Dynamical Refocusing Laser Guide Stars with Membrane Mirrors

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ABSTRACT

Laser guide stars created in the earth's sodium layer are the choice for all ELTs as adaptive optics reference. With the thickness of the sodium layer spanning up to 10km, the apparent image of the guide stars on the adaptive optics wavefront sensors is elongated. The further away sub-apertures of the WFS are from the guide star launch location, the more elongated the guide star appears on the sensor. To counteract the decreased signal from the elongation, usually an increased laser power is demanded or special format radial CCDs are proposed. Another known possibility is to utilize pulsed lasers and follow dynamically the propagating pulse on its way through the sodium layer, creating a sharp spot at the wavefront sensor location. Similar processes have been used for laser guide stars created with Rayleigh scattering in the lower atmosphere, increasing greatly the number of photons that can be received from the guide star.

We present here the design and first laboratory tests of such a dynamically refocus device, based on membrane mirrors. Driven acoustically at high frequencies the stroke and phase of the mirror can be controlled. With a compact appearance the system seems to be easy to use and could enable precise wavefront control with lower power pulsed lasers at ELTs and other telescopes.

Keywords: Laser guide star, dynamical refocus, ELT wavefront sensing

1. INTRODUCTION

Adaptive wavefront control is regarded nowadays to be one of the key elements to increase the scientific return that can be achieved with large telescopes. Doubtlessly a sharper view is of great benefit for lots of science cases- enabling higher resolution, a reduction of crowding noise or just shorter integration times. With the upcoming extremely large telescopes adaptive optics is included into the design from the beginning. Taking the European extremely large telescope as an example, the deformable mirror will be built directly into the optical train of the telescope. To allow for a good correction of the wavefront, a reasonable amount of photons need to be seen by the wavefront sensor. Lots of objects are simply to dim or have no suitable guide star close enough to deliver a proper signal for wavefront sensing. Therefore it is common sense that artificial guide stars are required for a lot of 8m class telescopes today, but even more for the upcoming extremely large telescopes. The creation of the artificial guide stars in the earth’s sodium layer is used today at multiple telescopes, e.g. the W.M. Keck on Hawaii or the VLT in Chile. With this technology a powerful 589nm laser excites the sodium atoms at 90km distance creating a fluorescence spot that then can be used for wavefront sensing. Due to the physics involved in the origin of the sodium layer, the atoms appear to extend over approximately 10km at the 90km distance. With this finite thickness of the layer the fluorescence along the laser beam is rather a line then a single spot. At small telescopes this effect is not really seen by the wavefront sensor. But with larger telescope apertures and an increasing distance between the lasers launch location and the receiving sub-aperture the layer thickness is resolved and the laser beacon appears elongated on the wavefront sensor. Depending on the type of wavefront sensor, this elongation reduces the performance of the system. For a Shack Hartmann sensor type the distant sub-apertures see an extended spot in one direction which reduces the signal to noise ratio and respectively the signal on the slope measurement.

A similar effect appears with the usage of Rayleigh guide stars, where the scattering of short wavelength lasers in the lower atmosphere is used. With the increasing distance of the propagating pulse the wavefront sensor is getting out of focus quickly, requiring a short gating to keep the laser beacon sharp.

A mean to counteract these effects is the usage of a dynamical re-focusing device. Proposed by Hart & Angel 2002 [1], for the use with Rayleigh beacons at the MMT, a fast moving mirror counteracts the defocus from the guide stars. In this setup a solid mirror is mounted to an aluminum resonator that is driven electromagnetically and oscillates at ~5kHz. The frequency of the oscillation is given by the resonance of the aluminum rod which therefore has to act as master clock.

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In this paper we describe the use of a membrane mirror for re-focusing. Driven acoustically this device is compact in size and can be easily tuned in frequency and phase. We will report here on two test setups with different membrane diameters, optimized for the use with either Rayleigh lasers or Sodium line lasers at an ELT.

