WFS Detector requirements/strategies for the E-ELT
### WFS types

#### High-Order NGS WFS

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Resolution 1</th>
<th>Resolution 2</th>
<th>Frame Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARMONI</td>
<td>1 / 150x150 px</td>
<td>500Hz</td>
<td></td>
</tr>
<tr>
<td>MICADO</td>
<td>1 / 150x150 px</td>
<td>500 Hz</td>
<td></td>
</tr>
<tr>
<td>METIS</td>
<td>1 / 450x450 px</td>
<td>500 Hz</td>
<td></td>
</tr>
<tr>
<td>Test Camera</td>
<td>1 / 740x740 px</td>
<td>500 Hz</td>
<td></td>
</tr>
<tr>
<td>[EPICS]</td>
<td>4 / 240x240 px / 2.5 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[EAGLE]</td>
<td>6 / 120x120 px / 500 Hz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Low-Order NGS WFS

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Resolution 1</th>
<th>Resolution 2</th>
<th>Frame Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAORY</td>
<td>3 / 80x80 px</td>
<td>500 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 / 512x512 px</td>
<td>500 Hz</td>
<td></td>
</tr>
<tr>
<td>HARMONI-LTAO</td>
<td>1 / 80x80 px</td>
<td>500 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 / 512x512 px</td>
<td>500 Hz</td>
<td></td>
</tr>
<tr>
<td>METIS-LTAO</td>
<td>1 / 80x80 px</td>
<td>500 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 / 512x512 px</td>
<td>500 Hz</td>
<td></td>
</tr>
<tr>
<td>Tel. Guiding</td>
<td>3 / 200x200 px</td>
<td>500 Hz</td>
<td></td>
</tr>
</tbody>
</table>

#### High-Order LGS WFS

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Resolution 1</th>
<th>Resolution 2</th>
<th>Frame Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAORY</td>
<td>6 / 740x740 px</td>
<td>700 Hz</td>
<td></td>
</tr>
<tr>
<td>HARMONI-LTAO</td>
<td>6 / 740x740 px</td>
<td>700 Hz</td>
<td></td>
</tr>
<tr>
<td>METIS-LTAO</td>
<td>6 / 740x740 px</td>
<td>700 Hz</td>
<td></td>
</tr>
<tr>
<td>[EAGLE]</td>
<td>6 / 740x740 px / 700 Hz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $0.5 \mu m < \lambda < 1 \mu m$
- $1.3 \mu m < \lambda < 2.5 \mu m$
- $\lambda = 0.589 \mu m$
E-ELT Detector types

CCD220 10x [20x]

HARMONI-SCAO
MICADO-SCAO
Tel. Guiding

[EPIICS]

Test Camera SCAO

NGSD/LGSD 19x [25x]

MAORY
HARMONI-LTAO
METIS-LTAO

METIS-SCAO

SAPHIRA eAPD 8x
e2v L3Vision CCD220

Store slanted to allow room for multiple outputs.

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

Gain Registers

Store Area

Image Area

Image Area

Store Area

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

OP 1

OP 2

OP 3

OP 4

OP 5

OP 6

OP 7

OP 8

Gain Registers

e2v CCD220:

→ 240x240 24 µm pixels
→ Split frame transfer CCD
→ 8 L3Vision EMCCD outputs
→ < 0.1 e- RoN at > 2,000 fps
→ Integral Peltier for cooling to -50°C
→ Dark current < 0.05 e-/pix/frame at 100fps
→ Available in both std Si, and Deep Depletion Si for higher red response
Next Steps for controller development:

- Increase frame rate to 2,500 fps to extend use to E-ELT XAO (Extreme AO).
- Upgrade planned to solve any obsolescence problems and improve ease of manufacture.
**LGSD/NGSD: Large Visible AO WFS Detector**

- **LGSD:** Large format 1760x1680 of 24µm pix
- **Up to 700fps**
- **< 3e read out noise**
- **Highly integrated**
  - Massive parallelism - 20 rows of pixels top/bottom
  - (40 in total) read out in parallel
- **Unlikely to be ready for first light instruments**
- **Still open question whether such a large format detector (20x20pixel per subaperture) is really needed**

---

**Natural/Laser Guide Star Detector (NGSD)**

- at advanced stage of development
- ~ ¼ of full size → non-stitched
- 880x840 of 24µm pixels – 10x10pixels per subaperture for LGS/NGS AO
- plan to use for first light instruments

---

<table>
<thead>
<tr>
<th>Control Logic</th>
<th>Multiplexer/serializer</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 x1760 single slope ADCs</td>
<td>Pre-amp &amp; Gain of x1/2/4/8</td>
</tr>
<tr>
<td>84x84 Sub-apertures, each 20x20 pixels</td>
<td>1760x1680 pixels</td>
</tr>
<tr>
<td>Pre-Amp &amp; Gain</td>
<td>44 LVDS Serial Links</td>
</tr>
<tr>
<td>Multiplexer</td>
<td>44 LVDS Serial Links</td>
</tr>
</tbody>
</table>

