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Visible and Infrared Wavefront Sensing detectors review in Europe – part I

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Abstract. The purpose of this review is to give an overview of the state of the art wavefront sensor detectors developments held in Europe for the last decade. A major breakthrough has been achieved with the development by e2v technologies of the CCD220 between 2004 and 2012. Another major breakthrough is currently achieved with the very successful development of fast low noise infrared arrays called RAPID. The CCD220, a 240x240 pixels 8 outputs EMCCD (CCD with internal multiplication), offers less than 0.2 e readout noise at a frame rate of 1500 Hz with negligible dark current. The OCAM2 camera is the commercial product that drives this advanced device. This system, commercialized by First Light Imaging, is quickly described in this paper. An upgrade of OCAM2 is currently developed to boost its frame rate to 2 kHz, opening the window of XAO wavefront sensing for the ELT using 4 synchronized cameras and pyramid wavefront sensing. Since this major success, new detector developments started in Europe. The NGSD CMOS device is fully dedicated to Natural and Laser Guide Star AO for the E-ELT with ESO involvement. The spot elongation from a LGS Shack Hartman wavefront sensor necessitates an increase of the pixel format. The NGSD will be a 880x840 pixels CMOS detector with a readout noise of 3 e (goal 1e) at 700 Hz frame rate. New technologies will be developed for that purpose: advanced CMOS pixel architecture, CMOS back thinned and back illuminated device for very high QE, full digital outputs with signal digital conversion on chip. This innovative device will be used on the European ELT but also interests potentially all giant telescopes. Additional developments also started in 2009 for wavefront sensing in the infrared based on a new technological breakthrough using ultra low noise Avalanche Photodiode (APD) arrays within the RAPID project. Developed by the SOFRADIR and CEA/LETI manufacturers, the latter offers a 320x240 8 outputs 30 microns IR array, sensitive from 0.4 to 3 microns, with 2 e readout noise at 1500 Hz frame rate. The high QE response is almost flat over this wavelength range. Advanced packaging with miniature cryostat using liquid nitrogen free pulse tube cryocoolers is currently developed for this program in order to allow use of this detector in any type of environment. Results of this project are detailed here.

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1. Introduction

The success of the next generation of ESO (European Southern Observatory) instrument [1] for 8 to 10-m class telescopes will depend on the ability of Adaptive Optics (AO) systems to provide excellent image quality and stability. This will be achieved by increasing the sampling and correction of the wave front error in both spatial and time domains. For example, advanced Shack Hartmann systems currently fabricated require 40x40 sub-apertures at sampling rates of 1-1.5 kHz as opposed to 14x14 sub-apertures at 500 Hz of previous AO systems. Beyond the e2v CCD50 developed for the ESO NACO instrument in the late nineties [2], new detectors of 240x240 pixels are required to provide the spatial dynamics of 5-6 pixels per sub-aperture. Higher temporal-spatial sampling implies fewer photons per pixel therefore the need for much lower read noise (<<1e-) and negligible dark current (<< 1e-/pixel/frame) to detect and centroid on a small number of photons. This detector development was jointly funded by ESO and the OPTICON European network [3] in the Joint Research Activity JRA2 [4], “Fast Detectors for Adaptive Optic". e2v technologies [5] was chosen in 2005 to develop a dedicated detector based on an extension of their L3Vision [6] EMCCD technology. Analysis [7] showed that the sub-electron read noise of L3Vision CCDs clearly outperformed classical CCDs even though L3Vision devices exhibit the excess noise factor F of $2^{1/2}$ typical of EMCCDs [8], [9].

The FIRST LIGHT IMAGING [10] spin-off now commercializes most of these developments and is specialized on very fast and low noise camera for scientific applications like adaptive optics and interferometry. Many camera systems have been sold by this company in the world to the best astronomical telescopes.

