

Diffractive Wavefront Sensor (DWS) applications for medium to large size telescopes

Diego Ayala-Cajas^{a,b}, Roberto López López^a, Luis Fernando Rodríguez-Ramos^a, and Félix Gracia Témich^a

^aInstituto de Astrofísica de Canarias, C/ Vía Láctea s/n, 38205 La Laguna, Tenerife, Spain

^bUniversidad de La Laguna, Departamento de Astrofísica, 38206 La Laguna, Tenerife, Spain

ABSTRACT

In an Adaptive Optics (AO) setup we implement the novel Diffractive Wavefront Sensor (DWS) in order to measure the wavefront distortion, and to test it as an alternative to the well-known Shack-Hartman (SH) sensor. The DWS can be built with a minimum of hardware, being in this case a single lens and a liquid-crystal-on-silicon Spatial Light Modulator (LCOS-SLM), these elements produce the diffractive pupils that are latter captured by a camera and processed to reconstruct the wavefront directly from the image using the Frankot–Chellappa algorithm. Experimental results indicate a high resolution, robustness against obscurations in the pupil plane (such as the ones caused by the structure of the secondary mirror in a telescope), and a simple implementation to filter diffraction caused by segmented mirrors (ubiquitous in large telescopes and extremely large telescopes).

Keywords: Diffractive Wavefront Sensor, Liquid-crystal-on-silicon, Adaptive optics, Digital adaptive optics, Fourier optics

1. INTRODUCTION

The atmosphere produces scintillation, jitter, and other aberrations on the image of a point source or star.¹ Typical Adaptive Optic (AO) measure the temporal and spatial changes of the wavefront through a Shack-Hartman (SH) wavefront sensor (WFS), and correcte it with Deformable Mirrors (DM) that have a reflective membrane with mechanical actuators in the back that move in real time to cancel the fluctuations.

However, SH sensors rely on a series of algorithms to reconstruct the information provided by the deviations of centroids given by a point-source that makes various focused spots onto an array of lenslets. Non-uniformity in illumination gave rise to algorithms of centroid gain such as the one by Marcos A.² In the case of large telescopes a very accurate mapping of the primary mirror must be performed when re-imaging the pupil, with tolerances less than 0.1%.³

Additionally the shade and diffraction in the pupil produced by the structures of the secondary mirror will be re-imaged at the SH sensor, in the case of Gran Telescopio de Canarias (GTC) this has been addressed by a careful design of masked sub-apertures, and also the rejection of centroids at the shade below the structure of the secondary mirror, as well as in the outer edges of the primary.⁴

Solutions for these problems have been found at the cost of increased complexity, hardware, algorithms, and high grade of specialization that makes one solution not adaptable from one telescope to another. This may be one of the factors that has made AO for telescopes currently still not the standard. AO systems will face more challenges in the incoming years, due to the construction of even larger telescopes with complex structures to hold mirrors in place, and large apertures that would require higher resolution of the wavefront as D/r_0 increases.

We propose the use of a Diffractive Wavefront Sensor, based on a diffractive mask placed in the focal point, it produces multiple versions of the entrance pupil which are directly captured by a camera. This approach enables

Further author information:

D. Ayala: diego.ayala@iac.es

efficient wavefront-gradient estimation through the computational light-weight Frankot–Chellappa algorithm, avoiding lenslet arrays and centroiding algorithms.⁵

The spatial resolution will closely match that of the number of pixels that the pupil illuminates on the camera's sensor,⁶ therefore it is expected an increase of resolution compared to the SH that relies on a short number of lenslets varying from 2x2 to a few thousands at most, the fabrication of smaller lenslets without compromising the image is also an stalling factor for this technology.

With DWS technology, it is expected that the wavefront reconstruction will not be affected by obstructions in the pupil plane, as it directly captures replicas of the pupil, then any obscuration will be re-imaged at the wavefront estimation directly, without the need of any additional algorithm.

We constructed a DWS that was added to an already existing AO system. Details of construction, and setting up are non-trivial, and will be discussed in next sections. Finally, we took some preliminary measurements that confirms a resolution higher to the SH we employed, and presents robustness with diffraction and obscurations in the pupil plane.

