# A DEDICATED L3VISION CCD FOR ADAPTIVE OPTICS APPLICATIONS

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Abstract: ESO and JRA2 OPTICON have funded e2v technologies to develop a compact packaged Peltier cooled 24 µm square 240x240 pixels split frame transfer 8-output back illuminated L3Vision CCD, L3CCD. The device will achieve sub-electron (goal 0.1e-) read noise at frame rates from 25Hz to 1.5 kHz and low dark current of 0.01 e-/pixel/frame. The development has many unique features. To obtain high frame rates, multi-output EMCCD gain registers and metal buttressing of parallel clocks will be used. To minimize risk, the baseline device will be built in standard silicon. In addition, a split wafer run will enable two speculative variants to be built; deep depletion silicon devices to improve red response and devices with an electronic shutter to extend use to Rayleigh Laser Guide Star, RLGS, applications. These are all firsts for L3CCDs. This paper will describe the requirements and outline the design established after careful consideration of the application, detector architecture, compact Peltier package, technology trade-offs, schedule and proposed test plan.

Key words: Adaptive optics, AO systems, Electron Multiplying CCD, EMCCD, L3Vision, L3CCD, readout noise, wavefront sensor.

# 1. INTRODUCTION

The success of the next generation of instruments (e.g. VLT Planet Finder, MUSE, HAWK-I) 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, future Shack Hartmann systems will require 40x40 sub-apertures at sampling rates of 1-1.5 kHz as opposed to 8x8 sub-apertures at 500 Hz of current systems. Detectors of 240x240 pixels will be 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 single or a small number of photons. Existing detectors do not have this combination of image area size, read out speed, and low noise performance. As the WFS detector has been identified as the critical component of future AO systems there is an urgency to develop better detectors.

Numerous European astronomy institutions, incl. ESO, have teamed up in the OPTICON network [1], and obtained funds in the joint research activity JRA2, "Fast Detectors for Adaptive Optics", from the European Commission to support the massive R&D effort to develop a new detector. After extensive market research culminating in a Call For Tender, e2v was chosen to develop a custom-designed detector based on an extension of their L3Vision [7] EMCCD technology. Analysis [1, 3] showed that the sub-electron read noise of L3Vision CCDs clearly outperformed classical CCDs even though L3Vision exhibits the excess noise factor of √2 typical of EMCCDs.

# 2. REQUIREMENTS

The OPTICON JRA2 science working group set the top level requirements after carefully considering the needs of AO systems for future instruments and their science programs. The following detailed requirements were established:

1. big pixels, square 24 μm (goal), to ease the optical system design, but not too large to produce excessive dark current (DC) or CTE problems.
2. versatility of a 100% fill factor and 240x240 square grid array of pixels that can be used by any WFS systems: SH, curvature, or

pyramid, with or without gaps (guard bands) between subapertures.

3. format size of 240 pixels being a number that is divisible by the number of output nodes, 8, and binning factors and aperture sizes of 1, 2, 3, 4, 5, 6 and meets the minimum pixel requirement of 40 subapertures x 6 pixels/subapertures.
4. low read noise of < 1 e-/pixel and goal of 0.1 e-/pixel.
5. range of operating frame rates from 25 frames/s (fps) for use when photon starved with faint-NGS (Natural Guide Star) to highest sampling rate of 1,200 fps for use with bright-NGS and LGS (Laser Guide Star).
6. easy to use; eight output nodes each operating at maximum pixel rate of 15 Mpixel/s, that provide a good compromise between the number of connections between the detector and the outside world and operational practicalities such as power dissipation, pixel rates and clocking rates.
7. low image smearing (<5%) when transferring from the image to store area; an undesirable effect that can be corrected.
8. cosmetically defects free as every defect will either complicate the centroiding or make it impossible to centroid a sub-aperture.
9. good spatial characteristics, PSF < 0.9 pixel FWHM over 460 to 950 nm, to accurately determine where the photons are detected.
10. very low Dark Current, DC, of < 0.01 e-/pixel/frame at 1,200 fps and < 0.04 e-/pixel/frame at 25 fps to minimize the large errors introduced by the quantum nature of DC; as the electron is the smallest unit. A single electron of DC creates a large error when centroiding on a small number or single photon event. DC includes contributions from the clock induced charge (fixed amount per frame readout), the image area during exposure ($\propto$ exposure time), the frame store and the serial register during readout ($\propto$ frame read out time).
11. Peltier cooled package for small compact size, maintenance free, and minimal support equipment so that the final assembled camera system can fit in the small volumes usually reserved for AO systems.
12. detection signal limit of 5 ke-. In normal operation, the system will be photon starved as there are not too many bright NGS and LGS will be operated at as low a power as possible. Well depth and output amplifier dynamic range can be traded to improve other parameters such as higher gain of output amplifier and lower clock amplitudes to transfer charge.

