Laser Operations at the 8-10m class telescopes Gemini, Keck and the VLT: lessons learned, old and new challenges.

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ABSTRACT

Laser Guide Star (LGS) assisted Adaptive Optics routine operations have commenced at three of the major astronomical observatories, in 2004 (Keck) and 2006 (VLT and Gemini) respectively. Subaru is also on the verge of putting its LGS facility into operations. In this paper we concentrate on the operational aspect of the laser facilities: we discuss common problems such as weather constraints, beam collisions, aircraft avoidance and optimal telescope scheduling. We highlight important differences between the observatories, especially in view of the valuable lessons learnt. While it is true that the three observatories have made quick progress and achieved important scientific results during the first years of operations, there is much room left for improvement in terms of the efficiency that can be obtained on sky. We compare and contrast the more recently implemented LGS systems of VLT and Gemini operated in service and queue modes to the more mature LGS operation at Keck that employs classical PI scheduled observing.

Keywords: Adaptive Optics, Laser Guide Star, Operations

1. INTRODUCTION

Adaptive Optics (AO) in astronomy has become a routine observing technique allowing diffraction limited observations at all major astronomical observatories. Adaptive Optics relies on the availability of a relatively bright “AO reference” star (natural guide star or NGS) to measure the atmospheric turbulence and remove its effects from the scientific images. The reference star’s brightness-limits range between 12 and 16 magnitudes in the optical (usually V or R band) and represent the main limitation to the use of AO assisted instruments. Moreover, because of angular anisoplanatism, atmospheric compensation by an AO system using a NGS can only be performed in a small area (of a radius of a few tenths of arcseconds) around the scientific target of interest, further limiting the number of targets that can be observed. Anisoplanatism combined with the brightness-limits result in a very limited fraction of the sky that can be observed with AO.

In order to mitigate this problem, the use of artificial beacons or Laser Guide Stars (LGS), generated by the backscattered light from Earth’s atmosphere, was already envisioned in the eighties[1,2]. Calar Alto and Lick Observatories were the first to routinely use a LGS assisted AO system for astronomical observations and the first refereed paper appeared in 1995[3]. Since those pioneering times, the use of LGS AO has rapidly gained momentum and three of the major astronomical observatories have equipped their instruments with it: Keck’s LGS became operational in 2004 (first light Sep. 9, 2003), followed by the Very Large Telescope (VLT) (first light Jan. 28, 2006) and Gemini North (first light March, 2005) in 2006. Subaru (first light Oct. 9 2006) will soon offer its system to the community.

The combination of a complex technology such as AO with the new and challenging LGS system proved to be more complicated than first envisaged, delaying somewhat the onset of stable (as opposed to shared-risk) on-sky operations at the telescopes. Since the first years, LGS AO has become a more mature technology. Operators and astronomers have gained “in-the-field” experience, which is now our valuable ally in pursuing the next generation AO projects, such as multi-laser star tomography and laser assisted multi-conjugate adaptive optics systems (e.g.. Keck’s NGAO[4], Gemini’s GeMs[5] and VLT’s Adaptive Optics Facility[6]).

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In the next sections we will discuss the main factors affecting LGS operations at Keck, VLT and Gemini, such as weather conditions and the constraints they put on scheduling and optimized observations, such as safety (aircraft collision) and neighbourly practices (i.e. how not to disrupt simultaneous observations on other close-by telescopes).

Figure 1: (left) Three lasers operating on Mauna Kea, From left to right, Gemini, Subaru and Keck II (Photo: Tetsuharu Fuse, Subaru, NAOJ). (Right) Laser propagating from Yepun during first light (ESO PR Photo 0607a, credit: G. Huedepohl) .

2. LGS SPECIFICATIONS AND AVAILABILITY

The LGS systems of the three observatories (see Fig. 1) share many commonalities: all three are sodium (Na) lasers, Keck's[8] and the VLT[9] use dye technology, with >10 W power at 589nm, corresponding to an artificial star magnitude of $9.5<V<11.0$, depending on laser power, beam collimation, and Na column density. Yepun's[*] LGS has demonstrated to offer sufficient return on the WFS with >4W on sky, with both SINFONI and NACO, the two instruments equipped with an AO bonnette. The LGS system on Keck II serves NIRC2, OSIRIS and NIRSPAO. At Gemini North a solid state technology LGS is used with the facility adaptive optics instrument Altair[7], in operations since 2003 and retrofitted with a new wavefront sensor to be used with the laser. Altair feeds NIFS and NIRI. Dye lasers reached technological maturity first, when compared to solid state lasers, although a significant effort was required to overcome certain technical limitations. The VLT is considering options to upgrade their dye laser to solid state and Keck is currently commissioning a solid state laser on the Keck I AO system. Gemini opted for solid-state lasers, which are relatively new in the field, but offer, in comparison with dye lasers, reduced technology risks and a chance to get ready for the subsequent 5-LGS needed by Gemini South's MCAO system[10], which uses a single 50 W laser.