2. SPOT ELONGATION

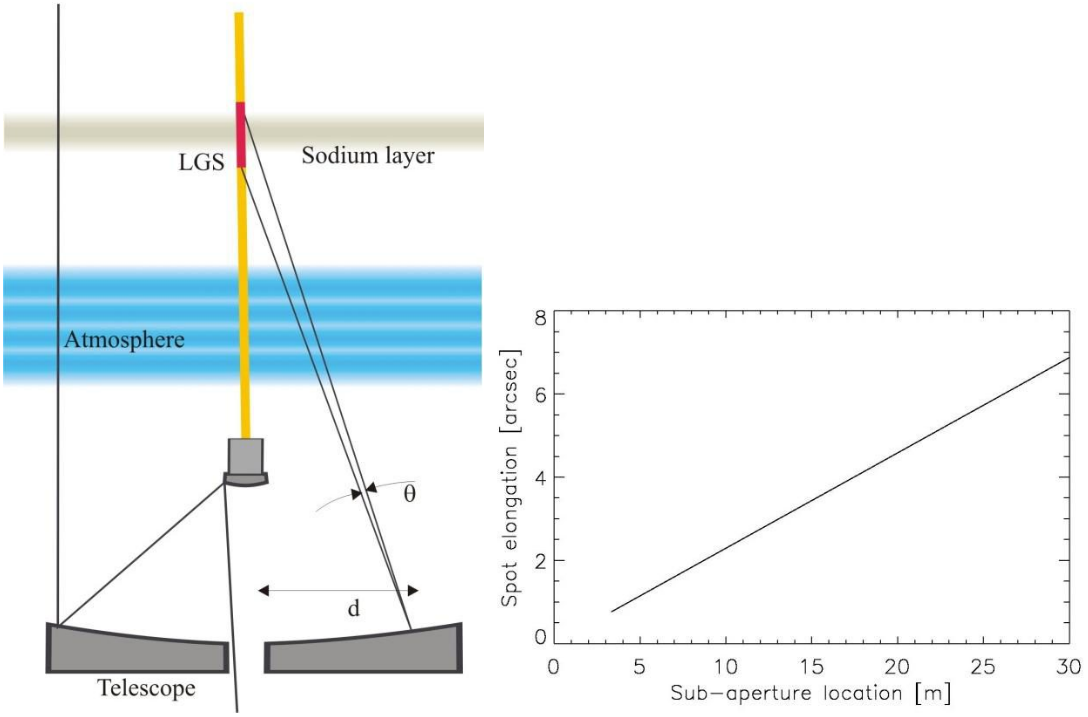

Figure 1: scheme of the laser guide star creation and origin of the perspective elongation. With the laser beam launched at a distance d from the receiving sub-aperture, the laser guide star is seen at an angle Θ due to the finite thickness of the sodium layer. With a side launched laser at an ELT the distance can be the full diameter.

As sketched in figure 1, the perspective elongation of the laser guide star origins in the thickness of the sodium layer. Any sub-aperture at a given distance d from the laser launch location will view the glowing laser plume from the side. Exactly the same effect appears when a Rayleigh laser guide star is used with longer range gating times. To the right in figure 1 the order of magnitude of this effect is shown for a sodium laser at 90km distance. With a 30m sized telescope and a central laser launch the elongation spans up to 4 arcseconds, and up to 8 arcseconds with a side launch geometry. The consequence of this elongation in the case of a Shack Hartmann type sensor is a reduced signal to noise ratio and reduced centroiding accuracy in the elongated direction. In the case of a pyramid sensor the smeared spot will even prevent the use of this type of sensor, which be a preferred sensor due to the excellent performance [2]. To counteract the loss in signal solutions have been proposed with either increasing the laser power, or even with specially built radial CCDs. Neither of those solutions is easy to realize. With implementing a pulsed laser system and a dynamical refocusing sharp spots can be created, resulting in a high signal to noise ratio, permitting pyramid sensors, allowing for less laser power and removing the light scattering from lower atmosphere.

3. REQUIREMENTS TO A RE-FOCUSING DEVICE

Implementing a pulsed laser guide star system permits a refocus to be used. The laser guide star implementation is not very different and would be launched as usual from the center or side of the main telescope. Only the pulse repetition rate needs to be adapted to the travel time up and down to the sodium layer. While the laser pulse is propagating upwards through the atmosphere, its image moves accordingly along the axis of the telescope. In the ELT case with an F# of ~20 the actual focus position movement between 85km and 95km guide star distance amounts to 1m. This change of focus appears on a timescale that is twice the travel time of the pulse through the sodium layer, i.e. 66µs. A dynamical re-focusing device needs to be able to follow this fast change in real time.

