Infrared wavefront sensing for adaptive optics assisted galactic center observations with the VLT interferometer and GRAVITY: operation and results

Stefan Hippler, Wolfgang Brandner, Silvia Scheithauer, Martin Kulas, Johana Panduro, Peter Bizenberger, Henry Bonnet, Casey Deen, Françoise Delplancke-Ströbele, Frank Eisenhauer, Gert Finger, Zoltan Hubert, Johann Kolb, Eric Müller, Laurent Pallanca, Julien Woillez, Gérard Zins, and GRAVITY Collaboration

Max-Planck-Institut für Astronomie, 69117 Heidelberg, Germany
European Southern Observatory Headquarters, 85748 Garching, Germany
Max-Planck-Institut für extraterrestrische Physik, 85748 Garching, Germany
Univ. Grenoble Alpes, CNRS, IPAG, Grenoble, France

Abstract

This article describes the operation of the near-infrared wavefront sensing based Adaptive Optics (AO) system CIAO. The Coudé Infrared Adaptive Optics (CIAO) system is a central auxiliary component of the Very Large Telescope (VLT) interferometer (VLTI). It enables in particular the observations of the Galactic Center (GC) using the GRAVITY instrument. GRAVITY is a highly specialized beam combiner, a device that coherently combines the light of the four 8-m telescopes and finally records interferometric measurements in the K-band on 6 baselines simultaneously.

CIAO compensates for phase disturbances caused by atmospheric turbulence, which all four 8 m Unit Telescopes (UT) experience during observation. Each of the four CIAO units generates an almost diffraction-limited image quality at its UT, which ensures that maximum flux of the observed stellar object enters the fibers of the GRAVITY beam combiner.

We present CIAO performance data obtained in the first 3 years of operation as a function of weather conditions. We describe how CIAO is configured, calibrated, and finally used for observations with GRAVITY. In addition, we focus on the outstanding features of the near-infrared sensitive Saphira detector, which is used for the first time on Paranal, and show how it works as a wavefront sensor detector.

Keywords: Near-infrared wavefront sensing, VLT interferometer, galactic center, CIAO, adaptive optics, SAPHIRA detector, GRAVITY

1. INTRODUCTION

What does a black hole look like? Do black holes really exist? Questions like these can actually be answered more quantitatively thanks to better and better observations. One of the most interesting observation areas in this context is the centre of the Milky Way, where the black hole with the largest angular diameter as seen from Earth is located. The compact radio source Sagittarius A* (SgrA*) at the very centre of the Milky Way has been observed over more than 5 decades (see Genzel et al. and references therein). In 2009, Gillessen et al. published a study which monitored stellar orbits around SgrA* for 16 years. They estimate the mass of SgrA* at about 4 million solar masses. At the distance of the GC of \( 8 \) kpc, the Schwarzschild radius \( R_S \) for a black hole candidate with that mass is \( 10 \mu\text{as} \), equivalent to a source diameter of \( 24 \) million km, or 0.16 astronomical units (AU).

Very long baseline radio interferometric measurements, observing the — gravitational lensing magnified — black hole shadow in the emission of SgrA*, give an angular source width of \( 37 \mu\text{as} \). This width is actually smaller than the expected width of \( 5 R_S = 50 \mu\text{as} \) because of gravitational lensing. The deviation can be explained using different models for the intrinsic structure of SgrA*.

Send correspondence to hippler@mpia.de
Due to the extremely high extinction in the visible spectral range, the GC can only be examined from the ground at radio and infrared wavelengths. In order to achieve the required spatial resolution in the order of $R_S$, phase-referenced observations at the VLTI in the infrared spectral range are suitable. The instrument to implement this is called GRAVITY and was proposed in 2005. GRAVITY had first light with all four 8 m UTs in May 2016.

Recent observations with the GRAVITY instrument allowed for the first time to measure the gravitational redshift in the light of a star orbiting SgrA* and approaching the GC to about 120 AU, i.e. 1400 $R_S$. Further results show that GRAVITY reaches an astrometric precision close to 10 $\mu$as. In imaging mode, GRAVITY can achieve angular resolutions with the 4 UTs down to 4 mas (milli-arcsecond).

For the same reasons that the infrared range was used to observe the GC with GRAVITY, the visible AO system MACAO, already in operation at the VLTI since 2003, had to be supplemented by an infrared based AO system. This addition, called CIAO, is discussed in more detail in the following sections.