The technical difficulties associated with dye laser technology also meant that both Keck and VLT had to devote quite some time during commissioning and during the first years of operations to optimize their systems on sky, with obvious delays in reaching peak performance and quite some downtime initially lost on technical problems. The maintenance requirements also meant that laser-assisted operations could not be offered on-demand, but had to be planned in advance and scheduled in blocks. This had a minimal impact on the *modus-operandi* of Keck which operates in a classic "PI visitor mode", aside from the obvious disappointment when astronomers lose their nights to technical problems. The

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[*] Yepun or UT4 is the 4th unit telescope at the VLT, the one equipped with the LGS system.

Keck II laser startup and operation support has become routine in that laser reliability is no longer a factor for scheduling considerations, although other issues like those discussed below lend themselves to block scheduling. However, this issue has a much larger impact on "service mode" (VLT) or queue-scheduling (Gemini) schemes, where the observations, which should be optimized according to best suited weather and observing conditions, are constrained within observing windows, typically a week or so each month. This significantly lowers the chances of getting the best conditions. In the case of Keck and VLT, thanks to the accumulated experience during the years, technicians are now able to align the system (one of the most time consuming tasks associated with the maintenance of a dye laser) in much less than the initial two days. The consequence is that both observatories have recently been able to offer their lasers for more nights. Keck has increased from the initial 12 nights/semester in 2001 to over 50 by 2006, while VLT, now routinely offers 8-9 nights (10hrs each nights) a month, up from the ~6-7 in 2008. As of 2009B, Gemini had the laser scheduled ~ 60 nights/semester, up from ~30 nights in 2007B.

Having a laser night scheduled and the system aligned ("availability") is only the beginning of the story in terms of operations. Once a night is allocated other factors contribute to the final "scientific" availability of the laser, or "LGS-time". First of all, one has to consider the additional technical downtime experienced once on sky. These include power losses/variability to wavelength instabilities, mechanical failures to both the laser system or the accessory components (e.g. the launch telescope), and software issues and interface problems (telescope-laser, laser-instruments. All observatories have experienced, sooner rather than later, a profusion of those technical issues, which made the initial technical availability figures on sky quite a depressing fact. It is reasonable to say, with a posteriori insight, that the problems are less system-specific and more the result of using a technology one order of magnitude (some argue more) more complex than even a typical NGS-AO system. The LGS system can be considered to be another "instrument" interfaced to the telescope, to an AO bonnette and to one or more instruments (two in the case of VLT and Gemini, and three in the case of Keck). The additional level of complexity could be compensated in time by the technical experience gained on sky, as any technicians at the observatories can confirm. And with rather impressive results: in the laser specific time-lost statistics published by Keck [21] the average 4-years technical downtime is ~3.5% of the total laser time, improving to ~3% when one considers the last 12 months of operations. Given a sufficient amount of dedicated resources and time, it is possible to bring the technical downtime to "physiological numbers". VLT, which is now in the 10-12% level, hopes to soon reach those levels once the experience gap, due to its late deployment on sky with respect to Keck, is closed. Over past two years there have been significant improvements to Gemini's laser. These include an improved operational mode with an improved staffing model, documentation, training and certification; regular (monthly) debriefings; hardware upgrades for reliability; and a full time laser operator/night leaving technical and engineering staff available for daytime work. This has led to increased reliability with nightly loss of usable time decreasing from 2.4% in 2007B to 0.12% in 2009B. However, there have been recent problems with the Gemini beam transfer optics which led to nightly loss of usable time increasing from 0% in 2007B to ~ 3% in 2009B.

Downstream of the achieved "technical" availability many factors contribute to the erosion of its figure: some of them are unavoidable, such as poor weather conditions, some others, such as the collisions with neighboring telescopes, can be avoided by means of careful planning, better forecasting, improved software tools and operational ingenuity. In the next sessions we will discuss these effects in greater detail.