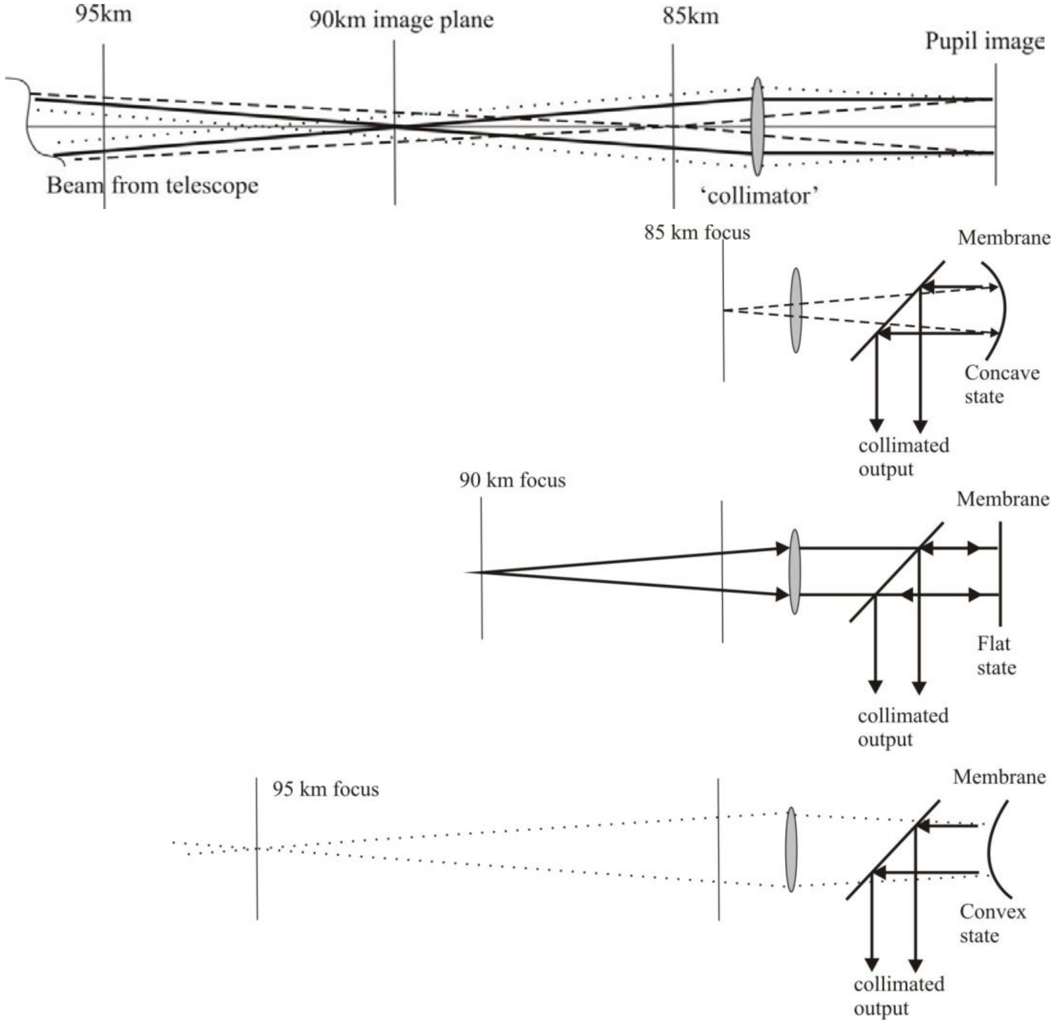

Figure 2: schematic on how one could implement a variable curvature membrane into the beam train after the 90km focus and a collimator before the wavefront sensor. With an ELT and an effective F#20 beam, the separation of the foci from 85 to 90 to 95 km amounts to 1m distance. This 1m focus change appears within 66µs.

The location of a membrane mirror for re-focusing would be in an image of the telescope pupil, appearing after a collimating optics in the beam train as shown in figure 2 on top. At this location the beam has always the same diameter and could be brought to collimation with a changing radius of curvature. In the lower three sketches in figure 2 the different states of the re-focus process are shown: with the laser pulse being at 85km, the lower end of the sodium layer, a concave shape of the membrane collimates the reflected beam. With the laser pulse passing the middle of the layer, the membrane would pass through its flat state and then moving to a concave state when the laser light from the upper end of the layer arrives.

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. Figure 3 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.

