The ARGOS wavefront sensor pnCCD camera for an ELT: characteristics, limitations and applications

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Abstract. While a large visible fast low-noise detector for a Shack-Hartmann wavefront sensor (SH WFS) for an ELT does not exist yet, the current CCD technology pushed to its limits already provides several solutions for the ELT AO detector requirements. One of these devices is the new WFS pnCCD camera of ARGOS, the Ground-Layer Adaptive Optics system (GLAO) for LUCI at LBT. Indeed, with its 264×264 pixels, 48μm pixel size and 1kHz frame rate, this camera provides a technological solution to different needs of the AO systems for ELTs, such as "first-light" low-order SH but as well possibly higher order sensing using pyramid WFS. In this contribution, we present the newly developed WFS pnCCD camera of ARGOS and how it fulfills future detector needs of AO on ELTs.

1 Introduction

As part of wavefront sensors, detectors are critical components of future AO systems for ELT. While the needs can be divided in several categories (e.g. [3]), we focus here on an existing high performance visible detector that could be used as a "low-order" SH but as well pyramid WFS: namely the ARGOS pnCCD camera.
ARGOS is the ground layer AO system for the Large Binocular Telescope (LBT), see e.g. [6]. With its three Laser Guide Stars (LGSs), ARGOS will

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enhance the imaging and spectroscopic capabilities of the near-infrared imager and multi-object spectrograph LUCI, see e.g. [7]. Its aim is to homogeneously correct a wide field of view and to provide a robust system with high observing efficiency, and as such to optimized the science throughput.
For this purpose, the ARGOS WFS uses a single detector to sense the wavefront from its 3 LGSs : the ARGOS pnCCD camera ([4]). The camera - developed by PNSensor GmbH - will therefore sense 3 SH arrays with 15×15 sub-apertures each 8×8 pixels wide at the high frame rate of 1kHz, see Figure 1.

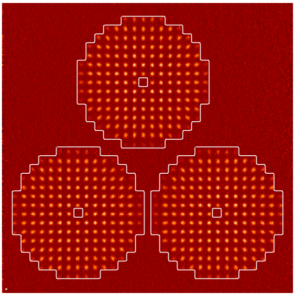

Fig. 1. The 3 SH pupil images as it will be sensed by the pnCCD at a frame rate of 1kHz. Each pupil is 15×15 sub-apertures of 8×8 pixels wide.

2 The ARGOS pnCCD camera system: description and characteristics

Originally developed for X-ray detection, the pnCCD can be used for fast optical application. Indeed, the pnCCD features split frame transfer, frame store operation and column-parallel readout, and therefore it reaches frame rates up to 1kHz. Its framerate together with its high quantum efficiency (QE), large imaging area and low readout noise, make it a technological solution for different AO applications. Figure 2 illustrates the QE for the

ARGOS pnCCDs. By using different kind of anti-reflective (AR) coating, the QE can be optimized for particular wavelength : for example, a maximum QE can be adjusted in the red and NIR region, see also [2].

The key specifications of the pnCCD, as used for ARGOS, are summarized in Tab. 1.

Table 1. Summary of key pnCCD specifications.

Parameter	Value
CCD type	column-parallel, split frame readout
Pixel in image area	248×256 pixels
Light shielded pixels for dark correction	$2{\times}8$ channels + $2{\times}4$ lines
Pixel size	$48 \times 48\ \mu$m
Frame rate	up to 1000Hz
Frame transfer duration	$< 40\ \mu$s
Quantum Efficiency at 532nm	~ 98 %
Readout noise (RON)	$<3e^-$ to $<4e^-$ (depending on the gain setting)
Dark current	$\sim 0.05e^-$/px/frame

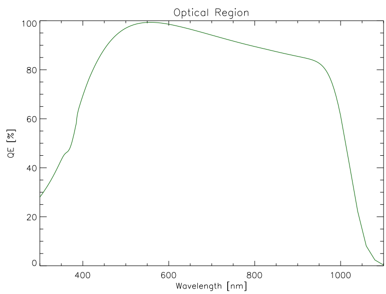

Fig. 2. Quantum Efficiency as optimized for ARGOS obtained by adjustment of AR coating.

