Available online at www.sciencedirect.com

SCIENCE DIRECT®

C. R. Physique 6 (2005) 1089–1098

COMPTES RENDUS

PHYSIQUE

http://france.elsevier.com/direct/COMREN/

MCAO for very large telescopes/OAMC pour les très grands télescopes

On practical aspects of Laser Guide Stars

François Rigaut [*], Céline d'Orgeville

Gemini observatory, 670, N. A'Ohoku place, Hilo, HI 96720, USA

Abstract

The Gemini Observatory has developed an extensive Adaptive Optics (AO) program, including Classical AO, Laser Guide Star (LGS) AO, Multi-Conjugate AO (MCAO), extreme AO (eXAO) and Ground Layer AO (GLAO). Most of these instruments use one or several LGSs. A laser has been in operation at Gemini since May 2005. Most of the laser related systems (beam transport, launch, safety systems) have been developed in house. These are major components, requiring a development effort not to be underestimated. In this article, we propose to share the Gemini experience in terms of practical issues and calibration requirements associated with the use of lasers in AO. ***To cite this article: F. Rigaut, C. d'Orgeville, C. R. Physique 6 (2005).***

Résumé

De l'opération et calibrations des étoiles laser. L'observatoire Gemini a un programme d'Optique Adaptative (OA) très complet, qui inclut l'OA classique, l'OA avec étoile laser (LGS), l'OA multi-conjuguée, l'OA extrême et l'OA conjuguée au sol (grand champ). La plupart de ces instruments utilisent une ou plusieurs étoiles laser. Une étoile laser est en cours de commissionnement à Gemini depuis Mai 2005. Les systèmes annexes (transport et projection du faisceau, systèmes de securité) ont été développés en interne. L'effort lié à ces développements ne doit pas être sous-estimé. Dans cet article, nous nous proposons de partager l'expérience de Gemini dans les domaines pratiques du développement, de l'opération et des calibrations liés aux étoiles laser. ***Pour citer cet article : F. Rigaut, C. d'Orgeville, C. R. Physique 6 (2005).***

Keywords: Adaptive Optics; Laser Guide Star; Multiconjugate Adaptive Optics; Atmospheric Turbulence; Instrumentation

Mots-clés : Optique Adaptative ; Étoiles Laser ; Optique Adaptative Multi-Conjuguée ; Turbulence Atmosphérique ; Instrumentation

---

1. Introduction

In this article, we review many aspects related to the implementation of LGSs in an AO system. No new concepts are presented, and the content will be fairly well known to LGS specialists. Instead, our goal is two-fold: we would like first to review LGS concepts for newcomers, and second to emphasize issues that are often discarded as easy, but in fact require significant efforts when building a LGS AO system.

The first section briefly recalls some fundamental properties and limitations of LGSs. The second section describes the Gemini AO program. Next, we present the laser and other subsystems of the LGS facility such as the Beam Transfer Optics (BTO)

---

[*] Corresponding author.
E-mail addresses: frigaut@gemini.edu (F. Rigaut), cdorgeville@gemini.edu (C. d'Orgeville).

1631-0705/$ – see front matter © 2005 Published by Elsevier SAS on behalf of Académie des sciences.
doi:10.1016/j.crhy.2005.11.014

and the Laser Launch Telescope (LLT). The fourth section looks at various LGS-specific aspects of the AO LGS Wavefront Sensor (WFS). Finally, the fifth and last section expands on internal and external safety issues associated with LGSs.

2. Fundamental limitations of Laser Guide Stars

We believe the future of AO lies in Laser Guide Stars: they dramatically increase the sky coverage while retaining, under certain conditions, high compensation performance. LGS are already being used with success at several facilities (AFRL [1], Lick, Keck [2], Gemini and soon ESO). However, LGSs have limitations, which are very briefly recalled in this section (but references are provided for those who need more information). Note that we are considering mostly the use of Sodium GS. All effects described below also apply to Rayleigh guide stars [3], generally with even more detrimental effects.

2.1. Tilt/quadratic modes problem

As soon as lasers were proposed to create guide star for adaptive optics [4], it was realized that the LGS could not be used to measure tip-tilt [5] because the upgoing beam, going through atmospheric turbulence, is deflected by an unknown quantity. This has been analyzed and commented upon at length in the literature [6,7].

In multi-LGS, multi-conjugate AO systems, this effect generalizes into anisoplanatism modes, which include not only tip and tilt, but also quadratic modes (plate scale modes) [9,10]: in MCAO, the goal is to compensate not only for the phase perturbation on axis, but also for the anisoplanatism over a finite field, and in particular, tilt anisoplanatism. Tilt anisoplanatism manifests itself as a dynamic variation of the plate scale in the field. To determine plate scale, one needs to be able to measure the separation between several stars in the field of view. However, the location of each MCAO-LGSs is affected by upward tilt, hence the problem.

