The Gemini South MCAO laser guide star facility: getting ready for first light

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ABSTRACT

The Gemini Observatory is in the final integration and test phase for its Multi-Conjugate Adaptive Optics (MCAO) project at the Gemini South 8-meter telescope atop Cerro Pachón, Chile. This paper presents an overview and status of the laser-side of the MCAO project in general and its Beam Transfer Optics (BTO), Laser Launch Telescope (LLT) and Safety Systems in particular. We review the commonalities and differences between the Gemini North Laser Guide Star (LGS) facility producing one LGS with a 10W-class laser, and its southern sibling producing five LGS with a 50W-class laser. We also highlight the modifications brought to the initial Gemini South LGS facility design based on lessons learned over 3 years of LGS operations in Hawaii. Finally, current integration and test results of the BTO and on-sky LLT performance are presented. Laser first light is expected in early 2009.

Keywords: laser guide star adaptive optics (LGS AO), multi-conjugate adaptive optics (MCAO)

1. INTRODUCTION

Back in the year 2000, the Gemini Observatory embarked on an ambitious program to build the first Multi-Conjugate Adaptive Optics (MCAO) system to be used as an adaptive optics facility for routine science observations at its 8-meter telescope in Chile. The GEmini Mcao System (GEMS) project[1] is now (May 2008) in its final integration phase: the MCAO bench, Canopus[2,3,4], is undergoing integration and testing in the laboratory at the Gemini South base facility, and the accompanying Laser Guide Star (LGS) facility is finally coming together at the Cerro Pachón summit. This paper presents a status update of the laser side of the GEMS project, with a special emphasis on the LGS facility subsystems that were designed, developed and/or are currently being integrated and tested in-house.

Following the Gemini-like "twin" concept, the Gemini South Laser Guide Star (GS LGS) facility was conceived from the start as a younger, bigger sibling of the Gemini North Laser Guide Star (GN LGS) facility. Both LGS facility designs were developed simultaneously through the conceptual and preliminary design phases[5], and, like siblings, they share many identical features. Their main difference however resides in their size: the GN LGS facility only provides one artificial star for LGS operation of the "conventional" GN Adaptive Optics (AO) facility, Altair[6], while the GS LGS facility must provide five equally bright artificial stars to the MCAO bench, Canopus.

The GN LGS facility saw first light in May 2005[7], and has been in normal operation supporting commissioning of the Altair LGS mode since June 2005, followed by regular science operation starting in February 2007. The past 3 years of LGS operation at Mauna Kea have provided a wealth of experience to the Gemini engineering group in general and the MCAO team in particular. Many lessons learned have already been applied to improve the GS LGS facility design in order to make future MCAO operations more efficient and reliable at Cerro Pachón.

First light of the GS LGS facility is currently expected early 2009. In the following sections, we will review the readiness of each of the four major subsystems of the GS LGS facility (laser system and infrastructure, beam transfer

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optics, laser launch telescope, and safety systems), and more specifically highlight significant design differences between the GN and GS LGS facilities as well as lessons learned from normal GN LGS operation over the past 3 years.

2. LASER SYSTEM AND INFRASTRUCTURE

2.1 Laser System

Unlike the "conventional" GN LGS AO system using a 10W-class laser to produce a single LGS in the Hawaiian sky, Multi-Conjugate Adaptive Optics (MCAO) operations in Chile will require five equally bright LGS arranged in a 1 arcmin square constellation pattern, thus prompting the need for a 50W-class laser to produce them.

Early on in the GEMS project (as early as year 1999), procurement of the GS laser system was identified as the riskiest item due to the technical challenges associated with the design and fabrication of a sodium laser about five times more powerful than the sodium lasers in use or in development at the time. An ambitious laser research and development program was launched that involved multiple collaborations with the broader AO and laser communities using Gemini, National Science Foundation, and US Air Force funding as well as many other resources to address the AO community need for 10W- and 50W-class sodium lasers for existing telescopes and future extra-large telescopes. Of prime interest to the GEMS project, the program eventually enabled the demonstration of two independent 50W-class lasers, the first in late 2004 by the US Air Force Research Laboratory[8] and the second in late 2007 by Lockheed Martin Coherent Technologies (LMCT)[9].

In September 2005, Gemini eventually subcontracted the design and fabrication of its 50W laser to Coherent Technologies Inc. (CTI, now LMCT), the same company that had designed and fabricated the 12W GN laser system[10,11]. The 50W laser design draws heavily from lessons learned with its older, less powerful sibling and incorporates similar, albeit improved diode-pumped solid-state 1064nm and 1319nm oscillators and associated control software and electronics. Multiple waveguide amplifiers are used to amplify the 1064 and 1319 beams to the power levels required for generation of a single 50W 589nm beam by sum-frequency mixing in a LBO non-linear crystal (the GN laser does not include amplifiers and uses a periodically-poled crystal which would not function at these higher powers). A complete description of the GS 50W laser, its performance, functional and operational specifications, current performance and all relevant technical details are provided in reference [9] also presented at this conference.

The 50W laser contract is now nearing completion: factory acceptance testing is planned for August 2008 at the LMCT facility in Colorado, and delivery is scheduled one month later at the Cerro Pachón summit in Chile, about a year and a half later than anticipated upon contract start. Key performance parameters such as the laser long-term output power, beam quality and wavelength stability are yet to be fully demonstrated but there is reasonable confidence that the laser will eventually meet those specifications. A close working relationship with the Guidestar Laser research and development team at LMCT made it possible, in spite of the heavy constraints imposed by LMCT's internal security policy and US Export Control Regulations issues, to provide in-depth, on-site training to the Gemini laser specialist who will later operate and maintain the GS laser system. More laser electronic and software training is expected to occur at the Cerro Pachón summit during the 6-month warranty period following delivery.