2. BUILDING A DWS

We made use of an already existing testbed for AO technologies implemented in the laboratories of Instituto de Astrofísica de Canarias. The wavefront is produced by a HeNe Laser (633nm), then aberrations are induced by a segmented DM, afterwards a polarizer allows only horizontal polarized light to pass to a beam-splitter that takes the light to two branches, one dedicated to the DWS, and the other one for phase-only correction of the wavefront through the use of an LCOS, in the same branch measurements can be done by a SH wavefront sensor (WFS) and a short-field camera. This testbed is shown in Fig. 1.

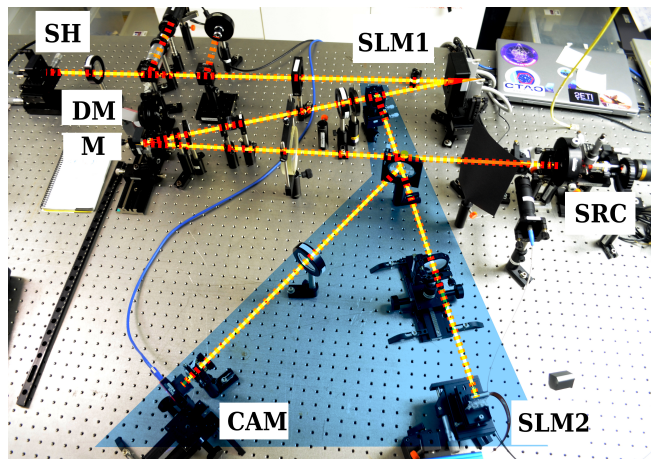


Figure 1. Testbed for AO with an LCOS-SLM, and a DWS added (highlighted in blue)

In our system aberrations can be induced in two forms: through a Deformable Mirror (DM) with 140 actuators that lacks of a reflective membrane, thus there is gaps between each one of the mirrors, this causes diffraction in a similar to a segmented primary mirror on large telescopes. Another way to cause aberrations is to introduce a phase mask, which can be seen as a big circular glass in the center of Fig. 1; additionally a rail was placed in order to exchange the DM for a flat mirror that wont induce diffraction.

Through the use of modifications made to open-source software for DM's⁷ we induce Zernike type aberrations that are measured by a (35 x 35 lenslets) SH and a short-field camera that records the observed Point Spread

Function (PSF) that are shown in Fig. 2.

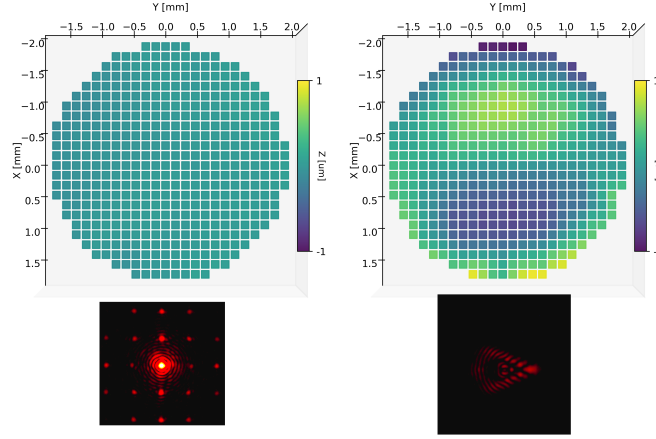


Figure 2. Measured wavefronts from the system without aberration (to the left), and with a coma type aberration (on the right).

One of the drawbacks using a segmented DM is the diffraction caused by the gaps between the actuators. This will cause a diffraction pattern in the PSF that can be appreciated (in the Fig. 2) as copies of itself in a rectangular manner. However, for reasons explained previously this diffractive pattern will be of use to test if the DWS can still operate under this conditions.

The phase-correction LCOS (SLM1) is used in ongoing experiments in AO, but it is deactivated in the scope of the incursion of the DWS, and can be considered as a 79% efficiency mirror.