Although this report is mainly about the AO system performance during GC observations with GRAVITY, there are many other areas in which GRAVITY can be used. This ranges from interferometric Exoplanet observations to mapping the cores of active galactic nuclei.

### 2. GALACTIC CENTER OBSERVATIONS WITH GRAVITY: REQUIREMENTS FOR CIAO

GRAVITY is an interferometer that can combine the light of the 4 UTs such that all combinations of 2 UTs, six in total, create interferometric fringes. As described in detail in 14–16, after passing the delay lines of the VLTI (see also fig. 1 and section 3) and the GRAVITY fiber coupler unit, the light of the 4 UTs is fed into single-mode fibers and then further relayed into an integrated optics unit where pairs of UT beams interfere. GRAVITY observes in the near-infrared (NIR) spectral range centered at 2.2 $\mu$m (K-band, 1.9–2.45 $\mu$m). The GRAVITY single mode fibers have a mode field diameter of 7.66 $\mu$m, sufficiently large to collect the image of a diffraction limited 2.2 $\mu$m point source. The fiber coupler injection optics has a f-number of 2.5. This focuses the (nearly) diffraction limited K-band point spread function (PSF) with a full width at half maximum (FWHM) of 5.5 $\mu$m into the fiber.

The task of CIAO is to create exactly this (nearly) diffraction limited K-band PSF at the entrance of the fiber coupler inside the GRAVITY beam combiner. The top-level requirements of GRAVITY for CIAO taken from 17 are listed in table 1.

The functional requirements are:
- provide wavefront correction
- provide near infrared wavefront sensing - allow for off-axis wavefront sensing

| Guide star magnitude in K-band | Guide star separation from science target [arcsec] | Telescope zenith angle [degrees] | Strehl number at $\lambda=2.2\mu$m [%] | Residual 2-axis image jitter [mas rms] |
|-------------------------------|-----------------------------------------------|---------------------------------|-----------------------------------|----------------------------------|
| 7a                            | 7                                             | 30                              | 25                                | 10                               |
| 7                             | 0                                             | 30                              | 35                                | 10                               |
| 10                            | 0                                             | 30                              | 10                                | 22                               |

a Galactic Centre supergiant IRS7-like case, see fig. 2(b)

All requirements could be fulfilled with a 9 x 9 Shack-Hartmann wavefront sensor based AO system running at a speed of 500 Hz. A 320 x 256 pixel HgCdTe avalanche photo diode (APD) array from Leonardo was selected as infrared detector (see section 4).
Figure 1. Schematics of the VLT interferometer optical path with 2 UTs. The CIAO units are located in the Coudé focal station of the respective telescope. Light from a celestial object is reflected by 9 mirrors (Telescope 2: M1-M9) and is in focus at the mirror M10, located in the Coudé focal station. STS units select 2 celestial objects within a field of view of 2 arcmin diameter. The light one object is relayed to CIAO, the light of the second object is relayed to the GRAVITY beam combiner, located in the beam combination lab. Delay lines compensate for optical path length differences between telescope 1 and 2, which have a distance corresponding to the baseline. Mirror M8 is the deformable mirror shared between MACAO and CIAO. Mirror M9 is a dichroic beam-splitter that reflects infrared light to CIAO and the beam combination lab, visible light is transmitted to MACAO (not shown). Background image: European Southern Observatory (ESO).

3. OVERVIEW OF THE CIAO SYSTEM

CIAO\(^{17\text{-}21}\) was built to equip the VLTI instrument GRAVITY with infrared sensitive adaptive optics. GRAVITY’s primary scientific object of investigation is the center of the Milky Way and there especially the massive black hole. The purpose of CIAO is to increase the sensitivity of GRAVITY. This is achieved by compensating for atmospheric turbulence and the associated almost diffraction-limited image quality of each individual UT. For the GRAVITY instrument this means a stable injection of light from two adjacent astrophysical objects into the 2 single-mode input fibers per telescope of GRAVITY. While GRAVITY is located in the beam combination lab (see fig. 1), the four almost identical CIAO units are located inside the Coudé focal stations of the four UTs. Each CIAO unit was designed to fit seamlessly into the VLTI infrastructure. An important element of the existing infrastructure, the 60 actuators bimorph deformable mirror of the MACAO optical AO system, is shared by CIAO.

Fig. 1 shows the VLTI optical scheme for the sake of simplicity for two UTs instead of all four UTs. Included are the locations of the star separator units (STS). Their purpose is to select two small fields of the sky and feed them forward towards the VLTI beam combination lab.\(^{22}\) Details about the STS are shown in fig. 2(a). The standard set-up for GC observations is shown in fig. 2(b).