3. LGS AO OPERATIONS AND WEATHER CONDITIONS

Weather downtime represents one of the few inescapable time losses, even on excellent sites such as Mauna Kea and Paranal. Aside from the obvious case of dome-closed, when no observations at all are possible, weather conditions seem to affect LGS operations more than normal and NGS-AO assisted operations. In the course of the past years, weather downtime statistics during LGS observations has contributed to ~27% weather downtime on Mauna Kea and up to 34% on Paranal: this latter figure has been refined to distinguish between dome-closed conditions (9%), clouds (~8%) and other meteorological causes (high humidity, high winds, poor seeing and short coherence time, 17%) in the course of 13 months of operations. Aside from the case when conditions are too poor to observe, one wonders whether something can be done to improve the "weather-clouds" and the "weather-other" statistics.

First of all one has to define what "clouds" means in terms of laser operations. Clouds can affect laser operations in various ways. In particular when thick clouds are present the laser light cannot go (and come) through without suffering significant attenuation (in some cases thick clouds can lead to dome-closed conditions, given that telescope operators are instructed to close if the risk of precipitation is non-negligible)

In all other cases, we are talking about "thin" clouds (including veils or patchy cirri condition), which can prevent or stop propagation particularly in the following cases:

1) The telescope is pointed at an object, the laser is propagating and the loop cannot be closed because the flux is too low. The typical criteria to judge whether the laser should be used is the amount of extinction, which should be lower than 1 magnitude to allow observations.
2) The telescope is pointed at an object, the laser is propagating and the loop is closed on the laser, but unstable: either it opens and/or the performance is highly variable, affecting the overall data quality.
3) The laser is pointing through clouds and, as a result of light scattering, it contaminates the sky, affecting either neighboring telescopes and their instruments or the propagating telescope itself.

In the first case, Keck uses photometric measurements from the tip/tilt sensor of the guide star to measure the extinction and, if less then 1 magnitude, laser propagation is attempted. The value of 1 magnitude extinction corresponds to the point at which laser return from cloud backscatter dominates the Na layer return and thus AO correction from the LGS is not feasible. One magnitude of extinction has also been judged as the point that aircraft detection (see section 5 below) is compromised so there are multiple reasons to halt laser propagation in these cloudy conditions. At the VLT, where LGS observations have, until recently, only been performed in service-mode, often it is preferred to execute no-AO or bright-NGS AO observations to avoid excessive downtime: in other terms, the availability of a large quantity of observing blocks (also called OBs, that is independent observational units) that can use thin-cirrus conditions and still produce high-quality science data, has somewhat induced a more conservative approach. In order to maximize the amount of time dedicated to LGS observations during an LGS window in the telescope schedule, a new policy has been recently introduced in Paranal to give priority to LGS over non-LGS observations. For Gemini, LGS programs take priority when the laser is operational and the observing conditions hold, i.e. seeing < 0.8″ and light clouds. There are exceptions for targets of opportunity and for high priority programs.

In the second case (unstable loop), while it is recognized that sometimes wavefront sensing is prevented or made difficult by the presence of variable cirrus conditions, not much has yet been done to quantify the effect in order to alleviate the problem, if possible. Additional studies are underway to quantify the effects of the clouds on the laser spots in the WFS and to see whether it is possible to modify the RTC algorithms to make the system less sensitive to laser spots variations (e.g. using cleverer weighted centroiding algorithms).

The third case (contamination of the other neighboring telescopes) is a specific type of collision which will be discussed in the next section. Note, however, that the cloud contamination in the wavefront sensor of the telescope propagating the laser beams is exacerbated by the on-axis central propagation of the laser (i.e. from behind the secondary, as in the case of the VLT and Gemini) rather than with the side propagation, as it is the case for Keck.

Weather loss due to bad seeing is a problem that affects wavefront sensors with small field of view sub-apertures, when compared to the spot size. The spot size depends on many factors, such the quality of the launch telescope, but it is obviously also affected by airmass (never observe at airmass higher than 1.6, if possible!) and the actual seeing. The seeing value beyond which laser observations are not possible is about 1.4" at the VLT, which accounts for 10% of the nights, according to the DIMM seeing statistics collected in 9 years of operations. Keck operates LGS AO in poor seeing conditions with use of a 2.4" sub-aperture and the ability to adjust centroid gain as a function of seeing and spot elongation.

