AO Wavefront Sensing Detector Developments at ESO

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

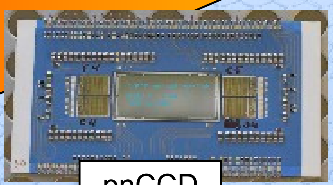
Mark Downing, Johann Kolb, Dietrich Baade, Olaf Iwert, Norbert Hubin, Javier Reyes, Philippe Feautrier, Jean-Luc Gach, Philippe Balard, Christian Guillaume, Eric Stadler, Yves Magnard, Olivier Boissin

ESO’s AO WFS Detector roadmap

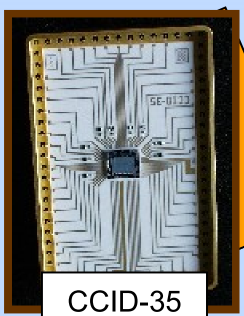
Future Challenges
E-ELT (2018 →)

Detectors in Production
(Today)


CCD220
e2v


pnCCD
PNSensor
MPI/HLL

Past Successes
(Late 1990s onwards)


CCID-35
MIT/LL


CCD50
e2v

LAOG
CNRS
Université de Provence

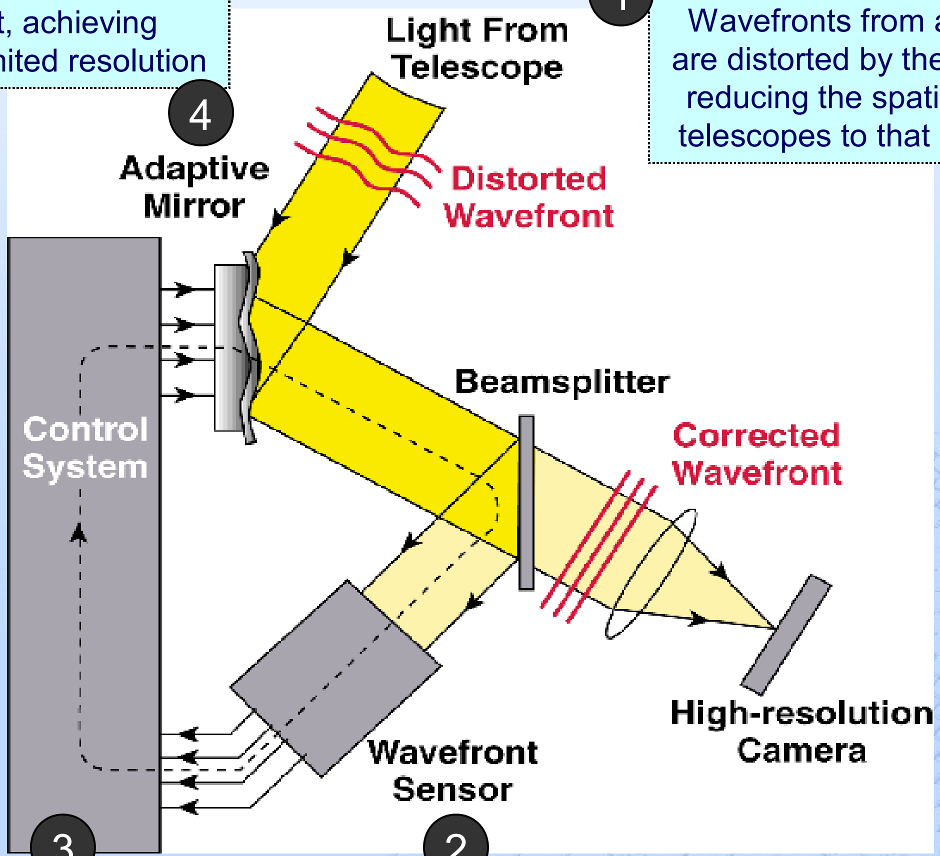
Adaptive Optics (AO)

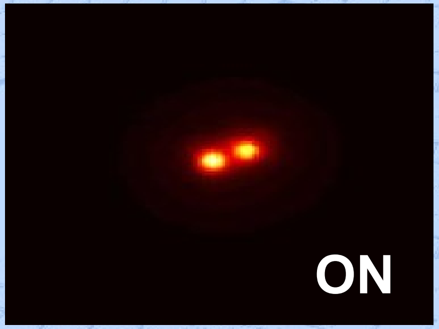
- removing the twinkle of the stars

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

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

1 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





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

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

AO Wavefront Sensing Detector Developments at ESO

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

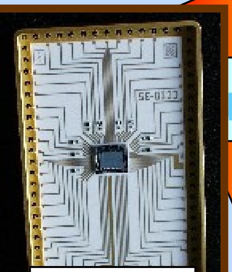
Mark Downing, Johann Kolb, Dietrich Baade, Olaf Iwert, Norbert Hubin, Javier Reyes, Philippe Feautrier, Jean-Luc Gach, Philippe Balard, Christian Guillaume, Eric Stadler, Yves Magnard , Olivier Boissin