13. linearity of < 2%. Analysis shows that this level of nonlinearity introduces insignificant errors. Nonlinearity can be corrected by a look-up table.

## 3. DESIGN

The design (Figure 1) is a 24 µm square 240x240 pixels split frame transfer 8-output back illuminated L3CCD, designated as the CCD220. The shuttered variant is designated as the CCD219.

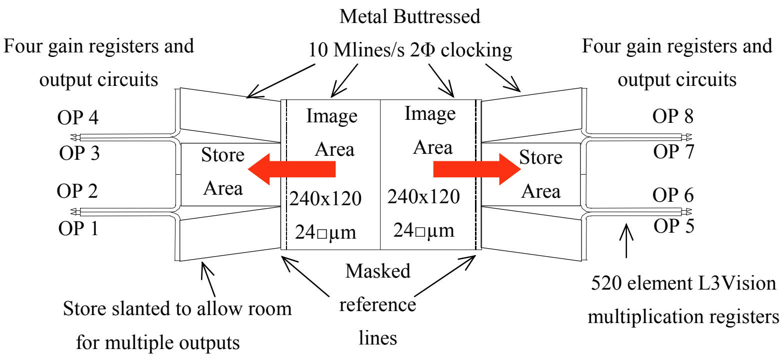


*Figure 1.* Schematic of CCD220.

The image and store area are built with metal-buttressed parallel clock structures to enable line shifts of 10 Mlines/s for total transfer time from image to store of 12 µs and low smearing of under 1.5% at 1,200 fps. Two phase clocking was chosen for simplicity, lower power dissipation, and symmetry of drive. See Gach *et. al.* [2] for a discussion of the benefits for the CCD controller of having a symmetric drive.

The store area is slanted out to make room for the standard serial registers (three phase clocking) to curve around (Figure 2) and provide space for the output circuitry. Each output will have a 520 element 16 µm standard L3Vision gain register whose gain is controlled by the voltage of the multiplication phase. The output amplifier will be a single stage (Table 1 for specifications) and of similar design to that employed on recent L3V CCDs. The gain register and output amplifier will be optimized for a gain of 1000, a value typically expected for AO applications, to provide an overall effective read noise of under 0.1 e-. The serial registers, gain registers, and output amplifiers are designed to operate up to 15 Mpixel/s to achieve a full goal frame rate of over 1,5oo fps.

The baseline device will be built in standard silicon and is low risk with guaranteed delivery of devices that meet minimum requirements. This meets the risk profile of both JRA2, who must produce a design report to the EU on a 2-3 year timescale, and ESO, who require working detectors for their next generation of instruments. A split wafer run will enable two speculative variants to be built. The first is to build devices in deep depletion silicon which will offer much better red response. High red response is important for applications that rely on natural GS such as VLT Planet Finder. The second is to build devices with an electronic shutter to extend the use of the detector to applications such as Rayleigh Laser Guide Star, RLGS, which require very short shutter times of µs. These short shutter times are not possible by mechanical means. RLGS systems can offer substantial savings in costs and development effort in that they can use commercially available pulsed lasers as opposed to specialized sodium lasers.

