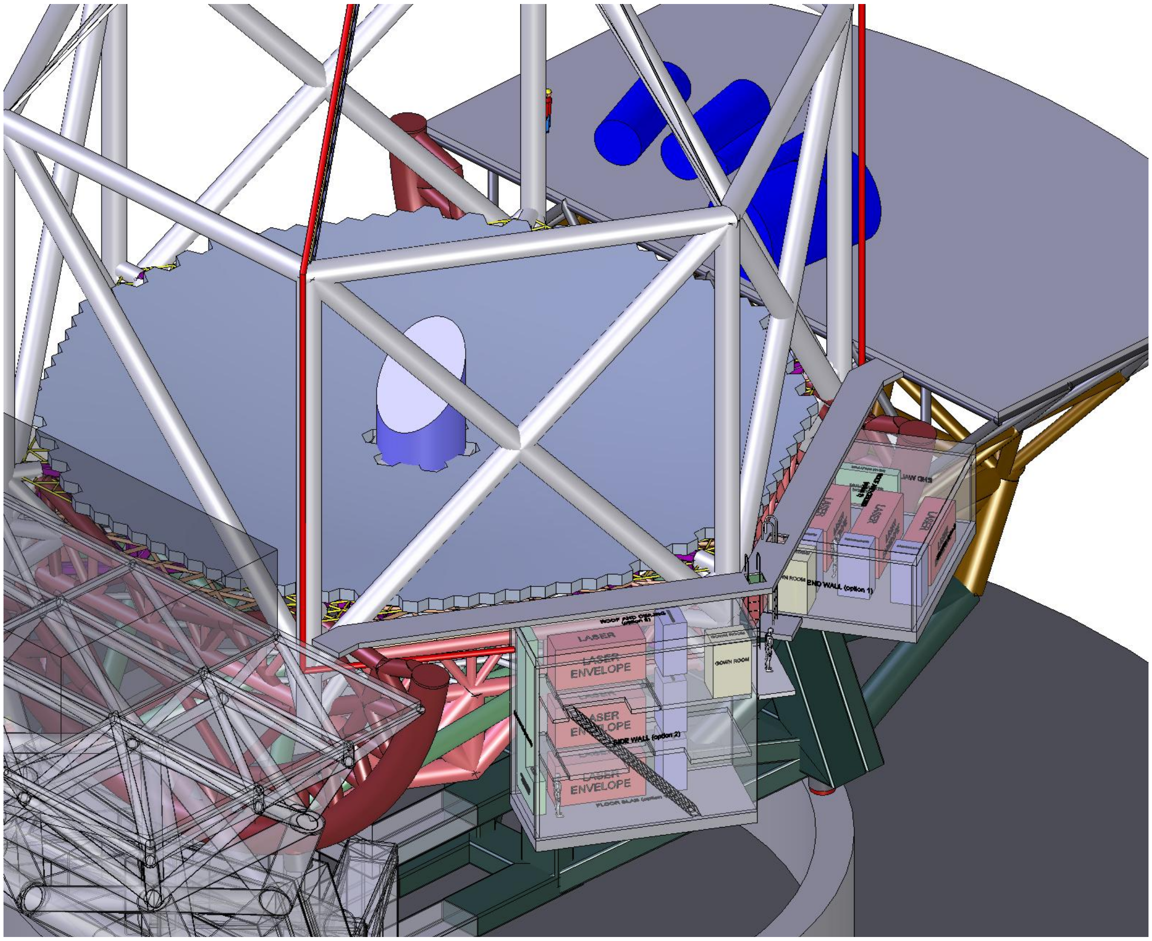

Figure 3: Laser system enclosure concepts shown mounted on the TMT. Only one would be employed in the baseline system.

The Laser Switchyard, which is installed in the Laser Enclosure for reasons of cleanliness and accessibility, performs several functions:

- Splits the 50W input laser beam(s) into the 17W or 25W beams for the AO asterisms
- Directs the beams to the output locations appropriate for each AO asterism
- Selects individual beams for diagnostic power measurements using shutters

The eleven possible AO configurations noted above are generated by beamsplitters (both 33/66 and 50/50) and mirrors mounted to an optical bench; these may be moved in and out of the beam to split and direct the laser beams to the output locations appropriate to the chosen AO system in use.