The CIAO units are designed to deliver nearly diffraction limited image quality in K-band for each UT. To achieve this, the light of a not too faint point source, i.e. the wavefront sensor (WFS) reference star, with
The star separator unit STS uses two field select mirrors FSA and FSB to pick the light of two objects focused on M10. Their light is then relayed via the folding mirrors FMA and FMB towards the output beams A and B. Before, however, the beams are compressed (BCA, BCB) and then forwarded via the pupil re-imagers PRA and PRB. Each output beam contains a field of view of about 2" x 2". Image: ESO.

Figure 2. STS optical layout and on-sky set-up for GC observations with GRAVITY. See text for details.

For GC observations, the WFS reference star is the bright M-type supergiant IRS7, located about 5.6" away from SgrA*. In this case, the STS beam B points to IRS7 and CIAO picks this beam using its movable off-axis AO mode selector (AOMS) unit accordingly. The light of the reference star is then relayed and focused via a fold mirror and a parabolic mirror to a focal plane inside the CIAO WFS cryostat (see fig. 3). Alternatively, the GRAVITY beam-combiner and CIAO can share the light of a source. In this case, STS beam A points to the science object and CIAO moves its AOMS on-axis unit to pick beam A. The difference between AOMS off-axis and AOMS on-axis is that the off-axis unit is fully reflective, while the on-axis unit is equipped with a beam splitter. The beam splitter reflects light towards CIAO and transmits light towards the GRAVITY beam-combiner. In the focal area of the CIAO cryostat there is a focal mask and a field lens. The lateral movable field lens together with an achromatic doublet images the pupil (image of the MACAO deformable mirror) through a bandpass filter onto the lenslet array of the Shack-Hartmann sensor.

The lenslet array, located in the pupil plane, focuses its images directly on the Saphira detector (see enlargement of cryogenic environment in fig. 3). The lateral movable field lens allows to stabilize the registration between the lenslet array and the deformable mirror in closed-loop operation. The lenslet array is optimized for a wavelength of 2.2 μm and a detector pixel size of 24 μm. It consists of 9 x 9 square lenses in a square geometry. Each square lens has a size of 192 x 192 μm² and a focal length of 2095 μm for a wavelength of 2.2 μm. The diffraction limited K-band PSF of a single lens has a FWHM of ≤26 μm, about the size of one detector pixel. The CIAO lenslet array requires exactly 72 x 72 pixels on the detector. Due to the multi-channel readout electronics, CIAO reads a rectangular area of 96 x 72 pixels on the detector. More details about the read-out modes of the Saphira detector are given in section 4.

Finally, the transmission of all optics up to detector at λ=2.2 μm for the two operating modes is T=0.15 for the on-axis configuration and T=0.32 for the off-axis configuration. These estimates include neither the quantum efficiency of the detector nor the atmospheric transmission.

4. THE SAPHIRA DETECTOR

Due to their high frame rates, high sensitivity, low noise, and low dark current, Saphira detectors have characteristic properties, especially for applications in astronomical adaptive optics, which were not available 10 years ago. The Saphira detector used in CIAO is a 320 x 256 pixel HgCdTe avalanche photodiode array with 24 μm square pixels. It is sensitive in the spectral range from 0.8 – 2.5 μm. Unlike other near-infrared arrays,
Saphira features an user-adjustable avalanche gain, which multiplies the photon signal but has minimal impact on the read noise. The CIAO Shack-Hartmann lenslet array, a 9 x 9 square design, is located in the pupil plane such that 68 of the 81 sub-apertures are illuminated (fig. 4). Each sub-aperture covers exactly 8 x 8 pixels on the detector, a total area of 72 x 72 pixels on the detector is evaluated for signal evaluation.

To realize an analog bandwidth for high frame rates, the CIAO Saphira detector array has 32 parallel outputs. To further increase the frame rates of sub-regions, the 32 outputs of the readout integrated circuit (ROIC) are organized to read 32 adjacent pixels of a row at the same time.