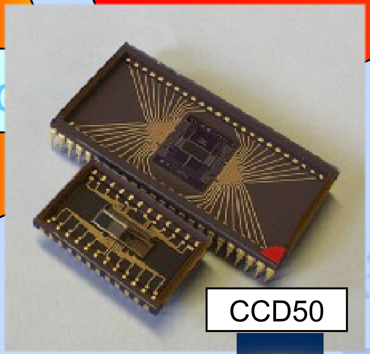
ESO's AO WFS Detector roadmap

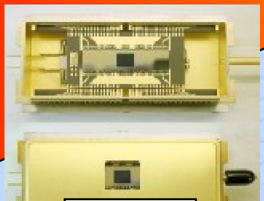
Future Challenges
E-ELT

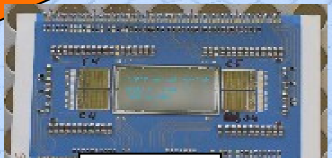
Detectors in Production
240x240 pixels
> 1200 fps
< 2e- RON

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


CCID-35
MIT/LL


CCD50
e2v

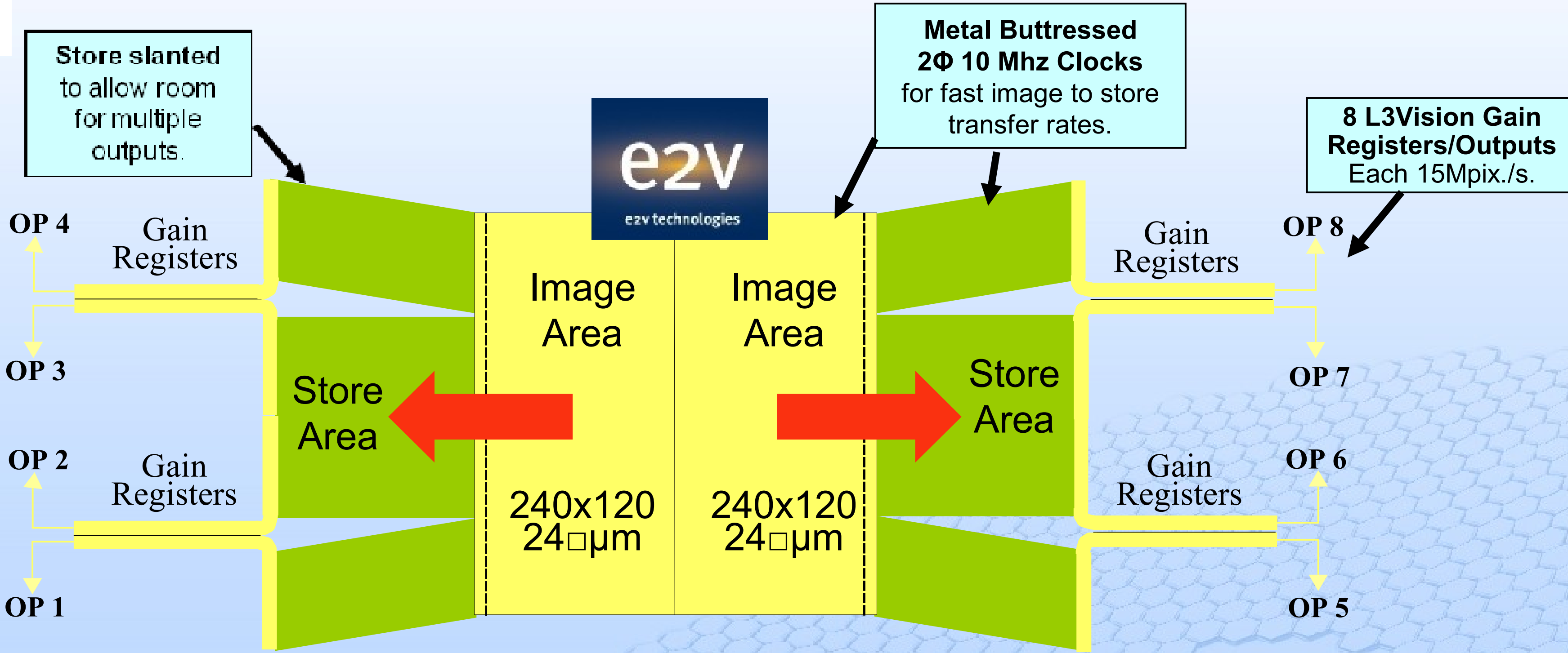

CCD220
e2v


pnCCD
PNSensor
MPI/HLL

FP6

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

e2v CCD220



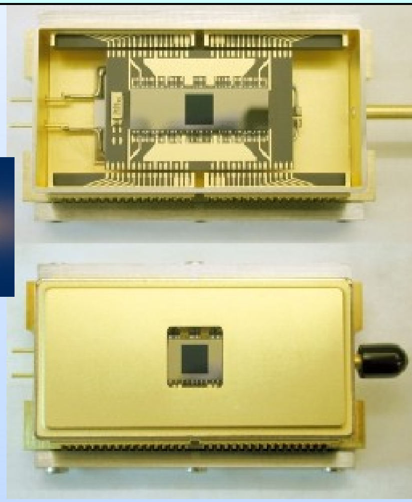
e2v CCD220:

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

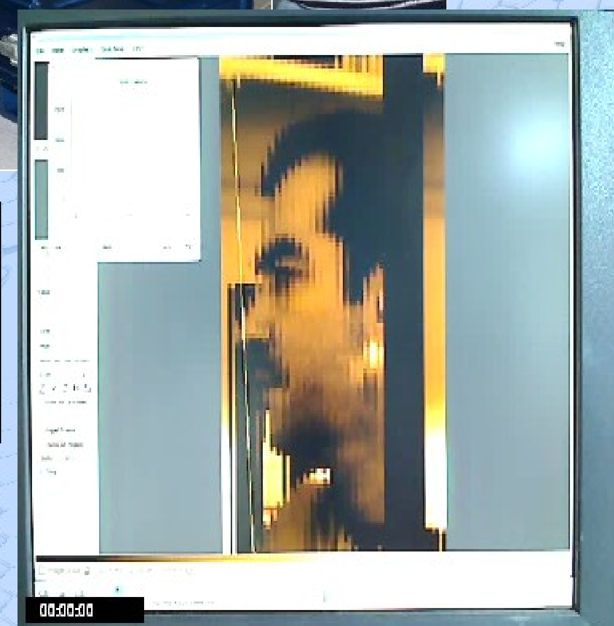
CCD220 Status

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

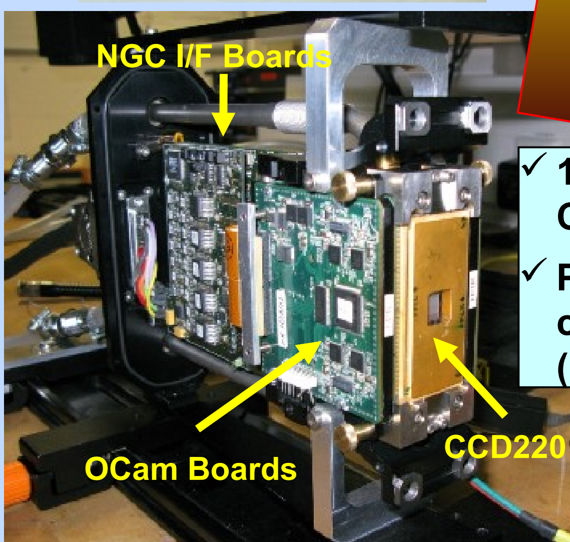
- ✓ **Four science devices in house**
- ✓ **Further 12 Std Si & 4 DD in production (Q4 2010).**



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



Technology transferred



- ✓ **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**

CCD220 Status

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

Technology transfer

- ✓ **Technology transfer to industry**
- ✓ **Go along to booth #306**

CCD220 Key Test Results
→ *devices meet specifications*

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

Requirement	Measured	Specification
Frame Rate:	> 1,300 fps	✓ >1,200 fps
Read noise: at gain of 1000 &1300fps	< 0.9 e-	✓ < 1.0 e-
Image Area Full Well:	> 200 ke-	✓ > 5,000 e-
Serial Charge Transfer Efficiency:	> 0.999999	✓ > 0.9998
Cosmeti[illegible] # of traps, bright/dark defects	[illegible]	[illegible]
Dark Current at 1200fps & -40ºC:	0.01 e-/pix/frame	✓ < 0.01 e-/pix/frame
Dark Current at 25fps & -40ºC:	0.04 e-/pix/frame	✓ < 0.04 e-/pix/frame

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

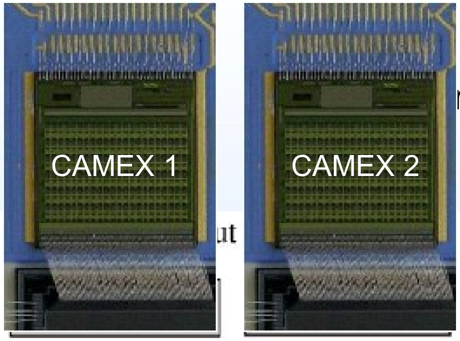
"OCam and CCD220 - World's Fastest and Most Sensitive Astronomical Camera"