Figure 4 shows the layout of the switchyard for two possible configurations. For the preferred NFIRAOS operation (left panel), each of the three 50W laser beams is split by a 50/50 beamsplitter, and the reflected beam is directed to an adjacent output. The right panel demonstrates the operation with laser 1 inoperative; the two laser beams are first split by a 33/66 beamsplitter and the transmitted beam is then further split by a 50/50 beamsplitter. The outputs are directed to the same location in each case.

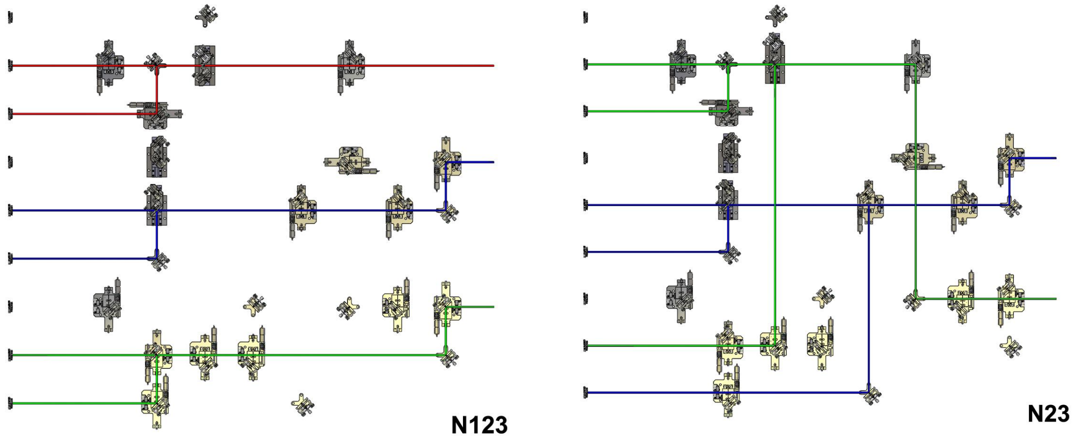

Figure 4: Left panel: Switchyard configuration in normal NFIRAOS operation at 25W per beam. Right panel: NFIRAOS operation at 17W per beam with only lasers 2 and 3 operating. The 50W laser beams enter from the right.

5. BEAM TRANSPORT OPTICS

At the output of the Switchyard, the beams are reformed into a compact configuration for transport up the telescope structure to the BTO Optical Bench (BTOOB) behind the secondary. In this concept, we assume that two mirrors per beam will be sufficient, although the actual number required will be dependent on the final geometry of the laser enclosure and the transport path. Three additional mirrors per beam will direct the light up the vertical structure, bend the beams at the juncture of the M2 support structure, and once again at the top end of the structure where the beams enter the BTOOB.

The baseline concept for the BTO optical path (BTOOP) is to arrange the nine beams in a 3×3 square pattern 140 mm on a side. The beams must be spaced sufficiently to avoid interference with adjacent mirrors at the points where the beam is bent, but close enough so that the structure enclosing the optics fits within the shadow of the secondary support truss. Figure 2 illustrates the path of the nine beams up the telescope truss, although only three are shown for clarity.

Two of the three sets of mirrors in the truss transport optics (labeled "Pointing Array" and "Centering Array" in Figure 2) are controllable in tip/tilt to maintain the centering and axial alignment of the beams when they reach the optical bench at the top end of the telescope, since there will inevitably be some flexure of the telescope structure with zenith angle. This is a low-bandwidth control which can be generated from a lookup table derived during the facility commissioning and verified during operation using the Diagnostic System (see section 6 below).

A set of three relay lenses in each beam control the diffraction spread of the Gaussian laser beams over the 50+ m trip to the telescope top end. They also reduce the sensitivity of the beam motion for a tip/tilt motion of one of the pointing or centering mirrors and thus relax their tilt sensitivity requirement.

It is clear that a fiber beam relay system would provide a dramatic simplification on the BTO design. However, the beam transfer requirements for TMT are significantly more stressing in terms of path length and peak power than the fiber-based relay systems now under development for Subaru and the VLT. Peak power levels will increase further if pulsed laser systems are utilized with duty cycles on the order of 1 to 10 percent. For these reasons, fiber transport was not considered for the baseline TMT LGSF, but developments in this area will be closely followed.