2. THE RAPID E-APD INFRARED WAVEFRONT SENSING DETECTOR

2.1. The RAPID 320x255 pixel e-APD array presentation

Infrared HgCdTe Avalanche Photo Diodes (APD) have been shown to exhibit single carrier multiplication (SCM) of electrons up to gains in the order of 10 000 associated with low excess noise factors F=1.05-1.2, record high gain-bandwidth product GBW>2.1THz and low dark currents. The technology used to manufacture APDs is similar to the one used for standard n on p HgCdTe diodes explaining why a high quantum efficiency (typically QE=80-95 %) is maintained from the visible wavelengths up to the infrared (IR) cut-off wavelength. They have inspired a large effort in developing focal plan arrays using HgCdTe APDs for low photon number applications such as active imaging in the range gated mode (2D) and/or with direct time of flight detection (TOF) (3D) and, more recently, passive imaging for wave front correction and fringe tracking in astronomical observations [11] funded by the RAPID programme.

The RAPID programme is a 4 years R&D project funded by the French "Fonds Unique Interministériel" in 2009. It includes several industrial and academic partners from the field of advanced infrared focal plane arrays fabrication (SOFRADIR, CEA-LETI) and of astronomical/defense institutes (IPAG, LAM, ONERA). The goal of this programme is to develop a fast and low noise infrared focal plane array of moderate format for astronomical fast application like adaptive optics wavefront sensing and fringe tracking for astronomical interferometers.

The main characteristics of RAPID are:

- Pixels Format: 320 x 255 pixels 30µm pitch
- Technology: HgCdTe, intra-pixel CDS and CTIA, 3 to 3.3 µm @ 77K
- Rectangular window can be defined with the start line and the end line of the window to be read.
- Noise: 1.5 e- with gain x30
- Frame rat: 1500 Hz, up to 2 000 Hz
- Dark signal: 100 e-/s measured, limited by setup background
- Power consumption: 122 mW

The e-APD HgCdTe technology allows to apply moderate multiplication gain without adding noise, therefore lowering the readout noise without almost no penalty. This is the only way to obtain the fast frame rates needed by wavefront sensing with readout noise lower than 3 e. This kind of performances can't be achieved by classical HgCdTe arrays, the APD technology is absolutely necessary.

The ultimate goal of the RAPID development is to demonstrate operation of the 320x255 pixels 30 microns pitch infrared array at 2000 fps with less than 2 e- readout noise. To achieve such readout noise and fast frame rate, APDs technology and intra-pixel Correlated Double Sampling were both needed. The floor plan of the device is shown in the Fig. 1, it includes 8 parallel outputs clocked at 20 MHz pixel rate defining 8 stripes of 40x256 pixels with one amplifier per stripe. The detector can be seen in the Fig. 2 during its integration in the pulse tube cryostat.

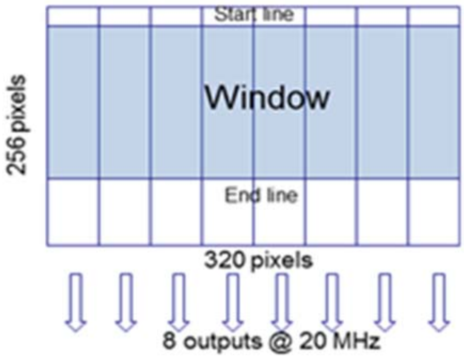

Fig. 1. the 1.6 kfps RAPID e-APD infrared detector configuration: 8 outputs 320 x 255 pixels with 30 µm pitch. A rectangular window with programmable start line and end line can be defined to speed up the frame rate.