Although alternative methods have been proposed, this issue is generally solved by using one (LGSAO) or more (MCAO) natural guide stars, for tip-tilt determination only. Because the whole pupil can now be used to collect photons and because the isokinetic angle is slightly larger than the isoplanatic angle, this natural guide star (Tip-Tilt GS) is easier to find. The resulting sky coverage—typically 30%—is always quite larger than with NGSs. Another promising solution is the polychromatic LGS, which, by using two laser lines (UV and NIR) and leveraging the atmospheric refraction, aims at providing 100% sky coverage down to visible wavelengths [8].

2.2. Cone effect

An LGS is created at a finite altitude: in the sodium layer for a sodium GS—between 90 and 100 km—and typically at 10–25 km for a Rayleigh GS. The light coming back from this light source to the telescope aperture defines a cone, whereas the light coming from an object at infinity—for which compensation is sought—defines a cylinder. This means that (a) all the turbulence above the LGS altitude is missed, (b) all the turbulence outside the cone, but inside the cylinder is missed and (c) the turbulence within the cone is not well sampled (a wavefront over a smaller circle is applied to the full cylinder surface). (b) and (c) are in fact different aspects of the same physical phenomena. (a) is generally not an issue with Sodium GSs, given their altitudes, and (b) and (c) are significantly less serious with sodium LGSs than with Rayleigh LGSs, which explains why the former technique is preferred over the latter, even though it is significantly more challenging to build a Sodium laser than a laser used to create Rayleigh GS. One can see at once from geometrical considerations that the cone effect will become more serious as the telescope diameter increases. Typically, the cone effect will reduce the Strehl by half at 1.25 micron on a 8-m telescope. This has been studied extensively in the 1990s [12,11].

It is difficult, if not impossible, to compensate for the cone effect. MCAO with laser, to a large extent, compensate for the cone effect. This is because MCAO provides tomography of the turbulent medium, and therefore implicitly (or explicitly in some mathematical treatments) provides an estimate of the height of turbulence, and thus—the altitude being known—the cone effect can be mitigated [13–15].

2.3. LGS elongation, structure and Sodium layer saturation

As we enter the era of truly giant telescopes (at least appearing such to a 20th century man), another limitation of Sodium LGS becomes important: LGS spot elongation. The sodium layer is typically 10 km thick, hence the emitting LGS is in fact a column less than 1 m in diameter and 10 km in length. This 'star', viewed from the side, will thus be elongated, by about $1''$ for an observer located 4-m off-axis from the laser projector. This is significant for the current class of 8 to 10-m telescope, and has been a strong incentive for projecting from the center of the telescope (behind the secondary mirror). This is the configuration retained by Gemini and ESO. By contrast, and mostly due to other considerations, Keck uses a side projector. Consequently, the LGS images (Shack–Hartmann sensor spots) in the Keck system have up to $2.5''$ elongation. If nothing was done to mitigate this problem, 30-m telescopes will have up to 4 arcsec spot elongation, and OWL up to $12''$! To further complicate this problem, the sodium layer has some internal structure that can evolve on timescale of minutes [16]. Because the Shack–Hartmann spots are essentially a mini-image of the sodium layer vertical abundance distribution, this means that the center of gravity will evolve with time. In a system where the laser is launched on-axis (behind M2), this fortunately means only a radial change of the spot centroid, which only translate in focus. In a side-projection system, the effect is much more complex, and other methods (like 'truth sensors') have had to be developed [17].

Another effect that played a role in laser design, and was the subject of rather heated debates in the late 1990s, is saturation of the sodium layer. There is a finite number of atoms in each velocity class (from respect to a 'rest' observer on the ground), hence only a finite number of incoming photons can be absorbed during, say, the 16ns lifetime of the D2 sodium line. After that, the layer is said to saturate. In fact, saturation was proven lately to be a non-issue [18], at least for the kind of power needed for the generation of LGS for 8-m telescopes (about 10–30 $\mathrm{W\,m^{-2}}$ at the sodium layer). These saturation issues were what started research on custom laser formats, such as the modeless laser oscillator [19], used in the polychromatic laser.

3. The Gemini AO program

High angular resolution and low thermal emissivity are the two corner stones of the Gemini science program. Adaptive Optics has therefore a prime role to play in the observatory mission. Early instrumentation included Altair, the AO system for Gemini North. The first instrument ever on Gemini North was Hokupa'a, the 36 element curvature system, on loan—and operated by—the University of Hawaii. To serve its large community—Gemini is an international consortium whose member countries are the USA, UK, Canada, Australia, Chile, Brazil and Argentina—Gemini has embarked on a large scale AO program, including Altair NGS (already operating since late 2002 on Mauna Kea), Altair LGS (an upgrade being commissioned, to be offered to the community for 2006 semester B), the Gemini South Multi-conjugate AO system (MCAO, first light planned for early 2007), an extreme AO system, for which funding has been approved, and finally a Ground Conjugated AO system, for which a multi-institute feasibility study has been completed earlier this year and site testing is underway.