To fit the required CIAO lenslet detector region (72 x 72 pixels) with this parallel design, a detector sub-region of 96 x 72 = 6912 pixels has to be readout. Pixel information is digitized using 5 MHz analog to digital converters (ADC). Considering clocking overheads, the time for a non-destructive readout of the CIAO detector sub-region takes 70.6 µs.\(^25\)

The maximum CIAO loop speed of 500 Hz therefore allows to oversample the detector sub-region up to 28 times using Fowler sampling techniques.\(^{25,30}\) In particular, this together with a proper electron APD (eAPD) gain setting significantly reduces effective detector readout-noise, down to below 1 electron per pixel. All 4 CIAO Saphira detectors are based on metal organic vapor phase epitaxy (MOVPE), and have been produced by Leonardo S.p.A. (formerly Selex ES).\(^{31}\) The CIAO Saphira detectors are so-called Mark3 devices. It should be noted that the GRAVITY fringe tracker, which compensates the differential piston based on measurements of a brighter off-axis astronomical reference source, uses a Saphira detector as well.\(^{32}\) Table 2 summarizes the most important CIAO detector characteristics.
(a) Microscopic image of a CIAO lens array with "blue" light reflecting chromium masks, defining the pupil boundaries. The scale is indicated by the red square.

Figure 4. CIAO lens design and footprint on the detector. See text for details.

(b) Footprint of the illuminated CIAO lenslet on the Saphira detector. Green circle diameter: 72 pixels.

Table 2. CIAO Saphira detector characteristics @ 95 K temperature, or as indicated

| Saphira detector number | #1  | #2  | #3  | #4  | Comment                  |
|------------------------|-----|-----|-----|-----|--------------------------|
| Readout noise [e⁻ rms/pixel]  | 1.24| 0.95| 1.17| 0.96| Fowler-4b                |
| Bad pixels [pixel/detector] | 63  | 39  | 78  | 40  | CDSc                     |
| Bad pixel in CIAO sub-region | 3   | 1   | 0   | 2   |                          |
| Detector gain [e⁻/ADU]      | 0.380| 0.387|0.388| 0.395| CDSc                     |
| eAPD gain [e⁻/e⁻]           | 30.11| 30.64|26.40| 27.15| CDSc                     |
| Dark current [e⁻/pixel/s]    | 478.6| 485.15|631.1| 630.85|                          |
| Quantum efficiency @90K [e⁻/γ] | 60%, 67%|      |      |      | H-band, K-band           |

a This is the effective readout noise, i.e. measured readout noise divided by eAPD gain
b Measured using 8 Fowler pairs sampling combined with subpixel-4 sampling
c Measured using correlated double sampling (CDS), i.e. 1 Fowler pair

We want to emphasize that the readout method is also decisive for the noise behavior of the detector. The CIAO SAPHIRA readout integrated circuit (ROIC) operates the detector on a frame by frame basis, i.e. the complete frame is reset and then at least two frames are readout to obtain a so called correlated double sampled (CDS) frame. Finally, the two frames are subtracted from each other. This is a well known technique to reduce various noise sources, including kTC noise, and was already established for CCD detectors readout in the early 1970s. Unfortunately, with the installed ROIC of the CIAO wavefront sensors, the duty cycle is only 50%. A newer version of the ROIC, which can readout and reset the detector on a row by row basis (so called rolling shutter mode), no longer has this problem.

Additionally, to further reduce readout noise, each pixel can be multiple times converted to digital values and then averaged. As mentioned above, for the CIAO sub-region, 28 non-destructive readouts are theoretically possible during a 2 ms exposure, e.g. 4 Fowler pairs times 2 subpixel conversions fit well. Such readout schemes are nowadays also used for CCD detectors.
5. STATISTICAL REVIEW OF THREE YEARS OF CIAO OPERATION

In this section we show the performance results of the CIAO system obtained for GC observations in the years 2017 to 2019. Using the configuration as shown in fig. 2(b), the results can be compared quite well, since the same reference star, IRS7, was always observed by CIAO. IRS7 has a K-band magnitude of K=6.5, which at an AO loop frequency of 500 Hz results in a WFS sub-aperture detector signal per frame of about 1000 photo-electrons. Taking into account the very low readout noise of the detector of about 1 photo-electron per pixel, CIAO can be operated with this configuration in a regime with a high signal-to-noise ratio.

To estimate seeing and atmospheric coherence time values, recorded time series of CIAO Shack-Hartmann slopes, and DM commands are analyzed during closed-loop operation. The procedure is based on analyzing 60 Zernike coefficients as well as DM command vectors. The Zernike coefficients are created from expanding the Shack-Hartmann slopes into Zernike polynomials. Together with the temporal power spectral density of the Zernike coefficients and the DM commands, the atmospheric seeing, atmospheric AO coherence time, and pseudo-Strehl numbers were determined (see e.g. Fusco et al. 2004, Snyder et al. 2016).