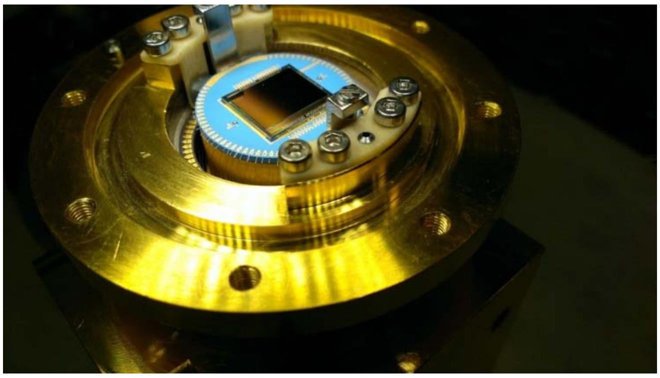

Fig. 2. the RAPID 320x255 IR APD array during integration by Sofradir in its cryostat cooled with a miniature pulse tube.

2.2. RAPID results

The multiplication gain of the APD mainly depends on the cut-off wavelength and the reverse bias voltage of the photodiode, also but with less sensitivity depends on the detector temperature. The gain increases with the bias voltage, the cut-off wavelength and decreases with the temperature.

The bias voltage of the photodiode, performed by the readout circuit, is driven by the CMOS technology used for the readout circuit. Increasing the cut-off wavelength increases the gain but also the dark signal and the need for colder temperature. A first trade-off of these constrains was to choose a cut-off wavelength of 3 to 3.3 µm with a CMOS technology well proven by SOFRADIR allowing -8V of reverse bias. An example of photodiode multiplication gain as a function of the bias voltage is given in Fig. 3.

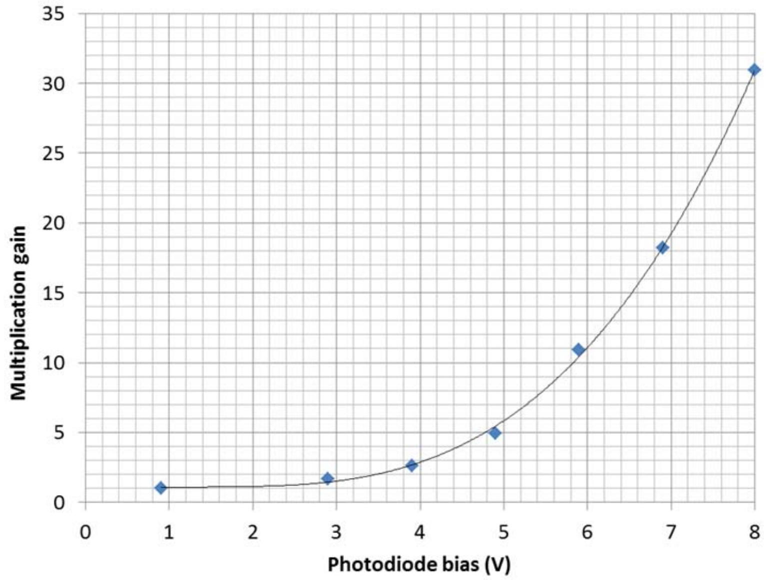

Fig. 3. mean multiplication gain of the APD array as a function of the photodiode reverse bias with 3.3 µm cut-off photodiodes.

The conversion gain is calibrated using the classical photon transfer curve method. The system noise is computed using frames of 2000 images recorded in dark conditions (black cover on the window) and a very small integration time (10 µs). The noise histograms of the 8 detector outputs are shown in Fig. 4 at 1600 fps and gain of 30. Readout noise as low as 1.5 e have been measured with the RAPID IR array at 1600 fps and a multiplication gain of 30. The readout noise variation as a function of the multiplication gain at 1600 fps and a detector temperature of 75K is shown in Fig. 5.