2.1 Physical implementation

According to the work of M. Cagigal et al. a diffractive element placed at the common focal plane of two lenses will cause the super-position of four sheared copies of the pupil in a manner illustrated on Fig. 3.⁶

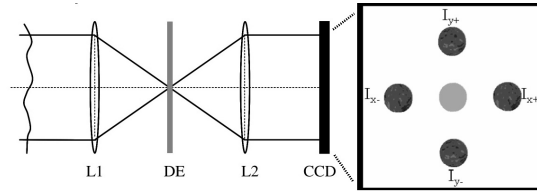


Figure 3. A setup consisting of a Diffractive Element placed at the common focal plane of two achromatic lenses, the pupil can be reimaged in a charge-coupled device (CCD).⁶

We based our DWS in this principle, but notoriously we use a single lens that first performs the Fourier transform of the input field, it gets multiplied by a phase mask instantiated in the reflective LCOS. The on-axis reflection is transformed again by the same lens to obtain collimated copies of the pupil. In accordance to the dependence of a single lens, the tip, tilt and translation movements of it have to be carefully controlled and tuned by appropriate mounts. Additionally, the diffractive replicas have to fit in the lens, the separation between each depends mainly in the geometry of the diffractive mask, in this aspect it is useful that we can modify the mask digitally through the use of LCOS-SLM technology, and finely tune this and other variables that will be explained latter.

LCOS-SLM's are built with resolutions that range from hundreds of thousands to millions of pixels, and can modulate the phase at any given pixel from 0 to 2π .⁸ In our case we use an Holoeye's ERIS 1.1 LCOS, with a $8\mu m$ pitch per pixel. This allow us to create mask of cosines distributed in the 1920×1200 pixels and that will act as the diffractive element that generates the four replicas. There is ample margin of tolerance as the optical axis doesn't have to be in exact middle point of the LCOS screen, because the mask can be digitally displaced over the surface until its center matches the position of the focal point. In this aspect DWS technology can present an advantage when compared to the pyramid wavefront sensor (PWFS) as prism defects and misalignments introduce error in the wavefront,⁹ and as it doesn't have to physically vibrate to adjust for gain.¹⁰

2.2 The digital diffractive mask

The diffractive mask $\Delta\phi$ can be described as a phase mask mapping of a cosine function with an slope in orthogonal spatial-frequency coordinates u, v , defined in Equation (1):

$$\Delta\phi(u, v) = 2\pi((A + Bu)\cos(ku) + (A + Bv)\cos(kv)), \quad (1)$$

Where A defines an offset term, B the linear slope, k the cosine modulation frequency. If we define the input pupil as $\Psi_{in}(x, y)$, then the output pupil $\Psi_{out}(x, y)$ can be defined as a convolution with the mask at the focal plane, expressed in Equation (2):

$$\Psi_{out}(x, y) = \mathcal{F}^{-1}\{\mathcal{F}\{\Psi_{in}(x, y)\} \cdot \Delta\phi(u, v)\}, \quad (2)$$

And due to the inverse Fourier transform presented in Equation (3) the cosine modulation generates two separated horizontal copies of the pupil whose separation depend on the value of k , and that have a proportional intensity to the values of the slope B ; the same is true for the vertical direction.

$$\mathcal{F}^{-1}\{\cos(ku)\} = \frac{1}{2}[\delta(x - \frac{k}{2\pi}) + \delta(x + \frac{k}{2\pi})], \quad (3)$$

As slight changes in all these terms will be determinant of the generation of the diffractive replicas, one could imagine that in the past the fabrication of a tailored diffractive element would have been a painstaking process. Fortunately, the phase mask generated by the LCOS can be controlled digitally, we implemented an user interface that can modify in real-time the offset A , the slope B , the spatial-frequency k , as well as it can move the mask in vertical and horizontal directions. One of the generated masks is shown in Fig. 4.

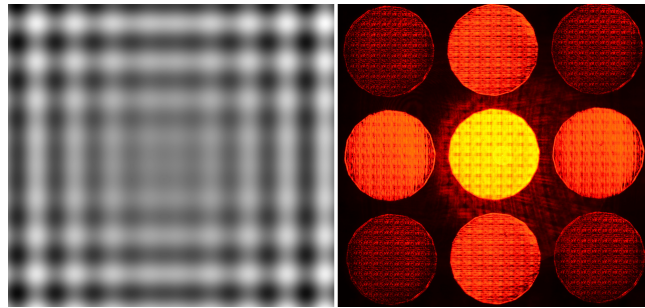


Figure 4. A phase retardance mask that is instantiated as a diffractive element in the LCOS (on the left). The diffracted replicas after fine tuning of the mask's parameters (on the right).