(a) CIAO estimated seeing vs recorded Paranal Astronomical Site Monitor (ASM) seeing.

(b) CIAO estimated K-band Strehl number vs CIAO estimated seeing.

Figure 5. Estimated CIAO seeing and CIAO performance results for 3 years of GC observations with GRAVITY.

(a) CIAO estimated coherence time vs recorded Paranal Astronomical Site Monitor (ASM) coherence time.

(b) CIAO estimated K-band Strehl number vs CIAO estimated coherence time.

Figure 6. Estimated CIAO coherence times and CIAO performance results for 3 years of GC observations with GRAVITY.
Figure 5(a) compares the CIAO calculated seeing with the seeing recorded by the Paranal Astronomical Site Monitor (ASM) at the time of the CIAO observation. Please note that ASM and CIAO point to different parts on the sky, and thus also different areas of the atmosphere.

Figure 5(b) shows for each CIAO unit the estimated K-band Strehl as a function of the estimated seeing for galactic center observations in the years 2017 to 2019.

Figures 6(a) and 6(b) show estimated coherence times vs ASM coherence times and CIAO K-band Strehl numbers vs estimated coherence times, resp.

6. SUMMARY

CIAO is an adaptive optics system, which in combination with the GRAVITY instrument, allows efficient interferometric observations with four 8m telescopes.

In the 3 years studied, typically all CIAO units achieved a K-band Strehl number of 0.67 (median, Fig. 7).

The first years of observations with CIAO and GRAVITY at the Paranal Observatory were very successful. More than 30 science papers have been published by the GRAVITY collaboration since 2017. We anticipate that this will continue.

