NA LASER GUIDE STAR AO WITH DYNAMICAL REFOCUS

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Abstract. Laser guide star adaptive optics performance is strongly affected by the LGS spot size. An increased spot size and deformation can be caused by uplink wavefront deformation and the thickness of the sodium layer. With the perspective elongation of the fluorescing stripe being imaged on the wavefront sensor, the signal to noise ratio of Hartmann type sensors is lowered; pyramid type sensors would not even work properly. With the upcoming extremely large telescopes this problem is getting a serious issue. In this paper we will discuss a possible solution to this problem: The use of pulsed lasers in conjunction with dynamical refocusing. Dynamical following the laser pulse as it propagates through the sodium layer not only removes the elongation of the laser guide star on the detector, but allows for pyramid sensors and removes the Rayleigh scattered light from the detection. This removes the perspective elongation and sharpens the LGS spot on the wavefront detector, finally leading to reduced laser power demands.

1. Introduction

Adaptive optics with laser guide stars is an inevitable tool to achieve the desired scientific output at current 8m class telescopes, and even more so for the upcoming extremely large telescopes. In the current planning phase sodium layer guide stars are foreseen in all three ELT projects [1,2,3]. While the launch location differs from center or side launch, all projects currently do rely on the use of Shack Hartmann sensors. With the large apertures of these telescopes the geometric elongation of the laser spots is no longer negligible and will lead to a significant decrease in accuracy. In the extreme case of a side launched laser beacon on a 40m class telescope the elongation in the most distant sub apertures amounts up to ~8 arcsec. In the following we illustrate the known spot elongation effect and compare the centroid measurement accuracy of a round and an elliptical spot. As a possible solution to the spot elongation problem we propose to make use of pulsed lasers and dynamically follow the focus location change as the pulse travels through the sodium layer. We have tested oscillating membrane mirrors as a possible refocusing device and found them suitable for this task. By dynamically removing the z-elongation in the telescopes focal plane the use of pyramid sensor will become feasible for the ELTs, as laid out in [4] and chapter 4.

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2. **Spot elongation**

When illuminating the Sodium layer with a laser, the whole column of atoms along the light path is fluorescing. Since the typical thickness of the Sodium distribution amounts to 10km, an accordingly long light source is created. In consequence the image of this column in the telescope focus appears extended along the optical axis as well. As sketched in Fig. 1 this geometry results in an elongated spot when imaged from an outer sub-aperture of the telescope. The amount of elongation seen by a given sub-aperture is simply dependent on the distance to the sodium layer and the distance from the launch location. As an example a 10m telescope will see a ~1arcsec elongated spot with a center launch geometry and 2 arcsec spots with a side launch. In current telescopes the effect on the wavefront measurement can be mitigated either with implementing a center launch, or by using large enough sub-apertures on a Shack Hartmann sensor. In the case of the proposed ELTs, the elongation of the spot rises accordingly. Assuming a 40m telescope with side launched lasers for comparison a 10km thick sodium layer will result in an ~8arcsec long spot on a Shack Hartmann sensor. Additional complexity is introduced by the natural variations of in the sodium layer: neither the average altitude, nor the distribution of the atoms is constant. The thickness may well vary between 8-22km, sporadic layers can occur and changes in the column density are frequently seen (e.g. [5]). Coping with the extended geometry and the variations in the Sodium layer requires Shack Hartmann sensors with a large number of pixels. Even special format CCDs are proposed [6] to adopt sub-apertures that are radial extended.

![Diagram of Sodium layer laser guide star detection](image)

*Fig. 1: Simple sketch of the geometric relations for Sodium layer laser guide star detection. The elongation of the spot simply depends on the distance from the launch location to the sub-aperture where the beacon is imaged.*
3. Shack Hartmann detection with elongated spots

To simulate the Shack Hartmann pattern for an ELT we used a Zemax model of the EELT and added a simple SH setup to it. Placing the LGS at a range of distances between 80-100km an image of the SH detector can be calculated for each distance. With summing up the individual images and applying a weighting function a realistic detector image is created. In this model it is relatively easy to incorporate the real optics of the telescope and any modeled sodium layer height distribution. In Fig. 2 the corner of the SH detector is shown with a 10km Gaussian Sodium distribution as input. The elongation of the individual spots can be seen as they would appear with a center launch geometry.

A well-known consequence of elongated spots is primarily the loss in signal to noise ratio of the detection, with the single axis error being proportional to the spot size divided by the signal to noise ratio:

$$\sigma \propto \frac{\theta}{SNR}$$

So, even in the photon noise limited case, the number of required photons to reach a given $\sigma$ multiplies by four when the spot size doubles. In a numerical calculation we have compared the standard deviation when measuring the centroid of round and elliptical shaped spots. In Fig. 3 several plots are shown, illustrating the loss in accuracy. Generally the numerical simulation follows the theoretical expectations, with the elongated spots requiring approximately four times the photons for a given $\sigma$.