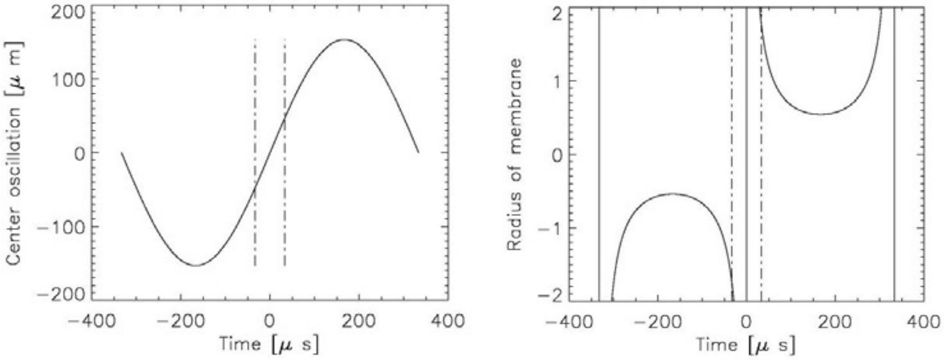

Figure 3: example of a sinusoidal motion of the membrane and the resulting radius of curvature. The two plots show an example that would be required for the refocusing of a 38m telescope, a 600mm focal length collimator and a used re-focus range of 1/10 of the motion. The driving frequency would be 1.5 kHz in this case.

Since it is most difficult to reach a high amplitude of the oscillation without exciting high order surface modes the following plot shows the correlation between the illuminated membrane diameter and the required maximum radius of curvature (at the extremes of the stroke). The plot is drawn for 1, 2 and 3kHz drive frequency. Basically one can learn from this plot that a large membrane diameter and a high oscillation frequency relax in return the demand on curvature.

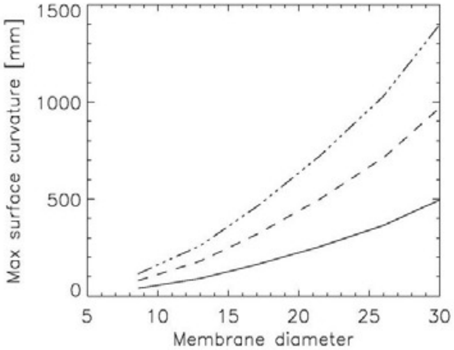

Figure 4: this plot shows how the required maximum membrane stroke correlates with the membrane diameter and the driving frequency. The plot is drawn for a 38m telescope. The solid line marks the 1 kHz oscillation, dashed is for 2 kHz, dash-dotted is for 3kHz. Basically –the larger the membrane i.e. the pupil image diameter, the less curvature is required. As well as higher the oscillation frequency, the fewer stroke is needed.

4. MEMBRANE MIRROR

As an experimental work we have been testing several membranes and two ways acoustically driving it. Basis of all membranes are nitrocellulose membranes strained over a frame and being aluminum coated. With three different sizes (12.7, 25.4, 50.8 mm) diameter and 2 and 5µm membrane thickness a range of membranes for either Rayleigh stars or sodium layer re-focusing was tried out.

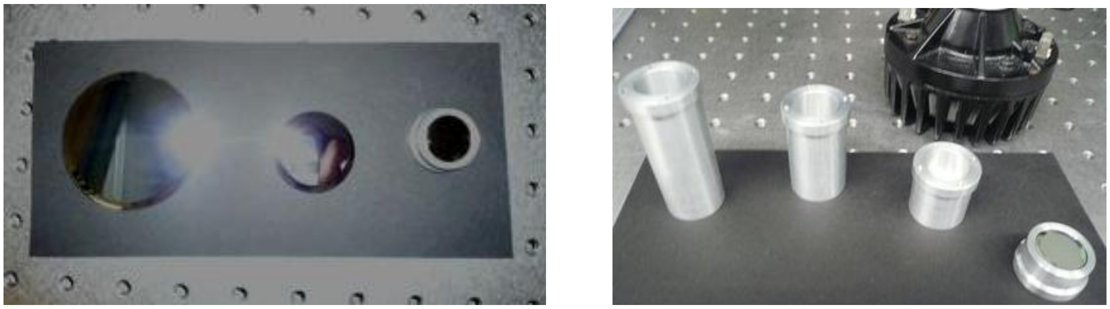

Figure 5: photographs of the used membranes. To the left from the 50.8, 25.4 and 12.7 mm clear aperture membranes, with the smallest one mounted. To the right the first open cavity with various resonator length tubes for realization of different frequency responses. In the background one of the used powerful drive speakers.