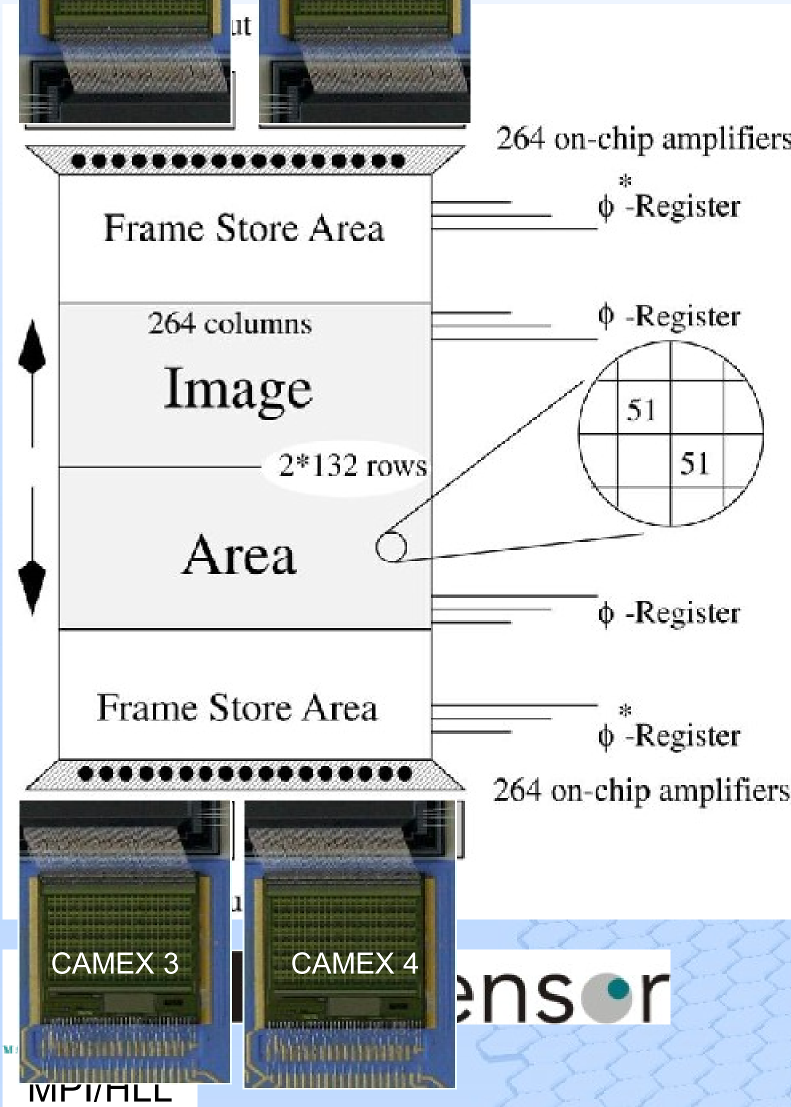
<u>Further optimization under way:</u>

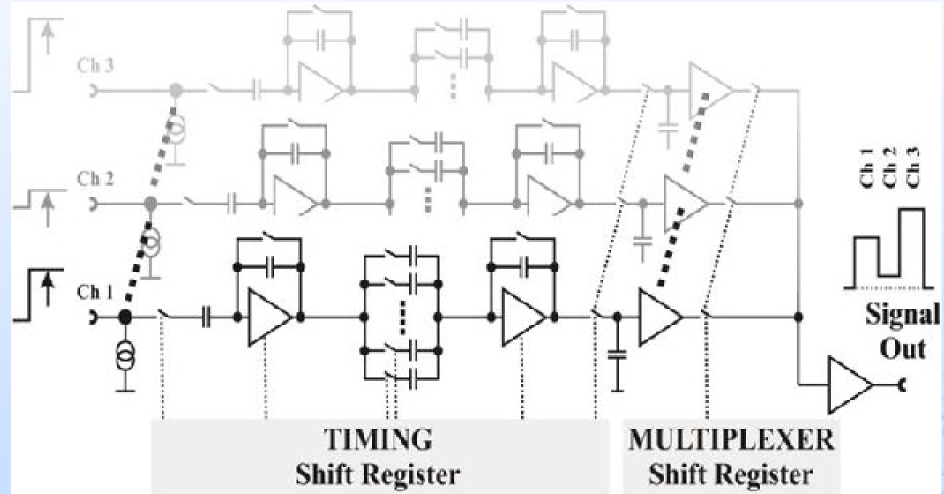
- Test Deep Depletion devices that offer much sought after higher red response.
- Reduce read noise closer to goal of 0.1 e-.
- Increase frame rate to 2,500 fps to extend use to E-ELT XAO (Extreme AO).