6. DIAGNOSTICS

The diagnostic system (Figure 2) picks off a small fraction (0.5%) of each of the laser beams and directs them through a beamsplitter into two camera systems, one focused at a relatively close distance, the other at infinity. The near-field camera is used to evaluate the intensity profile and quality of the laser beam within the LGSF. The far-field camera views the projected LGS at diffraction-limited resolution to evaluate its image quality. The two cameras together define the alignment of the laser beam, and provide the error signals used to drive the BTO pointing and centering arrays in closed loop. The diagnostic system contains a second beamsplitter to direct the light of a natural star backwards through the LLT to the near and far-field cameras as an independent check of the LLT image quality and to coalign the pointing of the LGS asterisms with that of the TMT.

7. ASTERISM GENERATOR

The requirements for the LGSF include the ability to project up to eight sodium laser guide stars in four different asterisms, as required by the TMT LGS AO systems (section 2). As mentioned above, the functions of laser redundancy and asterism generation are handled by two separate subsystems, the Laser Switchyard, located in the Laser Enclosure and the Asterism Generator, located on the telescope top end at the input to the LLT (Figure 2). The Asterism Generator accepts the active laser beams in a fixed pattern and distributes them to the desired radius and sky orientation corresponding to each AO system while maintaining the ability to switch rapidly between them. The Asterism Generator re-forms the fixed pattern of beams into these AO asterisms using three mirrors in each of the nine input beams. A fourth mirror is fixed at each of the 18 possible locations for all four AO asterisms, oriented so the beam is directed to the input pupil of the LLT.

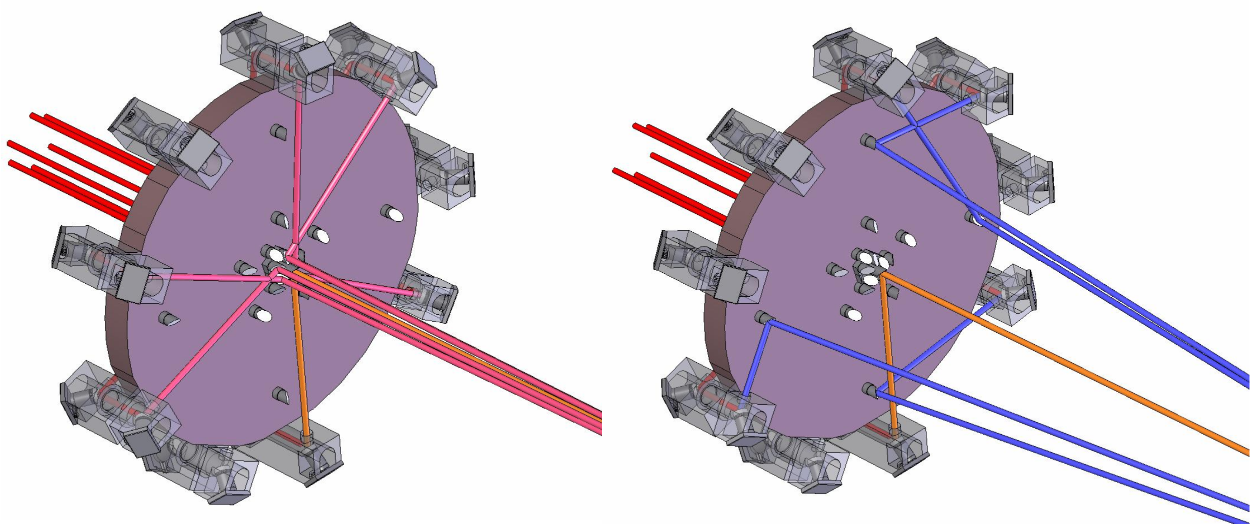

Figure 5: Asterism Generator configurations for the NFIRAOS (left panel) and GLAO (right panel) asterisms. The light path is from left to right. The input beams are reflected off mirrors on the back side of the plate to the two mirrors at the periphery. The third mirror can rotate in azimuth to direct the beam to selected mirrors fixed at the positions of the asterism beacons.