The effects of weather downtime can also be mitigated with the help of some tools, the use of which has been recently introduced. One good example comes from the Paranal Observatory, where sophisticated weather forecasting provides a powerful planning tool for the short term observational schedule (day-to-day up to one week). As seen in Figure 2, a service mode observation week can be optimized around the predicted periods of quiet wind (wind below 40m/s), leaving the most turbulent nights for less demanding, in terms of weather parameters, observations.

Despite its usefulness, weather forecasting is certainly not enough. In service mode/queue-scheduling the night operators face the difficult task of having to predict the behavior of the system, or adjust it to optimize performance, without having enough information concerning the weather conditions. In classical observing, the astronomer needs to take real-time decision to maximize its observing efficiency (telescope time is hard to get!) and to be ready to choose the best backup targets in case of bad weather.

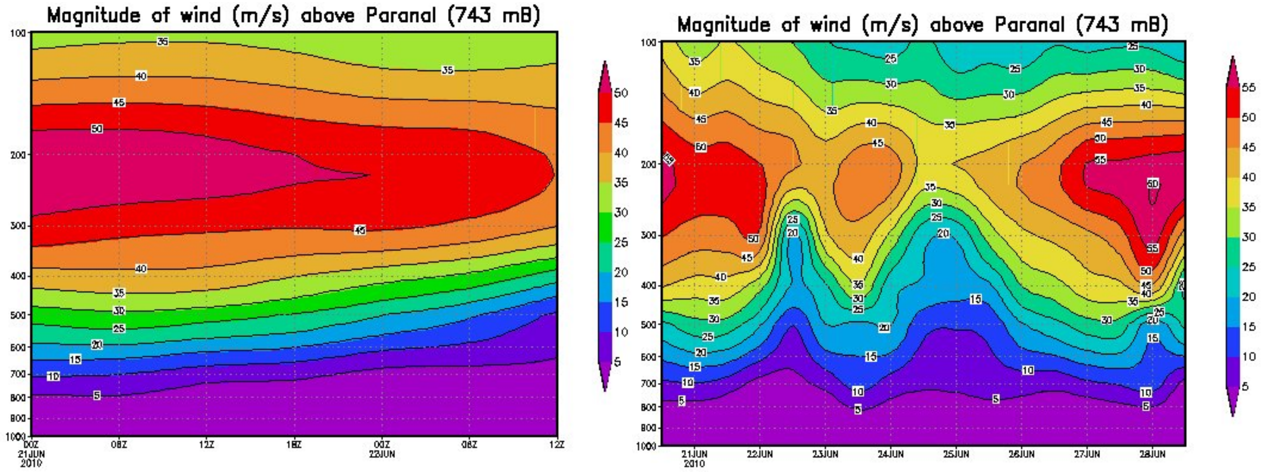

Figure 2: examples of weather forecasting at the Paranal Observatory. The strength of the wind at 12 km (200mB) is usually a good estimator of the stability of seeing. Winds in excess of 40m/s usually prevent good AO observations (with or without the laser). Looking at the one-week forecast (right) one observer could chose to observe more demanding targets (in terms of required AO performance) whenever no wind "bubbles" are present, such as the night between Jun 24 and 26 in the picture. The more accurate night forecast (left), with winds in excess of 50m/s, suggests that less demanding observations should be preferred.

In the case of clouds, aside from obvious cases, such as total coverage, which can be seen by simple all-sky cameras installed at almost every major observatory, there is no dedicated tool to help decide whether there are clouds, where they are, what type are they (thin veils, thick patches, etc). The impact of unknown weather conditions on the LGS observations is difficult to quantify. Currently Paranal is equipped with the all sky camera, which is just a visual tool, and LOSSAM (Line Of Sight Sky Absorption Monitor), which estimates the sky absorption from the variability of the average flux of a bright star used for seeing measurements. Being a line of sight instrument, LOSSAM alone cannot give a global view of the sky conditions, and it fails to measure under very bad seeing and with overcast sky. Recently, a new all sky instrument, called Lightmeter[19], has been tested and its performance compared to that of LOSSAM. The Lightmeter is able to measure the whole sky brightness in real time with specified sampling. Its plots can be used to distinguish between various meteorological conditions: thin or thick clouds can be easily recognized against the characteristic sky brightness plot as rapid modulations (Figure 3).

