Laser Guide Star Adaptive Optics detectors

2008-2012 contract

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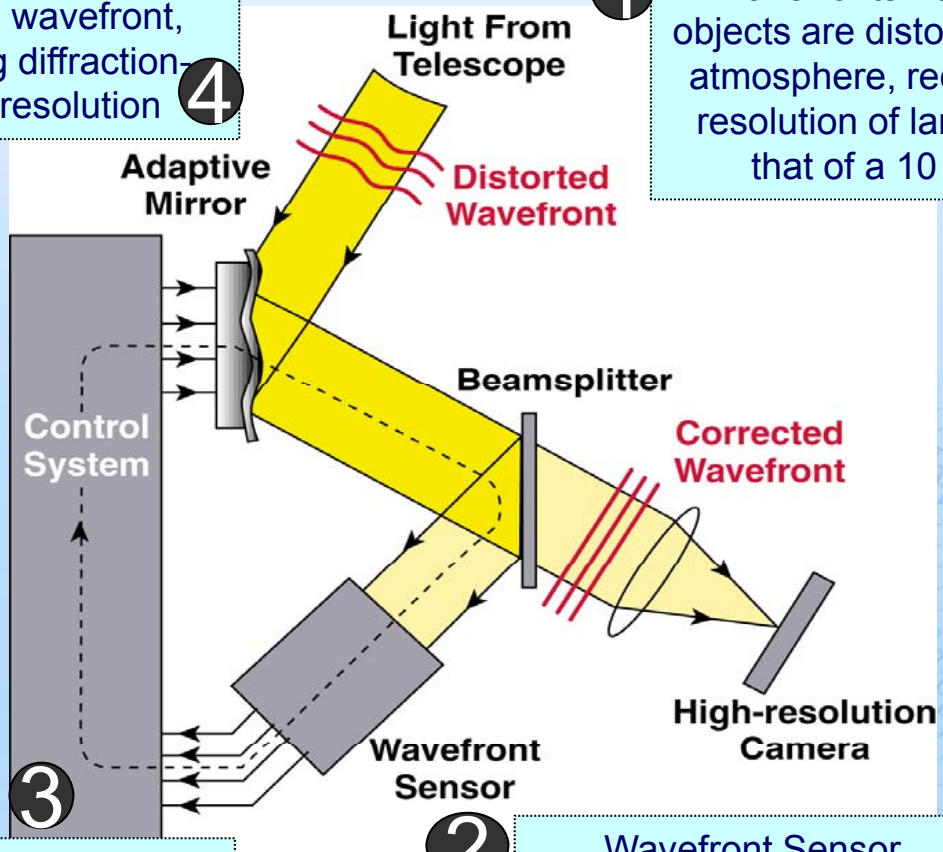
Adaptive Optics (AO)
- removing the twinkle of the stars

Deformable mirror compensates the distorted wavefront, achieving diffraction-limited resolution 4

