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► **To cite this version:**

Zibo Ke, Felipe Pedreros Bustos, Jenny Atwood, Anne Costille, Kjetil Dohlen, et al.. Performance of a complementary metal-oxide-semiconductor sensor for laser guide star wavefront sensing. *Journal of Astronomical Telescopes Instruments and Systems*, 2022, 8 (2), pp.021511. 10.1117/1.JATIS.8.2.021511 . hal-03669641

**HAL Id: hal-03669641**

**<https://hal.science/hal-03669641>**

Submitted on 16 May 2022

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# Performance of a complementary metal-oxide-semiconductor sensor for laser guide star wavefront sensing

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**Abstract.** The adaptive optics (AO) systems of future Extremely Large Telescopes (ELTs) will be assisted with laser guide stars (LGS) which will be created in the sodium layer at a height of  $\approx 90$  km above the telescopes. In a Shack-Hartmann wavefront sensor, the long elongation of LGS spots on the sub-pupils far apart from the laser beam axis constraints the design of the wavefront sensor (WFS) which must be able to fully sample the elongated spots without undersampling the non-elongated spots. To fulfill these requirements, a newly released large complementary metal oxide semiconductor (CMOS) sensor with  $1100 \times 1600$  pixels and  $9 \mu\text{m}$  pixel pitch could be employed. Here, we report on the characterization of such a sensor in terms of noise and linearity, and we evaluate its performance for wavefront sensing based on the spot centroid variations. We then illustrate how this new detector can be integrated into a full LGS WFS for both the ESO ELT and the TMT.

**Keywords:** CMOS detector, Wavefront sensing, Extremely Large Telescopes, ELT, TMT, Laser Guide Stars.

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Accepted for publication in SPIE [Journal of Astronomical Telescopes, Instruments, and Systems](#) on Apr. 14, 2022.

## 1 Introduction

The astronomical community has just launched the construction of the largest ground-based telescopes, with the European Southern Observatory's Extremely Large Telescope (ESO ELT) and its primary mirror of 39 m in diameter on one hand, and the Thirty Meter Telescope (TMT) and its 30 m primary mirror on the other hand. These telescopes will answer fundamental questions ranging from the detection and characterization of exoplanets<sup>1</sup> to the formation and evolution of the first galaxies of the universe.<sup>2</sup> In order to achieve their scientific goals, the TMT and the ESO ELT require the use of adaptive optics (AO) to compensate for the aberrations introduced by atmospheric turbulence in the wavefront of the objects under study.<sup>3</sup> An AO system needs a bright star within the field of view of observation to measure the wavefront distortions using a wavefront sensor (WFS), typically a Shack-Hartmann WFS. These distortions are corrected in real-time by applying a feedback signal into a deformable mirror located in the optical path of the telescope, resulting in a flattened wavefront and therefore a near diffraction-limited image delivered to the science instrument. If a bright natural star is not available, an artificial beacon (laser guide star or LGS) is created by means of optical excitation of a layer of sodium atoms between 85 km and 100 km in altitude using one or several lasers launched from the telescope.<sup>4,5</sup> The light emitted from the LGS is then used as a reference for the WFS in the AO system.

41 Laser excitation of the sodium layer produces a long column of fluorescent atoms whose exten-  
42 sion depends on the pointing angle of the telescope and the vertical density profile of the sodium  
43 layer. For an observer located only a few meters off-axis from the laser launch telescope (LLT), the  
44 LGS appears as an elongated object instead of a point source. The LGS spot elongation becomes  
45 dramatic for a 39 m-class telescope with side LLT configuration as the ESO ELT.<sup>6</sup> For example,  
46 the LGS produced by a 30 cm laser beam projected at zenith, will be seen by the sub-aperture of a  
47 Shack-Hartmann WFS opposite to the LLT on a 39 m diameter telescope as an elongated spot of  
48 about 10–20 arcsec long and about 1 arcsec width. The situation is less dramatic for the TMT, as it  
49 uses a central launch scheme, reducing the expected elongation by a factor  $\approx 2$  compared with the  
50 configuration of the ESO ELT. In all cases, the spot elongation depends on the pointing angle.

51 For a Shack-Hartmann WFS, the spot elongation introduces several issues. On the one hand,  
52 it reduces the signal-to-noise ratio since the same amount of photons once concentrated in a small  
53 spot are now distributed on a larger area on the detector, and on the other hand, it increases the  
54 wavefront error due to the growing uncertainty in the estimation of the center of gravity (CoG) of  
55 an elongated spot.<sup>7</sup> In addition, the spot truncation due to highly elongated spots not completely  
56 imaged on a given sub-aperture, leads to a bias in the estimation of the CoG in proportion to the  
57 fraction of truncation.<sup>8</sup>

58 Thus, the major challenges of LGS wavefront sensing at the ELTs scale lie on i) performing a  
59 robust wavefront analysis on a single object strongly extended and whose elongation varies across  
60 the pupil, and ii) developing a large, fast and low-noise wavefront sensor able to image the full pupil  
61 and, at the same time, provide enough sampling for both elongated and non-elongated spots. While  
62 several post-processing strategies to mitigate elongated elongated LGS have been developed,<sup>9–14</sup>  
63 we devote this work to the study of a recently-released complementary metal oxide semiconductor  
64 (CMOS) sensor intended to be used in a Shack-Hartmann WFS for the ESO ELT and the TMT.

65 In Sec. 2 we lay out the primary requirements of a LGSWFS for ELTs and give an overview  
66 of possible technological solutions. In Sec. 3 we characterize a candidate CMOS sensor for the  
67 LGSWFS. In Sec. 4 we provide an analysis of the impact of this type of sensor in wavefront  
68 sensing. In Sec. 5 we present two examples of implementation of this sensor in LGS WFS for ESO  
69 ELT and TMT. Finally, in Sec. 6 we assess our results and provide recommendations for the use of  
70 a CMOS sensor in the ongoing design of LGSWFS.

## 71 **2 A detector for LGS wavefront sensing**

### 72 *2.1 Requirements for ELTs*

73 To guarantee a correct measurement of the incident wavefront, the telescope pupil must be spatially  
74 sampled with a constant pitch of about 50 cm on the primary mirror. Taking as example the 39 m  
75 diameter telescope of the ESO ELT, the Shack-Hartmann wavefront sensor needs to accommodate  
76 at least  $78 \times 78$  sub-pupils.

77 In a linear regime the LGS spots must be sampled at the accepted Nyquist sampling criteria of  
78 2 pixels per FWHM. The minimum size of the LGS spot seen by the WFS depends on a number  
79 of factors like the laser beam size, telescope altitude, zenith angle, seeing, and thickness of the  
80 sodium layer. Statistical analysis of the LGS spot size at Paranal, shows a median angular spot size  
81 in the non-elongated direction of 1.5 arcsec FWHM and as low as of 0.95 arcsec FWHM in good  
82 atmospheric conditions.<sup>15,16</sup> Taking an LGS spot size of 1.0 arcsec, a pixel scale of 0.5 arcsec/pixel  
83 is required to fulfill the Nyquist criteria. Furthermore, if we consider a spot elongation of 16 arcsec

84 on the outermost sub-pupils (this is the case for a  $\approx 20$  km vertical thickness sodium layer and a  
 85 pointing angle of  $30^\circ$ ), then a total of  $\approx 32 \times 32$  pixels per sub-pupil are needed to avoid truncation  
 86 of the spot in the vertical or horizontal direction. To first order, a wavefront sensor with a full size of  
 87 at least  $2496 \times 2496$  pixels would be necessary to sample the ESO ELT pupil using 78 sub-pupils  
 88 across and avoiding truncation of the elongated spot while keeping the non-elongated direction  
 89 sampled within the Nyquist criteria. Following a similar approach, the TMT configuration would  
 90 require a wavefront sensor with  $960 \times 960$  pixels.

91 The minimum required photon return flux of an LGS generated with state-of-the-art 20 W lasers  
 92 is near  $4 \times 10^6$  photons/s/m<sup>2</sup>, therefore the photon flux in a square sub-pupil of 50 cm side length is  
 93 on the order of  $1 \times 10^6$  photons/s. Given the nominal integration time of 2 ms (500 Hz) required for  
 94 AO correction, and provided an estimated optical throughput of 35%, the number of photons per  
 95 frame on a single sub-aperture of the WFS is  $\approx 700$  photons. The detection signal-to-noise-ratio  
 96 (SNR) can be expressed as

$$\text{SNR} = \frac{N_P \times \text{QE}}{\sqrt{N_P \times \text{QE} + n_{\text{pix}} \times \text{RON}^2}}, \quad (1)$$

97 where  $N_P$  is the number of photons per sub-aperture per frame, QE is the quantum efficiency of the  
 98 detector, RON is the root-mean-squared (RMS) read-out noise in electrons/pixel/frame, and  $n_{\text{pix}}$   
 99 is the number of pixels used to sample the LGS spot. Assuming  $N_P = 700$  photons,  $\text{QE} = 0.7$ ,  
 100  $n_{\text{pix}} = 4$ , and  $\text{RON} = 3 \text{ e}^-/\text{pixel}/\text{frame}$ , we get an SNR of 21 for the case of a non-elongated  
 101 spot. Considering an elongated spot covering 16 arcsec, we require  $n_{\text{pix}} = 2 \times 32 = 64$  pixels  
 102 for which we get an SNR of 15. At this point, we approach the read-out-noise-limited regime  
 103 and, for example, doubling read-out noise ( $\text{RON} = 6 \text{ e}^-/\text{pixel}/\text{frame}$ ) gives an SNR of 9 for the  
 104 same elongated spot. Therefore, it is critical that the read-out noise of the sensor used for the  
 105 Shack-Hartmann WFS be as low as possible.

