The Importance of Sodium Laser Guide Star LIDAR during Open Loop Operation at Large Telescopes

Venice 2001

Beyond Conventional Adaptive Optics

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ABSTRACT

For 6-10m telescopes, the sodium laser guide star (LGS) is generally the preferred artificial star for high order image correction due to a reduced cone-effect compared to Rayleigh stars and will be until the feasibility of multi-conjugate adaptive-optics (MCAO) systems has been demonstrated. However, the sodium LGS has challenging maintenance requirements and is expensive in terms of the number of sodium photons detected per Euro compared to powerful, commercially available UV lasers for Rayleigh stars.

In this short paper, we explain how and why the use of a LIDAR system coupled with a sodium laser, or lasers in the case of LGS-MCAO, will be important at 6-10m telescopes. Firstly, it is important for diagnostics and man-power reasons to have a laser system whose performance on the sky can be optimized independently of the AO system. In particular, when the AO system is in 'open loop' operation, the returned flux and laser focus can be measured and logged in order to check for consistent 'on the sky' performance with previous observing nights and to predict the expected sodium photon counts at the wavefront sensor. Secondly, although there is no compelling reason for a sodium monitor at the science telescope, such an 'in situ' tool would provide relevant sodium layer statistics that should correlate with LGS-AO system performance at the telescope.

1. INTRODUCTION

Sodium laser guide stars are being considered for a number of large (8m) telescopes because they offer increased sampling of the atmospheric column seen through a telescope compared to the lower altitude option of a Rayleigh star. In order to make the use of sodium lasers competitive with that of Rayleigh star lasers in the future, their cost and maintainance requirements must be reduced. Indeed, experience with the MPIA/MPE ALFA (Hippler et al., 1998) laser (Quirrenbach et al., 1997) at Calar Alto Observatory in Spain, has shown that cost and manpower are important factors governing the design and operation of new sodium laser guide star systems. The proposed laser for the VLT (Rabien et al., 2001) makes use of the increased pumping efficiency of solid state Verdi lasers compared to the argon-ion pump lasers to pump a combination of two dye-jet lasers, thereby reducing the required input electrical power by a factor of about 25. Such a system will require a specialist technician to replace/clean optical components, change dye solutions and at the start of each night ensure the laser is tuned to 589nm. The cost of a 10W sodium laser like that planned for the VLT is $\sim$ 1.5Euro (Rabien et al., 2001) which is a large fraction of the cost of about 4 million Euro of the VLT LGS facility (Bonacini et al., 2000).

If sodium laser stars are used then efficient diagnostic tools are needed in order to speed up the LGS set-up time and hence, reduce observing time loss. One way to do this is to perform LGS-AO system calibration before sun-set (e.g. maintaining and tuning the laser, checking alignment of relay optics (or fibres) to the laser launch telescope), beam quality (collimation, wavefront) and polarization (e.g. Rabien et al, 2000). However, based on the experience of the MPIA/MPE ALFA team, a number of extra diagnostics are required for sodium LGS systems, namely those used to measure LGS spot size, flux, height of the sodium layer, and launch telescope focus. During closed-loop operation, the size and flux can be estimated from the wavefront sensor (WFS) during observations and relative changes in the height of the sodium layer can be tracked by the wavefront sensor.

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In addition, however, knowledge of the absolute height of the sodium layer is important during open loop operation in order to set-up the WFS initial focus position relatively quickly and a measurement of the returned sodium flux independently of the LGS-AO system allows the LGS-AO system performance to be pre-determined.

The need for sodium layer height measurements is explained in the following Section. In Section 3, the various methods for sodium layer height monitoring are described and compared. Then in Section 4, the LGS-LIDAR technique, its usefulness and how it works is explained in more detail. Next, in Section 5, LGS-LIDAR experiments from Calar Alto Observatory in Spain, recent results and conclusions are presented. In Section 5, a way to estimate the sodium column density from the LGS-LIDAR data is explained. The paper ends with the conclusions reached in this work.

2. THE IMPORTANCE OF A SODIUM LAYER HEIGHT MEASUREMENT

Loss of observing-time due to an un- or partly-automated operating procedure is a concern for AO-LGS system designers. The ALFA experience is that initial focusing of the laser launch telescope and WFS can be achieved using a common focusing technique of measuring the PSF at a number of focus positions about the optimal one, fitting a curve and reading off the best position. A more efficient way to focus the WFS on an LGS would be to determine the height accurately and independently of the WFS and then adjust the initial WFS focus position (or offset) according to a pre-calibrated WFS focus versus sodium layer height relationship.