Figure 3 shows the schematic pnCCD design for fast application composed of an image area, two frame store areas and four multi-channel readout ASICs (named CAMEX). More detailed characteristics of the pnCCD properties can be found in, e.g., [4] and [5].

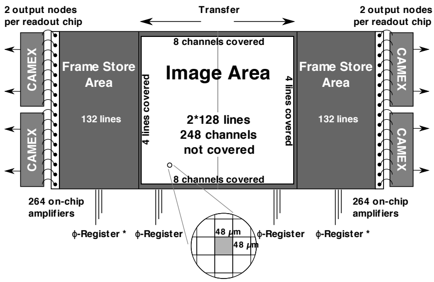

Fig. 3. Schematic layout of the split frame readout pnCCD having a frame rate up to 1kHz.

The pnCCD is embedded in a compact housing of $212 \times 120 \times 82$ mm. The cooling is performed by two double-staged thermoelectric (Peltier) modules, while the heat load is dissipated by cooling water, allowing an operation temperature around -35°C and hence negligible dark current at 1kHz frame rate. The camera housing is evacuated to about 1mbar and can be operated up to, at least, 40 mbar, allowing for low maintenance. The housing itself includes temperature and pressure sensors. Finally when tilted from -90° to +90°, the internal mechanical flexure results in less than 1/10 of a pixel movement in the x and y directions perpendicular to the optical axis. Figure 4 shows an ARGOS pnCCD camera housing with its entrance window, backplane electronics, and vacuum valve.

The electronics control rack of the camera fits in a 19″ rack and uses 6 HU. It includes a Peltier controller module, a housekeeping card, a pattern generator for all digital signals (which also allows for external synchronization), ADCs, a camera PC and newly developed power supplies. Those new power supplies are designed for compactness and optimized CCD performances, also discussed in Section 3. The camera PC, cPCI-based, contains a standalone software - currently under development - which allows CCD control but also autonomously ensures the pnCCD safety. An

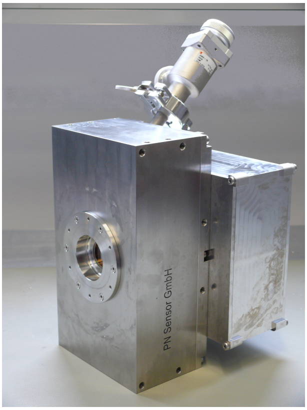

Fig. 4. pnCCD camera housing.

optimized version of the ADCs is as well currently under development and will be interfaced to a Basic Computing Unit (BCU), developed by Microgate s.r.l.. The optimized interface between CAMERA ADCs and BCU will ensure minimum latency and jitter in the data stream. The BCU itself is a DSP-based real time computer that performs the basic image reduction steps (plus our particular common-mode correction, see Section 3), compute the LGS slopes, control the LGS tip-tilt mirrors (field stabilization), acquire the tip-tilt slopes (from APD-based NGS sensing), and also offer the possibility to acquire additional slopes from either the current NGS AO (pyramid based, see [1]) or the Sodium laser (in the possible ARGOS upgrade, see [6]). Once a final slope vector is created, the BCU transfers it to the LBT secondary mirror where a similar DSP-based computer performs the phase reconstruction and control the DM shape.

3 AO performances

The readout of the pnCCD being column parallel, the pnCCD suffers of a time variant (line-by-line variation) offset, also called common-mode noise. This particular noise needs to be corrected by use of reference pixels: the basic scheme is to use eight reference covered channels similarly affected by the common-mode noise; in addition, we have also implemented in the BCU the possibility to use all pixels outside the three SH pupil images (*i.e.* pixels not exposed to any light, see also Figure 1). Nevertheless, this correction has been shown to be insufficient - for the ARGOS application - in some cases using our laboratory power supplies. Hence, we have started the development of new power supplies, more compact and reliable. Following our effort in investigating this noise and the development of this new power supplies, this noise is no longer considered to compromise the AO performances, which we also illustrate in the following.