106 This example shows that an adequate detector for LGS wavefront sensing requires a) a large  
 107 number of pixels, b) to operate at fast frame rates, and c) to have a very low read-out noise, as  
 108 specified before. Such a detector has not yet being developed as it is beyond the current techno-  
 109 logical capabilities, hence the final design of the wavefront sensor is constrained to the availability  
 110 of existing detectors that can partially or in full, satisfy the aforementioned requirements.

111 Different technological strategies have been followed to try to answer this challenge. On the  
 112 one hand, dedicated custom detector developments have been proposed both for the TMT and the  
 113 ESO ELT. For the former, the idea was to exploit the specific geometry of the LGS spots, and  
 114 a radial charge-coupled device (CCD) has been proposed to fit the spot elongations.<sup>17</sup> Indeed,  
 115 due to the central launch configuration, the spots seen by each of the LGSWFS Shack-Hartmann  
 116 will be radially oriented. The proposed design implemented sub-apertures of about  $4 \times 16$  pixels,  
 117 with a radial geometry adapted to the spot elongation. For the ESO ELT, a custom technological  
 118 development toward a large  $1600 \times 1600$  pixels sensor was also attempted,<sup>18</sup> resulting in a  $800 \times 800$   
 119 pixels detector (Large Visible adaptive optics Sensor Module, LVSM).<sup>19</sup> In this paper we explore  
 120 an alternative route offered by CMOS detectors, potentially offering large arrays, with low-noise  
 121 and high frame-rate.

## 122 2.2 CMOS technology for LGS wavefront sensing

123 CMOS detectors are becoming competitive with respect to traditional CCD for astronomical de-  
124 tection. The construction design of CCDs in which there is only one or few read-out amplifiers  
125 for the whole array, increases the overall detector latency as the charge from each pixel are read  
126 out sequentially through the amplifiers. In contrast, CMOS technology has one read-out amplifier  
127 per pixel allowing massive parallel readout through read-out buses, hence reducing the latency of  
128 the sensor array. There are several ways to implement this process across the whole 2D array.  
129 Classically, the sensor can be read line-by-line which is known as rolling shutter architecture. This  
130 architecture has the advantage to use only a few transistors per pixel (3 or 4) leading to simpler and  
131 lower noise CMOS imagers. However, each line of the array is exposed and read out sequentially  
132 so at different instants across the whole array. For objects moving at speeds comparable with the  
133 frequency of read-out, the images acquired with a rolling shutter sensor exhibit a distortion artifact  
134 called jelly effect. This is a potential disadvantage for wavefront sensing, because of the WFS may  
135 not be able to capture the state of the turbulence during one frame without introducing temporal  
136 shifts over the pupil spots.

137 However, in 1997 Fossum<sup>20</sup> introduced a more complex architecture using 5 transistors per  
138 pixel giving the ability to take a snapshot of the scene and store it in a memory which is then  
139 read out sequentially while the next image is integrated. In this scheme all pixels are read out  
140 at different instants, but exposed for the same amount of time, hence eliminating the temporal  
141 shifts in the final image. This architecture has the drawback of high read-out noise because of  
142 the Johnson–Nyquist reset noise that remains during read out. Later, more complex architectures  
143 using 6 transistors<sup>21</sup> or even 8 or 11 transistors architectures<sup>22</sup> permitted to integrate a correlated  
144 double sampling circuitry in each pixel that subtracts the thermal noise at the expense of a much  
145 higher pixel complexity. Usually these imagers use finer lithographic pitch CMOS processes to  
146 keep the ratio of detection diode and transistor surface at an acceptable level compared to simpler  
147 architectures. The memory zone needs to be metal shielded to avoid collecting light, therefore the  
148 pixel fill factor of global shutter devices cannot reach 100% by construction, even if they are back  
149 illuminated. To overcome this limitation, micro lenses are integrated in the sensor to concentrate  
150 the light falling across the pixel on the detection diode.<sup>23</sup> However, this also brings a reduction in  
151 the sensor’s sensitivity for oblique angle of incidence. This effect is seldom reported, but it plays  
152 an important role in the design of a wavefront sensor.

153 Recent developments in CMOS technology for astronomical applications<sup>24,25</sup> facilitated the  
154 rapid improvement in their performance that narrows or even surpass the gap with CCD. For  
155 example, the use of pinned photodiode reduces the dark current significantly,<sup>26</sup> and increasing  
156 the conversion gain or the implementation of source-follower transistor structures reduce read-  
157 out noise to sub-electron levels.<sup>27</sup> High quantum efficiency is another characteristic relevant for  
158 low-light applications, which has been addressed by using back-thinned CMOS sensors.<sup>28</sup> In ad-  
159 dition to achieving high performance, another advantage of CMOS detectors is their capability to  
160 be operated at room temperature or alternatively with simple water-cooling, without the need of  
161 cryocoolers. This feature drastically reduce the complexity of the instrument.

162 In the following sections, we report on the characterization of a large CMOS sensor and its  
163 impact on the performance of laser guide star wavefront sensing.

### 164 3 Characterization of a CMOS sensor

#### 165 3.1 Parameters

166 The sensor we evaluate is a Sony CMOS detector model IMX425LLJ on board of a C-BLUE One  
 167 camera manufactured by First Light Imaging.<sup>29</sup> The detector array has  $1604 \times 1104$  active pixels,  
 168 each of which with a square size of  $9.0 \mu\text{m} \times 9.0 \mu\text{m}$ . The active pixels include an analog-to-digital  
 169 converter of 8, 10, or 12-bits and global shutter read-out. The quantum efficiency reported by the  
 170 manufacturer is 0.70 at 590 nm.

171 In the following we present the characterization of read-out noise, angle of acceptance and  
 172 cosmetics of the CMOS sensor.

#### 173 3.2 Noise characterization

174 The main three sources of noise in an optical sensor are the read-out noise, the photon noise, and the  
 175 fixed pattern noise (FPN). Read-out noise arises from the process of reading the pixel data. Photon  
 176 noise is due to the quantum fluctuations of the light source and its occurrence is characterized by a  
 177 Poisson probability distribution. The FPN is caused by spatial inhomogeneities across the sensor  
 178 array in the analog-to-digital converter (ADC) embedded in each pixel.

179 In order to characterize the noises of the sensor, the photon transfer curve (PTC) can be ob-  
 180 tained. The PTC describes the relationship between the output signal at different flux levels and  
 181 the corresponding fluctuations (standard deviation) of the output signal.<sup>30</sup> We assume that the total  
 182 noise of the sensor in analog-to-digital units (ADU) is  $\sigma_{\text{Total}}(\text{ADU})$  and it can expressed as

$$\sigma_{\text{Total}}(\text{ADU}) = [\sigma_{\text{RON}}^2(\text{ADU}) + \sigma_{\text{PN}}^2(\text{ADU}) + \sigma_{\text{FPN}}^2(\text{ADU})]^{1/2}, \quad (2)$$

183 where  $\sigma_{\text{RON}}(\text{ADU})$  is the read-out noise,  $\sigma_{\text{PN}}(\text{ADU})$  is the photon noise, and  $\sigma_{\text{FPN}}(\text{ADU})$  is the  
 184 fixed pattern noise.

185 The total noise can be obtained as the standard deviation of the average flux on a certain region  
 186 in the sensor after offset subtraction. The photon noise in ADU can be expressed as

$$\sigma_{\text{PN}}(\text{ADU}) = \left[ \frac{S(\text{ADU})}{K(\text{e}^-/\text{ADU})} \right]^{1/2}, \quad (3)$$

187 where  $S(\text{ADU})$  is the average flux of the frame, and  $K(\text{e}^-/\text{ADU})$  is the average conversion gain  
 188 of the pixels.

189 The fixed pattern noise is stationary and it can be removed by taking the difference of two  
 190 consecutive frames acquired with the same exposure time.<sup>30</sup> Then, the sum of read-out and photon  
 191 noises can be expressed as

$$\sigma_{\text{RON+PN}}(\text{ADU}) = \left\{ \frac{\sum_{i=1}^{N_{\text{PIX}}} [F1_i(\text{ADU}) - F2_i(\text{ADU})]^2}{2N_{\text{PIX}}} \right\}^{1/2}, \quad (4)$$

192 where  $F1_i(\text{ADU})$  and  $F2_i(\text{ADU})$  is the output signal of pixels  $i$  of two consecutive frames within  
 193 a region of  $N_{\text{PIX}}$  pixels.