A final consideration on the weather has to do with its stability, or lack thereof. Even a night with an average 0.6" or better seeing but with variable coherence time, can diminish the scientific value of the data if the variability of these parameters is too high. This aspect that has not yet been quantified nor studied in detail, even though a preliminary analysis has shown that the seeing is better than 0.6" during one consecutive hour 7-10% of the time on Paranal. More studies are necessary to decide how critical is the impact of weather parameters instability of for LGS observations. Mitigating measures include, for instance, forcing the data acquisition system (whenever the science target allows it) to take shorter exposures for post-observations frame selection and/or to introduce (especially for service mode observations) more flexibility in the duration of the observational unit, typically in the range of 30 minutes – 1 hour, which could be fractioned into more blocks of shorter exposure time.

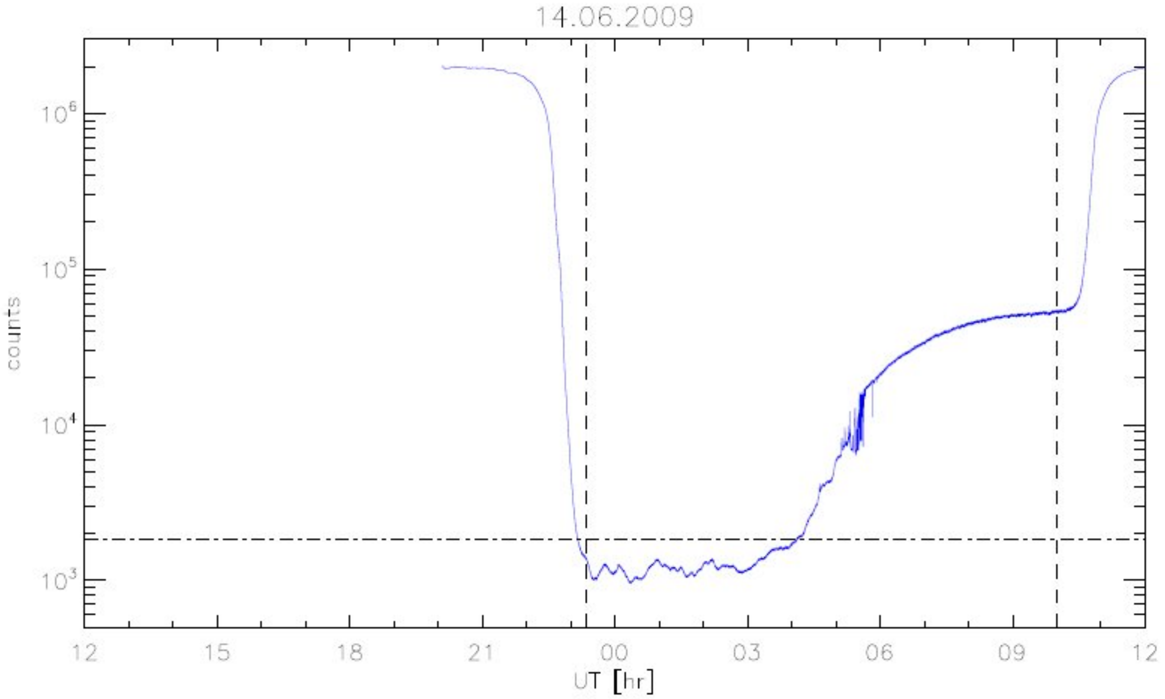

Figure 3: sky counts versus time: one can recognize the characteristic rising moon (66% illumination on that day) after 4UT, some thin clouds between 23 and 4 UT and patches of thin and thick (as shown by the fringes between 5 and 6UT). Then the sky was clear. In dark sky conditions clouds produce lower background measurements with respect to the nominal one (dashed-dotted line) since the clouds cover the light coming from the stars.

4. AN LGS TELESCOPE AND ITS NEIGHBORHOOD

In this section we discuss the interaction of the laser with the rest of an observatory, namely how the laser beam propagation may negatively affect the observations taking place at other telescopes on Mauna Kea or Paranal. Two sources of contamination can be expected: the laser guide star generated in the sodium layer at ~90km height and the Rayleigh and Mie scattered light.

The artificial laser star can be seen by any optical imager and WFS with their field of views intersecting an area of the sky containing the laser spot (note that the spot is typically seen as an elongated plume, out of focus). Its brightness may cause saturated images in sufficiently long exposures.