Based on the YAO simulation tool[1], we compare the ground-layer adaptive optics (one LGS at a 12km altitude) performances for different WFS detector backgrounds in various seeing and photon fluxes per subaperture conditions. No efforts are conceded here in optimizing the reconstruction, since we aim only at comparing different CCD backgrounds. The following backgrounds are considered, see also Figure 5:

1. no photon and readout noise,
2. photon noise and $4e^-$ RON,
3. the ARGOS PNCCD background, corrected for common-mode and with $\sim 4e^-$ RON (lower gain setting used in high flux regime),
4. former and uncorrected background from the pnCCD (displaying strong common-mode noise).

The results are shown in Fig. 5 for two photon number regimes over a large range of seeing conditions. It shows that the ARGOS pnCCD background (with a low gain setting) behaves as an ideal $4e^-$ RON background (as can be seen in the low flux regime). It also shows that the common-mode noise cannot be left uncorrected (at least with its previous power supply unit). Finally, as ARGOS will operate in a non-photon limited regime (nominally above 700 photons/sub-ap. and minimum 300 photons/sub-ap.), the delivered performances will be optimum : the CCD background will not have any impact.

[1] see also `http://frigaut.github.com/yao`

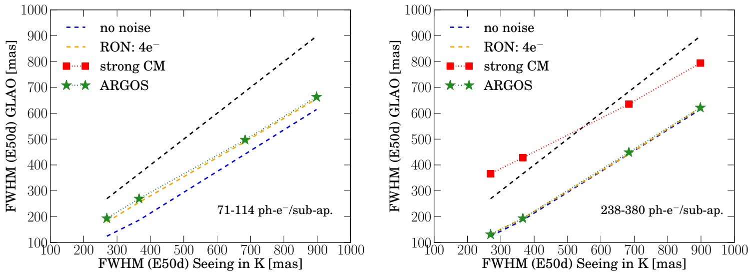

Fig. 5. Illustration of GLAO simulation with various WFS detector backgrounds : GLAO FWHM versus the uncorrected FWHM in the K-band (as a proxy for the PSF FWHM we use the 50% encircled energy diameter). *(Left)* low photon flux regime, as it can be seen the ARGOS CCD with its new power supplies and low gain setting is similar to a $4e^-$ RON CCD. *(Right)* higher flux regime, which is also approximately the minimum flux requirement for ARGOS. The performances predicted, in the later case, are optimum, and similar to those predicted by in-depth simulations for ARGOS, e.g., see [6].

4 Applications

The ARGOS pnCCD camera is currently in its final development phase and is being integrated to a system level.

This detector is at the current limit of the CCD technology and is becoming a mature state-of-the-art WFS camera. With its large imaging area (69696 pixels), 1kHz frame rate, excellent cosmetic, high QE (>98% at 532nm), low RON ($<3e^-$ with its highest gain), and very good PSF (FWHM < 1 pixel, see e.g. [4]), it is a solution to various AO detector needs for ELTs.

As it does not benefit of electron-multiplying registers, the ARGOS pnCCD is not best suited for extreme low light level AO applications. However, it does not suffer of the excess noise factor of EMCCDs, it benefits of an excellent QE (also tunable to the red and NIR wavelengths), and a high image full well capacity considering its fast pixel rate. Those advantages make it an excellent choice for non-photon limited AO applications and low-order WF sensing, e.g. 40x40 sub-ap. of 6x6 pixels each. Higher-order WF sensing could also be considered with pyramid WFS, in which case it would be similar to a SH array having as many as 124 × 124 sub-apertures, offering sufficient spatial sampling to full-fill ELTs WF sensing requirement.

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