194 After removing the fixed pattern noise, we can estimate the photon noise as

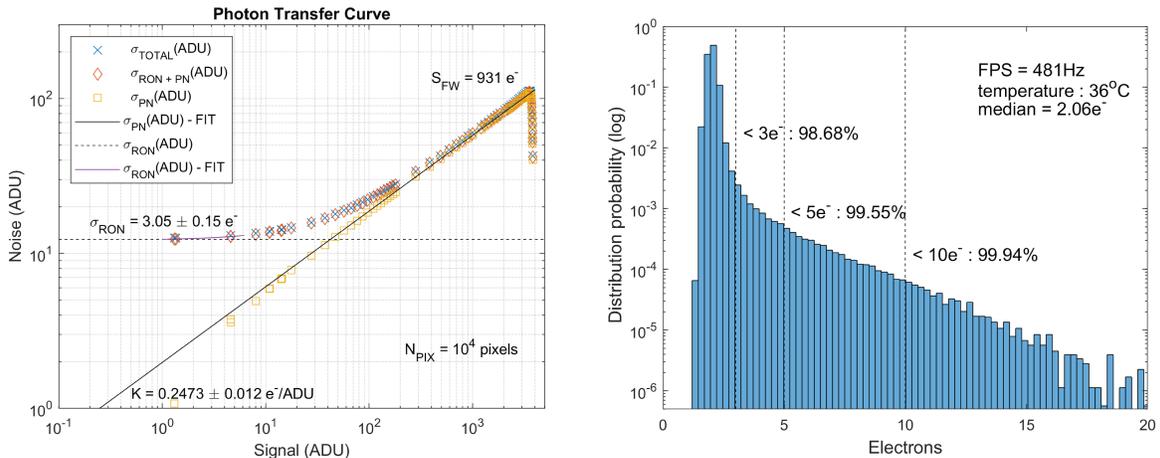
$$\sigma_{\text{PN}}(\text{ADU}) = [\sigma_{\text{RON+PN}}(\text{ADU})^2 - \sigma_{\text{RON}}(\text{ADU})^2]^{1/2}. \quad (5)$$

195 In order to get results in electron unit, we need to obtain the gain of the pixel which can be  
 196 expressed as

$$K(e^-/\text{ADU}) = \frac{S(\text{ADU})}{\sigma_{\text{PN}}^2(\text{ADU})}. \quad (6)$$

197 The measurements to characterize the PTC were performed as follows. A fiber-coupled light-  
 198 emitting-diode (LED) with central wavelength of 595 nm and linewidth of 80 nm was used as a  
 199 light source. The beam out of the fiber back-illuminated a diffuse white-translucent surface placed  
 200 in front of the sensor. Black tubing was used between the illuminated surface and the sensor to  
 201 minimize background light. The acquisition frame rate was set as 481 Hz, the sensor temperature  
 202 was 36°C. Although the light source over illuminated the full array, we only evaluated a region of  
 203  $100 \times 100$  pixels in the center of the sensor array to minimize errors due to illumination inhomog-  
 204 eneity. Illumination and frame rate were held constant over the measurements, only varying the  
 205 exposure time of the array.

206 The resulting PTC is shown in Fig. 1 (left). Three regions can be distinguished in the PTC:  
 207 the read-out noise region at low signal level, the photon-noise region at intermediate signal, and  
 208 the FPN region at high signal level. Since the read-out noise is the dominant noise source at low  
 209 signal level, it can be obtained in ADU units as the noise corresponding to a signal of 1 ADU,  
 210 which is found by linear fitting of the two lowest signal data points. With increasing signal, the  
 211 photon noise sets in and follows a linear relationship on the log-log coordinates as shown in yellow  
 212 squares and with a linear fit. At high levels of signal pixels start to saturate. The full well capacity  
 213  $S_{\text{FW}}$  characterizes the saturation point and it can be calculated by the product between the signal  
 214 value in ADU at the saturation point and the gain. Then, the estimated read-out noise, full well  
 215 capacity and gain are  $\sigma_{\text{RON}} = 3.05 \pm 0.15 e^-$ ,  $K = 0.2473 \pm 0.012 e^-/\text{ADU}$ , and  $S_{\text{FW}} = 931 e^-$ ,  
 216 respectively.



**Fig 1** (Left) Measured photon transfer curve of the CMOS detector. (Right) The histogram of read-out noise.

217 An alternative method consists in acquiring a series of dark frames with short integration time  
 218 (0.01 ms) and computing the temporal standard deviation of individual pixels. The distribution of  
 219 noise over the full array is shown as the histogram in Fig. 1 (right). The median read-out noise is  
 220  $2.06 e^-$ , which is consistent with the result obtained from the photon transfer curve. The tail that  
 221 appears on the distribution is attributed to random telegraph noise (RTN) arising from traps at the

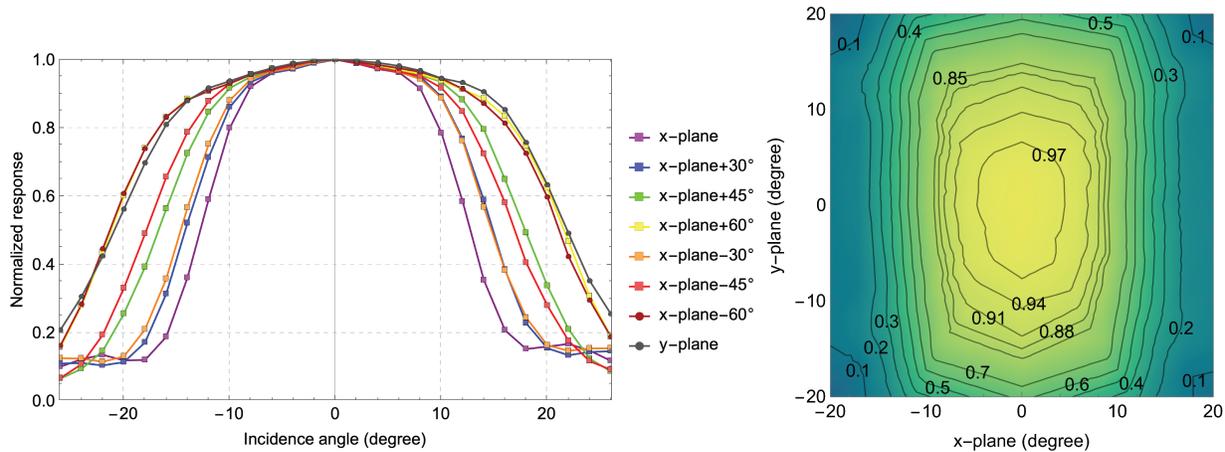
222 thin-layer interface in the source-follower gate region of metal-oxide-semiconductor field-effect  
 223 transistors (MOSFET) of individual pixels.<sup>31</sup>

### 224 3.3 Angle of acceptance

225 CMOS sensors have small microlenses at the surface of their pixels that enhance their photon  
 226 collection efficiency.<sup>23,32</sup> Although the on-axis sensitivity is improved, incident light at oblique  
 227 angles is focalized off the center of the photosensitive area into light-insensitive structures of the  
 228 pixel. This leads to a reduction in sensitivity for a light beam with a large angle of incidence. The  
 229 characterization of the angle of acceptance is critical for the optical design of the wavefront sensor  
 230 as it allows choosing the appropriate beam F-ratio that minimizes the detection losses.

231 The measurements setup is described as follows. The output beam from a fiber-coupled LED  
 232 source (595 nm central wavelength, 80 nm FWHM linewidth) is collimated with a 100 mm lens  
 233 to a 23 mm diameter beam. A filter of 10 nm FWHM width centered at 590 nm is used to narrow  
 234 the spectral width of the source around the sodium emission wavelength. A pupil of 4.2 mm clips  
 235 the beam that is imaged with a 1:1 lens system into the center of the sensor plane. The sensor is  
 236 mounted on a micrometric stage that allows on-axis and horizontal rotation. For an initial on-axis  
 237 position, the sensor is rotated  $\pm 26^\circ$  in the horizontal plane. A sequence of 100 frames is obtained  
 238 for each angular position. The resultant average of the 100 frames is calculated. A window of  
 239  $100 \times 100$  pixels centered in the circular footprint of the beam is used for processing. The average  
 240 of all pixels in the window is taken as the representative intensity of the pixels. Due to the reducing  
 241 irradiance on the sensor with increasing angle (the beam becomes elliptical on the sensor plane for  
 242 large incidence angles), a factor of  $1/\cos(\gamma)$  is applied to the normalized intensity values, where  $\gamma$   
 243 is the tilt angle of the sensor plane. After the full horizontal range is measured, the sensor plane is  
 244 rotated in the optical axis and a new series of measurements are taken by rotating the sensor around  
 245 the horizontal plane. Repeating this process, a complete angular sensor response is characterized.

246 Figure 2 shows the normalized response of the sensor in eight transverse planes. In the same  
 247 figure, a contour plot representation of the angular response is shown. The response of the sensor  
 248 is maximal at  $0^\circ$  incidence and decreases for larger angles. For each plane, the angular response is



**Fig 2** (Left) Normalized pixel angular response of CMOS detector in eight transverse planes (Right) Contour plot of the averaged-normalized angular pixel response.

249 symmetric around the normal, but the acceptance angle is wider in the vertical direction. This could  
 250 be explained by the presence of a rectangular photosensitive area elongated across the vertical axis.

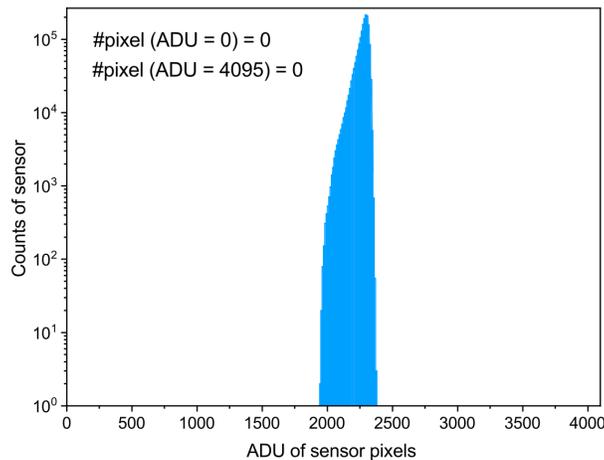
251 Any systematic mismatch between the microlenses and the pixels would result in a tilt of the  
 252 acceptance direction. In addition to the measurements presented in Fig. 2, we measured the angular  
 253 response on  $100 \times 100$  pixels windows located at the edges of the sensor in the  $x$  and  $y$  planes,  
 254 showing no difference among them in the direction of maximum efficiency nor in the angular  
 255 width. This indicates that the angle of acceptance is homogeneous over the sensor.

