AO Wavefront Sensing Detector Developments at ESO

Mark Downing, Johann Kolb, Dietrich Baade, Olaf Iwert, Norbert Hubin, Javier Reyes, Philippe Feautrier, Jean-Luc Gach, Philippe Balard, Christian Guillaume, Eric Stadler, Yves Magnard, Olivier Boissin

ESO’s AO WFS Detector roadmap

Detectors in Production (Today)

Past Successes (Late 1990s onwards)

Future Challenges E-ELT (2018 →)

CCD220
pnCCD
MPI/HLL

CCID-35
MIT/LL
CCD50

27/06/2010
SPIE 2010: AO WFS Detectors
Adaptive Optics (AO) - removing the twinkle of the stars

Wavefronts from astronomical objects are distorted by the Earth’s atmosphere, reducing the spatial resolution of large telescopes to that of a 10 cm telescope.

1. Wavefront Sensor measures deviation of wavefront from a flat (undistorted) wave
2. Control System computes commands for the deformable mirror(s)
3. Adaptive Mirror compensates the distorted wavefront, achieving diffraction-limited resolution
4. Light From Telescope

Control System OFF

Control System ON
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ESO’s AO WFS Detector roadmap

Past Successes
128x128 pixels
600 fps
< 5e- RON

Detectors in Production
240x240 pixels
> 1200 fps
< 2e- RON

Future Challenges
E-ELT

Past Successes
CCD220
pnCCD
CCD50
MIT/LL
CCID-35
MPI/HLL

27/06/2010
SPIE 2010: AO WFS Detectors
e2v CCD220:

→ Split frame transfer CCD
→ 240x240 24 µm pixels
→ 8 L3Vision EMCCD outputs
→ << 1 e- RON at 1,200 fps

Metal Buttressed 2Φ 10 Mhz Clocks for fast image to store transfer rates.

8 L3Vision Gain Registers/Outputs Each 15Mpix./s.

Store slanted to allow room for multiple outputs.

Metal Buttressed 2Φ 10 Mhz Clocks for fast image to store transfer rates.
CCD220 Status

- Four science devices in house
- Further 12 Std Si & 4 DD in production (Q4 2010).

Several Test Cameras in operation → built by LAM, LAOG, OHP

- 1st prototype of ESO’s NGC WFS Camera Head is operational
- Planned production of 18 cameras for VLT AO Facility (MUSE & HAWK-I) and SPHERE

Technology transferred
CCD220 Status

Technology transfer to industry

✓ Go along to booth #306
CCD220 Key Test Results

→ devices meet specifications

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Measured</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Rate:</td>
<td>&gt; 1,300 fps</td>
<td>&gt; 1,200 fps</td>
</tr>
<tr>
<td>Read noise:</td>
<td>&lt; 0.9 e-</td>
<td>&lt; 1.0 e-</td>
</tr>
<tr>
<td>at gain of 1000 &amp; 1300 fps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image Area Full Well:</td>
<td>&gt; 200 ke-</td>
<td>&gt; 5,000 e-</td>
</tr>
<tr>
<td>Serial Charge Transfer Efficiency</td>
<td>&gt; 0.999999</td>
<td>&gt; 0.9998</td>
</tr>
<tr>
<td>Cosmetic</td>
<td></td>
<td></td>
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<tr>
<td># of traps, bright/dark defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark Current at 1200fps &amp; -40°C:</td>
<td>0.01 e-/pix/frame</td>
<td>&lt; 0.01 e-/pix/frame</td>
</tr>
<tr>
<td>Dark Current at 25fps &amp; -40°C:</td>
<td>0.04 e-/pix/frame</td>
<td>&lt; 0.04 e-/pix/frame</td>
</tr>
</tbody>
</table>

Further optimization under way:

• Test Deep Depletion devices that offer much sought after higher red response.
• Reduce read noise closer to goal of 0.1 e-.
• Increase frame rate to 2,500 fps to extend use to E-ELT XAO (Extreme AO).

See talk Philippe Feautrier Tuesday 2pm session – 7736-34

“OCam and CCD220 - World’s Fastest and Most Sensitive Astronomical Camera”
MPI/HLL pnCCD
(Robert Hartmann, Sebastian Ihle, Heike Soltau, Lothar Strueder)

- Max Planck Institut / Halbleiterlabor
- pnCCD 256x256 pixels 51µm pitch
  - 450µm thick fully depleted
  - Excellent red response & no fringing
  - 300V backside bias for good PSF
- Target: RON < 3 e- at 1,000 fps
- Split frame transfer
- Fast readout → Column Parallel CCD
  → one output amplifier per column
- Total of 528 amplifiers but
  → CAMEX (mux 132 to 1) for easy I/F
  → Only 8 analog output nodes

27/06/2010
pnCCD: Testing at ESO funded by OPTICON FP6
→ Excellent QE, PSF, and low read noise

E:
→ Excellent QE into the “Red” → good for Natural Guide Star applications.
→ 450 µm thick silicon is able to collect the deep penetrating red photons.