The scattered light along the laser beam, once it intersects the field of view of other telescopes, can increase the sky background in all science images in the V and R bands, and be visible (and saturated!) in the spectra when the wavelength region contains the 589.5 nm line. It can also contaminate other wavefront sensors. The effect is a reduced sensitivity, image artifacts, and spectral artifacts for science instruments, guide systems, and the wavefront sensing systems.

A collision as defined in Summers et al.[21] occurs when "any portion of the cone volume determined by the field of view of the telescope intersects with any portion of the laser beam cone defined within the Rayleigh scattering limits or sodium florescence limits"

Example of collisions that affects operations between a laser-telescope and another telescopes are:

1) The laser light contaminates the WFSs of other AO units

2) The laser light hits thin clouds in the sky and back scattered light contaminates either the laser telescope itself or other telescopes with FoV intersecting the cloud.
3) The laser light enters, either as direct or indirect stray light, into an optical instrument sensitive at the laser's wavelength.

Point 1 (light contamination) does not represent a great concern: notch filters that pass all wavelengths except those in a stop band centered on 589.5 nm are used on auxiliary systems (other WFS, telescope guiding cameras), with the only exception of other LGS WFSs. In the latter case the collision must be avoided.
Point 2 (back-scattered light contamination) has not yet been proven to be a serious problem, neither in Paranal nor on Mauna Kea. Moreover, on Mauna Kea the laser propagation through clouds has been proven successfully. With more than one laser, geometrical considerations suggest that the presence of clouds might contaminate the sky significantly more than a single laser system. More tests should be conducted to measure the amount of back-scattered light when the laser hits a cloud and its effect on sensitive systems. Simulations of this effect are also in preparation, using, for instance, commercially available software such as ASAP[25], which allows light scattering analysis in optical systems and the atmosphere.

Before discussing possible solutions to point 3 (stray light), it is interesting to see how often these collisions occur and how their effects have been quantified.

A study done by Keck to analyze the frequency of collisions in the real case of the Mauna Kea Observatory, which comprises 13 telescopes, three of which currently equipped with single sodium lasers[11]. Using archived pointing coordinates data from two years of operations, they were able to produce an estimate of collision frequency. They tabulated the percentage of nights with and without collisions for different pairs of telescopes. Depending on the pair, no collisions occurred in 53-80 % of the cases. Not surprisingly, the collision frequency increases with the proximity of the two telescopes and with the diameter of the observing telescope. In the case of Paranal, no such study has yet been made. However., the shortest distances are those between UT4 and UT3 (57m) and UT4 with the VLT Survey telescope (VST) (~70 m). They are followed by UT4-UT2 (81m) and UT4-UT1 (121m). Vista is located ~1.3 km from UT4. The statistics from Mauna Kea shows a 47% of nights with collisions (34% single, 13% multiple) for the pair Keck2-Keck1 (~80 m distance), 38 % (29% and 9%) for the pair Gemini UH2.2 (100 m distance) and 28% (22% and 6%)for the pair Gemini-CFHT (~150 m). Similar numbers should then apply for Paranal, with a slightly worse statistics for UT3, penalized when VIMOS, an optical multi-object spectrograph, is in use. The VST will be similar to UT3/VIMOS in the number of collisions, since it will be used exclusively with OMEGACAM, a large field of view, optical imager, and it is also very close to UT4 (the smaller mirror diameter is probably compensated by the width of the large scientific FoV). From a geometrical point of view[12(Fig.. 3)], a collision happens when the distance between the laser beam cylinder and the telescope FoV cone at their closest approach is zero. In conclusion, for telescope pairs such as UT4-UT3 and UT4-VST the probability of collision(s) will be well in excess of 50%. The combined probability that in a given night either UT3 or VST or both will have one or more collisions exceeds 75% and that any of the UTs or the VST enters in collision with UT4 with one laser is greater than 90%.