MPI/HLL pnCCD

rtmann, Sebastian Ihle, Heike Soltau, Lothar Strueder)





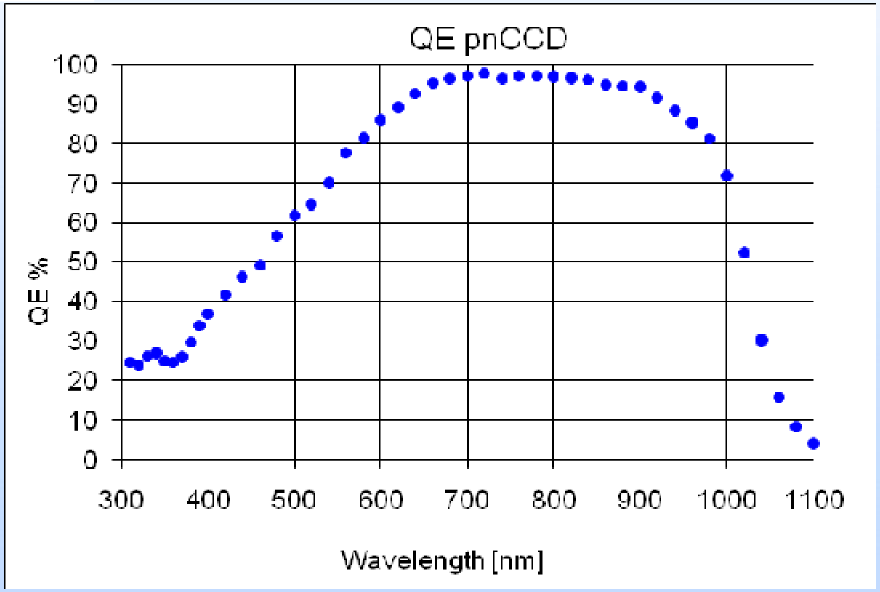


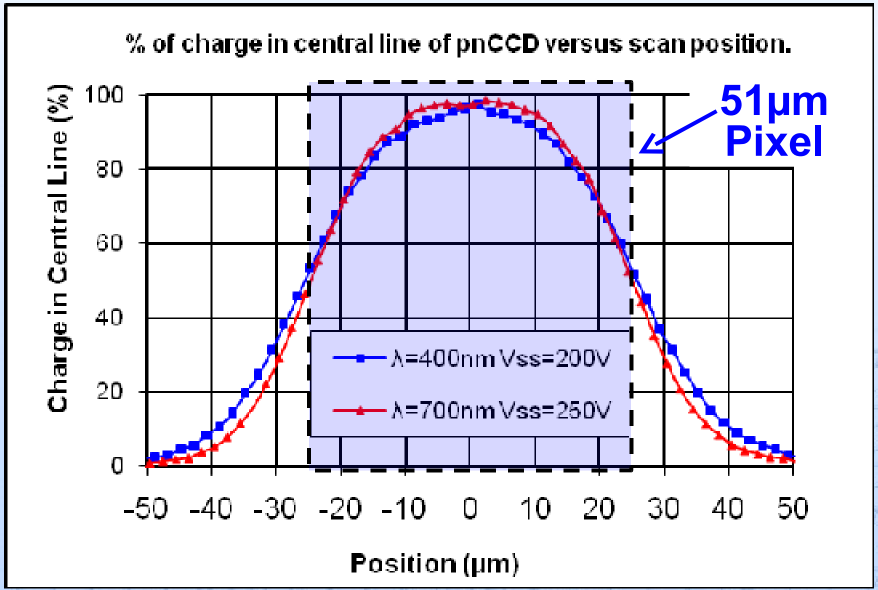
- Split frame transfer
- Fast readout → Column Parallel CCD
  - → one output amplifier per column
- Total of 528 amplifiers but
  - → CAMEX (mux 132 to 1) for easy I/F
  - → Only 8 analog output nodes

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

FP6

Spot scanning used to measure PSF





Q

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.

P

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.

AO Wavefront Sensing Detector Developments at ESO

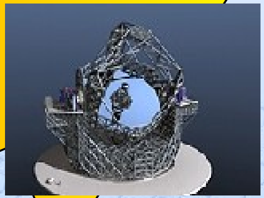
Mark Downing, Johann Kolb, Dietrich Baade, Olaf Iwert, Norbert Hubin, Javier Reyes, Philippe Feautrier, Jean-Luc Gach, Philippe Balard, Christian Guillaume, Eric Stadler, Yves Magnard , Olivier Boissin