The comparison gets even worse when considering that large detectors most probably will come with read noise, and that a round small spot requires fewer pixels on the detector. Performing the calculation for a 3 e- read noise, 12 pixel square detection for a 0.8x4 arcsec FWHM elongated spot and comparing this with a round spot in a 4 pixel area, one finds that 10 times more photons are required for the elongated spot to perform similar as the round one.

Fig. 2 EELT zmx model with the five mirror design and a simple SH zmx model. It consists of a collimator after the 90km focus, a mirror in the pupil plane and a re-imaging lens combination before the lenslet array. To the right a simulated SH spot pattern is shown for center launch geometry. The elongation in the outer sub-apertures spans up to 4 arcsec if the sodium layer extends over 10km.

Multi LGS configurations may partly help to overcome some of the negative effects that the elongation creates. Proposed are side launched configurations where the laser guide stars on the opposite side of the telescope always provide round spots where the other one has maximum elongated ones. This may help a lot in a ground layer AO setup. When precision control for diffraction limited work is required, compact round spots would be surely preferred to sample the turbulence volume at high accuracy. This can be achieved when using pulsed lasers in conjunction with dynamical re-focusing.
Fig. 3: Standard deviation on the centroid of Shack Hartmann spots. Top row shows the case of a 12 pixel square area with 0.5 arcsec pixel scale, with the top left being the case of a round spot with 1.5 arcsec FWHM with photon noise only present. Top right the same for the elongated spot of 1.5x4 arcsec. The middle row shows the same case but with adding 3 electrons of read noise. On the bottom two plots a comparison between the centroiding error of a round spot in a 4x4 pixel square and the elliptical case in a 12x12 pixel square is shown. The elliptical case needs 10 times more photons to reach the same signal to noise.
4. Pyramid wavefront sensing with elongated and re-focused guide star

It is well known that the pyramid sensor features a higher sensitivity with respect to the Shack-Hartmann sensor when operating with point sources under AO partial correction regime [7]. As discussed in [4], the use of the pyramid sensor with round (2D) extended sources decreases the overall sensitivity; the effect of the 2D extension being equivalent to the effect of tilt modulation. On the other hand, a z-elongated reference source reimaged atop of the pyramid introduces defocus errors which, in turn, cause a sensitivity loss that increases linearly with the radial distance from the pupil center. This effect is equivalent to the one caused by spot elongation on Shack Hartmann sensors.

We present below a preliminary estimation of the sensitivity improvement that guide star refocusing could bring to the pyramid sensor on a 39m telescope. We have simulated the response to KL modes of a pyramid sensor with 78×78 subapertures when using as a reference source: a diffraction-limited source, a 2D Gaussian extended object with a FWHM of 0.8arcsec, and an LGS launched from the center of the pupil with and without refocusing. In the latter case, the pyramid has been focused to the 90km Na layer. We have considered a Na layer extension of ±3.0km, reducing to ±0.5km with LGS refocusing. The case of the typical full Na layer extension of ±5.0km has not been simulated for this study since it required additional computing power, but this will be done in our future work. Details of the simulation implementation are given in [4].

The left plot of Figure 4 shows the noise propagation coefficients for a subset of KL modes, and for each of the considered reference guide stars. As expected, noise propagation increases with the effective size of the reference source, being the lower order modes the most affected. The plot on the right of Figure 4 shows the gain in sensitivity (i.e. the reduction factor in the variance of the propagated noise) when passing from a ±3.0 to a ±0.5km LGS z-elongation using guide star refocusing. The gain in sensitivity goes from a factor ~8 for the first ~100 modes down to a factor ~2 for the last modes considered. The gain in sensitivity represents also the reduction factor in the number of photons (and so laser power) required to the reach the same error variance obtained with a ±3.0km elongated spot. Note that we can expect this gain to be higher when considering LGS refocusing from a typical ±5.0km Na layer extension.

![Fig. 4. Left plot: Noise propagation coefficients for KL modes measured with a pyramid WFS. Four different reference sources considered: (white crosses) Diffraction-limited source (with a tilt modulation of ±5λ/D); (red rhombs) 2D Gaussian spot with 0.8arcsec FWHM; (purple squares) Refocused LGS: 2D Gaussian spot as before with an additional z-elongation of ±0.5km; (green triangles) Refocused LGS: 2D Gaussian spot as before with an additional z-elongation of ±3.0km. No tilt modulation has been applied when using extended objects. Right plot: Gain in sensitivity when passing from a ±3.0 to a ±0.5km LGS z-elongation using guide star refocusing.](image-url)
5. Membrane Refocus Optics

Implementing pulsed lasers and dynamical re-focusing removes the z-elongation of the LGS. This method has been used for the MMT Rayleigh guide star system to allow high altitude scatter detection [8]. While for the MMT system an image plane dynamical refocusing system was used, this method becomes difficult for the extreme stroke and optics F# that would be required for an ELT. To overcome the limits we have proposed the use of an oscillating membrane mirror in a pupil plane as refocusing device [9]. The basic principle is shown in Fig. 5.