SF:
→ Measured < 0.45 pixel over 400-900nm (exceeds specs of < 0.8 pixel).
→ Pixels could be halved in size (51µm/2) and still meet the requirements.

RON:
→ < 2.5 e- rms at 950fps.
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ESO’s AO WFS Detector roadmap

Past Successes

Detectors in production

Future Challenges

E-ELT (2018 →)

• Detectors required?
• Top Level Requirements
• Large Visible AO WFS Detector
AO Detector needs for E-ELT

2.5 kHz ultra low-noise detector
✓ possibly reuse CCD220

Low Order AO
Shack Hartmann Quad -Cell

Pyramid
Other WFS...
TipTilt Sensors
Guiding

Existing visible high performance detector (e.g. CCD220)

IR WFS
IR TipTilt sensors

Extreme AO

NGS - Natural Guide Star
NGS Ground Layer AO
NGS Single Conjugate AO

LGS - Laser Guide Star
LGS Multi-Conjugate AO
Laser Tomography AO
LGS Ground Layer AO

Large Visible AO WFS Detector

See talk Gert Finger Wed11:20am session – 7742-57
“Development of high-speed, low-noise NIR HgCdTe avalanche photodiode arrays for adaptive optics and interferometry”
Large Visible AO WFS Detector needed to sample the Laser spot elongation.

- AO systems operate at ~1 kHz frame rate
- Bright "guide stars" are required
- Only 1% of the sky is accessible with natural guide stars
- Sodium layer at 80-90 km altitude can be stimulated to produce artificial guide stars anywhere on the sky
- Pulsed laser can be used to range gate to limit laser spot elongation
Large Visible AO WFS Detector

Top Level Requirements
(developed from very detailed simulations)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array Format</td>
<td>1680x1680 pixels</td>
<td>Up to 84 x 84 sub-apert. each 20x20 pixels to sample the spot elongation</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>20-28 µm</td>
<td>Large</td>
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<tr>
<td>Wavelength</td>
<td>460-950nm (NGS) 589nm (LGS)</td>
<td></td>
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<tr>
<td>Frame Rate</td>
<td>100 to 700 fps</td>
<td>Fast, low latency</td>
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<tr>
<td>RON</td>
<td>&lt; 3 e- rms</td>
<td>Low noise</td>
</tr>
<tr>
<td>QE</td>
<td>&gt; 80 %</td>
<td>High</td>
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<tr>
<td>Dark Current</td>
<td>&lt; 0.5 e-/s/pixel</td>
<td>Low</td>
</tr>
<tr>
<td>Storage Capacity</td>
<td>&lt; 4000e-/pixel</td>
<td>Expect few photons</td>
</tr>
<tr>
<td>Cosmetics</td>
<td>&lt; 0.1% bad pixels</td>
<td>Good; very few bad sub-apertures</td>
</tr>
</tbody>
</table>

Ease of use/compact size:
→ low pin count; goal < 200 pins
→ integral Peltier – detector power dissipation < 5W
→ integrated read-out electronics - industry std digital I/F preferred
## Large Visible AO WFS Detector Development Plan

(Multi-phase, progressive risk reduction, development)

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<tbody>
<tr>
<td><strong>Several Design Studies</strong></td>
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<td>→ Investigated many different technologies</td>
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<td>→ Most promising - CMOS Imager, APD array and orthogonal EMCCD</td>
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<tr>
<td><strong>Several Technology Demonstrators</strong></td>
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<tr>
<td>→ All CMOS Imagers - judged most likely to succeed</td>
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<tr>
<td>→ Searched for most suitable pixel and test various video processing/ADC concepts</td>
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<tr>
<td>→ Results of &lt; 3e- RON at required speed have validated the CMOS approach</td>
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<td>→ Further optimization until mid 2011</td>
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<tr>
<td>→ CMOS Scaled Down Demonstrator</td>
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<tr>
<td>→ Retire architectural risks by fab. ~ 1/4 imager</td>
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<tr>
<td>→ Usable for first light E-ELT AO systems</td>
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</tbody>
</table>
With recent improvements CMOS now rival CCDs