The Gemini AO program covers multiple AO disciplines and enables a very broad base of science programs. Its step-by-step approach also allows one to bring the Gemini AO group up to speed, while the group not only supports the commissioning and operation of the various instruments, but also the integration, and sometimes design and fabrication, of some of the facility systems. This includes all laser related systems—except the laser itself—which were designed and/or integrated by Gemini personnel: Beam Transfer Optics (BTO), Laser Launch Telescope (LLT) and Safety Systems. The BTO relay the laser beam from the laser itself (attached at the level of the telescope primary cell) to the back of the secondary mirror. Part of this system is shown in Fig. 2. The LLT forms the second part of the laser launch system and was designed and fabricated by EOST. The various MCAO subsystems are being fabricated at present. The MCAO final integration is the responsibility of the observatory.

Gemini has thus studied extensively laser guide star systems for AO, and has recently acquired some experience in dealing with their reality. It is this experience that we propose to share in this paper, in addressing practical aspects/calibration issues related to the use of lasers.

3.1. Gemini MCAO

The Gemini MCAO system and its expected performance are now briefly described.

MCAO studies started in 1999 at Gemini. After a couple of years working with the Gemini community to build up the MCAO science case, MCAO received funding, based on the following characteristics: telescope diameter 7.9 m; 3 Deformable mirrors conjugated to 0, 4.5 and 9 km; DMs pitch of 50 cm (1 m for the upper DM); 5 Sodium LGSs on a 1 arcmin square pattern (including one in the center); 3 NGSs for TT and anisoplanatism modes; 800 Hz sampling frequency.

It is worth underlining that the main drivers for MCAO were not only the gain in field of view (a factor 10 to 20 with respect to classical AO), but also the PSF uniformity. PSF variation and calibration has been one of the main limiting factor for the full exploitation of AO in the astronomical community. The field and uniformity advantage will result in significantly better photometry, and will benefit many science programs, ranging from stellar population studies to galaxy morphology, and gravitational lensing.

Below is a short summary of MCAO performance:

- Average Strehl ratios, under median seeing conditions, vary from 45% to 80% (AO only) in the 1–2.5 micron range and 0–30 degrees zenith angles, with relative uniformity (relative Strehl ratio standard deviation) from ±1.5 to 7% rms. When including the other terms in the error budget, Strehl ratio under average conditions are 20% in J (relative rms over 1 square

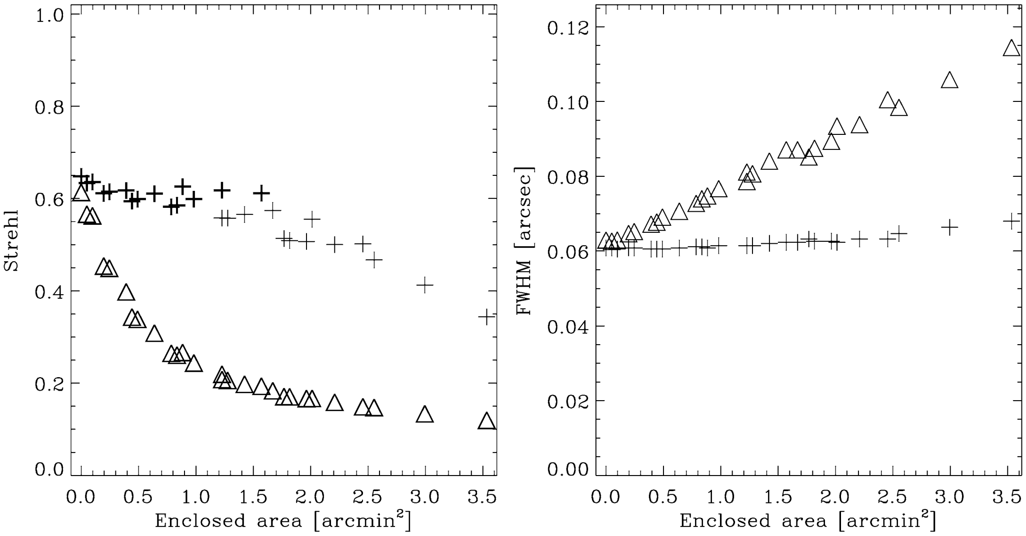

Fig. 1. MCAO example performance. K band Strehl ratio (left) and FWHM (right), for Classical AO (triangles) and MCAO (crosses). Reasonable assumptions for various terms in the error budget (windshake, static optical errors, etc.) are included.

Fig. 2. Side view of the Beam Transfer Optics (black boxes and silver tubes linking them). The beam is enclosed all the way from the laser box to the Laser Launch Telescope for safety reasons and to minimize dust deposits on optics and turbulence along the beam.

arcmin is 7%), 40% in H (rms 4%) and 60% in K (rms 2%). Fig. 1 shows an example of MCAO performance, compared to Classical AO. For more information on MCAO, see Ellerbroek et al. 2003 [14].

- The Strehl ratio degrades gracefully outside the 1 square arcmin central field. The usable field (with Strehl ratio above 50% of the peak value) corresponds to a full 2 arcmin field in H and K bands, and approximately to 1.5 arcmin at J.
- Three natural guide stars (NGS) are needed to get the best compensation from the MCAO system. Fortunately, the magnitude limits ($R \approx 19$) correspond to useful values for sky coverage ($\approx$15% at the galactic pole and $>$70% at 30 degrees galactic latitude), even when degrading effects such as sky background noise and windshake jitter are taken into account.
- The overall performance is a weak function of the exact match between the deformable mirror conjugation altitudes and the locations of the dominant turbulent layers.