---

22nd Oct 2015

E-ELT WFS Detectors
## Specifications of the NGSD (LGSD)

### Physical characteristics

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pixel array</strong></td>
<td>880x840 (1760x1680 pixels in LGSD)</td>
</tr>
<tr>
<td></td>
<td>- LGSD is 5x6cm and will require stitched design</td>
</tr>
<tr>
<td><strong>Pixel pitch</strong></td>
<td>24µm</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>Thinned backside illuminated CMOS 0.18µm</td>
</tr>
<tr>
<td></td>
<td>- TowerJazz; APD5; 6 metal layers; MIM capacitor</td>
</tr>
<tr>
<td><strong>Silicon</strong></td>
<td>High resistivity &gt;1000 ohm-cm → thinned to 12µm</td>
</tr>
</tbody>
</table>
**Specifications of the NGSD (LGSD) Read out**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rows read in parallel</td>
<td>20 (40 in LGSD) rows in parallel</td>
</tr>
<tr>
<td>Number of ADC’s</td>
<td>20x880 (40x1760 in LGSD) at 9/10 bits</td>
</tr>
<tr>
<td>Effective Bits of resolution</td>
<td>12/13 bits - 9/10 bits ADC plus 2 bits of programmable gain</td>
</tr>
<tr>
<td>Number of parallel LVDS channels</td>
<td>22 (88 in LGSD) at 210 Mb/s baseline, up to 420 Mb/s (desired)</td>
</tr>
<tr>
<td>Frame rate</td>
<td>700 fps up to 1000 fps with degraded performance</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>&lt; 0.5W (LGSD 2W)</td>
</tr>
</tbody>
</table>
NGSD Rev B Currently Under Test
- results very promising but some issues still to solve

**e2v Test Headboard/Controller**

**ESO adaption of the e2v Headboard interfaced to NGC**

Custom 63 mm square Aluminum Nitride 370pin PGA Package
### Specifications of the LGSD/NGSD Performance Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel full well $Q_{FW}$</td>
<td>$&gt; 4000 \text{ e}^-$</td>
</tr>
<tr>
<td>Linearity to full well</td>
<td>$&lt; 5%$</td>
</tr>
<tr>
<td>Pixel Read noise</td>
<td>$&lt; 3.0 \text{ e}^{-}_{\text{RMS}}$</td>
</tr>
<tr>
<td>Image lag</td>
<td>$&lt; 2 %$</td>
</tr>
<tr>
<td>Dark Current</td>
<td>$&lt; 0.5 \text{ e}^-/\text{pixel/frame}$</td>
</tr>
<tr>
<td>QE</td>
<td>$&gt; 90%$ at 589nm (BSI)</td>
</tr>
<tr>
<td>Point Spread Function</td>
<td>$&lt; 0.8 \text{ pixel FWHM}$</td>
</tr>
<tr>
<td>Read Noise at full speed</td>
<td>$&lt; 3.0 \text{ e}^{-}_{\text{RMS}}$</td>
</tr>
<tr>
<td>Cosmetics</td>
<td>$&lt; 0.1%$ bad pixels</td>
</tr>
<tr>
<td>Electrical Cross-talk</td>
<td>$&lt; 2%$</td>
</tr>
</tbody>
</table>

- **Already verified in BSI NGSD Rev B**
- **Yet to be measured but compliance expected**
- **Issues to be solved in Rev C**
Next Steps

- **Rev B** was a simple metal fix thus limited to what could be done, however, very successful in demonstrating that most requirements can be met.

- **Rev C** will fix hot pixels, reduce ron and cross-talk; solutions already identified
  - add Gettering layer to the process:
  - use ultra low threshold transistors in the pixel to further reduce ron:
  - modify design of circuit and layout to reduce ron and cross-talk:
Next Steps

• E2v and Caeleste are fully committed to make Rev C the final one.
• Redesign and simulations to be done after contract negotiations; need for further funding is most likely even though the contract is fixed price/spec.
• Rev C devices will be available towards the end of 2016.
• Development (and Funding) of design of Integral Peltier Package:
  – Current package is cheap generic, off the shelf, ceramic PGA with point to point tracking used to prove the technology;
  – Production package is a dedicated Integral Peltier Package for cooling to < -10°C with optimized tracking/ground planes.
NGSD Camera Prototype

- Expected housing dimensions ~ 128 x 143 x 155 (W x H x D).
- NGSD Camera will be mounted off its front face and have alignment pins for LRU.
- Prototypes of the electronic boards are in design/layout and will be used to readout the Rev B BSI device by 2Q 2016.
SAPHIRA (eAPD) – NIR AO WFS Detector

- High read noise at high speeds has in the past been an issue using scientific IR sensors (HxRG)
  → custom development required
- eAPDs made in HgCdTe material puts gain in the photodiode to amplify the signal before detection without a substantial increase in excess noise.
- Saphira key features:
  - Format: 320x256 array of 24µm NIR HgCdTe diodes.
  - Low noise Source Follower in the pixel.
  - 32 outputs at 5MHpixel/s to enable 2kfps readout; single sample
  - Non-Destructive Readout possible to beat down the noise by multiple sampling.
  - Designed with efficient sub-windowing read out in mind
- Very good working relationship forged with Selex
SAPHIRA Test Results