*Table 1.* Specifications of output amplifier.

| **Feature** | **CCD220** |
|---|---|
| Overall responsivity | 1.7 µV/electron |
| Node capacitance | 57 fF |
| Noise (rms with CDS ~ 15 MHz) | 45 electrons |
| Reset rms noise (dominates without CDS) | 100 electrons |
| Saturation (3V swing at node) | 1.0M electrons |
| Output impedance | 350 Ohms |
| Maximum frequency (settling to 1%) [1] | 15 MHz |
| Maximum frequency (settling to 5%) | 25 MHz |

No dump gate was included in the design as it was doubtful whether its response time to dump charge would be any faster than simply clocking the serial register, and if included would add excessive capacitance to neighboring registers and add pins to the package resulting in a larger package size and more heat load. Additionally, for deep depletion devices a much wider dump gate would be required to avoid parasitic effects resulting in an even slower dump time.

As well to reduce pin count, summing wells were not included as it was thought to be acceptable that with low read noise of 0.1e- binning could just as easily be performed off chip.

[1] Load capacitance (external and package) < 10 pF

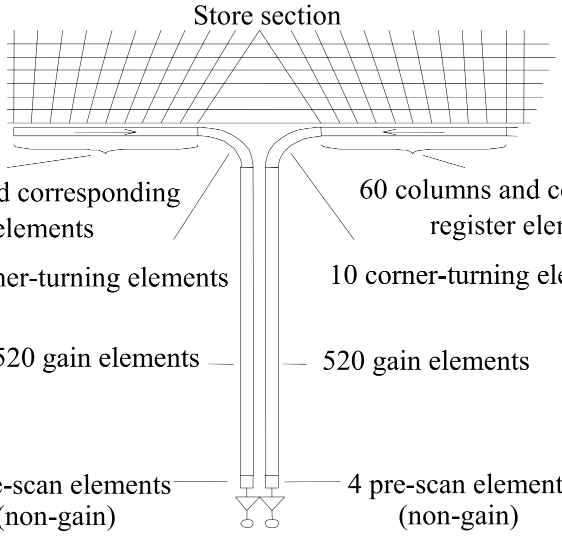


*Figure 2.* Details of serial and gain register.

## 4. PACKAGE

The devices will be mounted in a compact Peltier cooled package similar to that shown in figure 3. Peltier cooler and package will be custom-designed and able to cool down the CCD sufficiently to meet the DC requirements over the full operating frame rates. The estimated power dissipation of the CCD at 1,200 fps (worst case) is shown in Table 2. The Peltier cooler, ceramic chip carrier and CCD will be glued by a thermally conductive epoxy adhesive. The package will be sealed and filled with 0.9 bar of Krypton gas to minimize heat transfer to the outside.

*Table 2.* Estimated total and on-chip power dissipation of CCD220 at 1,200 fps.

| Section | Load | Delta V | Mean f | $W_{total}$ | $W_{on-chip}$ |
|---|---|---|---|---|---|
| Image | 4.2 nF | 10 V | 185 kHz | 78 mW | 23 mW |
| Store | 3.6 nF | 10 V | 370 kHz | 133 mW | 40 mW |
| Register | 1.5 nF | 10 V | 13.2 MHz | 2.0 W | 800 mW |
| HV | 0.4 nF | 45 V | 13.6 MHz | 11.0 W | 220 mW |
| Amplifiers | | | | 8x50 mW | 400 mW |
| **Total** | | | | | ~1.5 W |

The CCD220 die will have four fiducial crosses situated with two on either side of the device image area, in the region of the bond pads. These will be clearly visible through the package window for alignment purposes such as when attaching lenslet arrays. An AD590 temperature sensor will be glued to the ceramic chip carrier to provide sensor for temperature regulation. The sapphire entrance window will be of a high optical quality (double path wavefront error of < 50 nm rms), good surface quality (defects meet 5/2x0,05 DIN3140), and AR coated with transmission > 98% over range 400-950nm.