The effects of collisions (namely, the light contamination due to scattering) were measured during a campaign on Mauna Kea, using the Subaru's telescope AO system's wavefront sensor while Keck 2 was propagating its laser[13]. A similar study was conducted at the VLT during a commissioning run in 2006 (internal document). The measurements agree within ~10%. The Subaru experiment shows that the maximum surface brightness of the laser beam is ~16.2 mag/arcsec2. However, not surprisingly, this value changes as a function of the telescope size (with smaller telescopes being more affected than larger ones), the telescopes distance and the geometry of the collision[14]. The brightness was calculated to vary from 14.4 to 18.8 mag/arcsec2 for respectively 80 and 1000 m distance between the telescopes. In the case of UT3 and VST, but in general for all the telescopes on the platform, the light contamination can significantly affect optical imaging and spectroscopy. In addition, Gemini has recently instigated a program of systematically measuring the Keck II LGS Rayleigh scattering along it path from the telescope to the sodium beacon. The results are presented in these proceedings[15].

Finally, the effects of back scattering from the domes are not included in this analysis, but they may have some additional contamination effects.

Given the high probability of collisions during each night and the effects these may have on the science being done in the visible and on the efficiency of operations, it is clear that the only solution to the problem of collisions, is for any laser-equipped observatory to gain the ability to predict collisions using a real time software application. The Mauna Kea Observatory has been the first to implement an Observatory-wide dedicated anti-collision software: the Laser Traffic Control Software (LTCS)[16,21] has been developed and put in operations since 2002, the time loss has been lowered to less than 1%[20] .The impact of collisions in terms of time loss is not currently known for Paranal.

5. OTHER FACTORS INFLUENCING LGS OPERATIONS

Among other factors affecting operations at the telescope, both in terms of downtime and/or operational costs, are aircraft avoidance, low-Earth orbit satellites avoidance, scheduling and technical overheads. The amount of downtime for the first two items has been measured on Mauna Kea, and turn out to be rather low, of the order of ~1% or less. Paranal does not routinely measure the amount of downtime due to aircraft avoidance, probably because such events are rare.

Both summits of Mauna Kea and Paranal are rather isolated locations, but air traffic is still not negligible, therefore all measures have to be taken to avoid propagating lasers in the proximity of aircraft. Laser propagating observatories based in US must co-ordinate with the Federal Aviation Administration (FAA) and in Chile with the Dirección General de Aeronáutica (DGAC)[22,23]. These agencies have different requirements. On Mauna Kea human spotters, are used outside the dome and they can trigger a laser shutter in the event of an emergency – an aircraft flying into the beam - but who also can give warning to the observing staff to pause propagation until the aircraft has cleared the field. Furthermore these spotters are queried to give an “all-clear” prior to propagating the Laser at any time. The use of more automated systems are currently being investigated at Mauna Kea making use of an all sky camera and aircraft transponder information. A fully automated system will require FAA approval based on the observatories’ demonstration that these systems meet the safety requirements. Paranal uses an automated system, the Aircraft Avoidance System[17], which comprises two cameras attached to opposite sides of the telescope upper ring, each camera with a field of view of 60° and an on-board computer that can process images to look for aircrafts in a region of the sky affected by the laser propagation. In case an aircraft is detected, an alarm triggers the laser beam shutter and stops propagation.

In addition to aircraft safety issues, the US Strategic Command (formerly US Space Command) request that laser propagation be cleared with them to avoid collisions with spacecraft. This applies not only to observatories with sodium and/or Rayleigh beacons but to many other types of laser systems such as LIDAR, commercial, and other interests. The impact of clearance windows depend on a number of factors but most especially the pointing, laser power and operating wavelength. Clearance windows need to be approved ahead of time, typically 72 hours, although there are provisions for a faster turnaround ~ 12-24 hours. All requests are directed to the Laser Clearing House (LCH), which returns a list of approved windows. Closure windows occur when sensitive satellites come close to, or pass though the beam. These closure windows can range from a few seconds to a minute. Occasionally there are critical events that blanket all LGS propagation for hours at a time. This affects operations differently for classical and queue observing such as at Keck and Gemini respectively. For classical observing this requires flexible observing and a backup non-LGS plan. Queue observing requires care in preparation of the observing plans to optimize observing time schedules between closure windows, a significant impact on operations. Currently the VLT is not required to follow LCH procedures but propagation by AURA managed observatories in Chile, such as Gemini South and SOAR, will be required to. It is noted that the probability of a collision between the laser and a spacecraft is rather low.