– Under median seeing conditions, MCAO brings a 1.5 to 1.7 mag sensitivity gain over the 1–2.5 micron range on point sources with respect to seeing limited imaging. Gains with respect to HST/NICMOS, under the same conditions, are 0.3 (J) and 1.2 (K) magnitudes.

4. Laser, transport and launch systems

First, although 'yellow light' is used by many, the 589 nm line used in LGS AO (because it is one of the most efficient lines to use as far as cross-section and atom abundance is concerned) is not yellow. At least not at the power considered here. It is the same light used in city lights, and although the orange color of the latter is reinforced by red lines, the 589 nm is basically the same color. It even appears red to the eyes, at least when projected at 5–10 Watts levels and viewed from the side.

4.1. Laser

A photon, generated by a complex 589 nm laser, covers lots of ground before it is detected as part of a LGS AO guide star. At Gemini, we have elected to use a solid-state laser technology—developed by Coherent Technologies Incorporated—which at first proved more challenging to develop, but eventually offers interesting advantages compared to more classical dye laser technologies (Lick/LLNL, Keck/LLNL, ESO/Max Planck): for instance, solid-state lasers are cleaner, and are expected to require less maintenance than dye lasers (see Fig. 3). At Gemini, based on our short history of operation (about 15 nights as of August 2005), the laser typically requires 1–3 hours of preparation before the night, and usually behaves well from then on, with no manual intervention required. The power output varies between 7 to 13 Watts, with about 65% of this projected to the sky (upgrades to the BTO are underway to improve this last number). The laser is pulsed with 550 picoseconds pulses, and a 78 MHz repetition rate, which makes it appear continuous to the sodium atoms (the D2 line has a 16 nanoseconds life time). The pulse format enhances conversion efficiency in the non-linear PPSLT crystal, where two infra-red beams (1.06 micron and a 1.32 micron) are combined to output the 589 nm beam. Lifetime of the crystal has turned out to be an issue in the Gemini Altair laser. NSF-funded developments are underway to produce improved, power resistant crystals, with higher conversion efficiencies.

4.2. BTO and LLT

Whatever laser technique is used to produce it, this yellow photon must eventually be projected on the sky to form a laser guide star. At Gemini, we elected to use an on-axis projection system, sharing this choice with ESO, but not with Keck/LLNL, who chose to project their laser beam from the side of the telescope.

Projection from behind the telescope secondary mirror is challenging in many ways:

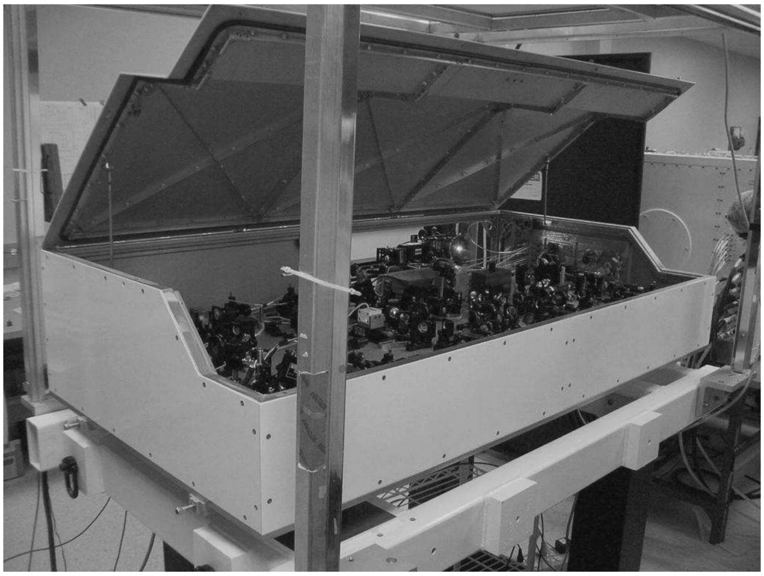

Fig. 3. The Gemini/CTI-built solid state 589 nm 13 W laser.