4.1 Small membrane in an open cavity

In a first setup the small 12mm membrane and the loudspeaker driver were backside coupled with a little acoustic cavity. The length of this cavity allowed then to tune the resonance frequency.

As a first test of the membrane we have been with taking static interferograms to check for the basic optical quality. Measuring with a Fisba interferometer against a λ/20 flat yielded the surfaces shown in figure 6. Basically this showed that the membranes are of excellent quality, mainly showing some astigmatism which could even be improved with stiffer ceramic frames.

In a second step we have setup a way to probe the radius of curvature of the membranes while oscillating. With sending a converging laser beam over the membrane surface onto a CCD, one can derive the radius of curvature from the resulting image size. To achieve an image in small time steps of the oscillation we used a pulsed diode laser (Coherent cube at 635nm) that can be triggered externally. A function generator delivers the required trigger for the laser and the sine wave signal that drives the loudspeaker. With the use of a delay generator between the function generator and the laser one can now record images that show exactly one state of the motion. In figure 7 a series of those images is shown. The outer diameter of the recorded spot together with the geometry of the setup is a measure of the surface curvature.

Figure 8 shows two plots that are derived with this measurement setup while driving the membrane at a 3.2kHz rate. The radius of curvature is resolved in 10µs steps and with driving the membrane to its extremes, amplitudes of 100mm curvature could be reached.

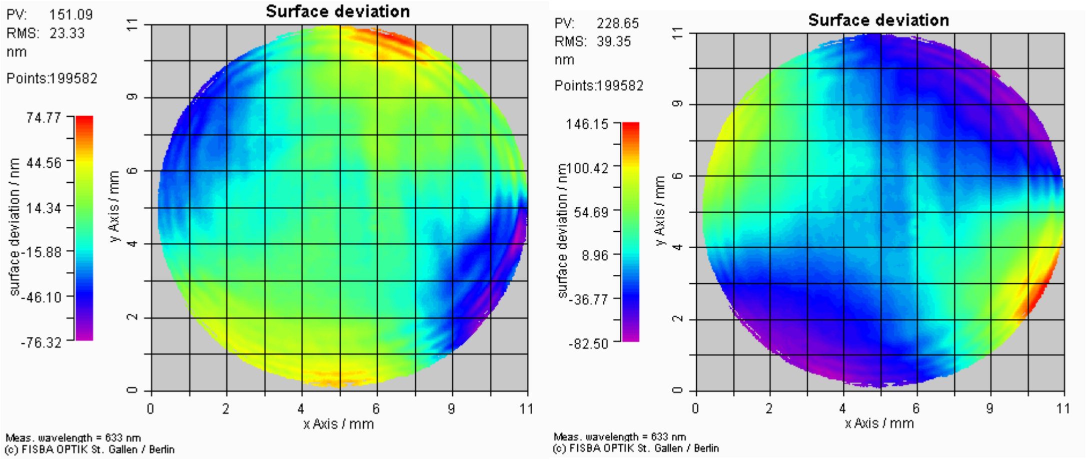

Figure 6: measured surface deviation of two of the membranes over a 10mm aperture. The main distortion comes from some astigmatism, that the manufacturer claims to originate from the aluminum frames the membranes are deposited on. This could even be improved with stiff steel or ceramic frames.