The benefits associated with operating similar laser systems at Gemini North and South will be significant. For instance it has already been noted that the GS laser design includes many improvements and upgrades based on lessons learned during 3 years of GN laser operation on the Mauna Kea summit. Conversely, we are also making plans to retrofit the GN laser and improve its reliability and ease of operation based on those upgrades. It will be possible for both lasers to share spare parts to a large extent, allowing Gemini to save on stocking up expensive components. Generally speaking, operation and maintenance knowledge gained over one system will benefit the other and vice-versa. The Gemini concept of supporting the operation of two telescopes with a single engineering team will thus be extended to the laser support team as well.

2.2 Laser Service Enclosure and Infrastructure

The GS laser bench and electronics enclosures will be housed in an environmentally controlled 10,000-class clean room called the GS Laser Service Enclosure (LSE). Unlike the GN LSE that was built on the GN telescope center section, thus moving both in elevation and azimuth with the telescope, the GS LSE will be located on an extension of the GS telescope elevation platform, similar to a Nasmyth platform, and will only move in azimuth. This major difference between the GN and GS LGS facilities is the direct result of the GS laser contract negotiation phase when the laser vendor insisted on designing the 50W laser for a fixed gravity environment in order to reduce technical risk. Although locating the LSE in a fixed gravity environment will certainly facilitate laser operation and maintenance to a large extent (no need to coordinate daily laser work with other telescope maintenance tasks requiring telescope motions in elevation), this change also resulted in significant additional work for Gemini to design, fabricate and install the corresponding platform extension. It also required a number of design modifications to the beam transfer optics (those will be described in the following section).

The LSE and laser infrastructure requirements, design, expected performance and a detailed description of all modifications to be made to the GS telescope are provided in reference [12] also presented at this conference. At this time (May 2008), completion of all laser infrastructure and final installation of the GS laser in the LSE is planned for late 2008.

3. BEAM TRANSFER OPTICS

3.1 Baseline Design

The Beam Transfer Optics (BTO) is a widely distributed subsystem of the LGS facility that includes motorized and non-motorized mirrors, lenses and polarization components, as well as various cameras, sensors and diagnostics. The main purpose of the BTO is to relay the laser light from the laser service enclosure up to the Laser Launch Telescope (LLT), located behind the GS telescope secondary mirror, where the five laser beams start propagation to the sky.

Up until late 2007 when LMCT eventually demonstrated that the GS laser could produce a single 50W laser output beam, the GS BTO design had to accommodate the possibility of transporting five independent 10W beams. Some recent design simplifications based on the use of a single 50W beam at the output of the laser instead of five 10W beams are still being evaluated at the time of this writing (May 2008), and those will be presented in the next section. To date BTO fabrication work has been mostly following the baseline BTO design that is described below.

The GS BTO baseline design is somewhat different from the design presented in reference [5] when the GS BTO was still a near copy of the GN BTO, only using five mirror arrays instead of single mirrors at various points along the BTO path. When it was decided to relocate the GS laser from the telescope center section onto the elevation platform extension, two components (one K-mirror and one mirror, i.e. a total of 4 reflective surfaces in addition to the previously planned 11 reflective surfaces) were added to relay the laser light along the elevation axis of the telescope from the GS laser output to the original BTO starting point on the center section.

The resulting, "baseline" BTO optical path on the GS telescope is presented in Figure 1. When the five laser beams exit the laser service enclosure, they first travel through the "laser output box", where one safety shutter, five alignment shutters and one or more polarizing optics are located. Next, the beams travel through the BTO "torque tube", passing through the Elevation K-Mirror (EKM) heading straight to the Elevation Fold Mirror (EFM) that redirects them to the Truss Pointing Array (TPA). TPA sends the five beams up along the telescope truss to the Truss Centering Array (TCA) where they are redirected to the Truss Fold Array (TFA). After reflection on TFA the laser beams pass through three relay lenses used to image the output of the laser system onto the LLT entrance pupil. Upon reaching the Top-end Ring Mirror (TRM), the beams are redirected through the laser vane duct up to the BTO Optical Bench (BTOOB). Inside the BTOOB, the five beams are received by the Fast Steering Array (FSA) which steers each of them independently to the X-Shaping Array (XSA) where the final five-star X-shaped laser constellation is formed. Finally the beams are reflected off the Centering Mirror (CM), pass through the BTOOB K-Mirror (KM), and are eventually reflected off the Pointing Mirror (PM) into the Laser Launch Telescope (LLT) for projection to the sky. A mirror can be inserted in the laser path between KM and PM so as to divert the laser light onto a power meter, thus enabling laser propagation through the entire BTO (minus PM) without projection to the sky.

Beside relaying the laser light from the laser to the LLT, other BTO functionalities include slow and fast compensation of telescope flexures and laser beam jitter, laser beam quality monitoring, beam shuttering, and laser polarization control. The Laser Bench Beam Stabilization (LBBS) system, another addition to the GS BTO prompted by the change in GS laser location, compensates for beam jitter introduced by the laser bench vibration isolation system by measuring on-axis beam pointing and centering with two position sensors located inside the TPA box, and driving two laser bench-mounted fast tip tilt mirrors in closed loop to compensate for any deviation from nominal alignment. The K-mirrors located in the torque tube (i.e. EKM) and the BTO Optical Bench (i.e. BTOOB KM) compensate for the laser constellation rotation due respectively to changing telescope elevation and Cassegrain rotator angle. TPA, TCA and TRM provide open-loop compensation of the telescope flexures via an elevation-based look-up table (LUT) to maintain alignment of each laser beam relative to the narrow, 12mm-wide laser vane duct, while CM and PM provide centering of the 5 laser beams onto the LLT primary mirror and accurate pointing of the LGS constellation on the sky via an elevation- and cass rotator angle-based LUT. Finally, the Fast Steering Array (FSA) mounted on the BTOOB-end of the laser vane duct compensates for uplink atmospheric jitter while the BTO Diagnostic System (BTODS), including both a far-field and a near-field camera, provides information about the laser beam quality on the BTOOB during normal laser operation, and LLT image quality when imaging starlight backwards through the LLT.