- First, laser launch systems have to be designed within a fairly limited space envelope. Optical launch designs with no central obstruction are often chosen, because a laser beam is Gaussian, with most of the power in the center. Gemini adopted an off-axis parabola design, which proved challenging to align. We are in the process of re-procuring a primary mirror for the launch telescope, the first one suffering from non-recoverable large aberrations consequent to a flaw in the thermal design of the mirror support.
- Second, it is often desirable to transport the laser beam hidden behind one of the secondary vane/spider, to minimize potential light scattering back to the (LGS) WFS. At most observatories, this is not an issue because of the large section of the said vane, but at Gemini, the vane section is 10 mm, designed to minimized the overall telescope thermal emissivity. The beam—expanded to 5 mm at this level to minimize beam divergence—has to be directed with sub-millimeter accuracy, and alignment must be maintained at all telescope elevations. This requires active compensation systems with close-loop control or, at least, flexure compensation look-up tables.
- Third, on-axis projection increases the number of relay mirrors, thus reducing the optical throughput. The laser path of the Gemini BTO + LLT systems, from the output of the laser and including the LLT primary, includes 10 mirrors (5 of which are served), 3 lenses, 2 dichroics, and 2 wave-plates. This puts heavy constraints on the quality of the various optical components, both in terms of wavefront error and optical throughput: laser power is expensive, thus should not be wasted during transport. Wavefront errors should also be minimized to enable a compact spot on the sky, therefore increasing the LGS WFS SNR to be able to reduce the laser power requirement (remember that the SNR on the Shack–Hartmann spot centroid determination depends on the spot FWHM and N_{photons}—the number of detected photons—as $\sqrt{N_{\mathrm{photons}}}/\mathrm{FWHM}$, so that decreasing the spot size from $2''$ to $1''$ at constant SNR is roughly equivalent to a gain of 4 in the number of required photons).[1]

However, projecting from behind the telescope secondary mirror has one major advantage: it minimizes the geometric elongation of the spot over the telescope pupil, and makes this elongation more symmetrical, thus easier to deal with.[2]

A fiber transport system, such as that designed by ESO [20], potentially has many advantages compared to an all-mirror system as used by Gemini, because it alleviates most of the problems listed above. But fibers come with their own problems, and their use at Gemini was precluded by high laser peak power (about 10 times the power of a true CW laser such as the Max-Planck dye laser used by ESO) and consequent non-linear effects in the fiber (e.g., Stimulated Brillouin Scattering) which would have limited fiber throughput to unacceptable levels. However, new fiber technologies, like hollow crystal fibers, offer the promise of much higher power thresholds for laser beam transport, and will most likely be the preferred solution for longer-term LGS AO projects.

5. LGS wavefront sensors

5.1. Optical design

It must be said and repeated that optical design for LGS WFS is noticeably more complex than for NGS WFS. Indeed the LGS is not only at a smaller and different range than the NGS, but the range also varies (typically from 90 to 200 km for a system operating from zenith to 60 degrees zenith angle). In a single LGS system, the problem boils down to designing an optical zoom that compensates for this variable range. This means not only compensating the first order focus, but also higher order aberrations (spherical) that result from using the telescope far from its optimal configuration. On top of that, not only wavefront quality, but also pupil distortion has to be controlled (generally to a level of 5–10% of a subaperture). In Altair, the Gemini North AO system, all of this means 3 moving elements and additional lenses compared to a traditional NGS Shack–Hartmann WFS.

In a MCAO system, the problem becomes even more complex. Not only the same conditions prevail (shorter and variable range), but the LGSs are *off-axis*, which means added complexity in the optical design as, again, wavefront quality and pupil distortion have to be controlled. In the Gemini MCAO system (5 LGSs), the LGS WFS was a subsystem in itself, subcontracted to tOSC (Anaheim, California). tOSC went through many iterations of the optical design and ended with what appeared like the simplest system, using 4 motion controls and many lenses.

---

[1] This is true if the read-out noise is negligible, which is generally the case for LGS applications: given the spot size—even at $1''$ FWHM—many photons are needed to meet the requirement in SNR.

[2] Due to purely geometric effects, and for a 10 km thick sodium layer at 90 km, Shack–Hartmann spots are elongated radially from the propagation axis with an amplitude of roughly $0.25''$ per meter off-axis.

5.2. Spot dithering (for quadcells)

Due to the finite LGS range, the spot size on the LGS WFS depends on the location in the telescope pupil of the Shack–Hartmann subaperture (geometric elongation, see above). If one uses quad-cell in each subapertures, a centroid gain has to be determined for each of these. Centroid gains, for quad-cells, is a way to translate the unitless signal from the quadcell to a meaningful physical signal in arcsec. Historically, quad-cells have been used more in the US community (Keck, Gemini, USAF) than in the European Community (COME-ON, ADONIS, NAOS, Alfa), which generally used many pixels across each subaperture spot. Quad-cell designs have the advantage that less read-out noise is injected into the measurement, therefore fainter limiting magnitudes can potentially be reached, although smart thresholding detection techniques can be devised—for multi-pixel configuration—to reduce this advantage. On the other hand, quad-cells suffer from quantization effect due to the large size of the pixels, and the need for centroid gains to get a meaningful signal.

Centroid gains are a function of the size and shape of the spots, and in turn depend for LGS operation on (a) the seeing, (b) the projected laser beam quality, and (c) the geometric properties of the sodium layer (range, thickness and profile). For the quadcell configuration, it was proposed some time ago to measure the centroid gain by inducing a known dither on the measured spot: imagine you are steering each spot along a circular motion of a known quantity, at a particular temporal frequency. The ratio of the measured motion at the said frequency (through lock-in detection or integration of the energy in a narrow band in the signal Power Spectral Density) and the known injected motion gives a direct measurement of the error in the centroid gain. If one steers the spots along a circle of 0.1 arcsec and one measures only 0.07 arcsec, one can immediately compensate the centroid gain estimation by this given factor $0.1/0.07$. This can be done for each subaperture, and for both the X and Y components.The obvious advantage of this method is that it requires no assumption on the image creation process and other possible unknowns in the system: the determination is done directly on the quantity that one is interested in, and the only limitations are (a) that it requires a good calibration of the device that does the dithering and (b) that the measurement is done often enough with respect to how fast the centroid gain evolves.