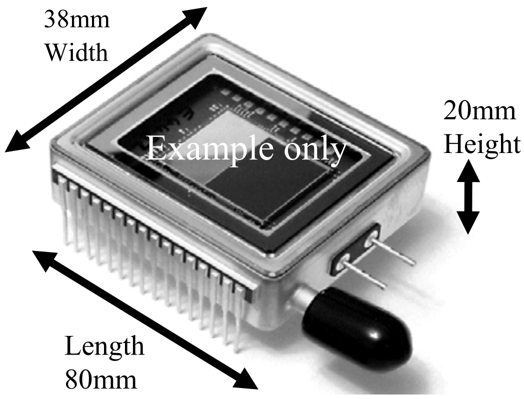


*Figure 3.* Photograph of CCD65 Peltier cooling package. The AO CCD220 detector will use a similar Peltier package. Dimensions shown are the requirements on the maximum package size.

## 5. SCHEDULE

The major milestones (Table 3) are CDR in Q3 2005, package review at end 2005, and final device delivery in Q2 2007. Test equipment and camera electronics is being developed by Gach *et al* [3] and will be loaned to e2v for testing. The same test equipment will be used by the IAC (JJD) to do acceptance test. ESO are developing the New General detector Controller, NGC, [4 5, and 6] to support the CCD220 for deployment on the VLT.

The test plan is for e2v to do parametric and functional tests and measure standard parameters such as noise, gain, cosmetics, dark current, smearing, and CTE and for IAC (Canary Islands) and ESO to do full acceptance tests plus measure the more exotic parameters such as crosstalk, PRNU, fringing, and PSF.

*Table 3.* Major milestones of CCD220 development.

| Milestone | Date |
|---|---|
| Kick-off meeting | March 2005 |
| CCD220 and Test Equipment Critical Design Review (CDR) | Q3 2005 |
| Package Design Review | End 2005 |
| Mechanical samples delivery | Mid 2006 |
| ESO supplied test equipment delivery | Q3 2006 |
| Devices delivery | Q2 2007 |

## 6. CONCLUSION

Several European institutions under the umbrella of OPTICON have formed a very good working relationship with e2v to develop a new 240x240 pixel wavefront sensor detector, CCD220, with subelectron read noise at 1,200 fps that will enable future AO systems to provide the image quality and stability to guarantee the success of next generation of instruments on 8 to 10-m class telescope. Baseline development is low risk by extending existing e2v L3Vision technology to multiple outputs and metal buttressing parallel clock structures. In addition higher risk (more speculative) but higher performance devices in deep depletion silicon and with electronic shutter will be developed in parallel. For compactness and low maintenance the CCD is mounted in an optimized Peltier cooled package.

References

1. P. Feautrier et al, “Zero noise wavefront sensor development within the Opticon European network”, this conference.

2. J-L. Gach et al, “A dedicated controller for Adaptive Optics L3CCD developments”, this conference.

3. T. Fusco et al, “Optimisation of Shack-Hartman based wavefront sensor for XAO systems”, Proc. SPIE Int. Soc. Opt. Eng. 5490, 1155 (2004).

4. J. Reyes et al, “NGC Front-end for CCDs and AO application”, this conference.

5. C. Cumani et al, “Software for the New General detector Controller”, this conference.

6. M. Meyer et al, “NGC Detector Array Controller Based on High Speed Serial”, this conference.

7. P. Jerram, P. J. Pool, R. Bell, D. J. Burt, S. Bowring, S. Spencer, M. Hazelwood, I. Moody, N. Catlett, and P. S. Heyes, ``The LLCCD: low-light imaging without the need for an intensifier," in Proc. SPIE, 4306, pp. 178-186, May 2001.