1. **Pinned Photo Diode** → low dark current (10 pA/cm²)
   → 0.5 e-/pix/frame with modest cooling (-10 DegC)

2. **High conversion gains** (200 µV/e-) → low RON of < 2e-
   - by reducing sense node capacitance < 0.8 fF

3. **Buried channel MOSFETs** → reduces/eliminates RTS signal noise

4. **Backside Illumination** → high QE

5. Build from **thicker high resistivity** silicon and ‘**substrate biasing**’
   → low crosstalk and good red response

**PLUS the long offered advantages of**

1. **Fast frame rates** → highly parallel readout: ultimate of amplifier per pixel.

2. **Low power** → µA instead of mA (CCD) transistor bias currents.

3. **Monolithic integration** of support circuitry; biases, sequencer, clocks, ADCs…
   → Offers a simple, easy-to-use digital interface.
Conceptual Block Diagram of Full Size Device

**Highly integrated**
- All analog processing on-chip:
  - correlated double sampling (CDS),
  - programmable gain,
  - bandwidth noise reduction,
  - ADCs
- Many rows processed in parallel to slow the read out per pixel and beat down the noise.
  - trade study shows 20-40 to be an optimum number
- Fast digital serial interface to outside world
  - power consumption calculated to be similar to high speed drivers to transport the analog signal off chip
  - better guarantee of achieving and maintaining low noise performance

**Natural Guide Star Detector (NGSD)**
- scaled down demonstrator
- ~ ¼ of full size → no stitching
Conclusion

- **Current detector developments at ESO are on track to meet current instrument needs.**
  - Measured results show that the CCD220 successfully exceeds the requirements.
  - Production of CCD220s at e2v is almost complete with staggered deliveries till end of year.
  - Development of the ESO WFS camera is very advanced with delivery of first prototype planned mid year, and
  - 18 camera systems will be built and delivered to VLT SPHERE and AOF in 2011 and 2012.

- **Preparation work for the next challenge, the E-ELT, is well under way.**
  - Multi-phase, progressive risk reduction development plan should guarantee that devices are available on-time that meet specifications.
  - Recent improvements make backside illuminated CMOS imagers attractive as wavefront sensors.
  - Measured results from Technology Demonstrators have clearly validated the CMOS imager approach.
THANK YOU
Add more outputs

Achieves lower read noise at fast frame rates by reading through multiple outputs.

### Table: Read noise of output amplifier

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Device</th>
<th>Pixel size</th>
<th>Format (pixels)</th>
<th>Frame Rate</th>
<th>Outputs</th>
<th>RON (rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E2v</td>
<td>CCD50</td>
<td>24μm</td>
<td>128x128</td>
<td>1000 fps</td>
<td>16</td>
<td>5e-</td>
</tr>
<tr>
<td></td>
<td>CCD39</td>
<td>24μm</td>
<td>80x80</td>
<td>1000 fps</td>
<td>4</td>
<td>10e-</td>
</tr>
<tr>
<td>MIT/LL</td>
<td>CCID-26/64</td>
<td>21μm</td>
<td>64x64</td>
<td>600 fps</td>
<td>4</td>
<td>6-7e-</td>
</tr>
<tr>
<td></td>
<td>CCID-26/12</td>
<td>21μm</td>
<td>128x128</td>
<td>1000 fps</td>
<td>16</td>
<td>5e-</td>
</tr>
</tbody>
</table>
Customize the architecture

Achieves lower read noise by minimizing the number of pixels read out by custom designing the architecture to the application.

**Polar Co-ordinate CCD** - talk about later

- 8x10 subapertures,
- RON < 1.2e- at 4 kfps and QE > 80%,
- Successfully used in upgrade to FlyEyes at CFHT.

See poster Kevin Ho, “Flyeyes: Upgrade of CFHT’s AO System Using an MIT-LL CCID 35 Sensor”

Sub-aperture design

Array design
Mark Downing, Johann Kolb, Dietrich Baade, Olaf Iwert, Norbert Hubin, Javier Reyes.
European Southern Observatory ESO (http://www.eso.org)

Philippe Feautrier, Eric Stadler, David Mouillet.
Domaine Universitaire LOAG (http://www-laog.obs.ujf-grenoble.fr/JRA2)

Jean-Luc GACH, Philippe Balard, Christian Guillaume, Olivier Boissin.
Laboratoire d'Astrophysique de Marseille LAM (http://www.lam.oamp.fr)