The real reason why it will be important to determine the height of the sodium layer accurately is that LGS focus errors due to sodium layer height variations may prohibit measurements of low order aberrations like focus and astigmatism (Dierickx 2001). Since the height and possibly the width of the sodium density profile are directly linked to this problem, there may a possible interest in tracking the sodium density profile during observations in order to search for correlations, or lack of them, with LGS-AO system performance. In the next Section, the advantages and disadvantages of various methods for monitoring sodium layer heights are outlined.

3. SODIUM LAYER HEIGHT MONITORING METHODS

There are three possible ways to follow variations in the height of the sodium layer, (a) tracking mean WFS focus changes (time-averaged changes in LGS focus), (b) observations from an auxiliary telescope and (c) LGS-LIDAR. Time averaged LGS focus drifts can be seen by the wavefront sensor and this is ideal during closed-loop operation. One dis-advantage with the use of a WFS for LGS focus measurement is that initial focusing of the WFS on the LGS can be difficult and time-consuming if the technique described in the previous Section is employed.

With a perspective technique, the LGS plume is viewed through an auxiliary telescope with a CCD imager typically. However, accurate height measurements are very difficult due to uncertainties in telescope pointing and locations. O' Sullivan et al. (1999) used a 2-D photon counting (MAMA) camera at the 2.2-m telescope at Calar Alto Observatory in Spain and discovered variations in peak height of the order of 400m on a time-scale of about 2 minutes. Michaille et al. (2000) used a CCD imager to observe the sodium layer plume from auxiliary telescope at La Palma (Canary Islands). They observed centroid position changes of the order of 2km on time-scales as short as 4 minutes. As noted by Ageorges et al. (2000), height changes of the order of 400m correspond to a phase variance of the order of 0.15rad ^{2} for the VLT at λ = 1μm which means that the Strehl would be reduced to about 86% of its potential value. The advantage of using an auxiliary telescope is that variations in the centroid height of the sodium layer could be monitored continuously without obstructing observations at the science telescope; the disadvantage is required capital expenditure for a system that will be unable to monitor absolute height of the sodium layer. Since it is desirable to track sodium layer centroid changes on time-scales of a few minutes (Ageorges et al., 2000, and references therein), a collecting aperture with a diameters greater than 3-4m is needed for signal-to-noise reasons based upon ALFA experiences with $\sim$ 2W of launched cw laser power. Therefore, for a factor of $\sim$ 3 increase, as expected for the VLT-laser, 1.5 - 2m telescopes should be suitable as auxiliary sodium monitors. Apart from the apparently unnecessary expense of building and running an auxiliary Na monitor, determination of the absolute sodium layer height is limited by telescope coordinate and pointing uncertainties to accuracies of the order of few km (e.g. see Michaille et al., 2000, Butler et al., 2000), which is insufficient for accurate height measurements for large ($\geq$ 8m) telescopes.

Another way to monitor the sodium layer is with a LGS-LIDAR system (Butler et al., 2000). LIDAR is a general technique for atmospheric profiling; it is a time-of-flight measurement that functions like a radar system. LGS-LIDAR can provide absolute height measurements with accuracies of about 150m and in addition, such a system allows the returned flux to be monitored in order to pre-determine the LGS-AO system performance independently of the AO system WFS. In the next Section, the main components of the LGS-LIDAR system used in August 2000 is reviewed.

4. SODIUM LAYER PROFILING WITH LIDAR

4.1. The Experimental procedure

The basic LIDAR technique used to study the sodium layer consists of sending short laser pulses of the order of μs at about a few Hz and collecting the returned photons in time bins of similar width to the outgoing laser pulses. By combining the returned photons from many laser 'shots', the backscattering profile of the atmosphere is obtained; the S/N will depend on the number of shots. To obtain maximum efficiency, a pseudo-random string of on/off 'non-return to zero' pulses lasting is used, during which the laser is on half the time. For the August 2000 observations the sequence length was 32.7ms (or 2^{15} bits at 1μs/bit). The length of the pseudo-random pattern is important for signal to noise reasons; for a 32Kbit sequence the auto-correlation noise is of the order of 10^{-3}. The density profile is then recovered by cross-correlating the measured flux distribution with the original pulse sequence. After continuously repeating the sequence for at least a minute (or a few seconds at an 8-m telescope), the sodium density profile can be determined with excellent signal-to-noise. Since the laser is only 50% on during this time, such a situation during closed-loop AO operation would seem to be unacceptable for S/N reasons.