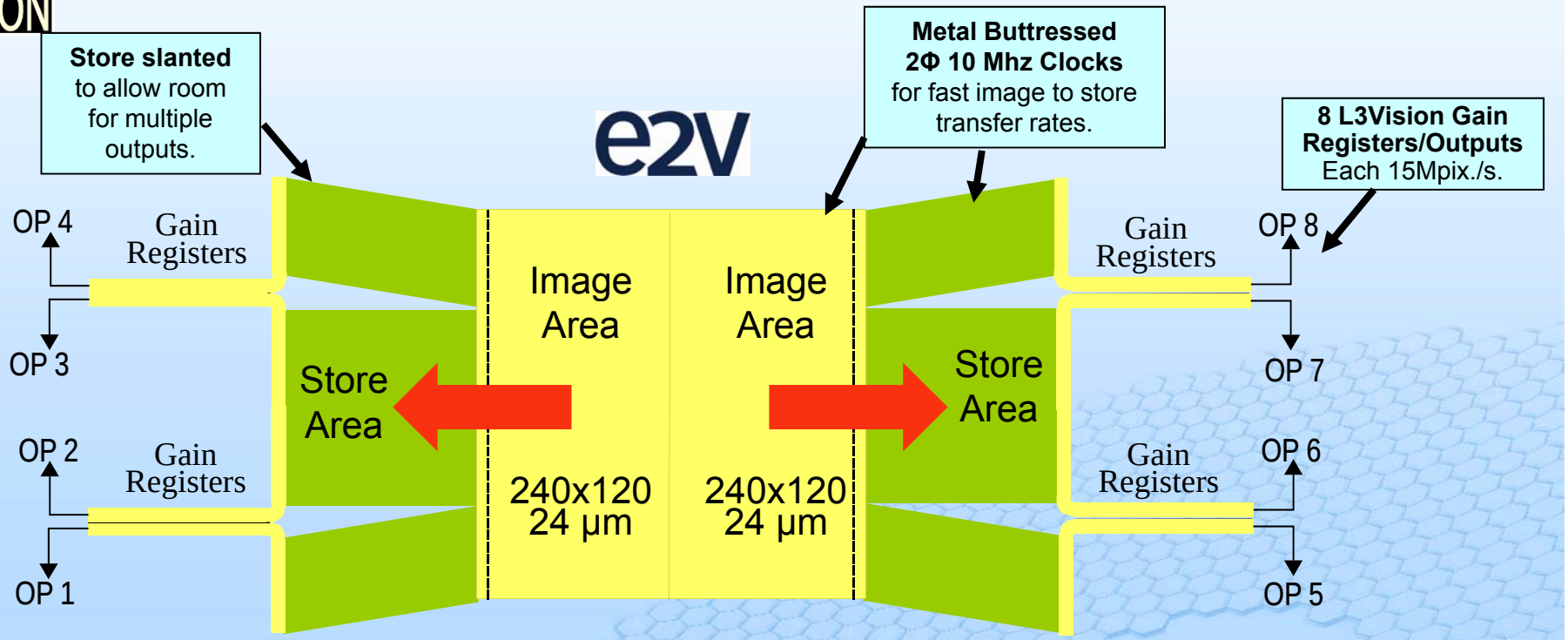
1 Wavefronts from astronomical objects are distorted by the Earth's atmosphere, reducing the spatial resolution of large telescopes to that of a 10 cm telescope



Control System computes commands for the deformable mirror(s)

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

e2v L3Vision CCD220

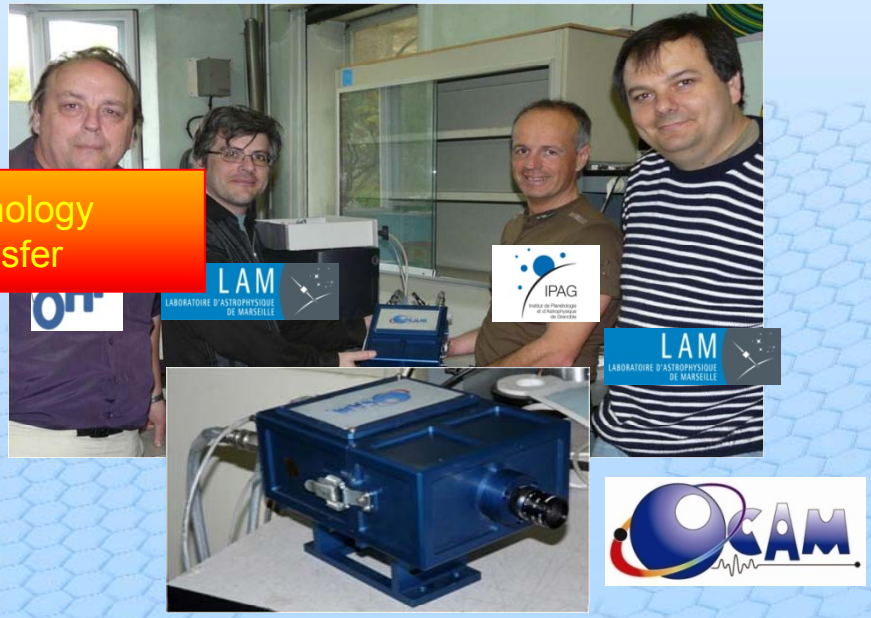


e2v CCD220:

- → Split frame transfer CCD
- → 240x240 24 µm pixels
- → 8 L3Vision EMCCD outputs
- → < 0.1 e- RoN at 1,500 fps
- → Integral Peltier for cooling to -45°C