256 We will show in section 4.3 how the angle of acceptance leads to light losses as a function of  
 257 the focal ratio of the incident beam on the detector.

### 258 3.4 Cosmetic

259 Because the size of the spot on the wavefront sensor is near a single pixel within the subaperture,  
 260 it is crucial that the sensor array is free of defective elements (also called cosmetic defects). Hot  
 261 (bright) or cold (dark) pixels in a subaperture would cause a bias in the centroiding calculation, or  
 262 a complete loss of the measurement if the defective pixel is located within the LGS spot.<sup>33</sup> Other  
 263 cosmetic defects may include pixels with temporal instability and non-linear behaviour.

264 To characterize the presence of defective pixels we take a flat illuminated image with mean  
 265 intensity at half the full-well-capacity, and we calculate the histogram (Fig. 3). We found no dark  
 266 nor bright pixels over the entire array, which rules out any loss in performance due to defective  
 267 elements.



**Fig 3** Logarithmic histogram of the flat illuminated image. No dead nor hot pixels are found.

## 268 4 Impact on LGS WFS

### 269 4.1 Centroiding error

270 The main sources of noise present in a wavefront sensor are photon noise and read-out noise. These  
 271 two sources of noise can be expressed as two additive terms in the error of the center-of-gravity  
 272 (CoG) estimator according to:<sup>34</sup>

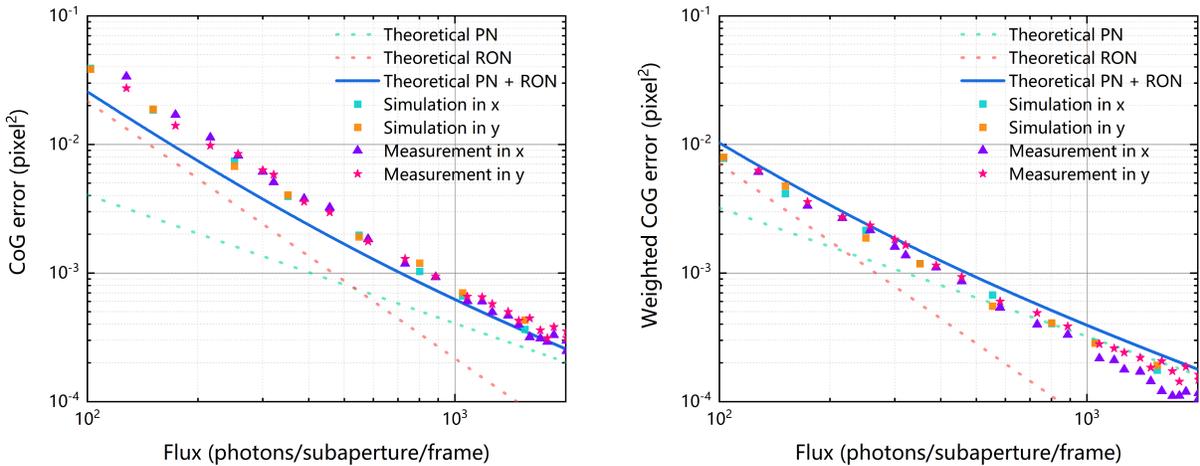
$$\sigma_{\text{CoG}}^2 = \underbrace{\frac{N_T^2}{8 \ln(2) S_e}}_{\text{Photon}} + \underbrace{\left( \frac{\sigma_{\text{RON}}}{S_e} \right)^2 \cdot \left( \frac{N_S^4}{12} \right)}_{\text{Read-out}}, \quad (7)$$

273 where  $N_T$  is the full width at half maximum (FWHM) of the spot on the image,  $N_S$  is the side  
 274 length of the sub-aperture in pixels,  $\sigma_{\text{RON}}$  is the read-out noise, and  $S_e$  is the number of photons  
 275 per sub-aperture and per frame.

276 Similarly, the weighted CoG (WCoG) can be expressed as:<sup>35</sup>

$$\sigma_{\text{WCoG}}^2 = \underbrace{\frac{N_T^2}{8 \ln(2) S_e} \cdot \left( \frac{N_T^2 + N_W^2}{2N_T^2 + N_W^2} \right)^2}_{\text{Photon}} + \underbrace{\frac{\pi(N_T^2 + N_W^2)^2}{128(\ln(2))^2} \cdot \left( \frac{\sigma_{\text{RON}}}{S_e} \right)^2}_{\text{Read-out}}, \quad (8)$$

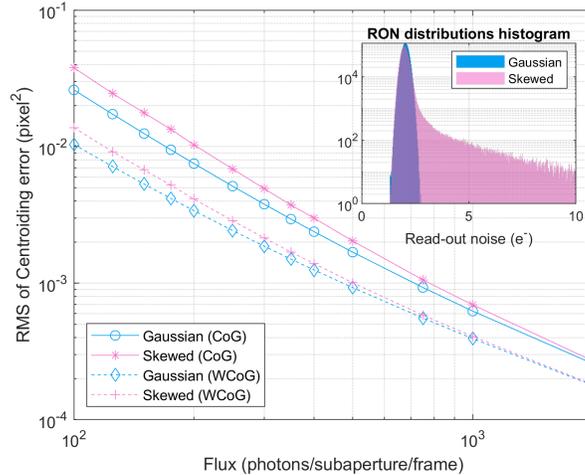
277 where  $N_W$  is the FWHM of a weighted gaussian function. We compare the theoretical centroiding  
 278 error using the expressions above versus simulated and measured center-of-gravity errors. Figure  
 279 4 shows the CoG and WCoG variance as a function of the input flux. Dashed lines show the  
 280 photon-noise and read-out-noise components of the theoretical centroiding variance according to  
 281 equations 7 and 8. We assumed  $\sigma_{\text{RON}} = 2.06 e^-$ , as measured previously. Using  $N_S = 5$  pixels and  
 282  $N_W = 4$  pixels, read-out noise dominates the centroiding error in the low-flux regime below  $\approx 4 \times$   
 283  $10^2$  (photons/sub-aperture/frame) in the case of CoG estimation, and below  $\approx 2 \times 10^2$  (photons/sub-  
 284 aperture/frame) for WCoG. The solid-blue line is the total variance of the CoG estimators. The  
 285 green and orange squares are simulated centroiding errors. A gaussian spot of FWHM = 1.5 pixels  
 286 was simulated on a  $13 \times 13$  pixels sub-aperture. Photon noise was added to the simulated spot,  
 287 as well as read-out noise following the skewed distribution shown in Fig. 1. The centroids of  
 288 500 simulated spots were estimated for each flux level using the CoG and WCoG methods. The  
 289 simulated data points in the figure show the temporal variance in the  $x$  and  $y$  direction of the  
 290 sequence. In addition, centroiding measurements were performed by focalizing a spot of FWHM =  
 291 1.5 pixels at the center of the sensor. The width was estimated by a gaussian fit on the measured  
 292 spot. A sequence of 500 frames with 2 ms integration time was obtained for each flux level, and  
 293 the variance of the CoG sequence was calculated which corresponds to the centroiding error shown  
 294 in Fig. 4. There is a good agreement between the simulated errors and the measurements, and a  
 295 reasonable agreement with the theoretical curves. The WCoG is able to reduce the centroiding  
 296 error by a factor of  $\approx 2$  at a nominal flux of 1000 (photons/subaperture/frame).



**Fig 4** (Left) Comparison of error variance of CoG among real measurements, simulation and theory. (Right) Comparison based on weighted CoG.

297 In the case of elongated spots the centroiding error scales with the spot FWHM ( $N_T$ ), and the  
 298 size of the window or the shape of the weighted gaussian function (as in the case of the WCoG)  
 299 would have to be adapted for each spot geometry on each sub-aperture. A reasonable strategy  
 300 would be to adjust the size of the weighting function to follow the elongation geometry, which  
 301 should minimize the centroiding noise. In this case, Eqs. 7 and 8 remain valid along the two axes  
 302 of the elongated spot, but should be scaled in proportion to the growth of the spot in the pupil along  
 303 the radial direction aligned with the laser launch position.

304 The effect of the measured read-out noise in the centroiding is shown in Fig. 5. Here, we  
 305 compare the resulting centroid error as a function of the photon flux (based on the simulations de-  
 306 scribed above) for a theoretical Gaussian RON distribution and for the measured RON distribution  
 307 (see inset plot). The fraction of pixels with RON higher than a theoretical Gaussian with equal  
 308 median value is 1.8%. The additional error introduced by the skewed RON distribution accounts  
 309 for a factor of  $<2$  for incoming flux above 500 (photons/subaperture/frame) in the CoG and WCoG  
 310 estimation.



**Fig 5** Centroiding error based on a theoretical Gaussian distribution of read-out noise and measured skewed distribution of read-out noise.