In fine, the GS BTO must be able to position the laser constellation within 1 arcsec blind pointing accuracy on the sky (via the PM/CM LUT) and stabilize each LGS within 0.05 arcsec based on closed-loop control information provided by the MCAO LGS wavefront sensors (via the FSA). Our experience at Gemini North shows that the FSA will likely achieve this requirement (the GN Fast Steering Mirror, FSM, does) but that the PM/CM LUT will likely need refinement as PM and CM typically achieve blind pointing accuracies on the order of a few arcseconds only, falling somewhat short of the 1 arcsec requirement which would enable immediate acquisition of the LGS on the Altair LGS Wave Front Sensor (WFS) and save precious seconds of MCAO pre-acquisition set-up time.

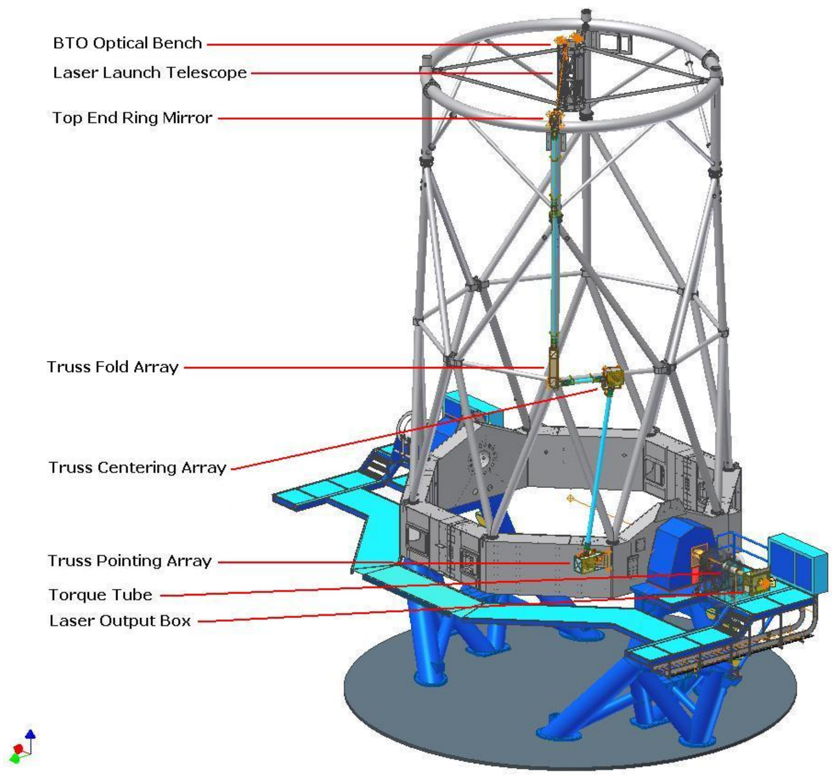

Figure 1: GS BTO optical path (baseline design)

For packaging reasons, the five laser beams leave the laser bench in an X-shaped constellation until TFA rearranges them in a line along the vertical part of the truss and through the laser vane. Individual laser beam size throughout the BTO varies between 5 and 6mm diameter at the $1/e^2$ intensity points (about 8 to 9mm 99% encircled energy diameter) as a compromise between the need to hide the laser beams behind the thin 10mm-wide secondary mirror vane and the desire to lower the laser power density on the BTO optics as much as possible. The entire BTO path is enclosed in tubes for safety reasons mainly, and the path is flushed with clean air to minimize dust deposition on BTO optics and prevent coating damage.

All slow motion tip tilt mirrors (TPA, TCA, TRM, CM and PM) are driven by Newport linear actuators CMA12CCCL while the fast tip tilt mirrors of the FSA and LBBS are driven by Physic Instrumente tip tilt piezo platforms. The K-mirrors are driven by a Newport precision rotary stage RGV-100. The controller chosen for the servo loops is the MAXv 8000 from ProDex that includes 8 configurable channels for servo or stepper motor control. The BTO also incorporates a set of sensors that provide temperature and pressure information inside the laser path enclosure, and temperature of the cooling system for the BTO electronics thermal enclosure located on the telescope center section.

Beam alignment inside the BTO can be monitored at any time using a total of six video cameras imaging the EFM, TPA, TCA, TRM, FSA and LLT primary mirror assemblies. All pointing and centering control loops are managed by an EPICS-based software that resides in a Motorola Power PC CPU running under VxWorks OS. The FSA has its own CPU running a faster dedicated program. All control electronics are in VME format. The BTO software provides interface to all the control loops and diagnostics as well. The BTO cabling is routed through the telescope trusses and secondary mirror vanes using opto-coupled differential signals to provide protection and avoid noise. Cables routed through the vanes are hidden from the telescope primary mirror.

Polarization control in the BTO remains undefined at this time, while we are still trying to assess how truly effective it would be to increase the sodium photon return above Cerro Pachón. Meanwhile provisions in mechanics, electronics and software have been made to provide the BTO with one or more motorized polarizing optics if needed.

3.2 Simplified Design

Two, independent modifications to the BTO baseline design are currently under final review by the Gemini MCAO team and upper management. We expect that both will effectively be implemented prior to technical commissioning of the GS LGS facility and first laser propagation to the sky.