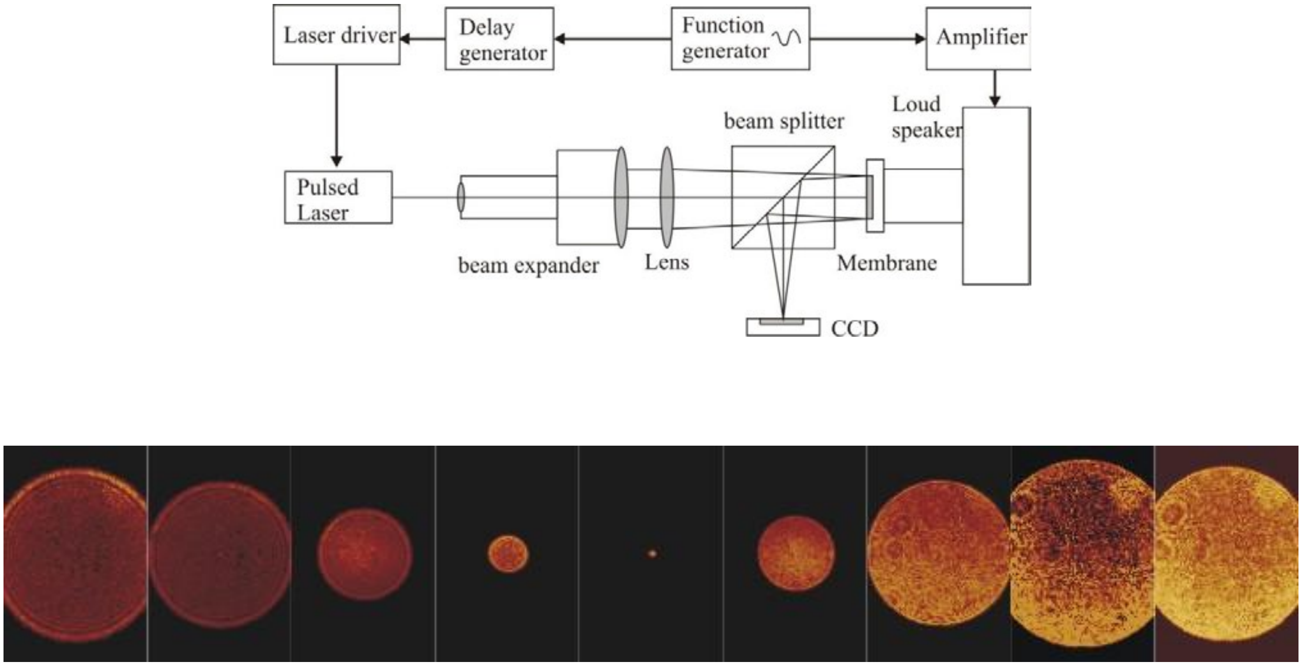

Figure 7: dynamically testing the membrane on stroke and curvature. The test setup consists of a pulsed laser probing ns slices of the motion. The illumination took place in a converging beam sent via a beam splitter onto the membrane. In the 'focal plane' a CCD is placed to record the resulting image. When driving the Membrane with a function generator, the laser pulses can be triggered with a variable delay. This enables to record the membrane at given curvature state. In the lower series of images shows a full oscillation period while running the 12mm membrane at 5kHz.

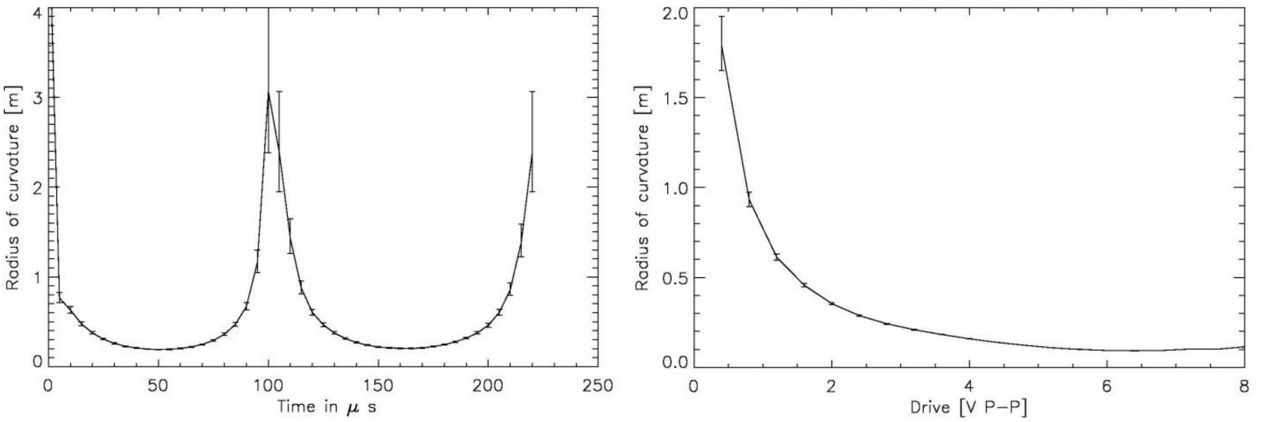

Figure 8: with measuring the diameter of the spot at the CCD plane one can deduce the surface radius of curvature. To the left the radius of curvature over one oscillation period is shown, resolved in 10µs steps. To the right the minimum achievable radius of curvature at a given drive power is shown. At the extreme one can push the 12mm surface between ±100mm radius of curvature in its lowest surface resonance.