To prevent any misinterpretation of the obtained mask and diffractive replicas, we clarify two aspects: First, although the mask shown in Fig. 4 was generated through the mentioned user interface, it was modified in its parameters in order to be shown in this article, a mask that is in actual use has a very high spatial-frequency and low local contrast which represented in printed form would be a grid of indistinguishable gray lines. Second, by the geometry and knowing that there is 4 pupil replicas, the DWS could be misinterpreted as an approach of the

well known Pyramid wavefront sensor, but as already explained, this is not the case, they operate on completely different hardware approaches, ending up with pupils that look quite similar.

Choice of the focal length was done to make the Airy disk illuminate no more than 2×2 pixels in the LCOS, this was confirmed through the instantiation of a radius and position variable vortex in the a surface of the LCOS. Shorter focal lengths would require smaller pitch of the pixels. The distance between the replicas is affected by this, as well as by the wavelength of choice due to the different refractive index in the LCOS.

After obtaining the replicas of the pupil a second beamsplitter takes the collimated light to the camera, given its sensor size, we chose to work with only one copy of the pupil in the vertical direction and the remaining in the horizontal. Thus the camera, that operates at 30FPS, is placed in an off-axis position as can be seen in Fig. 5.

2.3 Wavefront reconstruction

The recorded pupils contain the gradient information in the x , and y direction, which are proportional to the partial derivatives of the wavefront. The wavefront reconstruction is then performed in $\sim 11\text{ms}$ using the Frankot–Chellappa algorithm, which integrates the gradient field in the Fourier domain.

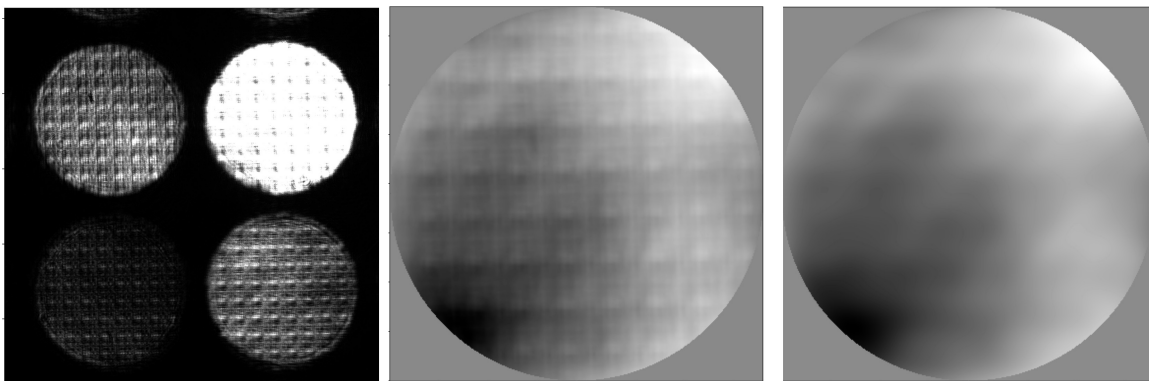


Figure 5. Capture of a flat DM and it's respective central, vertical, and horizontal pupils (to the left). The reconstructed wavefront without filtering (to the center), and with after low-pass filter (to the right).

As can be seen in Fig. 5 the diffraction of the segments in the deformable mirror are present as a grid like structure in the wavefront reconstruction. Therefore a filtering can be performed to eliminate the high frequency components. This filter was implemented digitally as a low-pass filter in the Fourier space within the Frankot–Chellappa algorithm.

It is also worth mentioning that another user interface had to be made in order to have fine control of the captured image and it's flats. The reconstruction need a correct definition of the exposure time (to avoid saturation of the sensor), usable radius (being the edges a source of noise), the center of each pupil (which may vary with re-alignment), value of the low-pass filter, orientation and mirroring compensation. The fine tuning (of the diffractive mask, the optical hardware, and this last mentioned parameters) is a time consuming job, and somehow trial-and-error process. Nonetheless the payout is seen in the resolution achieved, in our case we obtained a spatial resolution of 380×380 pixels, with a depth resolution of 10 bits in each pixel.