The first modification aims to take advantage of the possibility to propagate a single 50W beam all the way from the laser system on the elevation platform to the telescope top-end. The 50W beam would be divided in five 10W beams inside the Top-end Ring Mirror (TRM) assembly via a simple beam splitter arrangement before propagation through the laser vane duct up to the BTOOB (the BTOOB design would remain identical to the BTOOB baseline design). Following this approach, there would be no alignment shutter in the laser output box and no Elevation K-Mirror (EKM) in the torque tube, thus removing possible beam precession issues due to imperfect alignment of the five beam constellation into the EKM. In the Truss Pointing Array (TPA), Truss Centering Array (TCA) and Truss Fold Array (TFA) assemblies, only the center mirror would be used while the other four mirrors would be kept as spares. TPA, TCA, and TFA would thus respectively become the Truss Pointing Mirror (TPM), Truss Centering Mirror (TCM), and Truss Fold Mirror (TFM) similarly to their GN BTO counterparts. Finally, imaging the laser output plane onto the LLT entrance pupil (where all five beams overlap) would only require one, smaller diameter lens instead of the three, large diameter relay lenses thanks to the much reduced field of view requirement for relaying a single, on-axis beam.

Because this modification is mostly a simplification of the current BTO design, very little of the mechanics, optics, software and electronics would have to be redesigned, and reducing the number of BTO components would ensure significantly higher reliability for the entire system. Beside the need to procure mirrors with higher damage thresholds for TPM, TCM and TFM, the largest impact would concern the Top-end Ring Mirror (TRM) design. TRM would become the Top-end Ring Array (TRA) and include five mirrors, each of them mounted on a slow motorized platform as was also intended for TRM following lessons learned at GN. The purpose of motorizing TRM stems from the desire to reduce the relatively large beam motions observed on TCM and TFM when applying the TPM/TCM elevation-based LUTs used to compensate for telescope flexures.

The second modification consists in a fairly drastic simplification of the Laser Bench Beam Stabilization (LBBS) system, based on preliminary results provided by the GS laser vendor regarding the positioning accuracy and repeatability of the laser bench vibration isolation system. Based on these results, and Gemini's understanding of the dynamic behavior of the telescope elevation platform and center section, it is believed that beam motions induced by the laser bench and other telescope-induced vibration sources would actually not cause the beam to wander outside of the TPM mirror clear aperture. The LBBS fast tip/tilt platforms could thus be relocated out of the laser bench enclosure, for instance at TPM and TCM, and the LBBS sensors could be relocated at TRA. Simplifying the LBBS design even further, it appears that a single piezo tip/tilt platform could actually be used at TPM to maintain the beam position centered on TRA, while inducing beam motions of acceptable amplitude on FSA, and ensuring unvignetted laser propagation through the laser vane duct. The additional beam jitter induced by the LBBS fast tip/tilt platform would be well within the available dynamic range of the FSA fast tip/tilt mirrors and could therefore be taken out by the FSA while correcting laser beam jitter on the sky. Finally, the Gemini MCAO team is also looking into the possibility to do away with complex computer and software control for this simple one tip/tilt mirror/one sensor scheme, and use a PMAC controller instead. With all these modifications, the LBBS (Laser Bench Beam Stabilization) system would be renamed the LBS (Laser Beam Stabilization) system.

The main differences between the GN BTO design, GS BTO baseline design and GS BTO simplified design are summarized in Table 1 below.

GN BTO	GS baseline BTO	GS simplified BTO	Comments
11 reflective surfaces	15 reflective surfaces	12 reflective surfaces	Measured GN BTO throughput in normal operation (including not only mirrors but also all beam splitters and lenses in the main beam path) is 81% +/-4%
No LBBS or LBS	LBBS (two piezo tip/tilt platforms on laser bench, two position sensors at TPA, with closed loop computer control)	LBS (one piezo platform at TPM, and one position sensor at TRA, with closed loop PMAC control)	Compensates beam motion induced by laser bench vibration isolation system and other telescope center section vibration sources
No alignment shutter	Five alignment shutters in laser output box	No alignment shutter	Needed for individual alignment of five laser beams
No EKM	EKM in torque tube	No EKM	Compensates laser constellation rotation on TPA due to changing telescope elevation
No EFM	EFM in torque tube		Relays the laser beam(s) between the GS LSE and TPA/M
TPM (one slow tip/tilt platform controlled with elevation-based LUT)	TPA (five slow tip/tilt platforms controlled with elevation-based LUT)	TPM (one fast tip/tilt platform part of LBS mounted on one slow tip/tilt platform controlled with elevation-based LUT)	M=single mirror, A=Array of five mirrors
TCM, TFM	TCA, TFA	TCM, TFM	M=single mirror, A=Array of five mirrors
TRM (fixed)	TRM (one slow tip/tilt platform controlled with elevation-based LUT)	TRA (five slow tip/tilt platforms controlled with elevation-based LUT)	M=single mirror, A=Array of five mirrors; TRM/A LUT reduces amplitude of beam motion on TCA/M and TFA/M
No BTOOB KM	BTOOB KM		Induces constellation rotation on the sky to prevent field rotation on Canopus LGS WFS (based on Cassegrain rotator angle)

Table 1: Differences between the GN, GS “baseline” and GS “simplified” BTO designs

3.3 Estimated Performance

Overall the decision to use a mirror-based beam transport system, as opposed to a monomode fiber such as, for instance, the one used by the LGS facility for the European Southern Observatory Very Large Telescope, seems to have paid off as far as reasonably high optical throughput and reliability is concerned. As noted in Table 1, GN BTO throughputs have been measured between 85% initially (the requirement was 80%) and 77% more recently, showing the high potential for the GS BTO design (simplified or not) to achieve its own 75% throughput requirement. Note that no obvious coating degradation can be seen on GN BTO optics by simple visual inspection and we have yet to understand the reason why the GN BTO throughput would have decreased by as much as 8% over the past 3 years in spite of regular BTO optics cleaning prior to every LGS run. Finally, the BTO subsystem of the GN LGS facility has been fairly reliable since the beginning of LGS science operations, incurring little observation downtime. The highest occurrence of BTO faults has been related to the failure of some of the slow BTO mirrors to reach position and corresponding laser beam misalignments across the vane or on the LLT that eventually reduced LGS brightness so much that the Altair LGS WFS closed loop would diverge and open. Upgrading the low level software control of these mechanisms is currently in the works for GS, to be retrofitted later at GN. Based on these considerations, we do not expect any significant difficulties with the final integration and testing of the entire BTO train that will nominally occur in the last quarter of 2008.