We use a (known) pseudo-random sequence to modulate the laser pulses, with a total 'on' time of 50%. The pseudo-random sequence must be sufficiently long to exceed the maximum round-trip time under any circumstances but purpose for sequences much longer than about 1ms is to have reduced cross-correlation noise. If S_0 is the out-going laser pulse sequence then the returned stream of photons results from the convolution of S_0 with the sodium profile $N \otimes S_0$. The intrinsic sodium abundance profile, N, can be recovered from the data by cross-correlating it with the original pulse sequence, because the auto-correlation of the sequence is very close to being a delta-function. Thus we find

$$S_0 \otimes (S_0 \otimes N) \; = \; N$$

We use a variation of this by over-sampling, so although the pulses are 1 μs long we collect the returned photons in 0.5 μs time bins. Now to recover the sodium profile we consider the emitted laser pulse sequence as a sequence of impulses, S_1, two times longer in which each digit of S_0 is padded with zeros. If the profile of a pulse from the laser is denoted by L then we can consider the emitted sequence as $S_1 \otimes L$, and the returned flux is $S_1 \otimes L \otimes N$. We can calculate the following cross-correlation

$$S_1 \otimes (S_1 \otimes L \otimes N) \; = \; L \otimes N$$

which gives the convolution of the sodium profile with the pulse profile. Finally, a correction has to be made to this profile to compensate for the height at which each photon was scattered because the telescope mirror subtends a smaller solid angle for emission that originates higher in the atmosphere. The shape of the pulse profile, and any height offset which might arise due to timing delays, can be found by carrying out the procedure with the telescope dome closed: this provides a single scattering layer at almost zero distance (see Butler et al., 2000). The offset for the LGS-LIDAR system set-up at Calar Alto in August 2000 was measured to be 300m, corresponding to a time-delay of 1μs.

4.2. The laser and laser modulation

The ALFA-Laser system[3], situated in the Coudé laboratory of the 3.5m telescope at Calar Alto Observatory in Spain, is used to provide a sodium reference star in the Earth's sodium layer at about 90km altitude for high order adaptive optics correction. It typically has an V-band magnitude of 11. The laser system consists of a 5W Argon-ion (Coherent model Innova 400) pumped cw dye-jet laser (Coherent model 899-21) tuned to sodium D_2 line (589nm) with a 10MHz bandwidth. The laser is circularly polarized, pre-expanded and then sent to the 50cm diameter laser launch telescope via a remotely controllable series of relay mirrors[4]. The launch beam has a 15cm diameter and is 2.9m away from the science telescope optical axis.

The modulation of the cw laser beam may be performed using an acousto-optic modulator (AOM) which could be moved in/out of the beam using a linear-motorized stage to re-direct the beam to the AOM. The AOM is controlled by a radio frequency (RF) driver. During RF 'on' the beam is deflected to a selected 1st order diffraction spot; this may be sent to the laser launch telescope while other orders are blocked by a beam dump.

4.3. Data Collection

As we are interested in observing very short lived changes (e.g. due to 'sporadic' structures) in the sodium layer, a short exposure time is desirable. We used an actively quenched silicon APD (Avalanche PhotoDiode) (Perkin Elmer) with a QE $>$ 70%. Actively quenched APDs minimize the dead time after each detected photon to $\sim$ 40ns. Statistical simulations show that we only expect a maximum of 1-2 photons from the laser beacon to be detected every micro-second. Therefore, this dead time will not affect our measurements. The APDs have no read-out noise associated with them and the dominant source of noise is not any APD dark counts ($<$ 40 s^{-1}), but background counts, including sky counts and stray light around the sodium line transmission filter in the optical path in ALFA. However, much more serious was the presence of IR LEDs inside the ALFA bench, on motor encoders for example. Although every effort was made to remove these the overall background count rate was $\sim$ 6000-9000 counts s $^{-1}$, higher than in the Oct. 1999 run, perhaps because black-cloth covering ALFA to block stray external optical light was not used in Aug. 2000. This is not a problem, however, as the cross correlation is very good at rejecting background noise.