ESO’s AO WFS Detector roadmap

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

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

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

2.5 kHz ultra low-noise detector
✓ possibly reuse CCD220

NGS - Natural Guide Star

NGS Ground LayerAO

NGS Single Conjugate AO

LGS - Laser Guide Star

LGS Multi-Conjugate AO

Multi-Object AO

Laser Tomography AO

LGS Ground Layer AO

Large Visible AO WFS Detector

See talk Gert Finger Wed11:20am session – 7742-57

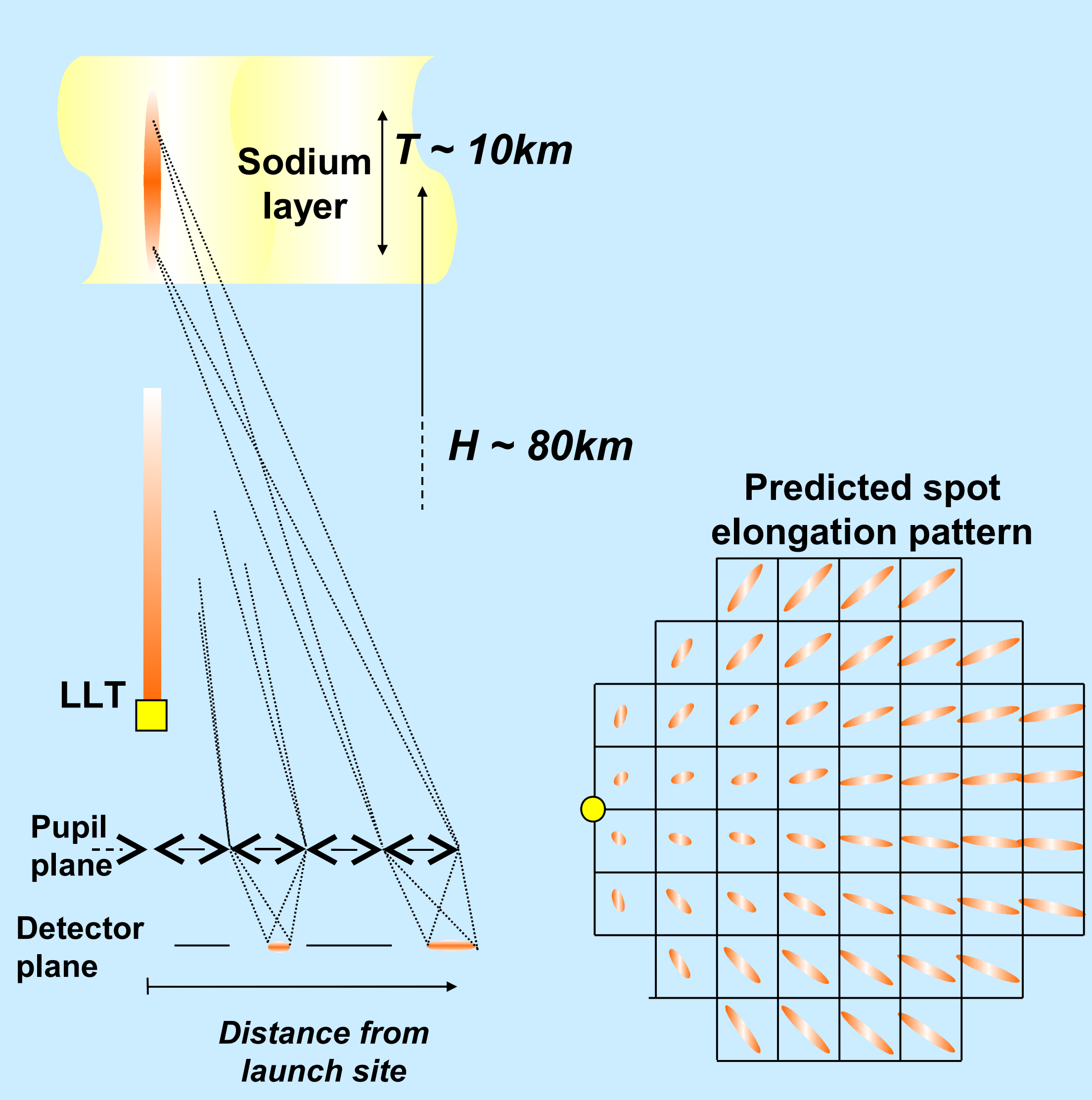
"Development of high-speed, low-noise NIR HgCdTe avalanche photodiode arrays for adaptive optics and interferometry"

Large Visible AO WFS Detector needed to sample the Laser spot elongation

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

Sodium Laser Guide Stars (589 nm)

- 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)

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

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

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

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

(Multi-phase, progressive risk reduction, development)

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Design Study	Design Study										
Technology Validation											

Several Design Studies

→ Investigated many different technologies

→ Most promising – CMOS Imager, APD array and orthogonal EMCCD

Several Technology Demonstrators

→ All CMOS Imagers - judged most likely to succeed

→ Searched for most suitable pixel and test various video processing/ADC concepts

→ Results of < 3e- RON at required speed have validated the CMOS approach

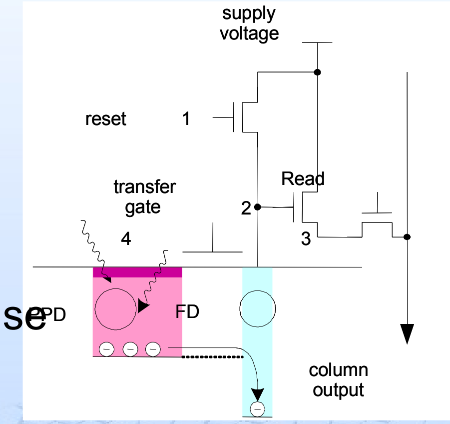
→Further optimization until mid 2011

→ Retire architectural risks by fab. ~ ¼ imager

→ Usable for first light E-ELT AO systems

With recent improvements CMOS now rival CCDs

ESO European Organisation for Astronomical Research in the Southern Hemisphere



1. **Pinned Photo Diode** → low dark current (10 pA/cm^2)
   → 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