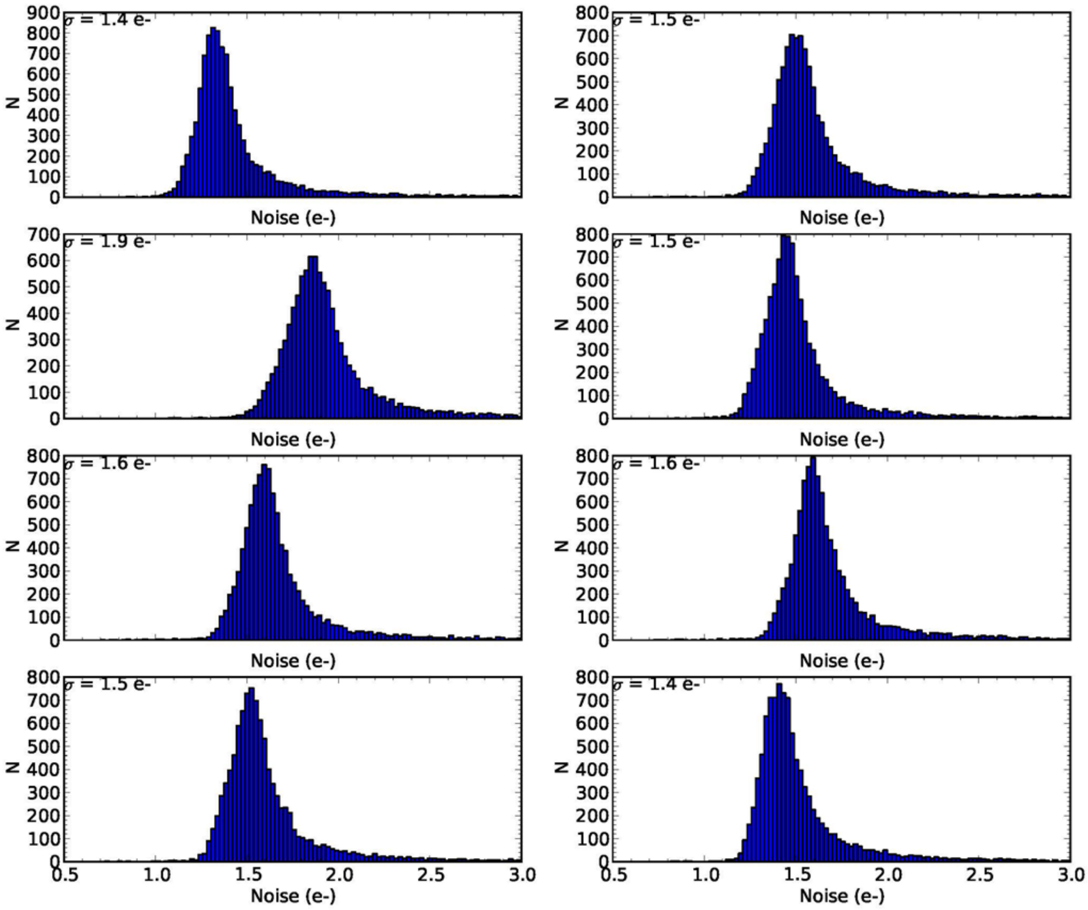

Fig. 4. noise histogram of 320x255 RAPID IR device at 1600 fps and gain ~ 30.