Figure 5 illustrates the functional operation of the Asterism Generator. The nine beams from the BTO relay are directed onto fixed mirrors on the back side (not visible in the figure), which direct the light to the periphery of the asterism generator plate. Depending on the AO asterism in use, only some of these beam positions, which correspond to the outputs of the Laser Switchyard, will be active. Nine pairs of mirrors are mounted at the periphery of the plate to direct the beams around the plate. The second of these two mirrors can rotate in local azimuth to direct the beams to selected fixed mirrors at the positions of the AO beacons in the input plane of the LLT. In the baseline concept, there are 18 fixed mirrors located at all of the possible beacon locations, aligned in tip/tilt to direct the beam from the steering mirror to the LLT input pupil.

7.1 Pointing and Centering Mirrors

The two mirrors at the periphery of the Asterism Generator will be controllable in tip/tilt to maintain centering of the beams on the LLT pupil and pointing of the LGS beacons on the sky in compensation for any flexure within the optical bench and pointing error of the LLT itself resulting from flexure of the telescope structure with zenith angle. They are analogous to the Pointing and Centering Arrays in the BTOOP (section 5) and will use low-bandwidth control generated from a lookup table derived during the facility commissioning, using an internal camera focused on the LLT aperture. As noted above, the second of the two mirrors (the third in the Asterism Generator train) also rotates in azimuth to direct the beam to the fixed asterism mirrors.

7.2 Fast Steering Mirror

The first mirror, on the back side of the Asterism Generator plate, is a high-bandwidth tip/tilt fast steering mirror (FSM) to compensate for jitter in the position of the LGS as measured by the associated WFS. These are analogous to the FSMs used in the Gemini LGS systems. The Gemini mirrors had a $\pm$ 1 mrad surface tilt range, yielding a $\pm$ 2 mrad beam tilt range in the BTO or $\pm$ 7 arcsec range on the sky. The budget for fast tip/tilt correction assigns a value of 50 mas to the 1-axis, 1σ laser pointing jitter, of which 10 mas is budgeted to the resolution of the fast steering mirror on the sky. This corresponds to a FSM tilt motion of 1.4 μrad, which we adopt as the budget for the LGSF.

8. LASER LAUNCH TELESCOPE

The LLT, as the name suggests, projects the LGS beacons into the sky. The LLT optics must expand the 5 mm $1/e^2$ diameter laser beam to ~ 300 mm diameter to obtain a near-optimal LGS spot size on the sky and minimize laser power requirements. We have concluded[5] that an LLT diameter of 500 mm is sufficient to transmit essentially all of a Gaussian beam with $1/e^2$ diameter of 300 mm, and that the gains from using a larger (e.g., 1000 mm diameter) LLT were minimal.

In addition to projecting the LGS beacons, the LLT is also used as a normal telescope to observe a bright star for diagnostic purposes of verifying the LLT image quality and determining the pointing of the LGS beacons with respect to the TMT and ensure that the LGS will fall into the small field of the AO WFS. The beamsplitter which directs a portion of the natural star light into the diagnostics must also have as great a transmission as possible at the 589 nm sodium laser wavelength to maximize the overall BTO throughput, so the natural star light used for diagnostics must be reasonably close to, but not at, 589 nm. This leads to a derived requirement for the LLT to be nearly achromatic, at least over a 20 – 40 nm range from the 589 nm sodium laser wavelength. This achromatic requirement, along with size and image quality considerations, led us to choose an off-axis reflective LLT over an on-axis refractive system. We also note that the off-axis LLT is being implemented for the Gemini LGS systems and anticipate that their experience will provide a useful baseline for the TMT system.

The layout of the LLT is shown in Figure 6. The LLT consists of a two-lens system, which acts effectively as a collimator, and the off-axis R-C telescope. The K-mirror located in the collimated beam acts as an image rotator to keep the LGS asterism fixed in the focal plane of each LGS AO system. A window at the top end of the LLT serves to protect the LLT optical surfaces from exposure to the outside environment and acts as the top end enclosure for the entire LGSF optical path, which will be maintained at a slight overpressure with clean dry air to minimize moisture and dust contamination of the optics. The window must be wedged to eliminate interference effects; in addition, it can be tilted by a small amount to feed the reflected light from the on-axis beacon back into the Diagnostic System as an additional check on the LLT image quality.