Scheduling issues and their effect on operations interest the VLT and Gemini. In theory, queue-scheduling offers the maximum flexibility to employ the sky-time as efficiently as possible. In practice, factors such as observing priorities and observational constraints affect laser operations significantly. At the VLT service mode observations are regulated by a clear set of priorities, mostly related to the scientific rank of a program, but also to the time constraints (Target of Opportunity) and the time already spent in the queues (e.g. carry-over programs, which have a high scientific rank and are carried over from one observing period to the other, if not completed). When preparing the short-time schedule each night, the astronomer selects those programs whose required observing parameters (e.g. seeing or airmass) are compatible with the current weather conditions and starts observations. At the beginning of operations, the priority ranking was executed regardless of the need for the corresponding observing blocks to use the laser. This led to a 14% of the laser time to be actually used for non-laser higher priority observations. This rule has recently been changed to give LGS OBs the highest priority, with few exceptions, freeing this 14% for LGS observations. Another 7% of the time was not used for LGS observation for lack of suitable OBs: this is usually the result of a combination of factors: LGS observations are more demanding, in terms of observational parameters, than non-LGS observations. Even in good weather conditions (e.g. 1" seeing, 2 ms coherence time) there may be cases when these parameters are not compatible with the LGS users' requirements and the operator has to observe non-laser targets instead. Another factor is the well-known concentration of targets coordinates in certain regions of the sky, which may result in paucity of targets in a given moment during an LGS run. Mitigating measures have obviously to do with a more generous population of the LGS queues to cover the widest possible observing parameter space. Additionally, one could introduce different rules than for non-LGs observations concerning the parameters constraints set by the users: currently AO operations in service mode make use of the same set of user's defined constraints: airmass, fraction of lunar illumination, distance from the moon and seeing. The latter is replaced by the desired Strehl ratio on target, even though the seeing value often replaces it, when Strehl measurements on target are not possible. These constraints are used by the operators to classify an OB as "completed" or "must-repeat". In the case of AO observations, and even more so for LGS OBs, the real time conditions and performance of the instrument drive the quality of the data in ways which are not easily predictable and are significantly different from those of optical and non-AO observations . In the VLT case, the ability of the operators lies in using all available information on the environment (including but not limited to seeing, moon, etc) and the telescope+instrument+AO system to achieve the desired data quality. On-sky efficiency and operations flexibility would benefit from some modifications to the current operational scheme. It is recommended to implement a scheme, where the seeing, the airmass and the moon constraints are left as "free" parameters to be optimized by the operators in real time, and only the final data quality, as measured by the Strehl ratio and/or other equivalent parameters (e.g. the ensquared energy), is the binding criterion for data classification.

Overheads, including telescope presets, laser preset, instrument presets, readout, etc, are an important factor limiting the open-shutter time. For VLT, it has proven difficult to compute these overheads separately from the LGS-time. We only know that these overheads may be significantly higher than the corresponding ones for non-LGS observations, due, for instance, to the need of spending some time presetting the laser, focusing it, checking that performance are OK and the additional acquisition of a tip-tilt star. Moreover, under unstable conditions, some systems may take some time to be tuned for optimal performance. Mitigating measures include the use of well-tuned observing templates and release of observing procedures that cover most of the possible flavors of target acquisition, aside from the obvious requirement to perform as many tasks as possible in parallel fashion. For Gemini observations it has been found that on-average an overhead of an extra 15 minutes of set-up time is required per observation over standard NGS observing which includes closing the LGS loops and laser spotter clearance before propagation. A detailed discussion of Gemini LGS operations is given in other papers[19,24]. Keck overheads and efficiencies are discussed in a separate paper[20.]. For Keck's classical observing, the PI is responsible for having a non-LGS program to perform in case the laser cannot be propagated. The observer is generally offered the choice of NGS AO observing with either OSIRIS or NIRC2, or the choice of seeing limited observing with NIRSPEC. The instrument switch overheads are not too great, typically only a few minutes, and thus offers the PI flexibility in backup programs. The decision to switch programs can be made in real time based on the circumstances.

6. CONCLUSIONS

Efficient laser operations are now a reality at three of the 8-10 meter telescopes equipped with instrument that may use a LGS. The W. M. Keck Observatory was the first of the three to commission and initiate routine science operations with the laser on sky, a record that has boosted the number of scientific publications to over 60 in just 4 years. VLT and Gemini hope to soon reach the same level of efficiency. In this paper we have discussed the most important factors that affect efficiency (and partly cost) of laser assisted operations. Similarities and differences among the three *modus operandi* play definitely a role, favoring one procedure over another, one tool over another, but the experience gained on the field, time and resources dedicated to the issue seem to be the most significant factors.

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