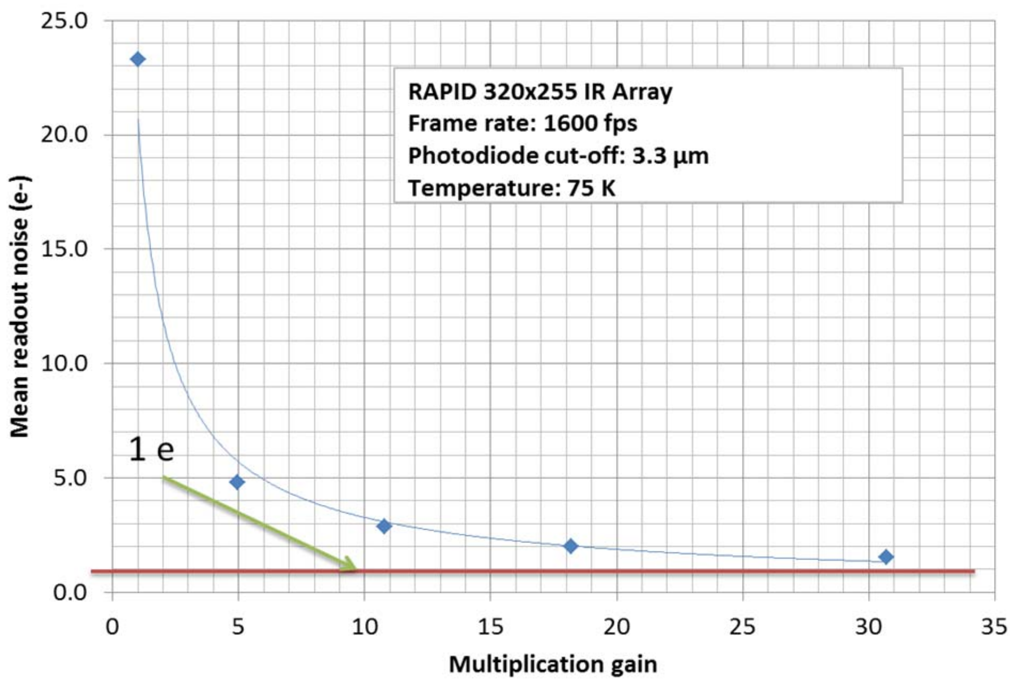

Fig. 5. mean readout noise (input referred) as a function of the multiplication gain.

An important specification of our system is the ability to be used in a vibration free environment. This is why we investigated the system vibrations by imaging a 10 µm pinhole on the infrared array using a SWIR focusing objective mounted with a C-mount on the cryostat. The centroid of the pinhole image is computed as well as the jitter (in pixels) of this centroid. The FFT of this jitter allows to obtain the jitter spectrum as shown in the Fig. 6. This figure shows that no vibrations due to our 50 Hz miniature pulse tube cooler can be measured.

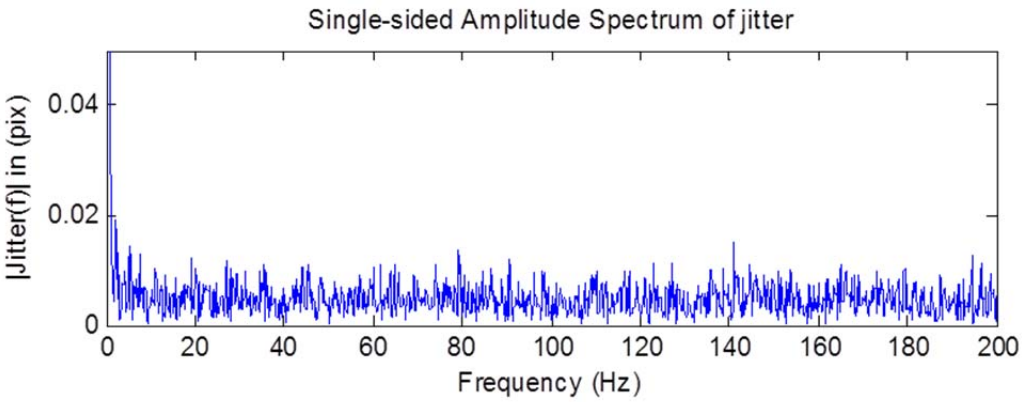

Fig. 6. jitter spectrum of the spot centroid demonstrating no vibrations induced by the 50 Hz pulse tube cooler.

3. The OCAM 2K camera

OCAM2, see Fig. 7, is commercialized by First Light Imaging [10]. OCAM2 is a ready-to-use camera with embedded parameters to run the CCD, factory optimized. OCAM2 has also been designed for ruggedness and can cope with more demanding environmental conditions, like accepting cooling water temperature up to 35°C and removing the need for an external chiller. The camera is fully sealed, includes the Thermo Electric Cooler controller inside the camera head, and needs only a standard +24V power supply for the whole system.

Fig. 7. the OCAM2 camera, 240x240 pixels EMCCD, from 1.5 to 2 kfps, <0.2 e noise, commercialized by First Light Imaging.