3. TESTSTING THE DWS

3.1 Defocus type aberration

A defocus type aberration was instantiated in the DM and captured by the SH and DWS sensors. The results are shown in Fig. 6.

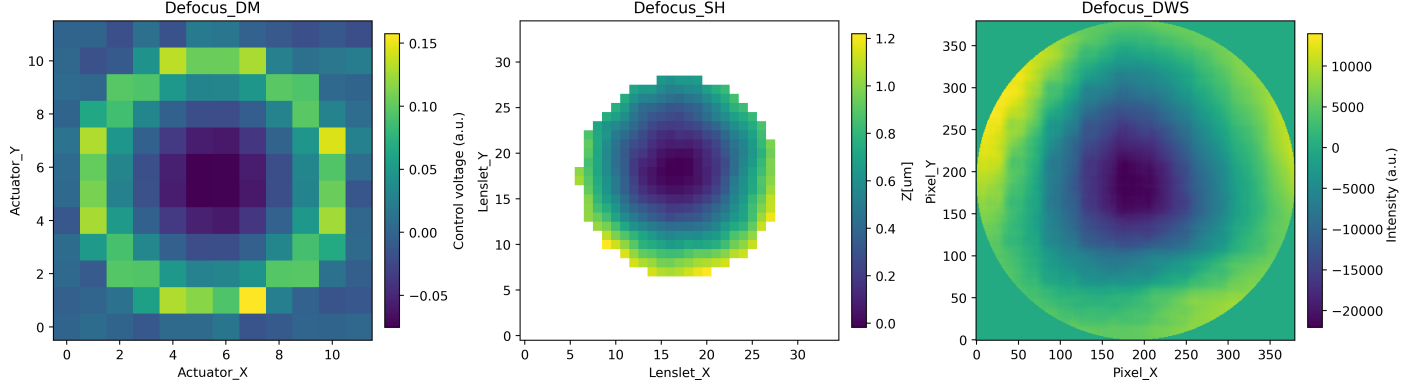


Figure 6. Control signal that drives the defocus in the DM (to the left). Measured aberration by the SH sensor (to the center), and with the DWS (to the right).

The spatial-resolution of the DWS is fairly superior (to the one of the SH) in the Fig. 6. Nonetheless, even after filtering, the structure of the DM still appears visible in a lesser extent for the DWS. In the case of the SH it was necessary to reduce the quantity of centroids used as the edges introduced noise that could be attributed to the diffraction and marginal rays produced at the DM. To have a better assessment, a cross-section of these measurements is shown in Fig. 7.

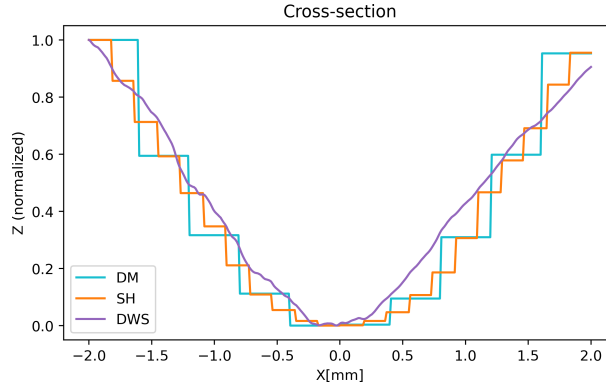


Figure 7. Horizontal cross-sections of the defocus aberration, the values of depth were normalized to 1 in order to compare what would be control voltages, wavefront depth and raw intensity in the DM, SH, and DWS respectively..

From the cross sections seen in Fig. 7 both sensors exhibit a measurement that closely match the expected deformation of the wavefront caused by the DM. The DWS's higher spatial resolution can be appreciated in this graphic as well. However, there is still non-symmetries present and a curvature that is slightly different from the DM, this suggest that additional algorithms could be needed to convert the intensity calculated so it can be interpreted as a real measurement of depth, thus values of depth from the DWS will be kept in this work as the intensity in arbitrary units calculated after the Frankot–Chellappa algorithm.