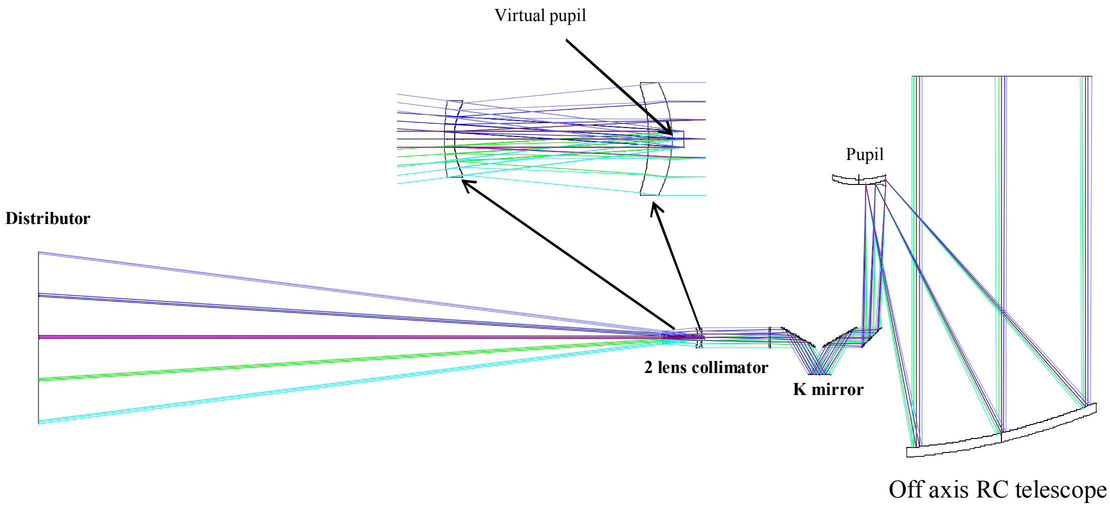

Figure 6: Optical diagram of the LLT. The output of the Asterism Generator is shown at the left. The inset shows a magnified view of the two-lens collimator.

8.1 LLT Trade Studies

During the course of the conceptual design, we considered both reflective and refractive designs for the LLT. The latter is attractive in having much more forgiving tolerances for assembly and misalignment due to gravity loading or thermal effects, but suffers from significant chromatic aberration which would make diffraction-limited imaging of a natural star for diagnostic purposes impossible over a typical 2 nm filter bandwidth. An achromatic doublet objective design proved more suitable for natural star diagnostics, but at the cost of degraded sodium laser image quality at the large field angles used for the GLAO asterism. In contrast, the reflective LLT is more compact, nearly achromatic, and provides diffraction-limited sodium LGS over the full field of view. In addition, the secondary is of a size and conjugation appropriate for a deformable mirror should the ULAO upgrade be implemented.

Initial tolerance studies suggest that the fabrication and alignment allowances for the reflective LLT are challenging, but should be feasible with a well-designed LLT mount. Depending on the experience of Gemini with their reflective LLT systems and the actual use of natural star diagnostics, as well as the decision on implementing ULAO as an upgrade to the TMT LGSF, we may revisit the LLT design prior to the construction phase of the project.

9. SAFETY SYSTEMS

According to the American National Standard Z136.1, the lasers planned for the TMT AO instruments are Class 4 lasers, the highest class defined by the norm. Class 4 lasers are powerful enough that even the diffuse reflection is a hazard. The lower power limit for CW and repetitive pulsed Class 4 lasers is an average power of 0.5W. The lower limit for single-pulse Class 4 lasers is 0.125J in 0.25s. Class 4 lasers require the application of the most stringent control measures inside and outside the observatory.

Inside the observatory, standard laser safety measures will be taken to protect the observatory personnel, laser technicians and the observatory hardware. These measures include the dedicated Laser Enclosure with appropriate warning system, dedicated protective equipment, enclosed beams outside the laser room and up to the Laser Launch Telescope, interlock and shutter systems.