The OCAM2 system is capable of driving all members of the CCD220/219 family at their nominal speed (1.5kframes/s) and transmitting the data at full speed through a CameraLink interface. The camera controller is able to drive deep depleted variants with multilevel clocking at voltage levels up to 24V with speeds of more than 10Mlines/s .

The controller handles the 8 L3vision outputs with high voltage clocking up to 50V voltage swing. A big effort has been made to have high voltage stability (less that 1mV/hour of drift) in order to ensure a constant gain over a long period. The system digitizes the CCD signal using correlated double sampling with 14 bits resolution. Standard interfacing of the camera is performed by using a PC computer running Windows OS fitted with a CameraLink full grabber and a proprietary software capable of gathering in real time the extremely high data rate of 220Mbytes/s produced by the camera.

By clocking pixels at 18.6 MHz, OCAM2 moved to OCAM2K [11] and is now able to acquire images at 2 Kfps without performances degradation, as shown in Table 1.

Readout noise as low as 0.13 e was obtained at 2 kps and gain 1000 with the 240x240 pixels EMMCCD of OCAM2K, see Table 1.

Table 1. OCAM2 and OCAM2K performances comparison

Test measurement	OCAM2	OCAM2K	Unit
Nominal speed (full frame)	1503	2067	fps
Mean readout noise (full frame, full speed), gain 1000	0.13	0.13	e-
Pure Latency	60	43	µs
Dark signal at full speed and temperature -45°C	0.0023	0.002	e-/pix/frame
Detector operating temperature	- 45	-45	°C
Peak Quantum Efficiency at 650 nm	94	94	%
Linearity at gain x1000 from 10 to 150 ke	<3	<3	%
Image area Full Well Capacity at gain x1, 1503 fps	300	300	ke^-
Parallel CTE at gain x1, 1503 fps	0.9999	0.9999	N/A
Serial CTE at gain x1, 1503 fps	0.9999	0.9999	N/A

The OCAM2K readout noise as a function of the multiplication gain is shown in Fig. 8.

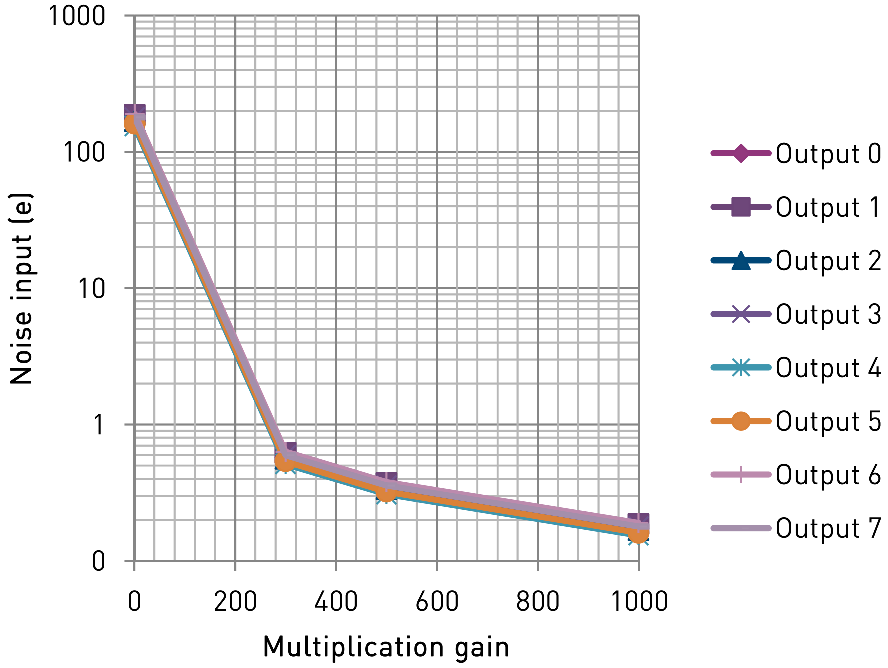

Fig. 8. the OCAM2K readout noise at 2 kfps as a function of the multiplication gain.

