High QE, Thinned Backside-Illuminated, 3e- RoN, Fast 700fps, 1760x1760 Pixels Wave-Front Sensor Imager with Highly Parallel Readout

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Outline

- ESO and European Extremely Large Telescope E-ELT
- Wavefront Sensing and Adaptive Optics
- Specifications of the E-ELT WFS
- Results of the Technology Demonstrator, the TVP
- WFS Architecture and Design
- The massive parallel data problem
  - Solution - balanced clock tree of 88 LVDS channels
Who is ESO?

- European Organization
  - 15 member states: Germany, France, Italy, Switzerland, Netherlands, Belgium, Portugal, Denmark, Sweden, UK, Finland, Spain, and Czech Republic, Austria, Brazil

- **Goal** – to provide astronomers with state-of-the-art observational facilities

Operates 3 sites in Chile
- Two optical observatories
  - Paranal (2600m)
  - La Silla (2400m)
- One submillimeter
  - Chajnantor (5000m)
Paranal
→ Very Large Telescope

- VLT consists of four 8.2 m Telescopes
- Flagship facility of European ground-based astronomy.
- Most productive individual ground-based astronomical facility.
Our Next Challenge → European Extremely Large Telescope (E-ELT)

- E-ELT - a 39.5 m diameter, fully Adaptive Optics telescope.
- The E-ELT will be the largest optical/near-infrared telescope in the world (its mirror diameter will be almost half the length of a football field).
- Construction planned to begin next year; design complete and accepted
Wavefront sensors

Some instruments also contain WFS detectors

WFS adaptor

WFS arms (contain 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.

Deformable mirror compensates the distorted wavefront, achieving diffraction-limited resolution.

Control System computes commands for the deformable mirror(s).

Wavefront Sensor measures deviation of wavefront from a flat (undistorted) wave.

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Large Visible AO WFS Detector needed to sample the spot elongation

**Sodium Laser Guide Stars**
- Frame rate ~1 kframe/sec → require bright “guide stars”
- With natural guide stars only 1% of the sky is accessible
- Sodium layer at 80-90 km altitude can be stimulated by Laser to produce artificial guide stars anywhere on the sky

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1/4 WFS image

- Natural Guide Star: **84x84** sub-apertures of **8x8** pixels $\rightarrow$ NGSD
- Laser Guide Star: **84x84** sub-apertures of **20x20** pixels $\rightarrow$ LGSD
ELT WFS DETECTOR
Multi-phase plan to progressively retire risk risks

<table>
<thead>
<tr>
<th>Design Study</th>
<th>Technology Validation</th>
<th>Development</th>
<th>Testing/Acceptance</th>
<th>Production Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Design Study</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2008</td>
<td>2009</td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
</tr>
<tr>
<td>Retire Pixel Risks</td>
<td>Technology Demonstrators</td>
<td>Natural Guide Star Detector NGSD</td>
<td>Retire Architecture/ Process Risks</td>
<td>LGSD Production</td>
</tr>
<tr>
<td>2013</td>
<td>2014</td>
<td>2015</td>
<td>2016</td>
<td>2017</td>
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<tr>
<td>2018</td>
<td></td>
<td>2015</td>
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</tr>
<tr>
<td>30 LGSD Science Devices</td>
<td>Authorize Production</td>
<td>Testing</td>
<td>Engineering exercise</td>
<td>NGSD Production</td>
</tr>
<tr>
<td>30 NGSD Science Devices</td>
<td>Authorize Production</td>
<td>Testing</td>
<td></td>
<td>LGSD Production</td>
</tr>
</tbody>
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## Specifications of the ELT WFS

### Physical characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pixel array</strong></td>
<td>Stitched design for two versions: “Natural Guide Star Detector” NGSD - 880x840 pixels then “Laser Guide Star Detector” LGSD - 1760x1760 pixels</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>Thinned backside illuminated CMOS 0.18µm</td>
</tr>
<tr>
<td><strong>Pixel pitch</strong></td>
<td>24µm</td>
</tr>
<tr>
<td><strong>Pixel topology</strong></td>
<td>4T pinned photodiode pixel</td>
</tr>
<tr>
<td><strong>Array architecture</strong></td>
<td>84x84 time coherent “sub arrays” of 20x20 pixels - LGSD image area size of 4x4cm</td>
</tr>
<tr>
<td><strong>Shutter</strong></td>
<td>Rolling shutter in chunks of 20 rows → synchronous detection within a sub-array.</td>
</tr>
</tbody>
</table>
## Specifications of the ELT WFS