4.2 25mm and 50mm membranes in a closed cavity

In a second step we have setup a 25mm and a 50mm membrane system where we would like to show that it already could be used for an extremely large telescope. At the same time we tried to improve the acoustic cavity and as well the measurement system. With the small open cavity the acoustic resonance drive turned out to be hard to calculate, as the length tends to be very short and the loudspeaker drive membrane tended to influence the resonance properties strongly. In the setup for the 25mm membrane we made use of a 'Helmholtz resonator' consisting of a 'bottle' type geometry. At the floor of the bottle the light can enter through a window and on the neck of the bottle the membrane is mounted. Above that the acoustic drive excites the oscillation. A photograph is shown in figure 9

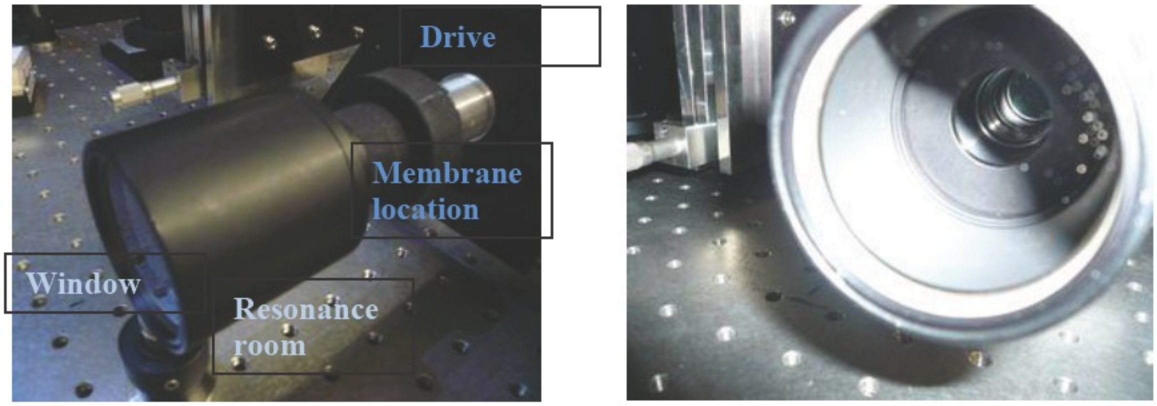

Figure 9: view of the closed resonance cavity. A 50mm glass closes the cavity and allows the light to enter onto the membrane that is located on the neck of the bottle. With this setup very low drive power is needed and the system is basically quiet.

With this geometry the calculated resonance of 1khz showed a very good match with a 1.04kHz detected resonance. Additionally the cavity seems to act very efficient and requires very low excitation power. With the closed cavity and the solid entrance window the noise outside –that tended to be extreme with an open cavity- is basically gone. The 50mm membrane has been mounted similarly, but with a larger neck and closer to the entrance window, which consequently increased the resonance frequency to 1.4kHz. With illuminating the membranes with a collimated light beam from the pulsed laser one could measure the resulting close focus position, and from that estimate the curvature of the membrane. The result is shown in figure 10. With increasing excitation power the amplitude gets larger and the reachable curvature gets smaller. The increase in excitation power has been carried until visible onset of higher order distortions took place. In summary the 25mm 2µm thick membrane could be exited until a curvature of 350mm radius, the 5µm thick to 320mm and the 50mm membrane as well down to 350mm curvature radius.