4. LASER LAUNCH TELESCOPE

4.1 Design Overview

The GS Laser Launch Telescope (LLT) is a 450mm diameter aperture projector located in the shadow of the 1.0-meter diameter secondary mirror of the Gemini 8-meter telescope in order to provide on-axis launch of the five LGS constellation for MCAO operations. With an unvignettted field of view of +/-1.2arcmin and a 60:1 magnification ratio, the LLT enlarges the five, 5mm diameter gaussian laser beams overlapping on its entrance pupil, to a 300mm diameter footprint beam (these are diameters at the $1/e^2$ intensity points) on its 450mm diameter primary mirror. All trade-offs that went into defining the top-level design specifications for the LLT are presented in more details in reference [5].

The LLT design consists in an unobstructed, afocal telescope using a diverging lens assembly followed by a fold mirror to expand the optical beam then direct it down towards an off-axis parabola (OAP) that provides collimated projection onto the sky. The opto-mechanical design includes a passive athermal focus mechanism that enables manual focusing of the LLT for broadband visible starlight (when imaging a star backwards through the LLT onto the BTOOB diagnostic far-field camera) or monochromatic 589 laser light (when projecting laser light to the sky).

The detailed design and fabrication of two identical LLTs (one for GN and one for GS) was contracted out to Electro-Optics Systems Technologies (EOST). A description of the early LLT opto-mechanical design was presented by the LLT vendor in reference [13]. Since then various modifications have been brought to the design following critical design review and acceptance testing. Although both LLTs met their image quality specifications at laboratory acceptance testing, early 2005 on-sky testing with star light then laser light of the GN LLT fitted first with the GN OAP, then with the GS OAP, showed that neither system performed well on the sky[7]. The culprit was found out to be thermal stress induced at the bond line between the ceramic central hub of the OAP support system and the glass that caused severe surface distortion of the central part of the OAP (where the laser power is concentrated). This resulted in unacceptably large LGS spot sizes on the sky and prompted Gemini to de-bond, re-bond and re-polish the GN OAP while the GS OAP was being used to proceed with technical commissioning of the Altair LGS mode. Subsequent testing in early 2006 of the GN LLT fitted with the re-worked GN OAP eventually showed that the problem had been satisfactorily resolved for that OAP. Gemini then proceeded to de-bond and re-bond the GS OAP but not re-polish it until further testing would show whether this would really be necessary.

4.2 On-Sky Performance Results

The GS LLT (fitted with the re-worked GS OAP) was installed on the GS telescope atop Cerro Pachón in late 2007. Results from initial on-sky testing with star light performed in December 2007 and January 2008 are presented below.

Because the LLT optical axis must be co-aligned within about 10 arcsec with the Gemini 8m telescope optical axis, the LLT alignment is performed in three phases. In the first phase, the LLT is aligned out of the Gemini telescope on the dome floor so as to experience the same temperature it will be used at during normal operation. Next, the BTO optical bench is fitted on top of the LLT, co-aligned with it, and removed. The LLT is then ready for installation on the Gemini telescope within the secondary support structure, and the BTO optical bench mounted back on top of it. In this configuration, the BTO diagnostic far field camera can be used to image star light backward through the LLT to assess, in the second phase, the LLT pointing with respect to the Gemini telescope optical axis, and in the third phase, the LLT image quality. For the second phase the Gemini telescope is pointed at a bright star, and a spiral search is performed until the star can be seen and centered on the far field camera. At that point, the Gemini telescope elevation and azimuth pointing offsets provide a measurement of the differential pointing between the LLT and the Gemini telescope. This information is used to shim the LLT at its interface with the secondary support structure and co-align its optical axis with the optical axis of the Gemini telescope within 10arcsec or so. The third phase consisting in fine-tuning the LLT image quality is performed in-situ by adjusting the OAP tip/tilt within its mount while the Gemini telescope is pointing (and tracking) a star at low elevations (~20deg).

Our first attempt to image a star through the GS LLT on the BTO diagnostic far field camera greatly benefited from experience gained during on-sky alignment of the GN LLT and, this time, the star was immediately found within the ~2arcmin field of view of the far field camera without the need to perform a spiral search. The LLT was subsequently shimmed to center the star on the far field camera, and in-situ fine alignment followed using the 3 rough pitch OAP adjustment screws, thus introducing variable amounts of coma and astigmatism. Whenever the star disappeared from the field of view of the far field camera, the telescope operator re-pointed the Gemini telescope to re-acquire the star on the far field camera. Using the fine-pitch, manual focus adjustment of the LLT, we also added varying amounts of defocus in order to help in visualizing and identifying aberration features in the image. Multiple extra-focal images were obtained on the nights of December 11 & 13, 2007, and January 28, 2008 (see examples in Fig. 2). Based on the OAP phase map that had been previously obtained in the laboratory, and a simulation tool predicting what extra-focal images would look like for known amounts of focus, coma and astigmatism, it was possible to reproduce all extra-focal images with high accuracy as shown in figures 2 and 3. This simulation not only provided us with a convenient alignment tool in order to optimize the LLT image quality on-the-fly, but also to predict what in-focus images would ultimately look like in given seeing conditions. As a side benefit, the good adequacy between experimental and simulated images also confirmed that other LLT and BTOOB optics involved in imaging the star on the far field camera do not degrade image quality beyond the OAP contribution.