## 311 4.2 CoG linearity

312 The spot size relative to the dimensions of the pixels, i.e. the spot sampling frequency ( $s$ ), can  
 313 have a significant impact in the linearity of the centroid estimation as the spot size approaches the  
 314 size of a pixel. Even at the accepted Nyquist sampling criteria of  $s = 2$  pixel per FWHM, centroid  
 315 non-linearities start to build up depending on the profile function on the detector.<sup>36</sup> Therefore,  
 316 the selection of the spot sampling frequency in a wavefront sensor is a trade-off between minimum  
 317 noise (small spot size) and high centroid linearity (large spot size). In this section we study how the  
 318 centroid varies as a function of the sampling frequency and as a function of the lateral displacement  
 319 of the spot over the CMOS sensor, and we compare with simulations.

320 The experimental arrangement consists of a fiber-coupled LED source with a fiber core of  
 321 400  $\mu\text{m}$  placed at a distance of 1300 mm from a lens of 24 mm clear aperture and 40 mm focal  
 322 length that forms an image of the source at the surface of the CMOS sensor located at 40 mm from

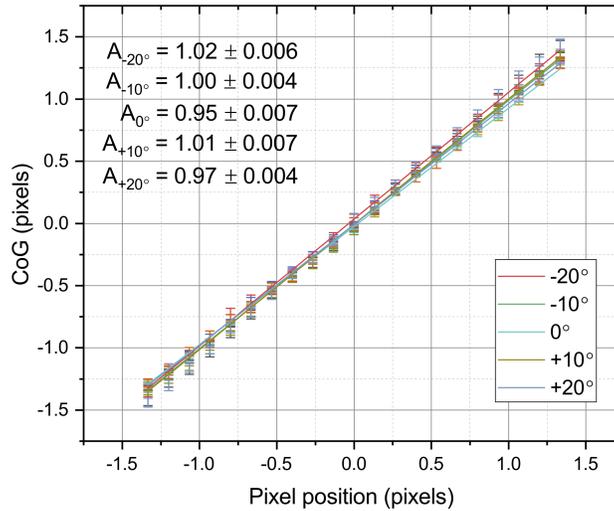
323 the lens. In this simple configuration, the magnification of the optical system is  $M = 40/1300 =$   
 324  $0.03076$ . The theoretical size of the image is  $12.3 \mu\text{m}$  or 1.36 pixels. A lateral displacement of  
 325 the source is also magnified in proportion to  $M$ . In the current setup, the source is laterally shifted  
 326 with a step of  $\delta_S = 40 \mu\text{m}$ , corresponding to a spot lateral displacement step of  $\delta_I = 1.2 \mu\text{m}$ .  
 327 We move the spot by  $25.2 \mu\text{m}$  in steps of  $1.2 \mu\text{m}$  over almost 3 pixels. For each step, we acquire  
 328 30 consecutive images and calculate the CoG for each frame. The average CoG relative to the  
 329 initial pixel position and the standard deviation of the CoG are calculated as a function of the pixel  
 330 position of the spot. In order to understand any possible effects of the acceptance angle in the  
 331 linearity of the CoG, we repeat the procedure at different tilt angles of the sensor such that the  
 332 CoG linearity can be evaluated for several angles of incidence.

333 The CoG at each angle of incidence  $\theta$  and for a given spot sampling frequency  $s$  can be repre-  
 334 sented as a linear function plus an oscillating term as follows:

$$\text{CoG}_{(\theta,s)}(x) = \underbrace{Ax + B}_{\text{Linear}} + \underbrace{W_s \sin(2\pi x + \phi_x)}_{\text{Residual}}, \quad (9)$$

335 where  $x$  is the pixel displacement,  $A$  and  $B$  are parameters of the linear CoG response,  $W_s$  is the  
 336 amplitude of CoG oscillations at a sampling frequency  $s$ , and  $\phi_x$  is an arbitrary pixel phase.

337 Figure 6 shows the calculated CoG relative to the initial pixel position as a function of the pixel  
 338 displacement for incidence angles between  $-20^\circ$  and  $+20^\circ$ . A linear fit is estimated for each data  
 339 set. The values of the slopes of the linear component of the CoG (parameter  $A$ ) for all tilt angles  
 340 are shown in the inset table in the same figure. The measured linear slope deviate less than 5%  
 341 with respect to the ideal linear response ( $A = 1$ ), showing a small effect on the linearity as a result  
 342 of the angle of acceptance.

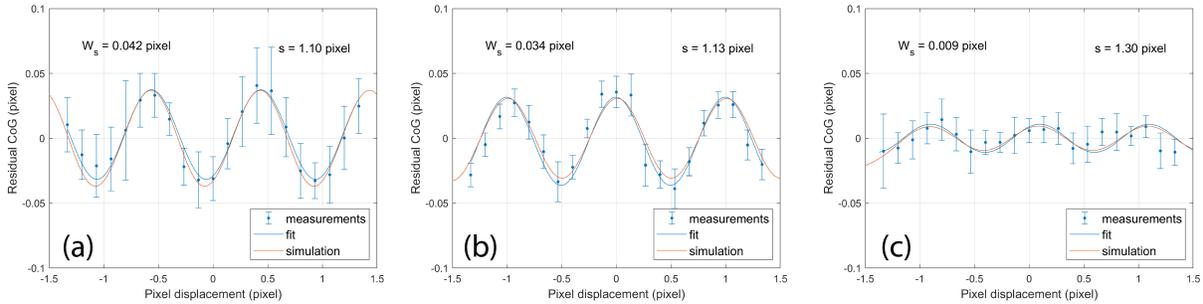


**Fig 6** Measured CoG as a function of the pixel displacement with the sensor tilted at five different angles. A linear fit is applied to each data set. The spot sampling frequency was estimated as 1.13 pixels FWHM. The linear slope parameter  $A$  for each data set is shown at the top left.

343 Figure 7 shows the residual of the data shown in Fig. 6, i.e. the difference between the measured  
 344 CoG's and the linear fit. This corresponds to the residual term of Eq. 9. We show the residuals  
 345 data obtained at normal incidence and for three spot sizes: 1.10 pixel FWHM, 1.13 pixel FWHM,

346 and 1.34 pixel FWHM, that were obtained by slightly shifting the focal plane in the optical axis  
 347 direction. The spot size are estimated using a Gaussian fit and their values correspond to the  
 348 spot sampling frequency  $s$ . For each measurement, a sine function is fit to the data (blue curve)  
 349 and the result of a simulation is also displayed (red curve). There is a good agreement among  
 350 simulations, the fit curve, and measurements. The amplitude of the residual CoG, i.e. the degree  
 351 of non-linearity, is described by the parameter  $W_s$  in Eq. 9. The value of  $W_s$  for each measurement  
 352 is shown in the figure. For the most undersampled case ( $s = 1.10$  pixel), the degree of non-  
 353 linearity reaches 4.2% of a pixel and for the least undersampled case ( $s = 1.34$  pixel) the degree  
 354 of non-linearity is reduced to 1.0% of a pixel. These measurements show that the increase in  
 355 CoG non-linearities in the CMOS sensor under study behave as expected, and that sampling the  
 356 spot frequency below the Nyquist criteria yield a degree of non-linearities that is relatively small  
 357 compared to the pixel size. Note that in the case of elongated spots, as expected for ELTs, the  
 358 sampling will be different along the short and long axes of the spots. The conditions reproduced  
 359 here correspond to the worst case expected for the short axis. In the elongation direction, the  
 360 sampling of the spot will likely be above the Nyquist criteria, hence the linearity error vanishes.

361 The estimated spot size and the linearity response include any cross-talk effect between adja-  
 362 cent pixels, however, we assume that cross-talk is negligible ( $<1\%$ ) based on studies performed  
 363 on a similar CMOS sensor<sup>37</sup> and the fact that microlenses minimize this effect.



**Fig 7** Residual CoG as a function of the pixel displacement compared to a sine fit function and simulations for a spot sampling frequency of (a) 1.10 pixels FWHM, (b) 1.13 pixel FWHM and (c) 1.34 pixel FWHM. All measurements obtained at normal incidence.

### 364 4.3 Transmission loss due to angle of acceptance

365 The angular response characteristic of the CMOS sensor gives rise to a transmission loss through  
 366 the focalizing element (e.g. lenslet array of the Shack-Hartmann wavefront sensor) as off-axis rays  
 367 are focalized into the sensor with a slanted angle of incidence.

368 The photon flux transmission due to the angle of acceptance can be estimated as:

$$\eta_{\text{acc}} = \frac{\int_{-\alpha}^{+\alpha} \hat{G}(x, y) dx dy}{H(\alpha)}, \quad (10)$$

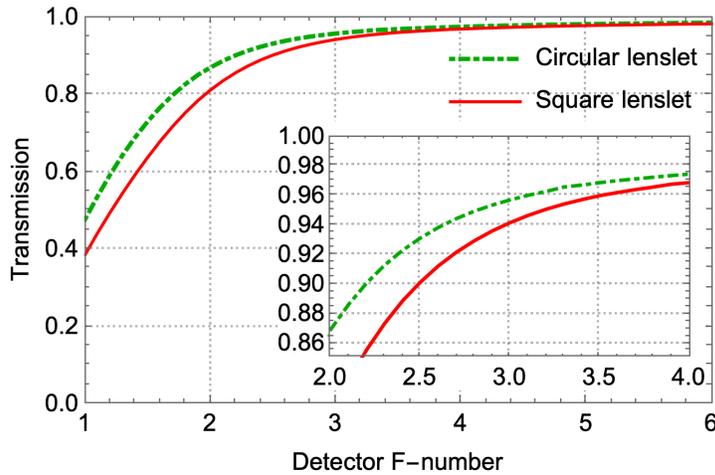
369 where  $\hat{G}(x, y)$  is an estimate of the normalized angular response obtained with interpolation of the  
 370

371 measured data over the horizontal and vertical angular directions (see Fig. 2),  $H(\alpha)$  is a function  
 372 that describes the lenslet window seen from the detector, and  $\alpha$  is the beam detector angle given  
 373 by

$$\alpha = \frac{1}{M} \arctan \left[ \left( \frac{\epsilon + 1}{2} \right) \frac{1}{2F_\ell} \right], \quad (11)$$

374 where  $F_\ell$  is the lenslet nominal side F-number,  $\epsilon \leq 1$  is the linear fill factor of the lenslet array,  
 375 and  $M$  is the magnification of any optical relay between the lenslet array and the sensor plane.  
 376 The beam F-number on the detector side is  $F_d = 1/(2 \tan(\alpha))$ . For the case of a square lenslet  
 377  $H_{\text{square}}(\alpha) = 4\alpha^2$  and for the case of a circular lenslet  $H_{\text{circular}}(\alpha) = \pi\alpha^2$ . These expressions  
 378 assume no loss between the lenslet array and the detector other than the detector angular response.  
 379 We also assume image telecentricity, i.e. the chief rays are always at normal incidence on the  
 380 detector, independent of the position of the lenslet over the pupil and of the distance of the object  
 381 from the center of the field of view.