Fig. 5: basic principle of a dynamical refocus membrane mirror in the pupil plane. While the laser pulse is travelling through the sodium layer, the image location moves towards the infinite focus. The membrane must change curvature accordingly: being concave when the pulse hits the lower portion of the sodium layer, over flat to convex when the pulse leaves the layer, always delivering a constant wavefront curvature towards the WFS.

With a collimating optics placed behind the telescope focus the image of the telescopes pupil is created at the location of the membrane mirror. While the laser pulse is travelling upwards through the sodium layer, the curvature of the oscillating membrane has to match the focus position accordingly. When the laser pulse is at the lower end of the layer, the membrane needs to be concave to collimate the reflected light. ~33μs later the image has reached the nominal 90km position, the membrane moves through the flat state of the oscillation, still keeping the reflected light collimated, as for the further oscillation, until the laser pulse leaves the top end of the sodium layer.

While conceptually simple, the oscillation speed requirements are demanding. Assuming for a first simple calculation that the oscillation of the membrane mirror is fully sinusoidal in its center, and the shape of the membrane is spherical, the required membrane size, oscillation frequency and stroke depend only on the size of the main telescope, the used collimator focal length and the chosen fraction of the sinusoidal motion one wants to use. Fig. 6 shows an example for a 38m Telescope, a collimator focal length of 600mm and a used range of 1/10 of the sine motion for refocusing. The consequences for this example would be that one needs a 25mm diameter membrane driven at a frequency of 1500Hz. The required total stroke of the membrane amounts then to 300µm and a minimum radius curvature of the membrane of 500mm at the extremes of the oscillation and a used range between ± 1.75m radius of curvature.
Fig. 6: example of a sinusoidal motion of the membrane and the resulting radius of curvature. The two plots on the left show an example that would be required for the refocusing of a 38m telescope, a 600mm focal length collimator and a used re-focus range of 1/10 of the motion. The driving frequency is 1.5 kHz in this case. The right plot shows that the optically required curvature from a zmx optimization matches well a sinusoidal motion, drawn as solid line over the zmx points.

To proof the feasibility of the concept we have been testing membrane mirrors made out of nitrocellulose. As an efficient drive method the membranes have been built into an acoustically driven Helmholtz cavity. This method has been proven a very efficient way to excite a standing acoustic wave. With the membrane being located at the neck of the bottle the surface nicely follows the pressure oscillation. The oscillation frequency, amplitude and phase can be adjusted easily in this setup. To measure the membranes curvature over time a pulsed laser beam has been used to ‘strobe’ the surface shape. With adjusting the phase offset between acoustic drive and the laser one can easily step through the curvature change. Fig. 7 shows a measurement that has been taken with a 25mm diameter membrane.

Fig. 7: measurements of the membranes curvature. To the left a sequence of a 25mm diameter membrane oscillation is shown. Over the 66µs the curvature of the membrane changes from -2 to 2m. The derived minimum curvature points over a given excitation are plotted to the right.

While surely more and longer term measurements would be required to develop a field usable device, these first test show that a membrane mirror can be driven with appropriate frequencies and stroke to be usable for an ELT scale telescope. Especially some properties make the membrane technology attractive, being very compact, easily adjustable in stroke, frequency and phase. Those membranes therefore could be adjusted to follow a master clock in the system e.g. defined by the pulsing lasers and an according delay generator.
6. Conclusions

While sodium line lasers are nowadays getting better available, still the whole generation and detection of the laser guide stars is a demanding and costly process. Loosing performance due to the extension of the sodium layer and the following extension of the LGS image in the telescope focal plane is highly undesirable. In Shack Hartmann type sensors the outer sub-apertures would require of order 4-10 times more photons to reach the same centroiding precision as round spots. With pyramid sensors the huge z-extension of the image in the focal plane results in a large error of the wavefront measurements. The use of pulsed lasers in conjunction with a dynamical refocus device brings several benefits for a LGS wavefront measurement:

• Removing the elongation from the spot of the LGS on the SH detector enhances the measurement accuracy greatly.
• With shrinking the spot size, one enables the use of much smaller detector formats.
• When compacting the z-extension in the focal plane of the telescope with dynamically re-focusing, the measurement error with pyramid sensors is greatly reduced.
• The use of pulsed lasers brings another benefit with it: it allows to gate the wavefront sensor, which in return suppresses the Rayleigh scattered light. Therefore it naturally removes the fratricide effect from the LGS detection.

With the proposed oscillating membrane mirrors the required curvature, stroke and frequency can be reached. Compared to other solutions, The proposed devices show the potential in enhancing the AO performance at relatively small effort.

7. References

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