This method is also used in NGS systems. In this later case, one could use, as dithering agent, an optical element in the NGS WFS path (i.e., after the separation from science and WFS beams)[3] In LGS systems, one can use an optical element in the launch system to actually dither the laser spot *on the sky*. In Altair, we use the fast TT mirror in the launch system to perform this function, with a dithering amplitude of 0.1 arcsec, to give enough signal compared to the spot size (currently between 2.0 and 2.5 arcsec FWHM, hopefully improved in the near future). A clean measurement of the centroid gain can be obtained at about a 0.1 Hz rate.

5.3. Rayleigh background

Most of the laser light that comes back into the AO system does not come from the LGS, but from Rayleigh low altitude backscattering (typically up to 30 km). In a single LGS system, there are several ways to get rid of the useless Rayleigh photons. One can use a spatial filtering (Section 5.3.1) or temporal filtering (Section 5.3.2).

5.3.1. Spatial separation

The Rayleigh light is spatially separated from the LGS itself because it does not come from the same altitude: therefore, viewed from the side, it will be angularly separated from it. Putting a field stop can therefore isolate the LGS from the parasitic Rayleigh. The separation from the top of the Rayleigh to the LGS is purely geometrical and depends on the distance between the projection axis and the subaperture location in the pupil, the zenith angle, and the seeing. At Gemini, we are currently using a 4 arcsec field stop which is not entirely adequate—i.e., some Rayleigh gets through—for the central subapertures[4] when the seeing is bad. This is another incentive to work to get a tighter LGS spot—currently, typical spot size is 2.2 arcsec FWHM, best case 1.5 arcsec—which will allow us to reduce the size of the field stop and thus get better Rayleigh filtering.

Note that the problem becomes more complicated when dealing with multi-LGS systems. In the Gemini MCAO, 5 LGS are projected. From basic geometric considerations, it is easy to see that, in a LGS system projecting from behind the secondary, it is unavoidable that some subapertures looking at LGS number N will be polluted by the Rayleigh light from some of the other LGSs. This is the so-called 'fratricide' effect. It is possible to circumvent this problem by using projectors located on the side of the telescope pupil[5] (one for each LGS), but at the expense of spot elongation (notwithstanding the much higher cost of such

---

[3] In Altair, because this method was not considered at design time, we have to use the Tip-Tilt mirror, and therefore use a very small dithering amplitude not to degrade the quality of the compensated image.

[4] Note that Gemini uses a 1-m diameter secondary mirror, so in the case of Altair (a 12 × 12 Shack–Hartmann system), the minimum distance from a valid subaperture to the laser projection axis is 1.04 m.

[5] Note that even this method will not completely eliminate the problem, as it does not work for the central LGS, only for geometry in which all LGSs are located on a circle.

an option). One way out is to use temporal limitation (see below), or to somehow calibrate out the Rayleigh background (this last option was retained for the Gemini MCAO system). Such a background calibration relies on a good stability of (a) the laser power, (b) the scattering properties of the atmosphere, and (c) the beam geometry.

5.3.2. Temporal separation

If the laser is pulsed, one can gate the Rayleigh light out, which comes back sooner than the LGS light. Simple calculations will set the limit conditions on the laser duty cycle and laser pulse rate versus the sodium layer distance/telescope elevation. This has been published and is not the subject of this article. Note, however, that making high power pulsed lasers with such format can be challenging (it has not been done to date). It also creates additional complexities in the system design, as the main AO loop/CCD integration has to be synchronized with the laser pulses (or vice versa).

6. Safety systems

The ensemble of safety systems is another area which is often dismissed as being straightforward, but, at least at Gemini, ended up requiring a sizable amount of effort and investment. These are multi-facetted but all result from the fact that a 10 W 589 nm laser (not mentioning a 50 W laser, as those needed for MCAO or GLAO applications) is not eye safe. It is obviously not when it is a few mm in diameter, neither is it when expanded for propagation, typically to 2–3 r_0 (the Gemini beam diameter is 30 cm at $1/e^2$ intensity points). Because the projected beam is collimated, it remains 'unsafe' up to high altitudes, including for aircraft pilots whose plane would—unluckily—cross the beam. The fact that sheer probability considerations—the sky is vast and the beam is small—geometry considerations—we generally propagate at zenith angles $\leqslant 60$ degrees—or time consideration—an aircraft crossing the beam at 250 km/h would cross a 30 cm beam in 4 millisecond—make this event highly unlikely has nothing to do with the need for safety systems. A 'collision' *is* possible, and no one wants to take the chance to bring down an airliner with 400 passengers aboard. In any case, laser safety standards for outdoor propagation require that dedicated safety systems be implemented.