4. The NGSD BSI CMOS 880X840 Detector for Laser Guide Star

A new fast detector development in the visible has been started by ESO and the OPTICON network in 2008 to develop new detector devices in the E-ELT framework, both for NGS and LGS wavefront sensing on extremely large telescopes [12]. The same consortium with ESO, e2v technologies and the French astronomical observatories (LAM, IPAG and OHP) decided to develop a long term program for this goal with joint funding from ESO and OPTICON under the 7th Framework Programme.

Very early in the project, it has been decided to move to new detector technologies based on CMOS devices. But if CMOS devices are now commonly used in low cost applications, this is not the case for demanding scientific imaging. To mitigate the risk of this technological step, the long term programme was divided into several phases, up to the LGSD (Laser Guide Star Detector) which is the final development. The different phases are "Technology Demonstrators" (TVP), the "Natural Guide Star Detector" (NGSD) and the LGSD. The main issue with Laser Guide Star wavefront sensing is the spot elongation due to the finite distance of the laser guide star produced by the stimulation of the sodium layer of the atmosphere at about 90 km. This cone effect due to the angle between the telescope axis and the laser beam axis induces that LGS spots are elongated. The main consequence is that the LGS sub-aperture requires more pixels than with NGS whereas all other parameters of the AO detector remain the same: frame rate, pixel size, quantum efficiency, dark current and up to a certain level the readout noise. Maintaining fast frame rate (~ 1 kHz) and low readout noise lower than 3 e while increasing the detector format is impossible with the current detector technology. This is the reason why a new devices family is under development to cover this new exciting challenge for the E-ELT.

The main specifications of the NGSD are given in Table 2.

In addition, First Light Imaging is developing a compact camera system based on this device. This camera will be available by 2015.

Table 2. the NGSD 880x840 BSI CMOS device for LGS wavefront sensing.

Pixel number (including dark reference pixels)	"Natural Guide Star Detector" NGSD - 880x840 pixels with 840x840 sensitive pixels
Detector technology	Thinned backside illuminated CMOS 0.18µm
Pixel Pitch	24µm
Pixel topology	4T pinned photodiode pixel
Sub-aperture	20x20 pixels
Array architecture	42x42 sub-apertures of 20x20 pixels
Pixel full well	4000 e-
Read noise including ADC	< 3.0 e^-_{RMS}
ADCs configuration	20 x 880 column ADCs, 9 (goal 10) bits
Number of parallel LVDS channels	22
Serial LVDS channel bit rate	210 Mb/s baseline, up to 420 Mb/s (desired)
Frame rate	700 fps up to 1000 fps with degraded performance

5. Conclusion

Wavefront sensing detector developments are now carried out in Europe for next generation of telescope. Infrared wavefront sensors, called RAPID and based on a 2 kfps 320x255 pixels infrared APD arrays, are also currently produced and tested already demonstrating read noise lower than 2e at this frame rate. This infrared detector is produced by SOFRADIR [13]. A commercial camera based on this innovating detector will be commercialized by First Light Imaging [10]. A long programme has started in 2004 for developing large CMOS detectors for the E-ELT with several phases, all detectors are fabricated by e2v. The current phase consist in the production of a 880x800 pixel fully digital CMOS detector which should provide 3 e- read noise at 700 Hz (1000 Hz with degraded performances) and optimal QE. This detector, called NGSD, will be used for natural and laser guide start systems on Extremely Large Telescopes. A camera system based on the NGSD, commercialized by First Light Imaging, will be offered by 2014.

This paper illustrates a long term and coordinated wavefront sensor development involving cutting edge detectors and camera systems industry associated with ESO and academic French laboratories (LAM, IPAG and OHP).

6. Acknowledgments

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