Outside the observatory, the laser beams are a potential hazard to aircraft, satellites and a potential nuisance to neighbor telescopes. An aircraft detection system is necessary to shut down the laser beams in time to avoid illumination of the aircraft. Even if air traffic is very limited around the TMT observatory, no risk of aircraft illumination can be permitted. If the TMT observatory is implemented in a site where laser propagation can be a nuisance to neighbor telescopes, an agreed policy between the telescopes will be needed to define and regulate when the lasers can be propagated in order to avoid interference during nighttime observations.

The TMT Laser Safety System (LSS) will be modeled on the Gemini Safe Aircraft Localization and Satellite Avoidance (SALSA) System, and will be composed of four main sub-systems:

- An aircraft detection system dedicated to aircraft and cloud detection, which itself is constituted of two systems:
  - the all sky camera system, consisting of one or two all sky cameras (ASCAM) working in the visible with a 180 degree field of view to provide complete sky coverage. The purpose of these cameras is to detect the navigation or anti-collision lights of aircraft moving toward the laser beams and to determine if there is a risk of collision with at least one of the laser beams. The cameras will be located outside the telescope in weatherproof units and (in the case of multiple cameras) in two different locations.
  - the boresighted camera system, an infrared camera (BOCAM) with a narrow field of view mounted on the telescope and boresighted with the Laser Launch Telescope. The purpose of this camera is to detect aircraft very close to the laser beams by their thermal infrared emission, as a backup to the ASCAM. In addition, this system will serve to detect clouds prior to their intercepting the laser beam.
- A Laser Traffic Control System (LTCS) dedicated to the detection of beam collision with neighbor telescopes or with an aircraft detected by the ASCAMs
- A Laser Interlock System (LIS) dedicated to shutter the laser beams upon events received from the detection systems or from other AO sub-systems
- An earth-orbiting Satellite illumination Avoidance System (SAS) dedicated to predict illumination of a satellite by a TMT laser beam

The TMT Laser Safety System software components are controlled by the Adaptive Optics Sequencer (AOS). The heart of the Laser Safety System is the Laser Interlock System, which monitors the events from the aircraft detection system, from the Laser Traffic Control System and from the other AO sub-systems and generates interlock demands to stop AO loops and close shutters. The TMT Laser Safety System is autonomous, and the interactions with the Adaptive Optics Sequencer are limited to opening and closing the safety shutters and to monitoring the interlocks events/interlocks demands of the Laser Interlock System. The Adaptive Optics Sequencer does not interact with the LTCS or with the aircraft detection camera systems.

10. CONTROL AND SOFTWARE

The current design of the BTO/LLT system will utilize a total of 135 actuators (87 servo motors, 30 simple DC motors and 18 piezoelectric actuators) and monitor approximately 30 sensors. Because the components of the BTO are spread across the telescope structure up to the secondary, we have chosen to implement a highly-distributed control architecture which will utilize commercially available motion controllers. This will reduce the complexity of the software by having multiple smaller sub-systems in charge of smaller sets of responsibilities.

The control of the BTO components has been split into four principal electronic assemblies:

- The switchyard electronics assembly
- The Truss Centering Array electronics assembly
- The Truss Pointing Array electronics assembly
- The bench electronics assembly

Each of these assemblies consists of an electronic enclosure, several motion controllers, and some power supplies. The bench assembly also includes the BTO/LLT CC and the BTO/LLT DC. Figure 7 shows a conceptual layout of the control architecture for this system.