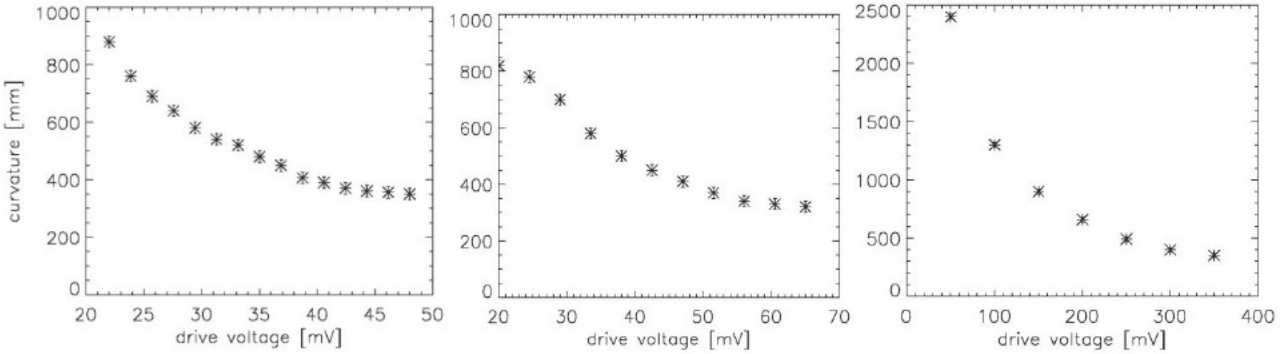

Figure 10: maximum curvature of the membrane surfaces at the extremes of the oscillation at various drive power. Left: the 25mm membrane with 2µm thickness, middle: the 25mm membrane with 5µm thickness, right: the 50mm membrane 5µm thick. Both smaller membranes driven at 1040Hz, the large 50mm membrane at 1.4kHz. The curvature was measured from the focus distance when shining a collimated light beam onto the membranes and tuning the delay between phase and laser pulse.

With the method of illuminating the membrane with the pulsed laser (a 532nm YAG in this case) and adjusting the delay we have been able to measure the instantaneous curvature of the surface out of the resulting spot size at a given distance. Using a screen at 2500 and at 1000mm distance from the membrane we have checked the curvature at the transition between concave to convex state- exactly where one would use the membrane. The resulting plot is shown in figure 11 for both membranes.

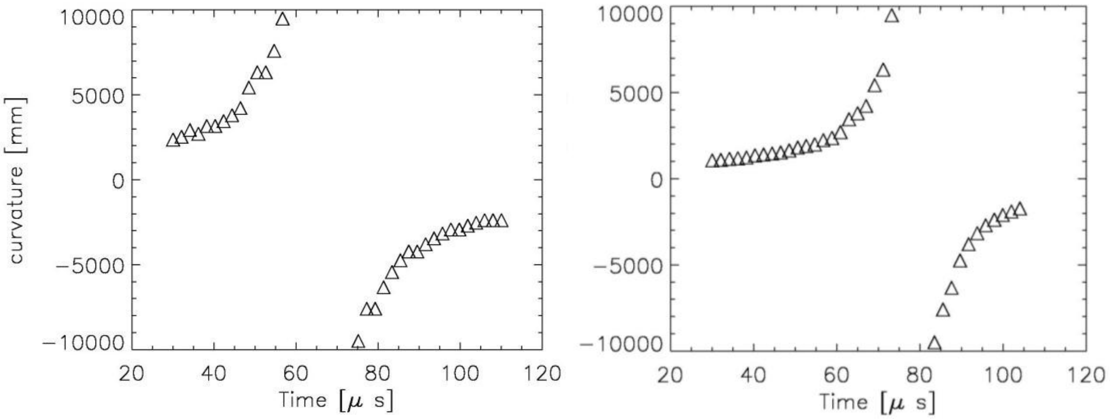

Figure 11: measured curvature over time for left: the 25mm membrane at 1kHz, right: the 50mm membrane at 1.4kHz. Within a 60μs range that is required to re-focus a light pulse coming from the sodium layer both membranes could oscillate between a -2m to + 2m radius of curvature, which is just good enough for the 25mm 1kHz case, but always sufficient in the 50mm 1.4kHz membrane case.

5. CONCLUSIONS

We have calculated the needs for a membrane based re-focusing device that could be used at large telescopes to keep sodium and Rayleigh guide stars sharp on a wavefront sensor. Utilizing such a re-focus in conjunction with pulsed lasers has clear benefits.

- Remove the need for special CCDs in a Shack Hartmann wavefront sensor.
- Eliminate spot elongation .
- Lower the power requirement for the laser.
- Enable the usage of pupil plane wavefront sensing, especially enable pyramid wavefront sensors.
- With the use of pulsed lasers stray light from the lower atmosphere the ‘fracticide effect’ can be removed.

The membranes we have tested so far can reach a stroke and surface curvature strong enough to be used as re-focus device- even for extremely large telescopes. With implementing the membranes in a closed cavity the device is relatively compact, adjustable in amplitude and phase and easy to use. While a wide parameter field still needs to be evaluated and plenty of optimization can be done to the oscillating membrane, these first measurements clearly show the ability of this technology to enable above listed advantages of pulsed lasers in conjunction with dynamic refocusing.

REFERENCES

[1] Lloyd Hart et al., "Dynamically refocused Rayleigh laser beacons for atmospheric tomography”, Proc. SPIE 4494, (2002).

[2] Esposito S. et al., “Large Binocular Telescope Adaptive Optics System: new achievements and perspectives in adaptive optics”, Proc. SPIE 8149E, (2011)