382 Assuming  $\epsilon = 1$  (no apodization in the lenslet array) and the measured angular response of  
 383 the CMOS sensor, we estimate the transmission through a Shack-Hartmann wavefront sensor as  
 384 a function of the detector F-number for the case of a circular and square lenslet configuration, as  
 385 shown in Fig. 8. A reduction in transmission of 4% and 6% occurs at  $f/3.0$  for the circular and  
 386 square lenslet, respectively. Smaller beam F-ratios lead to a stronger reduction in transmission as  
 387 the beam is focalized at larger angles. This analysis shows that purely geometric considerations  
 388 in the design of a Shack-Hartmann wavefront sensor with a CMOS sensor, result in light losses  
 389 that should be taken into account to minimize the impact in the overall throughput of the optical  
 390 system.



**Fig 8** Transmission efficiency due to angle of acceptance of a CMOS sensor as a function of the detector side beam F-number.

## 391 5 Examples of implementation of a CMOS detector into a LGS WFS

392 In this section we provide a preliminary design of a full LGS WFS arm for the ESO ELT and  
 393 the TMT. For the former, we take as an example the Laser Tomography Adaptive Optics (LTAO)  
 394 system of HARMONI,<sup>38</sup> which will make use of the 6 LGS provided by the ESO ELT. For the

395 latter, we show the implementation for NFIRAOS,<sup>39</sup> the TMT Multi-Conjugate Adaptive Optics  
 396 (MCAO) system. The goal of this section is not to report on a final design for the these instruments,  
 397 but rather to show that a practical implementation of the CMOS sensor described in this article is  
 398 feasible in LGS WFS.

### 399 5.1 HARMONI design

400 The main parameters of the LGSWFS for HARMONI are summarized in Table 1.

**Table 1** Specifications of the HARMONI LGS WFS.

Parameter	Value	Comment
ESO ELT primary mirror diameter	39 m	Size of the pupil
# LGS	6	Side launch provided by 4 launch stations (2×2 + 2×1)
# Subaperture	68×68	Spatial sampling of 57 cm. Square lenslets.
# pixels per subaperture	16×16	with at least 15×15 useful pixels
LGSWFS pixel scale	1.1 arcsec/pixel	Required for sampling LGS spots
Subaperture Field of View	16.5 arcsec	Side FoV. Required for minimizing truncation

#### 401 5.1.1 Lenslet Array

402 To decrease the maximum angle of arrival on the detector from LGSS, we propose to use a double  
 403 lenslet concept. Figure 9 shows the ray tracing for a classical lenslet and a double lenslet<sup>1</sup>. The  
 404 double-lenslet has the advantage of creating a telecentric image and of reducing the steepest beam  
 405 angle by half. For the case of a classical lenslet placed on top of the detector, the maximum beam  
 406 angle at the edge of the sub-aperture is given by

$$\theta_m^{\text{single}} = \arctan \frac{d_\ell}{f_\ell} = \arctan \frac{1}{F_\ell} \approx \frac{1}{F_\ell}, \quad (12)$$

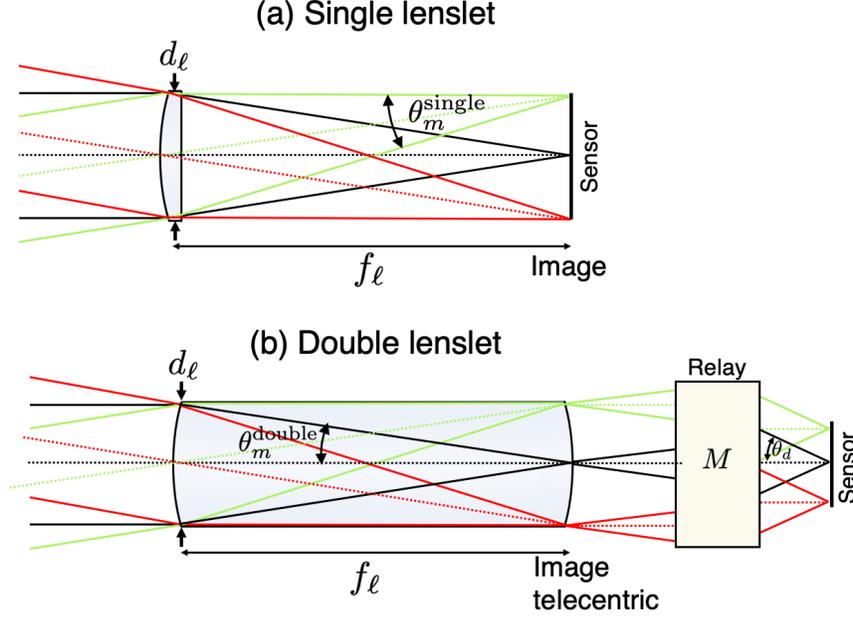
407 where  $d_\ell$  and  $f_\ell$  are the lenslet diameter and focal length, respectively, and  $F_\ell$  is the lenslet focal  
 408 ratio. However, for a double lenslet with equal focal length on each curved face, the maximum exit  
 409 beam angle from the second lenslet face (a telecentric image plane) is equal to the on-axis beam  
 410 given by

$$\theta_m^{\text{double}} = \arctan \frac{d_\ell}{2f_\ell} = \arctan \frac{1}{2F_\ell} \approx \frac{1}{2F_\ell}. \quad (13)$$

411 The maximum beam angle in the double-lenslet configuration is one half with respect to the  
 412 maximum beam angle of a single lenslet, and it is also equal for on-axis and off-axis objects, i.e.  
 413 it provides the same beam angle over the full field of view (FoV).

414 For LTAO, a FoV of at least 16×16 arcsec<sup>2</sup> is required. As described above, one of the chal-  
 415 lenges imposed by the CMOS detector arises from the acceptance angle. The optical design of the  
 416 lenslet array must then be carefully thought in order to minimize flux loses at the coupling with the  
 417 detector.

<sup>1</sup>Although individual lenslets have a square geometry, we assume inscribed circular optics in the following calculations. Diagonal beam apertures are  $\sqrt{2}$  faster than side beam apertures.



**Fig 9** Schematic ray tracing comparison between (a) single lenslet in front of the detector and (b) double lenslet fabricated in the same substrate. In the double lenslet, an optical relay is required to re-image the telecentric focal plane on the detector plane. The maximum incidence angle on the sensor plane is reduced by half with respect to the single lenslet, and chief rays are parallel to the optical axis across the full FoV.

418 The acceptance angle is linked to the maximum focal ratio that can be accepted by the detector.  
 419 The focal ratio of the beam onto the detector plane is determined by specific parameters and the  
 420 following formula:

$$F_d = \frac{N \cdot d}{D \cdot \beta}, \quad (14)$$

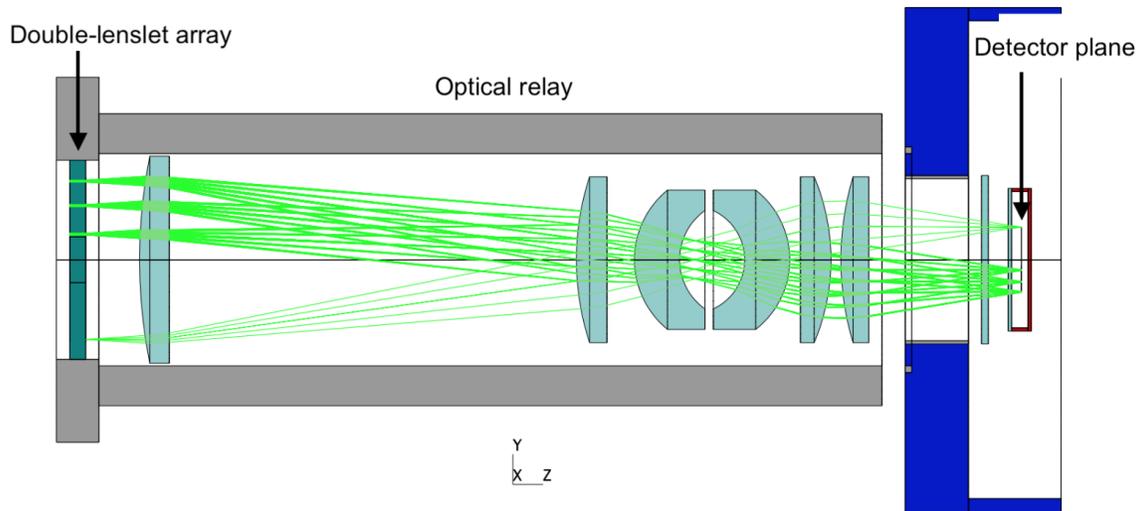
421 where  $N$  is number of sub-apertures,  $d$  is the pixel size,  $D$  is the telescope pupil diameter and  
 422  $\beta$  is the on-sky pixel scale. For  $N = 68$ ,  $d = 9 \mu\text{m}$ ,  $D = 39 \text{ m}$  and  $\beta = 1.1 \text{ arcsec/pixel}$ ,  
 423 the detector beam focal ratio is  $F_d = 2.94$  corresponding to a beam detector angle  $\theta_d = 9.64^\circ$ ,  
 424 following the relationship  $\theta_d = \arctan(1/(2F_d))$ . A total of 68 sub-apertures require 1088 pixels,  
 425 or 16 pixels per sub-aperture. If we consider 1 guard pixel between sub-apertures (for alignment  
 426 margin purposes), there are 15 useful pixels per sub-aperture, covering a total FoV of 16.5 arcsec.