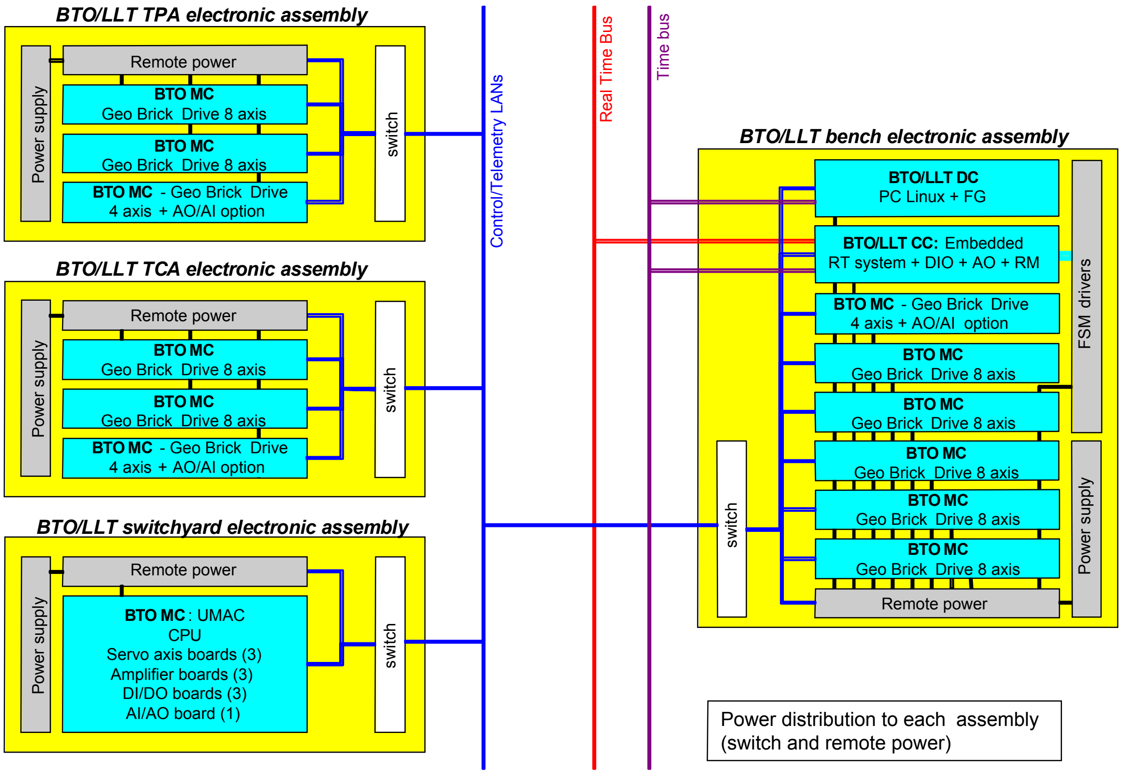

Figure 7: BTO/LLT electronics assemblies

11. UPGRADES AND STATUS

11.1 Fiber Transport of Laser Beams

Several potential upgrades to the TMT LGSF were considered as part of the conceptual design. As noted above in section 5, the use of hollow-core fibers to transport the laser beams could result in significant simplification of the BTO relay system and even permit the Laser Enclosure to be located off the telescope. Although progress in this technology is encouraging, the effort to develop this into the baseline concept is not warranted at this time, although we intend to monitor progress over the time interval prior to the start of the preliminary design effort.

11.2 Advanced Laser Systems

The use of µs-pulsed lasers would reduce laser power requirements for TMT AO systems by about a factor of 2.8, and would also eliminate or significantly alleviate several sources of wavefront error associated with dynamic, random variations in the sodium layer profile[8]. These features are particularly desirable, and are in fact almost requirements, for the long-term upgrade plans for the NFIRAOS and MOAO AO systems, which would require, at minimum, a power upgrade from the baseline system by a factor of four, as the WFS subaperture size is reduced from 0.5 m to 0.25 m. Additionally or alternatively, ms-pulsed lasers would eliminate Rayleigh backscatter interference between separate laser beacons (“fratricide”) and improve the performance of all TMT LGS AO systems. We intend to monitor the progress towards these pulse format options and make a final decision on the baseline laser system in 2009 at the start of the TMT construction phase.

11.3 Uplink Adaptive Optics Upgrade

The ULAO upgrade, which effectively incorporates low-order AO into the LGSF to compensate for the impact of atmospheric turbulence on the projected laser beacons, could theoretically reduce laser power requirements by approximately 33 percent for upgraded TMT AO systems with subaperture sizes of 0.25 m. However, the cost and complexity of these laser systems remains TBD, while it is clear that a ULAO system would require additional deformable mirrors, wavefront sensors, and perhaps even additional Rayleigh laser beacons, depending upon the desired level of performance (ironically, sodium guidestars with signal levels derived from error budgets for near IR AO systems may not be suitable for obtaining high Strehl at 589 nm). Additionally, a separate ULAO may be required for each laser beacon if the diameter of the asterism is large, for example the 5 arcmin asterism for the TMT MOAO system. Although we have incorporated ULAO as a placeholder in the optomechanical layout (Figure 2), it is not under serious consideration as a future upgrade option at this time.

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