3.2 Phase mask type aberration

In this test the DM was replaced by a flat mirror, and the aberration was produced by a phase mask, resulting in the wavefronts shown in Fig. 8.

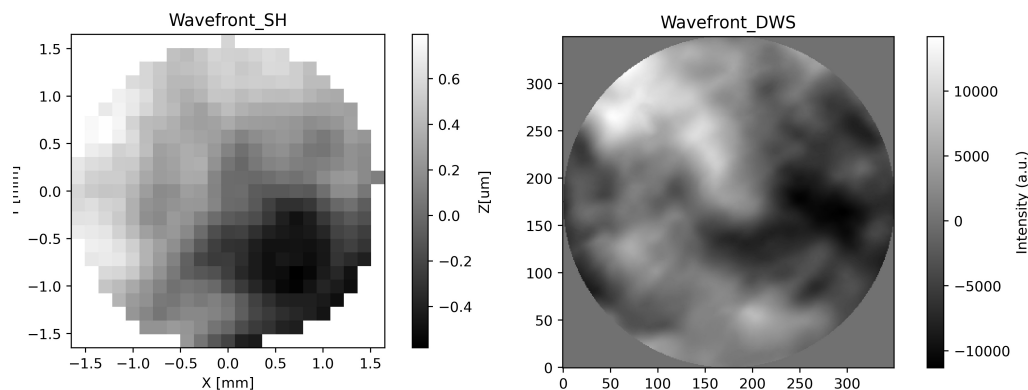


Figure 8. A phase mask induces an atmospheric type perturbation to the wavefront, and it is measured by the SH (to the left), and the DWS (to the right).

Once the diffraction caused by the DM was removed, the Fourier filtering was by-passed as well. The result is an image of the wavefront by the DWS that has an spatial resolution of two orders of magnitude higher than that of the SH sensor.

3.3 Central obstruction

In a brief test performed in the test bench we introduced a central obstruction similar to that one of a telescope's secondary mirror, in addition we instantiated a atmospheric type perturbation in the DM in order to see low-pass filter is distorts the wavefront under this difficult conditions. The obtained captures are shown in Fig. 9.

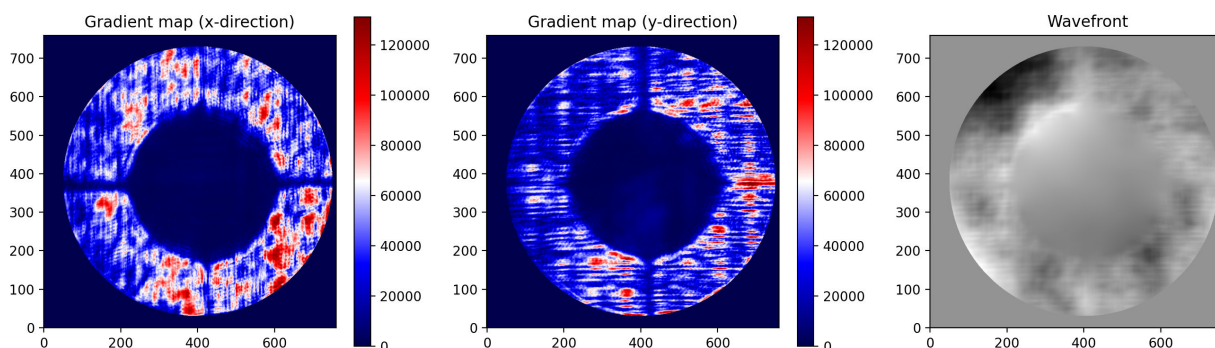


Figure 9. Atmospheric type turbulence and central obscuration is captured in the DWS. Horizontal, and vertical pupils are shown (to the left and the center), as well as the reconstructed wavefront (to the right).

The wavefront obtained (and seen at the right of Fig. 9) confirms that a central obscuration in the entrance pupil will be re-imaged as a flat shape in the wavefront without any additional algorithm. A measurement with the SH was not possible due to the instrument inability to calculate the wavefront, according to the manufacturers software which prompted: "insufficient centroids illuminated" type error.