427 The maximum beam angle from the telecentric image plane  $\theta_m^{\text{double}}$  is related to the detector  
 428 beam angle  $\theta_d$  as  $\theta_m^{\text{double}} \approx \theta_d \cdot M$ , with  $M$  the magnification of the relay. Using  $M = 1/2.45$ , then  
 429  $\theta_m^{\text{double}} = 3.94^\circ$  and  $F_\ell = 7.27$  (Eq. 13). Considering the pupil of 24 mm and 68 sub-apertures, a  
 430 double lenslet array with  $353 \mu\text{m}$  lenslet pitch is required. The focal length of the lenslet can be  
 431 found as  $f_\ell = F_\ell \cdot d_\ell$ , which gives  $f_\ell = 2.57 \text{ mm}$ . Both powered surfaces of the double-lenslet  
 432 are manufactured in the same substrate made of fused silica with index of refraction  $n = 1.4584$  at  
 433  $589 \text{ nm}$ , therefore the double lenslet must have a thickness of  $f_\ell \times n = 3.75 \text{ mm}$ .

### 434 5.1.2 Optical Relay

435 Due to the wide FoV required for LTAO, the focal length of a lenslet array placed in front of the  
 436 detector would be very short (near 0.5 mm as it can be calculated in the previous section), which  
 437 makes it technically difficult to assemble inside the detector chip. This problem is common with

438 other ELTs instruments, and similar conclusions apply to NFIRAOS as well. The implementation  
 439 of an optical relay between the lenslet and the detector increases the overall size and the number of  
 440 elements in the WFS, but it also relaxes the manufacturing complexity and tolerances of the lenslet  
 441 array design. It also allows for a better management of the beam angles and acceptance within the  
 442 detector. Therefore, an optical relay has three purposes: i) decouple the lenslet array focal plane  
 443 from the detector focal plane, ii) reimagine the telecentric image plane from the double-lenslet array  
 444 at the detector plane, and iii) compress the pupil size from the lenslet array pupil to the detector  
 445 size. The pupil diameter on the lenslet array is fixed to be 24 mm, due to other optical and man-  
 446 ufacturing constraints. The pupil size on the detector is 9.792 mm, hence the magnification factor  
 447 is  $M = 1/2.45$ . In order to provide high optical performance, both in terms of image quality and  
 448 distortions, a six-lenses design has been proposed as shown in Fig. 10. The overall performance  
 449 of this relay has been specified such that the distortion shall be less than  $\pm 0.03$  sub-aperture with  
 450 respect to a perfect grid, with a variation of less than  $\pm 0.01$  sub-apertures within operating con-  
 451 ditions during the instrument lifetime. In terms of optical quality, the relay does not degrade the  
 452 quality of the spot image when taking onto account the quadratic sum of the contributors to the  
 453 wavefront error budget. This relay also preserves the telecentricity, as this is an important factor for  
 454 coupling light with detector pixels (see Section 5.1.1), and the telecentricity error is less than  $\pm 1.5^\circ$   
 455 at the detector level. Although the system contains a large number of optical surfaces, the penalty  
 456 in terms of transmission budget is minor since highly efficient monochromatic anti-reflective (AR)  
 457 coatings are available. High performance coatings with less than 0.25% reflectivity are considered  
 458 here.



**Fig 10** Ray tracing diagram of the HARMONI LGS wavefront sensor, depicting the double-lenslet array, optical relay and detector. The overall length of the relay is about 150 mm.

459 In summary, the HARMONI design employing a double sided lenslet array with an optical  
 460 relay has several advantages:

- 461 • Reduction of the beam angle after the lenslet array.
- 462 • Creation of a telecentric image.

- 463 • Using a thick substrate of 3.75 mm, the focus of the lenslets can be on the backside of the  
464 substrate, therefore printing the same lenslet with the same focal length.
- 465 • Reduction of the size of the optics inside the relay.
- 466 • Reduction of the distortion of the relay optics.

467 The technical feasibility of such double lenses has been verified with industrial companies, and  
468 no issues have been identified. A prototype has been built and tested, showing the conformity of  
469 the lenslet built with HARMONI specifications.

## 470 5.2 TMT NFIRAOS design

471 The current baseline for NFIRAOS is provided in table 2.

**Table 2** Specifications of the NFIRAOS LGS WFS.

Parameter	Value	Comment
TMT primary mirror diameter	30 m	Size of the entrance pupil
# LGS	6	Central launch provided by a single launch station
# Subaperture	75×75	Spatial sampling of 40 cm
LGS WFS pixel scale	1.0 arcsec/pixel	Required for sampling LGS spots
Subaperture Field of View	11 arcsec	Required for avoiding truncation

### 472 5.2.1 Detector configuration

473 One interesting feature of the CMOS detector is that the read-out architecture can be configured to  
474 skip rows. One can therefore decide to only read a region of interest (ROI), the full width of the  
475 detector, and the maximum frame rate is increased in proportion to the number of rows skipped.  
476 Since TMT has a smaller diameter and will launch its LGSs from behind the secondary mirror,  
477 NFIRAOS will see significantly less-elongated spots than HARMONI. The FoV of the NFIRAOS  
478 WFS subapertures does not need to be as large and therefore only a portion of the detector can be  
479 read. This opens a tradeoff space between the number of sub-apertures, the number of pixels per  
480 sub-aperture and the maximum frame rate.

481 For NFIRAOS, simulations show that a 10 arcsec sub-aperture field of view is sufficient for all  
482 simulated sodium profiles with no penalty due to truncation and a pixel scale of 1 arcsec is optimal  
483 except for very poor seeing conditions ( $r_0 \approx 0.1$  m) where a larger pixel scale could provide better  
484 performance. We add one extra pixel per sub-aperture to accommodate slope offsets. It was also  
485 found that slightly over sampling the pupil with 75×75 sub-apertures, compared to the 60×60  
486 deformable mirror (DM), helps to reduce the wavefront reconstruction error, especially in poor  
487 seeing conditions or higher signal level cases than our conservative baseline.

488 The minimal number of pixels required to accommodate the NFIRAOS configuration is 825×825  
489 (11 pixels per sub-aperture over 75 sub-apertures). However, the CMOS camera will read 848×1608  
490 pixels. The extra pixels are allocated among various optomechanical tolerances, as described in  
491 the next section.

492 With this design, the maximum achievable frame rate is slightly over 600 Hz which is still  
493 acceptable for the expected LGS signal levels and wind speed.

494 5.2.2 ROI flexibility and tolerancing

495 The WFS concept permits loosening or even avoiding various traditionally tight tolerances due to:  
 496 the flexible readout region; the 23 additional pixels; and an array of  $100 \times 100$  lenslets.

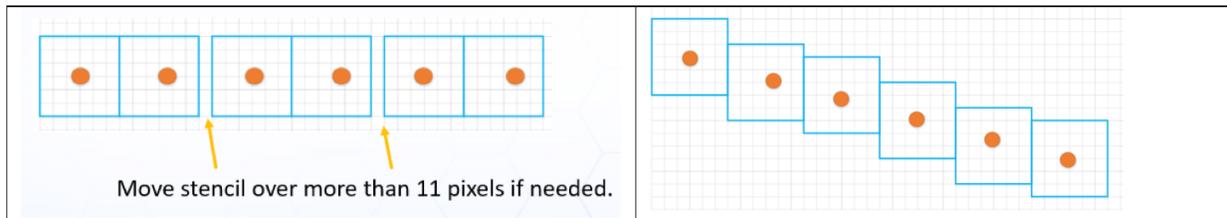
497 For example, oversampling the  $60 \times 60$  DM actuator grid completely removes the strict align-  
 498 ment tolerances to register actuators to lenslet corners, which are usually needed for a Fried geom-  
 499 etry. Furthermore, to handle DM pupil illumination shifts at the oversized  $100 \times 100$  lenslet array,  
 500 software can select an arbitrary set of lenslets. However, tolerances on magnification of the pupil  
 501 image remain constrained, because sub-apertures are discretized into 11 pixels. E.g. to read  $76 \times 76$   
 502 sub-apertures would require 11 rows of pixels, too large a fraction of the 23 pixel margin.