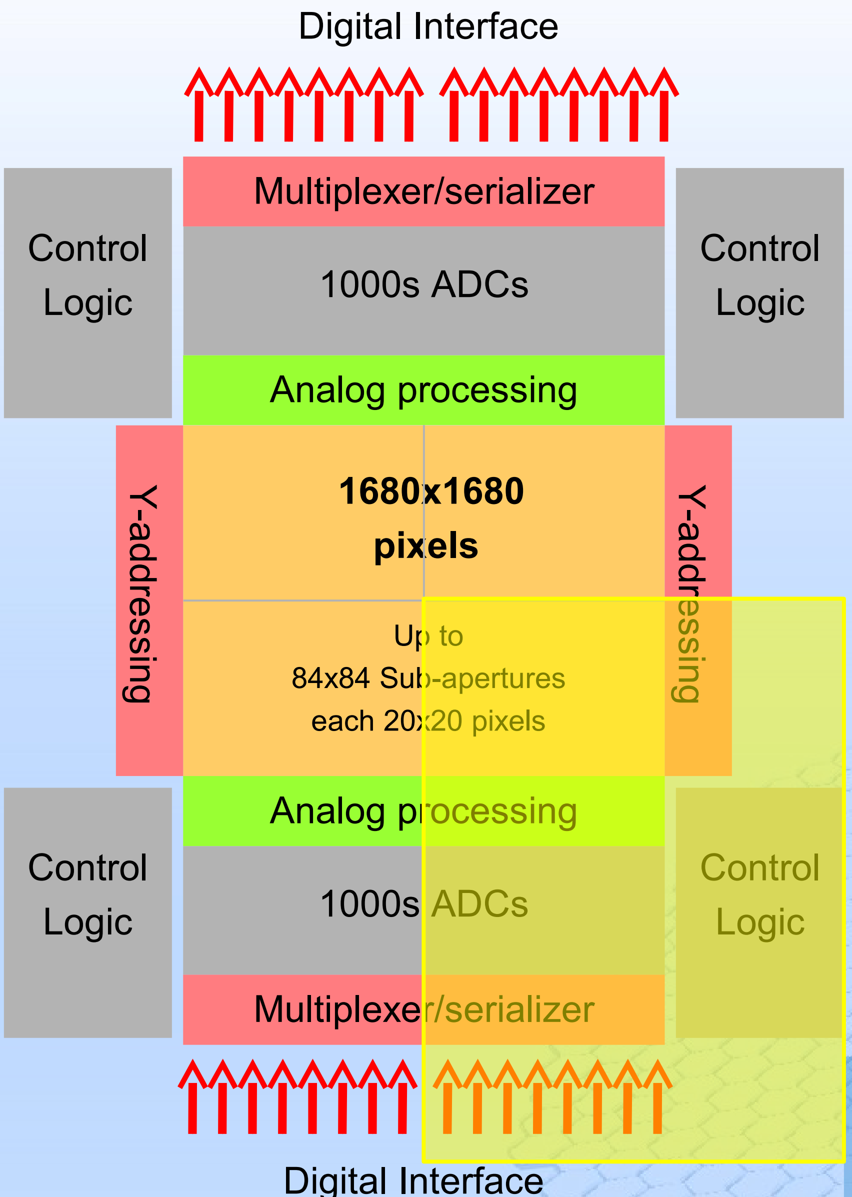
PLUS the long offered advantages of

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

ESO
European Organisation for Astronomical Research in the Southern Hemisphere



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

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

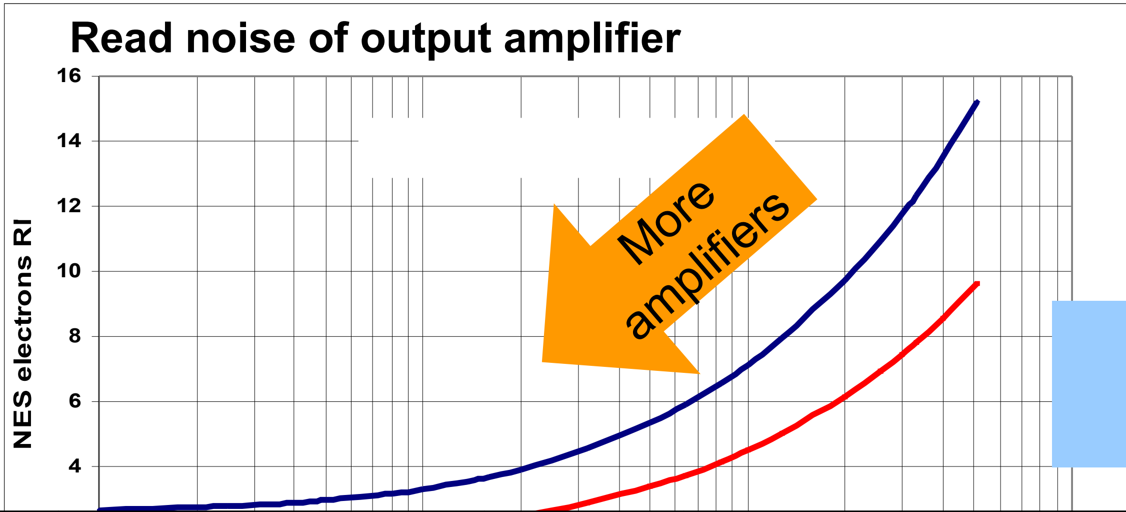
- Current detector developments at ESO are on track to meet current instrument needs.
  - Measured results show that the CCD220 successfully exceeds the requirements.
  - Production of CCD220s at e2v is almost complete with staggered deliveries till end of year.
  - Development of the ESO WFS camera 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

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

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



5-10e-