The photons were collected by an APD (SPCM-AQR-14) and sent to a multi-channel scalar (Fastcomtec MCD-2), synchronized by the trigger signal from the pseudo-random sequence generator, which counts the photons detected in sequential time slots, each of which are half the pulse width in order to satisfy the Nyquist criterion. The details of the detector installation are given by Butler et al. (2000). The APD module outputs a TTL pulse every time a photon is received. A similar TTL sync signal is produced from the signal generator at the start of every 32Kbit long pseudo-random sequence. These two signals are received by a Multichannel Scaler (MCS) where timing information is recorded. The MCS card used in August 2000 consists of 128k channels, each of which was set to correspond to a 0.5μs interval. When the sync pulse is received the MCS starts at the first channel, and will increment its value if it receives a count from the APD within 0.5μs. After this time it moves to the next channel and again counts the number of pulses coming from the APD. This procedure continues until the next time a sync pulse is received, when the MCS starts from the first channel again. As each interval is 0.5μs long, and each laser pulse is 1 μs, returned flux is over-sampled by two so that there is sufficient timing resolution to satisfy Shannon's sampling criterion.

5. CALAR ALTO EXPERIMENTS

In this section, some results from a recent LGS-LIDAR run at Calar Alto Observatory are presented as an example of what can be achieved with an LGS-LIDAR system.

5.1. Recent LGS-LIDAR at Calar Alto Observatory

LGS-LIDAR was performed on 19/8/00 at the Calar Alto Observatory 3.5m telescope; the set-up was as described in the previous Section. The seeing was 0.6$''$ in K-band and the APD count rate during beam modulation ranged from 10,000 counts (at 0.2W) to 17,000 counts per 32.7ms. The uncertainty in sodium density profiles from the August 2000 experiment is much poorer than in those from the October 1999 run (Butler et al., 2000) due to a lower modulated laser power of up to about 0.3W compared to 1W during the previous run.

For the first 35 minutes each "integration" lasted 5 minutes in order to improve the signal-to-noise and have some sensitivity to large shifts in centroid height. After this the alignment of the new APD in ALFA was checked and corrected during the experiment in order to maximize the rate of detected sodium-LGS photons. For the remainder of the LIDAR observations, the integrations were 1 minute long with some loss in signal-to-noise, despite re-alignment of the APD. Due to a strong un-modulated component in the out-going laser beam, it was necessary to perform the cross-correlation described in Sub-section 4.1 with data from the un-modulated LGS and subtract a suitably scaled copy of it from the sodium layer profile. The effect of this subtraction on the background density profile is negligible. Each adjacent pair of 1 minute exposures were combined to increased signal to noise.

A representative sample of sodium density profiles is presented in Fig. 1 and the variation in centroid height over time is plotted in Fig. 2. Due to the presence of noise, the centroid measurement is sensitive to the size of the centroiding window. For each 'exposure' the centroid height is taken to be the median of the centroids measured with centroiding windows in the range $\pm$15-18.5km about the approximate centroid, and the $\pm 1\sigma$ error bar plotted in Fig. 2 is estimated as the rms centroid value.

We see that the sodium profile peaked at about 90km in altitude and had a FWHM of about 6km on that occasion. The FWHM is plotted as a function of UT time for exposures of 2 minute or longer in Fig. 2; the trend in the sodium layer centroid height is variations of less than 300m over time-scales of minutes.

5.2. Results

Due to the uncertainty in centroid measurements, it is difficult to say anything firm about sodium layer temporal variations; but variations of the order of 400m on time-scales ranging from $\leq$ 2 minutes to a few minutes to an hour appear to occur. One thing is clear; that is, a robust measurement of the absolute height can clearly be determined with a LGS-LIDAR technique with a time resolutions down to a few minutes on a 3-4m telescope, given laser power greater than a few hundred milli-watts. The accuracy of the absolute height measurement can be improved with increased laser power.