On top of this possible 'pilot blinding' issue, there is another type of 'external' issue: satellite avoidance. Many satellites are equipped with stabilization sensors, or other type of sensors functioning at visible wavelengths. These are at risk to be blinded (if not damaged) by the highly collimated laser beam. Thus, even though it is not a requirement for most civil astronomical observatories, it is politically responsible to have laser propagations cleared by a central organism (the 'laser clearing house' of Space Command in the United States).

Other, more classical types of safety issues include personnel safety and hardware safety. The possibility of blinding someone working in the vicinity of the laser, or triggering a fire is very real (as we have experienced at Gemini), and should be taken very seriously.

At Gemini, we have several layers of safety systems:

- for 'external' safety issues:
  - spotters, i.e., humans that watch the sky for approaching aircrafts and clouds
  - an 'all-sky camera', i.e., a camera with a fish-eye lens, together with the software to detect planes (and possibly clouds)
  - a thermal camera, with a field of 15 degrees, as a last resort to detect the heat emitted by the reactors of an airliner that would not have been detected by previous safety layers.
  - a Laser Traffic Control System (LTCS), that checks possible 'collisions' of the propagated laser with the line of sight of neighbor observatories and shuts down the laser when such a collision is detected.
- for 'internal' safety issues, Gemini has put in place a complex set of rules and interlock systems.

6.1. Safety cameras

Our dedicated All-Sky Camera takes images every 7 seconds. These images are processed on the fly (1 sec processing time) to detect moving objects. Aircrafts appear to be detected with a probability higher than 99%, with a lead time of a minute or so. The Mauna Kea ASCAM has been damaged by sun light, and is in the process of being replaced. Successful tests of our software have been done with sequences of images taken at Palomar observatory, where the density of airplanes is much higher than at Mauna Kea (less than one plane spotted per night at MK). The moon is an issue: it is difficult for a fully automated ASCAM to stay absolutely clean; most of these devices are protected by a transparent hemispheric shell, which is (a) generally not of very good optical quality, thus likely to induce speckles/ghosts and (b) open to the elements and is prone to accumulate dust quite rapidly. This spreads the moon light over a large area of the CCD, thus preventing detection of moving objects. This issue is not yet solved. A retractable protecting dome and an optical quality shell are being considered.

6.2. Laser traffic control

When in an heterogeneous observatory like Mauna Kea, one must keep good relationships with one's neighbors. Propagating a 589 nm laser beam across the line of sight of a neighbor telescope when the later is doing spectroscopy or guiding on a very faint target is not the best recipe to insure this [23]. A group was created several years ago at Mauna Kea to deal with this situation [21]. It was decided, soundly enough, that the telescope propagating the laser (active) should give way to passive telescopes. A software [22] was written that computes, and predicts, collisions. Each telescope is responsible to (a) post its current pointing coordinates, (b) post a 'laser impacted/non-impacted' state and, for the laser active telescope, process the 'collision' signal and shutter its laser. The collision predictions/status are available through a web interface. During technical commissioning of the Altair LGS mode at Gemini (including significant time spent propagating at zenith), we have experienced collisions at the level of 1–4 a night, with downtimes from 5 to 20 mn. We typically elect to switch to a different science target when the down-time is calculated to exceed 10 mn.

6.3. Propagation clearance

For observatories under US jurisdiction, propagation clearance must be sought from the US Space Command's Laser Clearing House (LCH) for satellites, and from the Federal Aviation Administration (FAA) for planes (on top of the ASCAM/spotters), even though—in our case—Mauna Kea is a no-flying zone. These administrations are contacted several days in advance (typically 3 days for the LCH). For satellite avoidance, a list of possible targets is sent, with observing time windows. The LCH replies on a day-to-day basis with a go/no-go for individual targets.

6.4. Spotters and insurance

As a temporary measure, while waiting for our other safety systems to be commissioned and approved by the FAA, Gemini uses spotters, i.e., people hired to spend time outside the observatory, checking the sky for approaching airplanes, or clouds that could perturb other observatories by increasing low altitude backscattered laser light. We hope eventually to be able to get rid of this crew, to reduce laser operation overheads and augment flexibility in scheduling laser runs.

It turns out that the observatory has had to take an insurance, despite all the safety measures, just in case the laser would bring down an airplane. This might or might not be needed by other AO laser operations, but should be considered early in any LGS AO project. Insurance fees are non-negligible and should be accounted for early on in the budget.

6.5. Interlock systems

Last but not least, safe laser propagation inside and outside any observatory is regulated by well-defined standards and regulations.