REFERENCES

[1] R. Genzel, F. Eisenhauer, and S. Gillessen, “The Galactic Center massive black hole and nuclear star cluster,” Reviews of Modern Physics 82, pp. 3121–3195, Oct. 2010.
[2] S. Gillessen et al., “Monitoring stellar orbits around the massive black hole in the galactic center,” The Astrophysical Journal 692, pp. 1075–1109, Feb. 2009.
[3] S. S. Doeleman et al., “Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre,” Nature 455, pp. 78–80, Sept. 2008.
[4] R.-S. Lu et al., “Detection of Intrinsic Source Structure at 3 Schwarzschild Radii with Millimeter-VLBI Observations of SAGITTARIUS A*,” The Astrophysical Journal 859, p. 60, May 2018.
[5] J. Woillez et al., “Vlti status update: three years into the second generation,” Proc. SPIE 10701, p. 1070103, July 2018.
[6] F. Eisenhauer et al., “GRAVITY: Observing the Universe in Motion,” The Messenger 143, pp. 16–24, Mar. 2011.
[7] F. Eisenhauer et al., “GRAVITY: The AO-Assisted, Two-Object Beam-Combiner Instrument for the VLTI,” in The Power of Optical/IR Interferometry: Recent Scientific Results and 2nd Generation, A. Richichi, F. Delplancke, F. Paresce, and A. Chelli, eds., p. 431, 2008.
[8] Gravity Collaboration et al., “First light for gravity: Phase referencing optical interferometry for the very large telescope interferometer,” Astronomy & Astrophysics 602, p. A94, June 2017.
[9] Gravity Collaboration et al., “Detection of the gravitational redshift in the orbit of the star s2 near the galactic centre massive black hole,” Astronomy & Astrophysics 615, p. L15, July 2018.
[10] Gravity Collaboration et al., “Detection of orbital motions near the last stable circular orbit of the massive black hole SgrA*,” Astronomy & Astrophysics 618, p. L10, Oct. 2018.
[11] Gravity Collaboration et al., “Spatially resolved rotation of the broad-line region of a quasar at sub-parsec scale,” Nature 563, pp. 657–660, Nov. 2018.
[12] M. Schöller, “The very large telescope interferometer: Current facility and prospects,” New Astronomy Reviews 51(8), pp. 628 – 638, 2007. Observation and Data Reduction with the VLT Interferometer.
[13] GRAVITY Collaboration et al., “GRAVITY Science,” The Messenger 178, pp. 19–49, Dec 2019.
[14] P. Yang et al., “Characterization of the transmitted near-infrared wavefront error for the GRAVITY/VLTI Coude Infrared Adaptive Optics System,” Optics Express 21, p. 9069, Apr. 2013.
[15] O. Pfuhl et al., “The fiber coupler and beam stabilization system of the GRAVITY interferometer,” Proc. SPIE 9146, p. 914623, July 2014.
[16] K. Perraut et al., “Single-mode waveguides for gravity. i. the cryogenic 4-telescope integrated optics beam combiner,” Astronomy & Astrophysics 614, p. A70, June 2018.
[17] Y. Clénet et al., “Dimensioning the gravity adaptive optics wavefront sensor,” Proc. SPIE 7736, p. 77364A, July 2010.
[18] S. Schéthauer et al., “Ciao: wavefront sensors for gravity,” Proc. SPIE 9909, p. 99092L, July 2016.
[19] C. Deen et al., “System tests and on-sky commissioning of the GRAVITY-CIAO wavefront sensors,” Proc. SPIE 9909, p. 99092N, July 2016.
[20] S. Kendrew et al., “Gravity coude infrared adaptive optics (ciao) system for the vlt interferometer,” Proc. SPIE 8446, p. 84467W, Sept. 2012.
[21] S. Hippler et al., “Near-infrared wavefront sensing for the vlt interferometer,” Proc. SPIE 7015, p. 701555, July 2008.
[22] J. Nijenhuis et al., “Simultaneous observation of two stars using the PRIMA Star Separator,” Proc. SPIE 7013, p. 70133F, July 2008.
[23] X. Dai, S. Hippler, and E. Gendron, “Experiments of two pupil lateral motion tracking algorithms using a Shack-Hartmann sensor,” Journal of Modern Optics 64, pp. 127–137, Jan. 2017.
[24] G. Finger et al., “SAPHIRA detector for infrared wavefront sensing,” Proc. SPIE 9148, p. 914817, Aug. 2014.
[25] G. Finger et al., “Sub-electron read noise and millisecond full-frame readout with the near infrared eAPD array SAPHIRA,” Proc. SPIE 9909, p. 990912, July 2016.
[26] L. H. Mehrgan, G. Finger, F. Eisenhauer, and J. Panduro, “GRAVITY detector systems,” Proc. SPIE 9907, p. 99072F, Aug. 2016.
[27] D. E. Atkinson et al., “Next-generation performance of SAPHIRA HgCdTe APDs,” Proc. SPIE 9915, p. 99150N, 2016.
[28] G. Finger et al., “On-sky performance verification of near infrared eapd technology for wavefront sensing at ground based telescopes, demonstration of e-apd pixel performance to improve the sensitivity of large science focal planes and possibility to use this technology in space,” Proc. SPIE 11180, p. 111806L, Jul 2019.
[29] S. B. Goebel et al., “Overview of the SAPHIRA detector for adaptive optics applications,” Journal of Astronomical Telescopes, Instruments, and Systems 4, p. 026001, Apr. 2018.
[30] A. M. Fowler and I. Gatley, “Demonstration of an Algorithm for Read-Noise Reduction in Infrared Arrays,” *The Astrophysical Journal* **353**, p. L33, Apr. 1990.

[31] I. Baker, C. Maxey, L. Hipwood, and K. Barnes, “Leonardo (formerly Selex ES) infrared sensors for astronomy: present and future,” *Proc. SPIE 9915*, p. 991505, July 2016.

[32] S. Lacour et al., “The GRAVITY fringe tracker,” *Astronomy & Astrophysics* **624**, p. A99, Apr. 2019.

[33] M. H. White, D. R. Lampe, F. C. Blaha, and I. A. Mack, “Characterization of surface channel CCD image arrays at low light levels,” *IEEE Journal of Solid-State Circuits* **9**, pp. 1–12, Feb. 1974.

[34] C. Alessandri et al., “Optimal ccd readout by digital correlated double sampling,” *Monthly Notices of the Royal Astronomical Society* **455**, pp. 1443–1450, Jan. 2016.

[35] C. Cruz de la Torre and J. de Vicente Albendea, “Digital correlated double sampling CCD readout characterization,” *Proc. SPIE 10709*, p. 1070920, July 2018.

[36] T. Fusco et al., “Naos performance characterization and turbulence parameters estimation using closed-loop data,” *Proc. SPIE 5490*, pp. 118–129, 2004.

[37] A. Snyder, S. Srinath, B. Macintosh, and A. Roodman, “Temporal characterization of Zernike decomposition of atmospheric turbulence,” *Proc. SPIE 9906*, p. 990642, 2016.