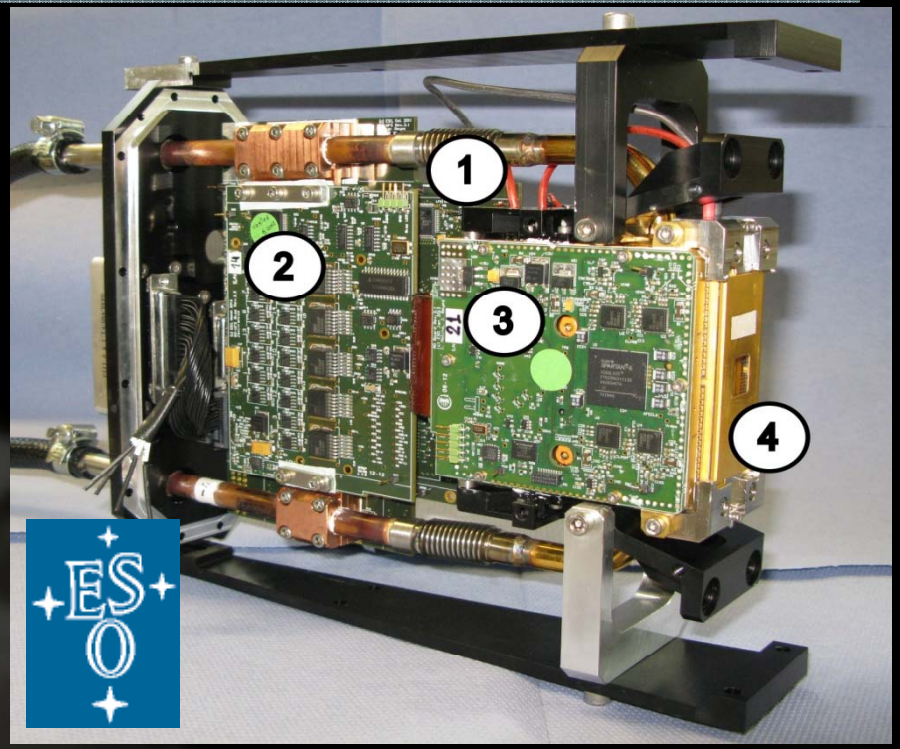
Commercially available Cameras using CCD220