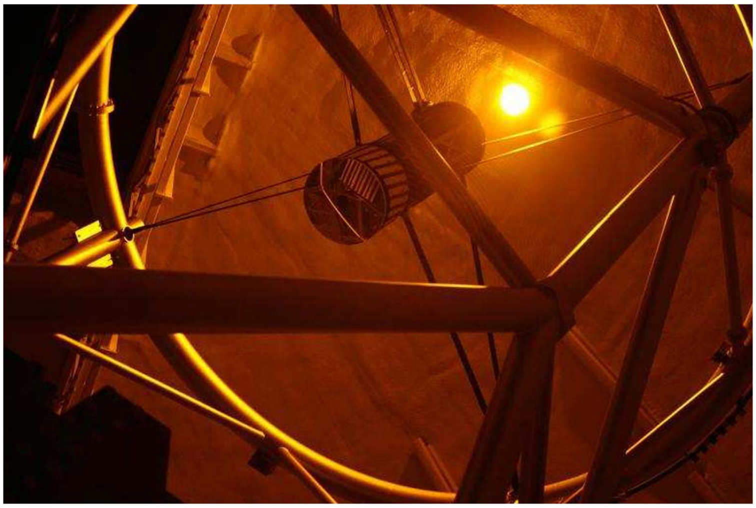

Fig. 4. Image of the laser beam on the inside of the dome. The laser generally provides a beam with M2 $\leqslant 1.2$.

The detailed safety measures to be implemented will depend on the type of laser and the detailed laser path. However general guidelines apply, such as the need to appoint a Laser Safety Officer (LSO) and provide the LSO with appropriate training to carry out a thorough hazard evaluation analysis and derive the corresponding control measures to ensure that the risk level (for both personnel and hardware) is always minimal in all situations. A hardware-based, fully automated system will typically be preferred to implement the interlock system that will handle the large number of inputs required from all the LGS AO facility and telescope subsystems and generate the corresponding outputs to ensure safe laser operation at all times.

At Gemini, we designed our Laser Interlock System (LIS) as a subsystem of the PLC-based Gemini Interlock System (GIS). The LIS currently receives inputs from the safety shutter, the laser, the BTO, the spotters and Altair, and determine the action to be taken, if any. Safety issues which involve personnel safety and/or require a fast response time typically result in closing the fast safety shutter or powering down the laser, while other safety issues (e.g., beam collision detected by the LTCS) only result in shuttering the laser beam at the input of the LLT, thus maintaining closed-loop BT alignment of the laser beam to the top-end. The LIS not only controls the safety shutter and sends signals to the laser and BTO to close their own shutters, but it also send signals to stop or pause the various open and closed loops implemented across the LGS facility and the AO system itself.

7. Conclusion

The future of AO lies in Laser Guide Stars: they dramatically increase the sky coverage while retaining high compensation performance. Several types of lasers now exist and have been demonstrated in the field. Even though, the laser itself was—and remains—the most important subsystem (beside the AO system itself), implementing a LGS requires much more than a laser. All the launch systems, AO LGS WFS and the various—but mandatory—safety systems represent significant additional complexities and investments, at least for the first LGS systems—while the technology is still being developed.

Acknowledgements

The Gemini Observatory is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under a cooperative agreement with the National Science Fundation (NSF) on behalf of the Gemini partnership: the NSF (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil), and CONICET (Argentina).

References

[1] R. Fugate, SPIE 2201 (1994) 10–21.
[2] J. Melbourne, et al., Astrophys. J. 625 (1) (2005) L27–L30.
[3] L.A. Thompson, et al., SPIE 5490 (2004) 90–96.
[4] R. Foy, A. Labeyrie, Astron. Astrophys. 152 (2) (1985) L29–L31.
[5] J.D.H. Pilkington, Nature 330 (1987) 116.
[6] F. Rigaut, E. Gendron, Astron. Astrophys. 261 (2) (1992) 677–684.
[7] R. Ragazzoni, in: N. Ageorges, C. Fainty (Eds.), Laser Guide Star Adaptive Optics for Astronomy, Kluwer Academic Publishers, Dordrecht, 2000, p. 125.
[8] M. Schöck, et al., MNRAS 337 (2002) 910–920.
[9] B.L. Ellerbroek, F. Rigaut, JOSA A 18 (10) (2001) 2539–2547.
[10] R. Flicker, Astron. Astrophys. 400 (2003) 1199–1207.
[11] R. Foy, in: N. Ageorges, C. Fainty (Eds.), Laser Guide Star Adaptive Optics for Astronomy, Kluwer Academic Publishers, Dordrecht, 2000, p. 107.
[12] M. Tallon, R. Foy, Astron. Astrophys. 235 (1–2) (1990) 549–557.
[13] E. Viard, et al., Appl. Optics 41 (1) (2002) 11–20.
[14] B. Ellerbroek, F. Rigaut, et al., SPIE 4839 (2003) 55–66.
[15] M. Le Louarn, MNRAS 334 (4) (2002) 865–874.
[16] C. d'Orgeville, et al., SPIE 4839 (2003) 492–503.
[17] A. Bouchez, et al., SPIE 5490 (2004) 321–330.
[18] C. Denman, et al., SPIE 5707 (2005) 46–49.
[19] J.-P. Pique, S. Farinotti, JOSAB 20 (2003) 2093–2101.
[20] D. Bonaccini, et al., Messenger 114 (2003) 15–19.
[21] P. Wizinowich, et al., SPIE 3353 (1998) 290–299.
[22] D. Summers, et al., SPIE 4839 (2003) 440–451.
[23] Y. Hayano, et al., PASP 115 (814) (2003) 1419–1428.