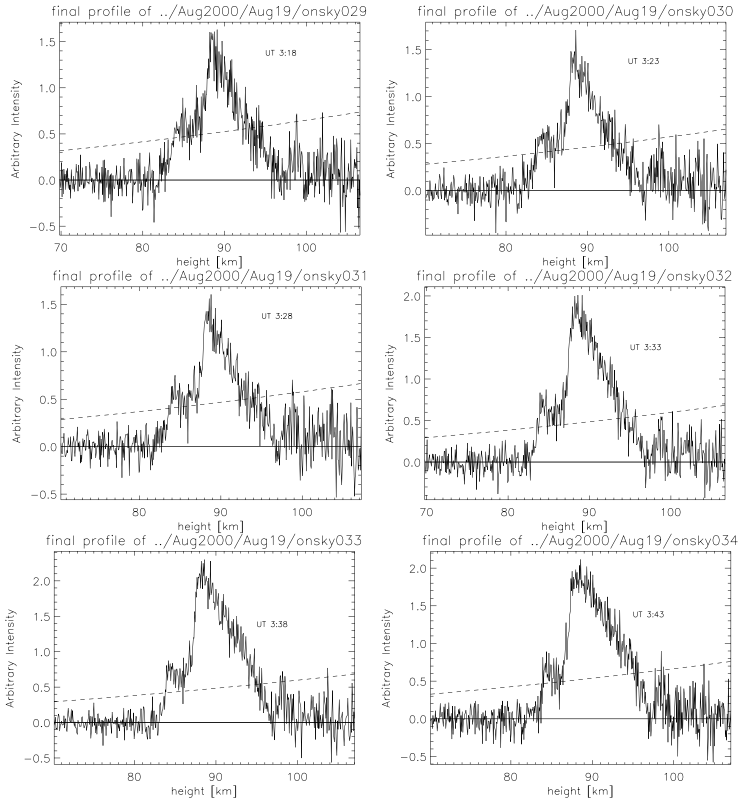

Figure 1. Selected recovered profiles.

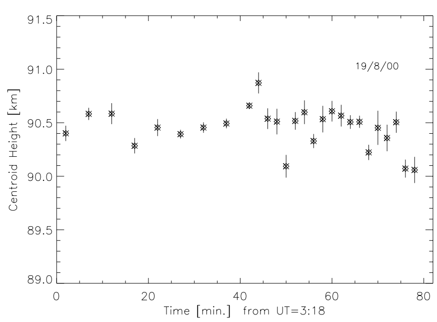

Figure 2. Centroid height as a function of time on 19/8/00.

6. HOW TO MEASURE THE SODIUM ATOM DENSITY

Even assuming that the S/N of the backscattered sodium layer profile is excellent, it is difficult to calculate the abundance of sodium atoms at an altitude of 90km with uncertainties less than about 20% as a result of uncertainty in both the atmospheric transmission, assuming the detection efficiency is known accurately. Unfortunately, increased sodium flux only shows up as reduced cross-correlation noise in the proposed LIDAR scheme.

Since the sodium LGS intensity (W m^{-2}) at the telescope pupil (Davies et al., 2000) can be expressed as

$$I_{\rm obs} = \frac{1.2 P_1 T_{\rm atm}^2 \sigma N_{\rm Na}}{4\pi H^2} \tag{1}$$

where P_1(W) is the launch laser power, T_{atm} the atmospheric transmission, and H (m) is the distance of the Na layer from the telescope, the sodium column density $N_{\rm Na}$ can be estimated if reasonable values are taken for σ, the homogeneously broadened cross-section of the D_2 transition, as well as for the other parameters.

If one takes H = 90.4km (Fig. 2), σ = 8.8 $\times$ 10^{-16}m^2, $T_{\rm atm}$ (589nm) = 0.7 each way, an estimated power of the modulated laser immediately prior to the launch telescope of 0.2W (low due to poor alignment of the 1st order diffraction beam selector), the sodium column density was derived as about 4-6 $\times$ 10^{13} m^{-2}. Uncertainties in the reflectance of the launch and science telescope mirrors form most of the uncertainty; at Calar Alto dust blown over from the Sahara gradually accumulates after every washing/aluminization of the primary mirror.

The value determined previously (March 1998) at Calar Alto Observatory (37^{o}N) using a CCD imager is $\sim$ 6 $\times$ 10^{13}m^{-2} and typical values measured from absorption in the solar spectrum on Kitt Peak and in the stellar spectra of αLeo and αAql on Mt. Hopkins at a latitude of 32^{o}N, are 2-6 $\times$ 10^{13}m^{-2} (Ge et al., 1997, 1998). However, there are variations of the sodium layer on time-scales of a hours, to days to months (e.g. see Ageorges et al., 2000, and references therein) and therefore comparisons of sodium column densities measured at different epochs is difficult.

7. CONCLUSIONS

LGS-LIDAR is a simple tool for diagnosing sodium layer LGS-AO systems in terms of returned flux independently of the AO system. In addition, it is a fast and accurate way to measure the absolute height of the sodium layer, a value that is important for initializing the focus position of the wavefront sensor.

Experience of sodium monitoring using the LGS-LIDAR technique and the perspective technique of monitoring from an auxilliary telescope indicates that the LIDAR approach is fast, more accurate and a reasonable option, for S/N reasons, at an astronomical observatory when it is important to track centroid height variations of the sodium layer with accuracies of less than 150m on time-scales of a few minutes or less.

ACKNOWLEDGMENTS

The assistance of T. Ott and S. Rabien, was invaluable to the success of the experiment. Prof. R. M. Redfern is thanked for the construction and provision of the pseudo-random pulse generator used in 2000.

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