Real-time measurement of the Na layer profile for tomographic reconstruction: experimental results and its application to the E-ELT case

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Abstract. Extremely Large Telescopes are being designed with integrated AO modules and most of their instruments will rely on them for their optimum performance. To reconstruct the wavefront we need to use Guide Stars as references, but the absence of enough Natural GSs to have a good sky coverage make it necessary the use of Laser GSs. Several technical challenges have to be solved in order to perform a good wavefront reconstruction using LGSs. In the case of Na LGSs we need to know the height at which the LGS is focused and the profile and extension of the Na layer. We propose the use of a plenoptic camera to obtain this information. The plenoptic camera was originally created to allow the capture of the Light Field, a four-variable volume representation of all rays and their directions, that allows the creation by synthesis of a 3D image of the observed object. This 3D reconstruction make it possible to retrieve the distances at which the objects are, and for this reason it is especially adequate to measure the height variations of the LGS beacons. This novel approach provides real-time information on the Na layer profile that can be introduced in the reconstruction algorithm to solve the problems derived by the spot elongation. Also we can compute at which height is focused the LGS, overcoming therefore the two challenges mentioned before. We present in this paper the laboratory results obtained with a setup simulating the laser spot and the telescope equipped with the plenoptic camera that proof that the expected height of the layers is retrieved. We also present our plans to implement on-sky tests of our system using the Na LGS of the Optical Ground Station in the Observatorio de Tenerife, and the application of this advanced concept to the E-ELT.
1 Introduction

Some of the most important science goals of any Extremely Large Telescope are high-redshift galaxies and the re-ionization of the early universe. In both cases, high performance wide-field Adaptive Optics is a critical requirement. For this reason Multi-Conjugated AO systems will be built on those telescopes, but they need several Guide Stars for the real-time compensation of the atmospheric distortions over a wide field. There are not enough bright Natural Guide Stars to cover the whole sky. Therefore, Laser Guide Stars are needed to operate such systems. Among them, Sodium LGSs are widely used. They are generated by the back-scattered light from the sodium layer in the mesosphere. Due to the vertical extension of the layer, the LGS is seen as an elongated source from the Wave Front Sensor subapertures located far from the launching point of the laser. This elongation affects the calculation of the centroid in the WFS and the SNR, and therefore it has to be estimated.

2 The mesospheric Na layer

The altitude and linear vertical size of the Na LGS are usually assumed to 90 and 5-10km respectively, adopting the standard mesospheric sodium levels. But the Na layer is strongly affected by global and local effects, either seasonal or very short time scaled. Sporadic bright layers can appear at different heights with an extension down to 500 meters. These variations may change the Na centroid in a range of cents to thousands meters even in a few minutes interval affecting the centroid algorithm performance. Therefore, it is required to measure on real-time its distribution vs. height. This 3D distribution can be measured with a plenoptic wavefront sensor.

3 The plenoptic wavefront sensor

The plenoptic wavefront sensor, also known as the plenoptic camera, was originally created to allow the capture of the Light Field [1], a four-variable volume representation of all rays and their directions, that allows the creation by synthesis of the image as seen from virtually any point of view.

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The plenoptic camera – how it works

The plenoptic camera captures the Light Field, a four-variable \((x,y,u,v)\) volume representation of all rays and their directions. The microlenses sample the spatial coordinates \((x,y)\) and the pixels sample the angular coordinates \((u,v)\).

As can be seen in Fig. 1, a microlens array with the same f-number than the telescope is placed at its focus, in such a way that many pupil images are obtained at the detector, each of them representing a slightly different point of view. The use of the same f-number guarantees that the size of the image of the pupil is as big as possible, without overlapping with its neighbor, providing thus optimum use of the detector surface. In order to understand the behavior of the plenoptic wavefront sensor, it is important to identify the direct relationship existing between every pupil point \((u,v)\) and its corresponding image for each microlens. Every pupil coordinate \((u,v)\) is imaged through each microlens in a way that all rays will arrive to one of the pupil images, depending only on the angle of arrival. This fact clearly indicates that the image can be reconstructed by post-processing the plenoptic data, selecting the value of the corresponding coordinate at every microlens \((x',y',u',v')\) and building an image with all of them.