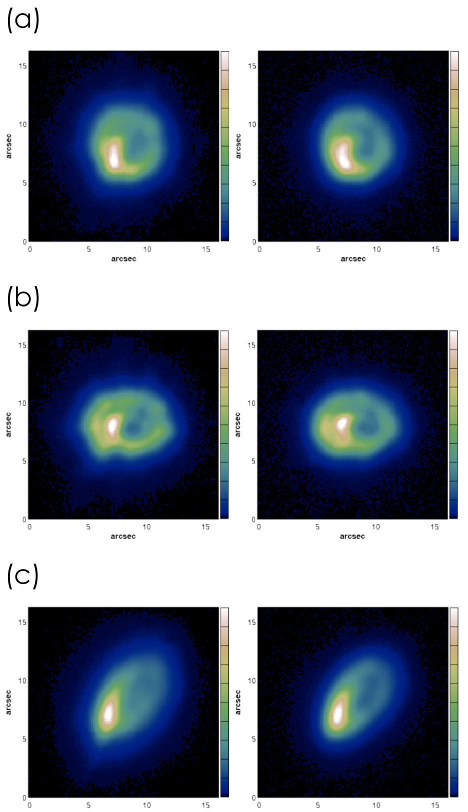

Figure 2

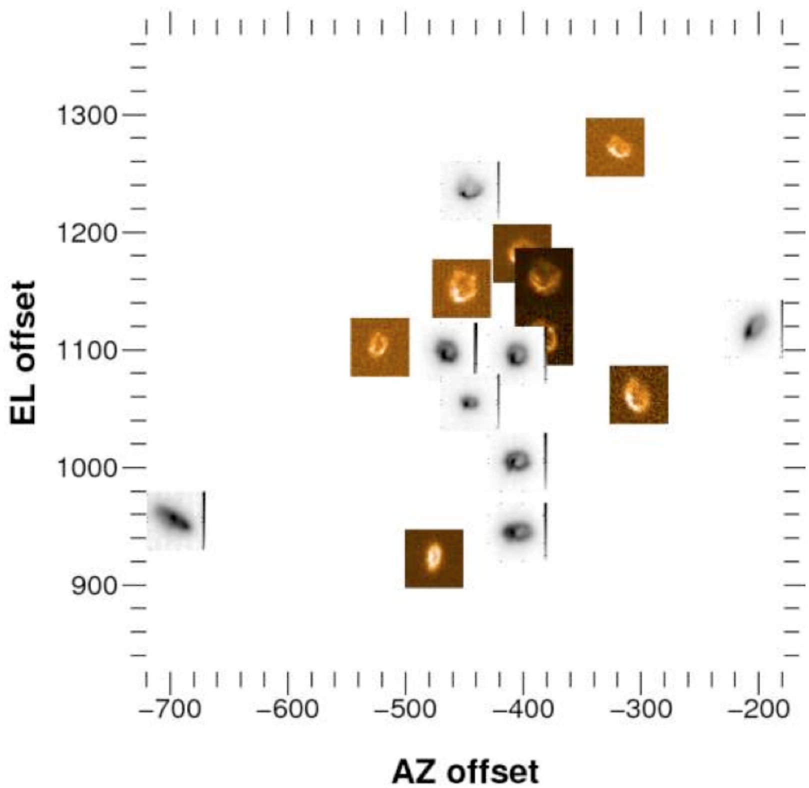

Figure 3

Figure 2: ***Left:*** **Experimental extra-focal LLT images of a bright star where each image is the average of 200 to 500 short exposures of 50 to 200ms duration.** ***Right:*** **Corresponding simulated images using the known OAP phase map and the appropriate fit coefficients for the seeing and defocus/astig/coma/trefoil/spherical aberrations.**

Figure 3: Map of all LLT images of bright stars obtained on Dec. 11 and 13, 2007 (color) and Jan. 28, 2008 (black and white) plotted at the corresponding telescope pointing offsets used to center the star on the acquisition camera hot spot.

Using the simulation tool described above, we thus estimate that in median seeing conditions (0.7arcsec @ 700nm) at Cerro Pachón, and after final on-sky optimization of the OAP alignment and focus, the GS LLT should deliver a star image with a 50% encircled energy diameter of 1.07arcsec, corresponding to 0.88arcsec Full Width at Half Maximum (FWHM). Note that this result does not include local LLT seeing internal to the LLT outer tube that we suspect may be a non-negligible contributor to the uplink seeing term in the LGS spot size error budget. For comparison purposes, the smallest GN LGS spot sizes measured in 0.6arcsec seeing at 589nm by the Gemini acquisition camera over the full 8m diameter aperture of the Gemini telescope have a ~1.3arcsec FWHM, corresponding to an intrinsic LGS spot size of

~1.0arcsec at FWHM with the downlink seeing and geometric elongation contributions removed. As a reference, projection of a diffraction-limited gaussian beam by a perfectly aligned, unaberrated LLT in median Cerro Pachón seeing conditions (0.7arcsec @ 700nm) would create a LGS spot size with a 50% encircled energy diameter of 0.89arcsec, corresponding to 0.80arcsec FWHM. Laser propagation first light expected early 2009 at Cerro Pachón will eventually determine how large the GS LGS spot sizes will be compared to our estimates.