Manufacturer	Device	Pixel size	Format (pixels)	Frame Rate	Outputs	RON (rms)	
E2v	**CCD50**	**24µm**	**128x128**	**1000 fps**	**16**	**5e-**	**~**
	CCD39	24µm	80x80	1000 fps	4	10e-	~
MIT/LL	CCID-26/64	21µm	64x64	600 fps	4	6-7e-	~
	CCID-26/12	21µm	128x128	1000 fps	16	5e-	~

Customize the architecture

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

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

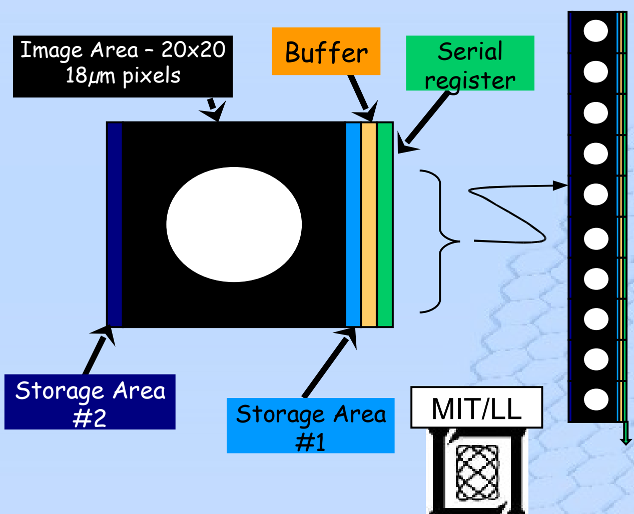
Polar Co-ordinate CCD - talk about later

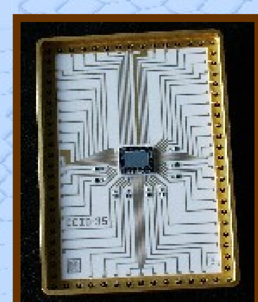
Curvature CCD, CCID-35 – R. Dorn (ESO), J. Beletic, and B. Burke (MIT/LL).

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

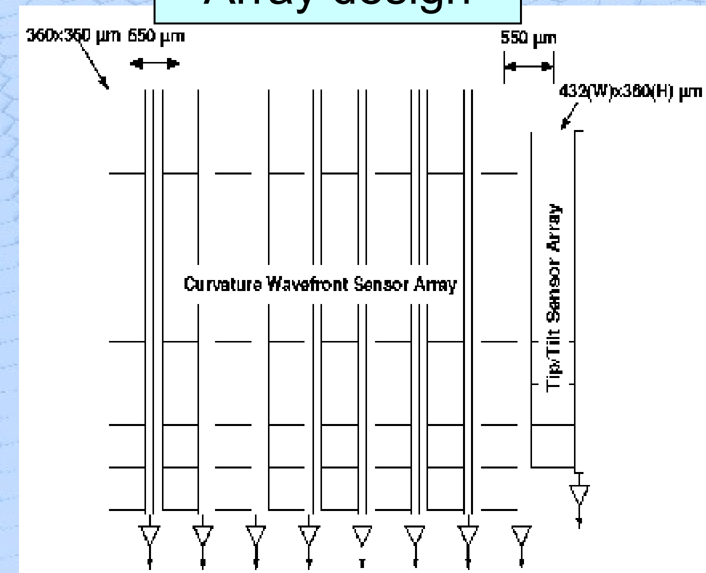
See poster Kevin Ho, "*Flyeyes: Upgrade of CFHT's AO System Using an MIT-LL CCID 35 Sensor*"

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)