4. CONCLUSIONS

We built and tested a Diffractive Wavefront Sensor, which is novel type of wavefront sensor with minimal quantity of components that can have hundreds times more spatial-resolution than that of the well-known Shack-Hartman sensor. Tests conducted suggest that the sensor can have a direct pupil image of the wavefront, even when obstructions are present. A low-pass filter was included in the reconstruction algorithm, and can filter diffraction caused by segmented mirrors.

The sensor has a great potential of use in large telescopes, not only as they employ of segmented mirrors that cause diffraction, and structures that create obscurations in the pupil plane, but also because high resolution of the wavefront is of special importance as a large aperture will encompass a high D/r_0 .

The instrument is still under test, there is many parameters that can change it's performance and sensibility, as a LCOS is employed as a diffractive element this parameters can be changed digitally in most cases. Nonetheless, there is still tests to be done in order to achieve a characterization of the instrument.

It is worth mentioning that all LCOS-SLM devices work only with linearly polarized light. This poses a challenging scenario in astronomy, in future work two LCOS-SLM will be used, rotated 90 degrees with respect to each other, and the use of a Wollaston prism will separate the orthogonal linearly polarized components without a considerable loss. One of the beams can be ready for use in a Diffractive Wavefront Sensor, while the other can be directed to a secondary LCOS that can perform AO from the direct image of the wavefront obtained, yet these endeavors are still under research by our team.

ACKNOWLEDGMENTS

The authors of this manuscript want to thank to all the researchers and staff at Instituto de Astrofísica de Canarias, their hard work enables us to investigate on new approaches while at the same time giving us access to the most advanced telescopes in Europe. Special thanks to the good management at the Optics Laboratory by José Luis Rasilla, and to the outstanding optical engineer Felix Gracia whose knowledge and expertise are fundamental to unravel some of the mysteries of light we encounter in the laboratories, and telescopes. D.A.C. is "personal contratado predoctoral del Programa de Astrofísicos Residentes del IAC".

REFERENCES

- [1] Tyson, R., [*Principles of Adaptive Optics*] (11 2015).
- [2] Dam, M. V., "Measuring the centroid gain of a shack-hartmann quad-cell wavefront sensor by using slope discrepancy," *Journal of the Optical Society of America A* **22**, 1509–1514 (08 2005).
- [3] Piatrou, P. and Chanan, G., "Shack-hartmann mask/pupil registration algorithm for wavefront sensing in segmented mirror telescopes," *Applied Optics* **52**, 7778–7784 (11 2013).
- [4] Bonnet, H., Esselborn, M., Kornweibel, N., and Dierickx, P., "Fast optical re-phasing of segmented primary mirrors," *Proceedings of SPIE - The International Society for Optical Engineering* **9145**, 91451U (07 2014).
- [5] Ayala, D., Cagigas, M. A., Cagigal, M. P., López, R. L., and Rodriguez-Ramos, L. F., "Design and simulation of diffractive wavefront sensors for ground-based optical communications links," *SPIE Optical Systems Design 2026* (2026).
- [6] Cagigal M.P., V. P., "Wavefront sensing using diffractive elements," *Optics Letters Vol. 37, Issue 18, pp. 3813-3815* (2012) (2012).
- [7] Antonello, J., Wang, J., He, C., Phillips, M., and Booth, M., *Interferometric calibration of a deformable mirror* (Mar. 2020).
- [8] Wang, X., Wang, B., Pouch, J., Miranda, F., Fisch, M., Anderson, J., Sergan, V., and Bos, P., "Liquid crystal on silicon (lcos) wavefront corrector and beam steerer," *Proceedings of SPIE - The International Society for Optical Engineering* **5162** (12 2003).

- [9] Deo, V., Gendron, E., Rousset, G., Vidal, F., Buey, T., and Cohen, M., “Assessing and mitigating alignment defects of the pyramid wavefront sensor: a translation insensitive control method,” *A&A* **619**, A56 (2018).
- [10] Ragazzoni, R., “Pupil plane wavefront sensing with an oscillating prism,” *Journal of Modern Optics* **43**(2), 289–293 (1996).
- [11] Taissir Heritier, C., Verinaud, C., and Correia, C. M., “Oopao: Object oriented python adaptive optics,” *Adaptive Optics for Extremely Large Telescopes (AO4ELT7)* , 50 (2023).