Using the above LLT image quality measurements and OAP laboratory phase map, as well as experimental measurements of the Canopus LGS WFS CCD pixel edge diffusion and other instrumental effects, we were able to further model and quantify the relative impact of LLT aberrations on the MCAO-corrected science path output Strehl ratio. Modeling results show that residual high-order effects in the GS LLT OAP surface figure are small but not negligible, with a potential for causing about 5% of absolute Strehl loss at the MCAO bench output in H band in median conditions for seeing and sodium photon return as well as making assumptions on the MCAO loop gain and noise propagation behavior. We also found that in median Cerro Pachón seeing conditions, the major contributors to noise would seem to be, by order of importance: (1) pixel edge diffusion, (2) LLT internal seeing, and (3) LLT OAP aberrations. From these results, we concluded that some effort should be made to improve air circulation within the LLT tube in order to reduce local seeing, and that re-polishing of the GS LLT OAP might be in order. However management concerns over putting this critical piece of the GS LGS facility at risk while no spare is at hand eventually prevented us to proceed with OAP re-polishing at this time.

Because the GS LLT OAP will be exposed to the open air throughout LGS runs (a remote-controlled cover protects the OAP when not used) and will get dusty like other Gemini telescope optics, maintaining a high LLT throughput will also likely be an issue during normal operation. Recent reflectivity measurements taken on the GN LLT indeed showed a 10% reflectivity loss over 3 years in spite of monthly CO_2 cleanings of the OAP. We may modify the LLT tube design not only to enable better air circulation and reduce local, internal seeing, but also to allow easier in-situ wash of the OAP. Finally, although the OAPs were initially aluminum-coated by the LLT vendor and should theoretically have met their reflectivity specification, the enhanced aluminum coating seems to under-perform in practice. As a result, we are also exploring the possibility to recoat both GN and GS LLT OAPs with a higher reflection coating at 589nm. At this point, all LLT improvements under consideration will only be planned as future upgrades, and the GS LLT is basically ready for laser first light.

5. SAFETY SYSTEMS

5.1 Overview

The GS LGS facility safety systems are part of the Gemini Laser Safety Program which was defined and carefully implemented over the years to ensure safe laser operations at the Gemini Observatory. The Gemini Laser Safety Program conforms to the American National Standard for the Safe Use of Lasers ANSI Z136.1-2007, thereby ensuring compliance with the US Occupational Safety and Health Administration (OSHA) requirements. Compliance with those standards includes but is not limited to designating one Laser Safety Officer per site (Hawaii and Chile), performing a Safety Hazard Analysis and developing the corresponding Control Measures to ensure safe laser operation at all times.

The GS LGS facility "safety systems" encompass all systems, control measures and procedures dedicated to ensuring personnel and equipment safety during the use of the GS laser and propagation of its class IV 50W laser beam indoors and outdoors. The safety systems include the Laser Interlock System (LIS), the All-Sky Camera (ASCAM) and the Boresited Camera (BOCAD) being developed as part of an aircraft avoidance system to replace the use of human observers (also called spotters), procedures to interface with the Dirección General de Aeronáutica Civil de Chile (DGAC Chile), and procedures to interface with the US Space Command for satellite avoidance. By extension, the safety systems also include the Laser Traffic Control System (LTCS) that regulates the use of lasers among neighbor observatories. Each system is described in more details below.

5.2 Laser Interlock System

The Laser Interlock System (LIS) stands at the heart of the LGS facility safety systems. Conceived as an offspring of the Safety Hazard Analysis and resulting Control Measures, the LIS receives inputs from all AO and LGS facility subsystems and performs real-time logic to determine whether the situation warrants for any of them to take action, then informs the necessary subsystems of what action must be taken. The on/off laser status and the open/closed state of all shutters along the laser beam path (the laser shutter, safety shutter, BTO shutter, and LLT cover) are for instance being monitored by the LIS in order to determine whether the laser beam is not being propagated, being propagated to the top-end of the telescope or being propagated to the sky. The LIS is also in direct, hardware control of the "safety shutter", the rapid shutter located just after the GS laser shutter that forms the first line of defense whenever a situation involving personnel safety occurs (e.g. unauthorized access to the laser beam path, aircraft detection by a spotter, etc.).

The GS LIS is very similar to the GN LIS with the exception of a few added inputs and outputs related to the GS BTO differences with its northern sibling. The LIS is a subsystem of the Gemini Interlock System sharing the GIS PLC Allen Bradley 5/40 processor. Most of the I/O points are located in a PLC rack inside the BTO thermal enclosure while others are in the existing GIS racks. These are located in the center section rack, off-telescope rack and computer room. The LIS has about 80 – 100 I/O points, most of them complimentary TTL signals.

Final integration and test of the GS LIS is planned for late 2008 once all other LGS facility components have come together. Based on the fairly successful results we have had in commissioning the seemingly complex GN LIS (we did not experience any open-ended interlocking scenario for instance), we are confident that integration and test of the GS LIS will not cause undue delays in the GEMS project and quickly enable safe, automated operation of the GS LGS facility.