503 The most innovative use of the extra pixels is to handle slope offsets larger than the notional  
 504 1 arcsecond budget for non-common path aberration (NCPA) calibration. But that budget applies  
 505 per sub-aperture. The square regions of pixels for each spot do not have to lie on a square grid.  
 506 By adding “leap pixels” periodically between sub-apertures (Fig. 11 left), larger dynamic range of  
 507 offsets can be calibrated, providing they are slowly varying across the pupil, which is the case for  
 508 low-order aberrations.

509 One important situation is differential focus among six LGS WFSs. Time-varying global (com-  
 510 mon) distance to the sodium layer will be compensated by changing the optical path length to the  
 511 WFSs via a trombone consisting of two mirrors in a  $V$  on a moving stage. However, one trombone  
 512 cannot exactly compensate focus for all LGSs unless they are built and installed perfectly. Differ-  
 513 ential focus produces a different magnification of the spot pattern among the WFS, and deducts  
 514 from the slope budget. However we can fix it in software by “stenciling”  $11 \times 11$  pixels from the  
 515 image. The stencils are chosen to always keep the slope offset within 0.5 pixel of the center.

516 Note that to avoid collisions between sub-aperture ROI stencils, we can only add space between  
 517 them. So for e.g. astigmatism where the calibrated spot pattern is compressed in one axis and  
 518 expanded orthogonally, the trombone controller calibration would be biased to always expand the  
 519 pattern.

520 As shown in the right panel of Fig. 11, clocking of the lenslets versus the detector is handled  
 521 in software. Note that because the outer active DM actuators are not in a circle, but actually a  
 522 polygon with flat sides of several actuators in a line, clocking the spot pattern as shown does mean  
 523 that WFS spots at vertices of the polygon do move outwards by approximately a pixel.



**Fig 11** (Left) Leap Pixels for low order NCPA. (Right) Software defined stencils for clocking lenslets versus detector.

524 However, the most difficult constraint remains the profile tolerance (single digits of microns  
 525 for tilts plus piston) of the detector with respect to the lenslets due to defocusing in fast beams.  
 526 When NFIRAOS operates at  $-30^\circ\text{C}$  thermo-mechanical analysis of the camera design indicates  
 527 that the detector moves  $\approx 20 \mu\text{m}$  axially towards the lens mounting interface and the optical relay  
 528 shrinks in the opposite direction, compared to room temperature. We will jointly optimize the  
 529 athermalization of the relay lens barrel, described below, to account for both.

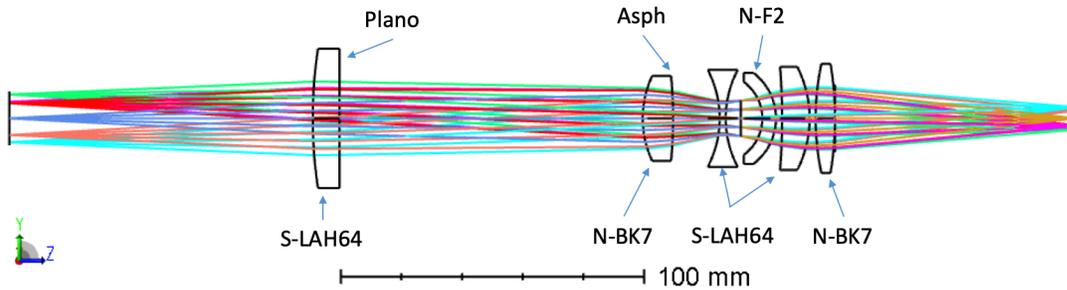
530 5.2.3 *Lenslet array*

531 For NFIRAOS, we have  $N = 75$ ,  $d = 9 \mu\text{m}$ ,  $D = 30 \text{ m}$ ,  $\beta = 1 \text{ arcsec/pixel}$ , providing a  
 532 focal ratio of  $F_d = 4.64$  at the detector. The steepest angle of incidence at the edge of the field  
 533 of view with a conventional lenslet array would be  $\theta_m^{\text{single}} = 12.2^\circ$  resulting in light loss due to  
 534 the limited acceptance angle of the CMOS pixels. This angle, and therefore the loss, would be  
 535 further increased because of our proposed scheme to skip pixels in order to use larger slope offsets  
 536 (section 5.2.2). This motivates the use, like HARMONI, of a double-sided lenslet array, illustrated  
 537 in Fig. 9.(b) where the second surface acts as a field lens to produce a telecentric image at the  
 538 detector, thus reducing the steepest angle by half. For the proposed NFIRAOS design, the main  
 539 parameters of the required lenslet array are  $210 \mu\text{m}$  pitch, a radius of both surfaces of  $0.945 \text{ mm}$  and  
 540 thickness of  $3 \text{ mm}$ . Such a lenslet array is considered well within the capabilities of manufacturers.

541 5.2.4 *Optical relay*

542 For NFIRAOS, the pupil diameter on the lenslet array was chosen to be  $15.75 \text{ mm}$ , leading to  
 543 a relay with magnification  $M = 1/2$ . Smaller pupil sizes make the relay shorter and therefore  
 544 easier to package, but the lenslets become faster, and therefore significantly more challenging and  
 545 expensive to fabricate. The  $15.75 \text{ mm}$  pupil diameter was chosen as a reasonable tradeoff.

546 The proposed relay is shown in Fig. 12. It has six lenses and is actually quite similar to that of  
 547 HARMONI. The only possibly concerning element is the F2 lens, which exhibits a large curvature  
 548 that could be costly to fabricate.



**Fig 12** Ray tracing diagram of the lenslet, optical relay and detector. The overall length of the relay is about  $380 \text{ mm}$ .

549 This relay design has excellent image quality and distortion over the full field of view. The  
 550 distortion is  $<0.01\%$  and the maximum RMS wavefront error across the FoV is  $0.012 \text{ waves}$  ( $7 \text{ nm}$ )  
 551 with a variation of  $0.005 \text{ waves}$ . The design includes one aspheric surface on N-BK7 to help  
 552 control the wavefront error at the edge of the FOV. The asphere has two terms (4th and 6th order)  
 553 and  $\approx 50 \mu\text{m}$  of departure.

554 The full optical path from the sodium layer, through TMT and NFIRAOS, and through the  
 555 lenslet and relay to the detector, has been modeled. The images from the top and bottom of the  
 556 sodium layer are easily resolved in the model. The glasses chosen for this design are all highly  
 557 transmissive in the visible spectrum, with a bulk absorption of  $<1\%$ . The overall throughput will  
 558 therefore depend on the quality of the coatings. As in HARMONI, NFIRAOS plans to use high  
 559 performance monochromatic dielectric coatings.

## 6 Conclusion

We have evaluated the performance of a CMOS sensor compatible with the current requirements of wavefront sensor of laser guide stars in the context of extremely large telescopes.

We have shown that the read-out noise of  $\approx 3 e^-$  is achievable for a large sensor array. The statistical distribution of read-out noise over the sensor shows a tailed shape which is characteristic of CMOS sensors. The impact of this read-out noise excess in the centroid estimation accounts for a factor of  $< 2$  above 500 photons/sub-aperture/frame.

The average angular response of the sensor was characterized showing a two-axes symmetry with full width half maximum of  $42.6^\circ$  in the vertical direction and  $25.4^\circ$  in the horizontal direction. The angle of acceptance leads to a light transmission loss depending of the beam aperture on the sensor. For a square lenslet, a drop of 10% in transmission is found for a beam focal ratio on the detector of  $F_d = 2.5$ . We provide the calculated transmission curves for circular and square lenslet shapes as a reference for wavefront sensor designers using this type of detectors.

The error of center of gravity was employed as a metric to evaluate the performance of the detector to wavefront sensing. We simulated and measured the CoG errors as a function of the photon flux and found a good agreement between theory and experimental results. The centroiding linearity was measured for different spot size and angles of incidence. The rising of non-linearities in the estimation of the CoG is in agreement with our simulations and shows that for a sampling frequency of 1.36 pixel per FWHM (Nyquist undersampled), the degree of non-linearities is 1.0% of a pixel.

Finally, we show two examples of practical implementations of this detector in LGS wavefront sensors for ESO ELT/HARMONI and TMT/NFIRAOS adaptive optics systems. The need of additional relay optics between the microlens array and the detector is common in both cases due to the differences in size between the CMOS sensor and the pupil. Moreover, the telecentric double-sided lenslet array in the HARMONI design, also adopted in NFIRAOS, comes as an innovative solution to achieve the required sub-aperture FoV despite the CMOS architecture intrinsically limiting the acceptance angle into the pixels. In the case of NFIRAOS, only a sub-region of the detector needs to be read, which allows operating at higher frame rate, as well as greatly relaxing key opto-mechanical tolerances. For HARMONI, a larger LGS elongation is expected and all pixels of the detector are needed to accommodate a larger sub-aperture FoV that minimizes truncation over most of the pupil. These two examples show that this type of detector is very suitable for LGS wavefront sensing on extremely large telescopes.

### *Acknowledgments*

Z.K. acknowledges financial support from China Scholarship Council award no. 201806010330. This project received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 893150. This work also benefited from the support of the WOLF project ANR-18-CE31-0018 of the French National Research Agency (ANR). This document has been prepared as part of the activities of OPTICON H2020 (2017-2020) Work Package 1 (Calibration and test tools for AO assisted E-ELT instruments). OPTICON is supported by the Horizon 2020 Framework Programme of the European Commission's (Grant number 730890). This work was supported by the Action Spécifique Haute Résolution Angulaire (ASHRA) of CNRS/INSU co-funded by CNES. This work has been partially supported by the LabEx FOCUS ANR-11-LABX-0013

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