The use of plenoptic optics for wavefront measurement was described by Clare and Lane [2], for the case of point sources. For depth extraction the plenoptic sensor acts as a multiview stereo system; whereas, for wavefront phase extraction, it can be understood as a global sensor containing as extreme cases the Shack-Hartmann sensor and the pyramid sensor (2x2 microlens array at telescope focus). The tomographic capability of the plenoptic sensor was demonstrated by Rodríguez-Ramos et al.[3],[4]. Due to the finite sampling of the \((u,v)\) plane the object space is also finitely

Fig. 1. The 4D lightfield, 2D spatial \((x,y)\) and 2D angular \((u,v)\), is captured by a plenoptic sensor.
Due to the finite sampling of the \((u,v)\) plane the object space is also finitely sampled. Depending on how the pixels are combined, we retrieve the focused image of the object placed at one distance or another, as can be seen in Fig. 2. There are different algorithms that refocus more or less planes at different distances. This 3D reconstruction makes possible to retrieve the distances at which the objects are. For this reason it is especially adequate to measure the height variations and vertical distribution of the LGS beacons. This novel approach provides real-time information on the Na layer profile that can be introduced in the reconstruction algorithm to solve the problems derived by the spot elongation, giving a more complete alternative to other methods.

4 Measuring the Na profile: laboratory results

The plenoptic image captured by CAFADIS is shown in Fig. 3. Using an array with \(N \times N\) microlenses and a sensor with \(M \times M\) pixels/microlens creates a \(N^2 \times M^2\) pixels image. This image is processed with the plenoptic software programmed for GPUs, allowing reconstruction times of ms. The fastest variations of the Na profile have been found to be \(\approx 1\text{Hz}\) (Chun et al.[5]).

The super resolution algorithm gives \((2p - 2)\) refocused planes, with \(p\) equal to a prime number smaller than half the number of pixels behind
Multi-conjugate AO and the need of LGSs

The Sodium Laser Guide Star

The mesospheric Na layer

The plenoptic camera: how it works

how can it measure the 3D Na profile

laboratory results

Application to a real case: the E-ELT

Future work: on-sky tests

Conclusions

Measuring the Na profile

– laboratory results

Plenoptic raw image

Fig. 3.

Super (spatial) resolution algorithm: \((2p^2)\) refocused planes, with \(p\) equal to a prime number smaller than \(\#\) pixels/2

Measuring the Na profile – laboratory results

Fig. 4. Laboratory results: each image corresponds to a different focused depth.

each microlens. For our experiment we used a F/19 lens with a diameter of 17.8 mm. A microlens array with 110 micron pitch and a sensor with 12 pixels behind each microlens. Processing the information with the super-resolution algorithm, gives 8 refocused planes, as can be seen in Fig. 4. In
Fig. 5. Laboratory results: when all the images are combined we retrieve a completely focused image of the complete object. Left, the image taken with a non-plenoptic sensor; center, the all-in-focus image combining the 8 focused images obtained with the plenoptic sensor; right, the map of distances, each grey zone gives the depth of a focused plane.

Fig. 6. Laboratory results: as can be seen, the predicted distances correspond to the distances measured in the lab, within 1 mm accuracy

Fig. 5, we can see the map of distances, with each grey zone corresponding to the part of the image that is focused at each distance and the all-in-focus image combining the 8 focused planes of Fig. 4. The predicted distances correspond to the distances measured in the lab, within 1 mm accuracy, as is shown in Fig. 6. Extrapolating to the sky, that means a 200 m precision, covering 28 km, in real-time. Ideally we would like to resolve more planes, and it is possible to increase the depth resolution with the Radon algorithm. It would give \((2N – 1)\) refocused planes with \(N\) equal to the number of pixels.
5 Application to a real case: the E-ELT

In Fig. 7 we show the result of applying this concept to the E-ELT. No new technology is required for that, it could be done using existing elements. For a 42 m diameter F/15 telescope, a plenoptic sensor featuring a microlens array with a pitch of 350 micron, 58 pixel/microlens, and 200x200 microlenses in total would resolve 114 planes, from a height of 84 km to 96 km, which means 107 meters resolution in depth.

6 Conclusions

Plenoptic cameras can be used to take real-time measurements of the mesospheric Sodium layer profile, improving the quality of the wavefront reconstruction for MCAO. Lab results prove the feasibility of the technique. It can be applied to the E-ELT with off-the-shelf tools, no instrument development required. The map of distances for the Radon algorithm will
be implemented in the incoming months to increase depth resolution. We plan to implement on-sky tests at Observatorio del Teide using the Na LGS facility placed at the Coudé focus of the ESA's Optical Ground Station and the nearby 1.5 m Telescopio Carlos Sánchez to place the plenoptic camera. Images will be taken in parallel with the IAC80 telescope in order to validate the results.

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