5.3 Aircraft Avoidance

Ever since Gemini initiated laser operations at Mauna Kea in 2005, the Observatory has been closely following the example set by the neighboring W. M. Keck Observatory with respect to obtaining laser propagation approval by the US Federal Aviation Administration (FAA). Outdoor laser propagation of the Gemini laser beam involves using human observers, or "spotters", to monitor the sky for approaching aircrafts at all times during LGS runs and to remotely close the safety shutter (via the LIS) in case of possible aircraft "collision" with the laser beam (something that rarely occurred over the past 3 years of laser operations). A total of 5 spotters is required per night during a LGS run, with 2 spotters monitoring the sky while 2 spotters are resting in 1-hour shifts. The additional, fifth spotter is responsible for driving the spotter crew up and down the mountain, ensuring that spotter monitoring standards are maintained, and turning over spotter logs (aircrafts detected below/above 20 degree elevation, shutter events, clouds) at the end of a run for future statistical analysis by Gemini. The need for spotters is a heavy price to pay for LGS operation, not only in spotter salaries (an estimated $265k is spent annually to support some 200 LGS nights) but also in logistics, when nearly every department within the Observatory is involved in the spotter business in order to recruit, schedule, train and manage them. GN spotters are currently contracted out of a temp agency and the spotter pool is shared with Keck, sometimes creating scheduling conflicts when not enough spotters are available during simultaneous LGS runs at both observatories. Most critically, human observers do work in a very harsh environment (work at night, in the cold, and at 4200m altitude) and remain prone to failure due to fatigue, high altitude sickness, or simply lack of commitment to the task.

For all these reasons, Gemini is very keen on replacing spotters with an automated aircraft detection system and obtaining FAA approval to proceed without the requirement for human observers. To achieve that goal, Gemini has teamed with the Keck Observatory and others in order to develop a two-tiered, camera-based system using a visible All-Sky Camera (ASCAM) and an infra-red Boresited Camera (BOCAD), and find a common approach to sensitize the FAA to the unusual needs of astronomical observatories. More details on the status of the ASCAM development and the strategy laid out to obtain FAA approval to propagate astronomical lasers without spotters are presented in references [14] and [15] respectively.

The situation for the GEMS project in Chile is slightly different from the situation in Hawaii in that we do not need to interface with the FAA but with the Dirección General de Aeronáutica Civil (DGAC) instead. So far the DGAC has been very supportive of our desire to get rid off spotters and we are currently discussing possible ways to interface directly with the DGAC database and obtain real-time information above aircrafts flying over Cerro Pachón during future LGS runs. It is likely though that Gemini will still end up using spotters at Cerro Pachón for at least the first few months of laser operations until such times as we and the DGAC both feel confident that the Gemini automated aircraft detection system combined with DGAC-provided real-time flight information is reliable enough to waive the requirement for human observers.

5.4 Satellite Avoidance

It is believed that civil observatories are not required to apply for the US Space Command authorization to propagate lasers outdoors. However, because the Gemini Observatory must abide by the US National Science Foundation rules in all matters, it is still unclear at this time whether Gemini is actually required to comply or not with satellite avoidance requirements. Requirement considerations notwithstanding, Gemini has long since chosen to comply with satellite avoidance procedures and has been submitting LGS target lists to Space Command prior to each and every night of laser propagation at Mauna Kea. While the added logistics of preparing the list, submitting it to Space Command 3 to 4 days in advance of a LGS run and checking possible closure times every day of the run weighted on the Observatory resources, this logistical overhead at least did not affect GN LGS AO science operations much as there was rarely, if ever, any satellite avoidance-related downtime until December 2007. At that time, Space Command proceeded to some internal re-organization and adopted a new tool called the "laser deconfliction Spiral 3" to compute "open windows". Implementation of that new tool has had a significant impact on GN LGS AO operations from December 2007 onward as there are now many small and highly fragmented "closed windows" during which Space Command requests that there be no laser propagation. This has resulted in up to 4 more hours spent each day of a LGS run by the Gemini Queue Coordinator to prepare the observation plan (the "queue") for the upcoming night, and also occasioned a significant loss of observed hours when science targets could not be observed due to conflicting open window durations during the limited times when such targets were available for observation. The Gemini Observatory is nevertheless determined to comply with satellite avoidance requirements not only in Hawaii but also in Chile, and it is currently still unclear how large an impact satellite avoidance procedures will have on future MCAO science observations[16].

5.5 Laser Traffic Control System

The Laser Traffic Control System (LTCS) is somewhat atypical among the LGS facility safety systems in that it does not aim to protect personnel or equipment from laser damage but is meant to protect science observations by neighbor observatories from laser light pollution (Rayleigh scatter by the low-altitude atmosphere and sodium fluorescence). For the GEMS project in Chile, Gemini simply plans to duplicate the GN LTCS[17,18] that was developed and implemented at Mauna Kea in collaboration with the W. M. Keck Observatory. Unlike in Hawaii where a dozen or so of observatories share the Mauna Kea summit, the only close neighbor of the GS telescope atop Cerro Pachón is the Southern Astrophysical Research Telescope (SOAR) telescope, to be joined much later by the Large Synoptic Survey Telescope (LSST). Based on data obtained at Mauna Kea, it appears that telescopes located on nearby Cerro Tololo should not be affected by laser pollution, and as a result those telescopes do not plan on adopting the LTCS. Implementation of the GS LTCS prior to laser first light in early 2009 should therefore be straightforward.

6. CONCLUSION

With photon returns at or above the required 160 photons/cm^2/s at the primary mirror of the GN telescope throughout the year when the 10W-class GN laser output power is reasonably high, and LGS spot sizes on the order of 1.3arcsec FWHM as seen by the Gemini 8m telescope acquisition camera, typical performance of the GN LGS facility are an indication that the GS LGS facility, with five 10W-class laser beams and fairly similar BTO and LLT optical train, has the potential to meet its performance specification for MCAO operation at Cerro Pachón. Moreover, many lessons learned over the past 3 years during commissioning and normal operation of each subsystems of the GN LGS facility (laser, BTO, LLT and safety systems) have already been applied to their southern siblings. Together with the significant experience gained earlier in the North by the MCAO team, this will contribute to easing up the GS LGS facility integration and test phase and its technical commissioning on the sky. As of this writing (May 2008), meeting the planned January 2009 laser first light remains largely dependent on the GS laser being delivered as expected in September 2008 and the laser infrastructure being completed on time for laser installation on the telescope by the end of 2008.

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