- Low noise validated at 1kfps:
  - Full frame (DCS): 0.8 e- rms
  - Window 96x72 pixels (16 Fowler pairs): 0.4 e- rms
Readout noise versus number of Fowler pairs

- Window 96x72 pixels
- APD gain 39 and 76
- Integration time 1 ms
- Preprocessing of Fowler sampling and subpixel sampling in FPGA of 32-channel ADC board
GravItY PAE: fringe tracker

- APD gain 1
- bias voltage 620 mV
- 48 spectra read at 1 KHz
- 3 rows per spectrum
- 72x32 pixel
- double correlated
- 4 subpixel samples
- DIT=850 µs
- frame time 145 µs (18.1 µs possible with setup)
- increase bias voltage to increase APD gain
GRAVITY PAE: fringe tracker

- APD gain 1.82
- bias voltage 2.61 V
GRAVITY PAE: fringe tracker

- APD gain 4.47
- bias voltage 5.59 V
GRAVITY PAE: fringe tracker

- APD gain 16.16
- bias voltage 8.58 V
• APD gain 75.96
• bias voltage 12.20 V
• 48 spectra read at 1 KHz
SAPHIRA MOVPE

- LPE has high QE in K-band of 82% at T = 45 K
- MOVPE (Metalorganic vapour phase epitaxy)/mesa now established and deployed in GRAVITY instrument. Achieves high gain and few defects at 100K with 1000 frames per second and <10 electron/sec/pix dark current

solid state engineering
next step: 512x512 or 1kx1k SAPHIRA eAPD ROIC

Multiplex advantage for windows:
64 parallel video channels also for windows

Logic circuitry
• Multiple redundancy
• Triple majority voting on registers
• Low VDD and masking for glow suppression
• Multiple independently re-settable windows
• Read-Reset-Read per row scanning option
• Multiple non-destructive readout

Diagnostic and repair register
• Logic fault sensing and reporting
• Redundant logic block replacement
• Global reset and auto set-up

Multiplexer analog circuitry
• Internal blanking to eliminate crosstalk
• Variable skew rate on nodes for bandwidth control

Pixel block
• 15 µm pixels
• Input for P-on-N eAPDs or conventional photodiodes
• High voltage tolerance for APD diodes
• Current limited pixels to protect power consumption from short circuits
• Voltage clamp to avoid influence from nearby brightly illuminated pixels
• Variable gain
• X-Y addressed reset to allow independently resettable windows
• Protection from silicon glow sources
• Switchable reference pixels for first 128 columns
• Switchable reference mode for each row readout

Output buffers
• 32 or 64 parallel outputs
• Class AB
• 20 MHz capable
• Separate power line for low glow
• Reference output for EMC cancellation

CMOS technology
• XFab (fabrication in Germany)
• 0.18 µm, 3V3 process
• 5 levels of metal
• 5V module
• Radiation hardened design
• Very low power

SPI interface register
• Serial ROIC control
• Triple majority voting
• Auto default mode
• Register read-back option

1024 x 1024 pixels
128 columns reference pixels
21.3 mm
19.3 mm

Logic circuitry
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• 20 MHz capable
• Separate power line for low glow
• Reference output for EMC cancellation

CMOS technology
• XFab (fabrication in Germany)
• 0.18 µm, 3V3 process
• 5 levels of metal
• 5V module
• Radiation hardened design
• Very low power

SPI interface register
• Serial ROIC control
• Triple majority voting
• Auto default mode
• Register read-back option

1024 x 1024 pixels
128 columns reference pixels
21.3 mm
19.3 mm
Large format SAPHIRA eAPD

- Cost of development of large format SAPHIRA (ROIC and first samples) - $1.3 million
- Size of array to be determined in range up to 1k x 1k
- Pixel size to be defined. Small pixel size (<15 um) may require different ROIC silicon process and some more APD development.
- Some development money in ESO budget for 2016 but full funding will require (equal?) cost sharing with others; e.g. TMT and GMT.
- Schedule: first prototype samples in 10-12 months starting early 2016.

- Current development ongoing to get panchromatic response to use same noiseless sensor for optical and infrared.
Controller for large format SAPHIRA: NGC

512x512 pixels
- frame rate with 64 10MHz outputs: 2441 single sample (1220 CDS) frames/s.
- NGC system already exists

1Kx1K pixels
- 64 20MHz outputs → frame rate of 1220 single sample (610 CDS) frames/s
- readout noise < 1 electron rms.
- 32-channel 20MHz ADC board for NGC still has to be developed.
Possible integrated package with cold filter

- CCC for array with 384 x 288 pixels Pixel Pitch 20µm
- Array Operating Temperature 90 to 120K
- Window Material Germanium
- Cold Filter Material Silicon
- Cold Filter Thickness 0.4mm
- Weight 350g
- Power Consumption 6W steady state
- Cooling Engine Rotary Stirling engine