### Performance

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsivity</td>
<td>100 to 160 $\mu$V/electron</td>
</tr>
<tr>
<td>Pixel full well $Q_{FW}$</td>
<td>4000 e$^-$</td>
</tr>
<tr>
<td>Read noise including ADC</td>
<td>$&lt; 3.0$ e$^{-}_{\text{RMS}}$</td>
</tr>
<tr>
<td>QE</td>
<td>QE above 90% over the visible range → BackSide Illumination (BSI)</td>
</tr>
<tr>
<td>Image lag</td>
<td>$&lt; 0.1$ %</td>
</tr>
<tr>
<td>MTF</td>
<td>ideal and symmetric in X and Y by design</td>
</tr>
</tbody>
</table>
Highly integrated

- All analog processing on-chip:
  - correlated double sampling (CDS),
  - programmable gain,
  - ADCs
- Many rows processed in parallel to slow the read out per pixel and beat down the noise.
  - trade study showed 20-40 to be the optimum number
- Fast digital serial interface to outside world
  - power consumption 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
<table>
<thead>
<tr>
<th>Specifications of the ELT WFS Read out</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of rows read in parallel</strong></td>
</tr>
<tr>
<td>40 (LGSD) or 20 (NGSD) rows in parallel</td>
</tr>
<tr>
<td><strong>Number of ADC’s</strong></td>
</tr>
<tr>
<td>40x1760 (LGSD) or 20x880 (NGSD)</td>
</tr>
<tr>
<td><strong>Number of parallel LVDS channels</strong></td>
</tr>
<tr>
<td>22 (NGSD) or 88 (LGSD)</td>
</tr>
<tr>
<td><strong>Serial LVDS channel bit rate</strong></td>
</tr>
<tr>
<td>210 Mb/s baseline, up to 420 Mb/s (desired)</td>
</tr>
<tr>
<td><strong>Frame rate</strong></td>
</tr>
<tr>
<td>700 fps up to 1000 fps with degraded performance</td>
</tr>
<tr>
<td>2 to 3 Gpixel/s = 20 to 30 Gb/s over 88 parallel LVDS channels</td>
</tr>
<tr>
<td><strong>Power dissipation (spec)</strong></td>
</tr>
<tr>
<td>Maximum 5W , including the 88 LVDS drivers</td>
</tr>
<tr>
<td><strong>Actual LVDS driver dissipation per channel</strong></td>
</tr>
<tr>
<td>6.0 mW @ at maximum data rate. 4.5 mW in sub-LVDS</td>
</tr>
</tbody>
</table>
Demonstrated performance on Technology Validator - TVP

- In a nutshell
  - All features of NGSD/LGSD
  - 60x60 pixels,
  - Same pixel and ADC driving
  - 1200 (60x20) column ramp ADCs
  - > 700 frames/sec

- To optimize the pixel:
  - transfer gate and transistor geometries were varied in 12 pixel variants
  - threshold voltage of nmos transistors was varied
  - Implants to improve image lag were varied
Demonstrated performance on Technology Validator - TVP

• Key performances have been validated
  – \(< 3.0e^{-}\text{RMS}\)
  – Full well 4000...8000 e-
  – Conversion gains 100...160 \(\mu\text{V/e-}\)
  – Image Lag \(< 0.1\ %\)
  – Best pixel and implants found to go forward to next phase, NGSD

• Not tested in TVP:
  – Massive parallelism
  – Array of LVDS IO
  – Back Side Thinning & Back Side Illumination
Pixel designed for best centroiding performances, TCAD simulations

Y / center

X

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LGSD/NGSD Stitching Plan

1 of 88 readout channel
One readout channel (of 88)

40 Columns of ADCs = 2 sub-arrays

20 rows of ADCs

110MHz Double Data Rate

clock

sync

parallel to serial

LVDS output

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How to drive 210 MHz over 4cm?

Reference case for speed and skew

Skew>2ns

R/2 \Rightarrow \text{Speed} \sim *4

C/2 \Rightarrow \text{Skew} \sim /4

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Capacitive load

Fast clock

R/4
C/4(?) \Rightarrow \text{skew} \sim 1/16

Fast clock

R/8(?) \Rightarrow \text{skew} \sim 1/64
C/8(?)

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Fast clock

1/4

Capacitive load

Capacitive load

Capacitive load

Capacitive load

3/4

Fast clock

R/4

C/4

[skew ~ 1/16]

R/8(?)

C/8(?)

[skew ~ 1/64]
How to implement this when stitching?
Summary

- Preparation work for our next challenge, the E-ELT, is well under way.
- ESO has formed a good partnership with e2v and Caeleste.
- Multi-phase, progressive risk reduction development plan should guarantee that devices are available on-time that meet specifications.
- Measured results from the TVP have clearly validated the CMOS imager approach.
- The best pixel design that meets the requirements has been found to go forward to the next phase, the NGSD.
- The next phase, the NGSD, starts in January 2012.

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Thank You

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