Technology transfer

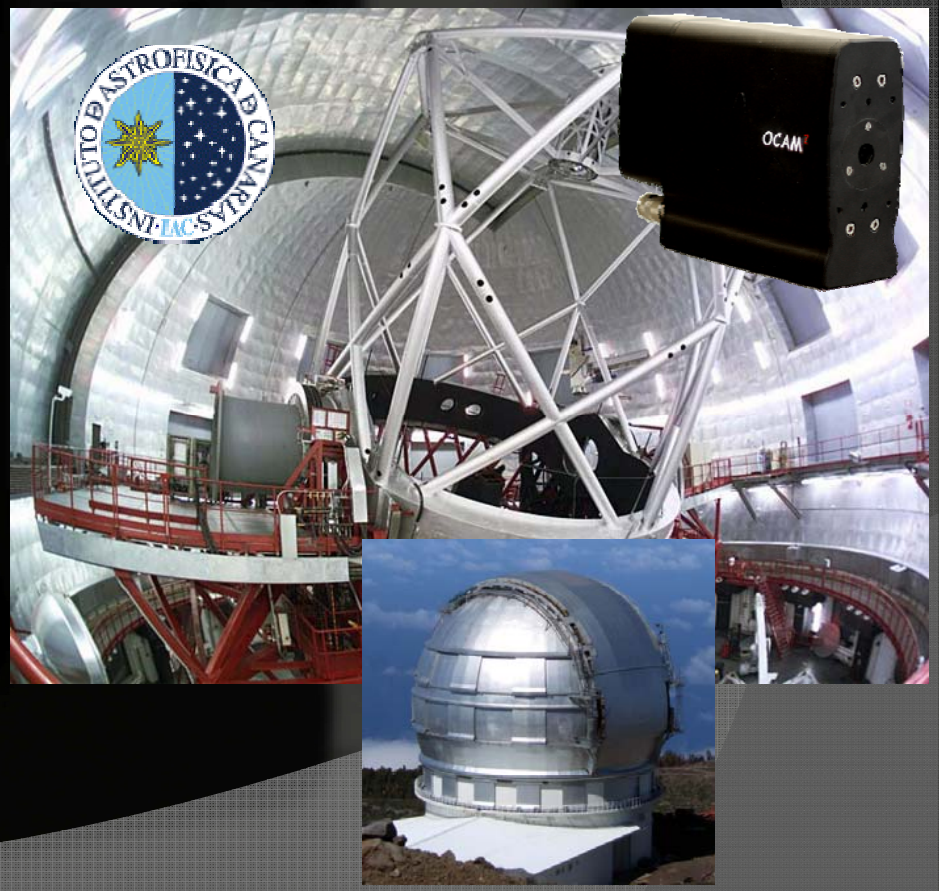


OCAM2 technology in Europe

ESO WFS camera *with Ocam technology (First Light front end)*.



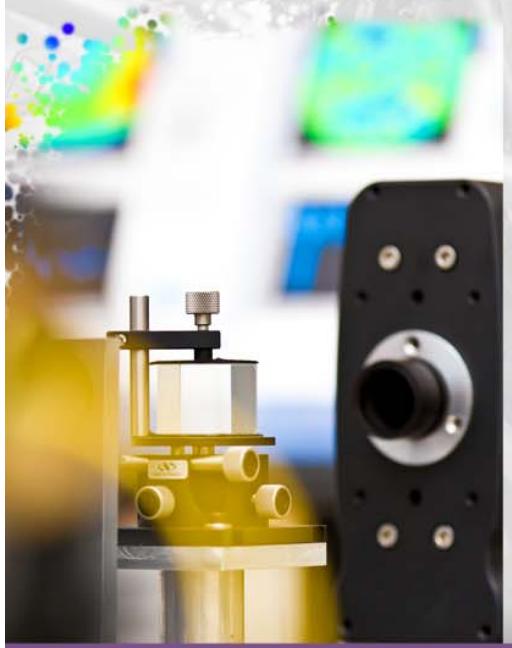
OCam2: WFS camera for Grantecan
Delivery of 2 systems Oct 2011

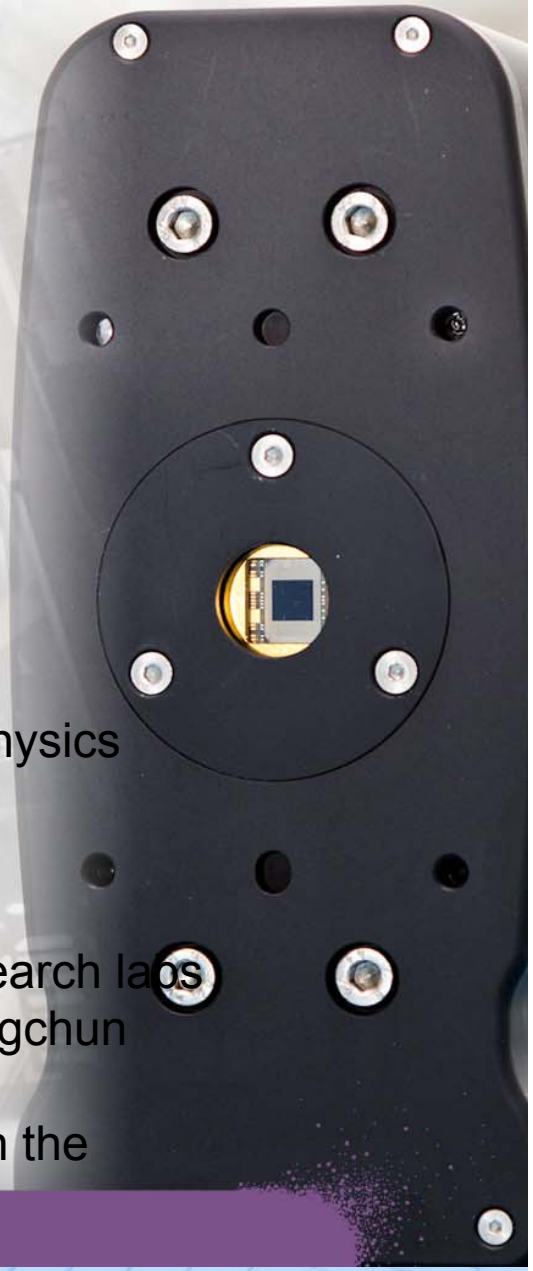


www.firstlight.fr

FIRST LIGHT

ADVANCED IMAGERY





7 employees ~ 1M€/yr turnover

First references:

- ESO
- Research School of Astronomy & Astrophysics (RSAA), Australian National University
- GMT
- Grantecan (Canary)
- Several solar telescopes in China or research labs (Yunnan Astronomical Observatory, Changchun Institute of optics…)
- Contacts with almost all big telescopes in the world (Subaru, Gemini)

CCD220 Impressive (Measured) Test Results

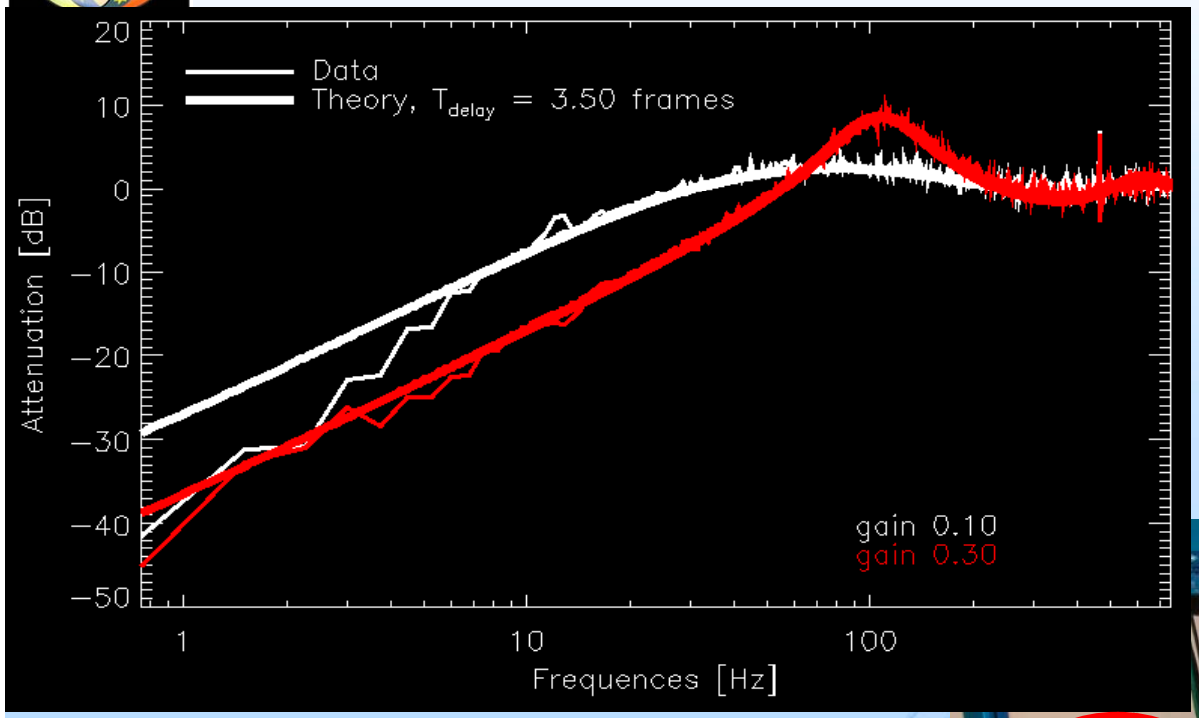
Requirement	Measured	Specification
Frame Rate:	> 1,500 fps	✓ >1,200 fps
Read noise: at gain of 1000 &1500fps	< 0.1 e-	✓ < 1.0 e-
Image Area Full Well:	> 200 ke-	✓ > 5,000 e-
Cosmetics: # of traps, bright/dark defects	0	✓ < 25
Dark Current at 100fps & -40ºC:	< 0.02 e-/pix/frame	✓ < 0.04 e-/pix/frame

- ✓ Key goal specs are met
- ✓ Deep Depletion (highly sought after for better red response) is working as good as standard silicon device.

<u>Next Step:</u>

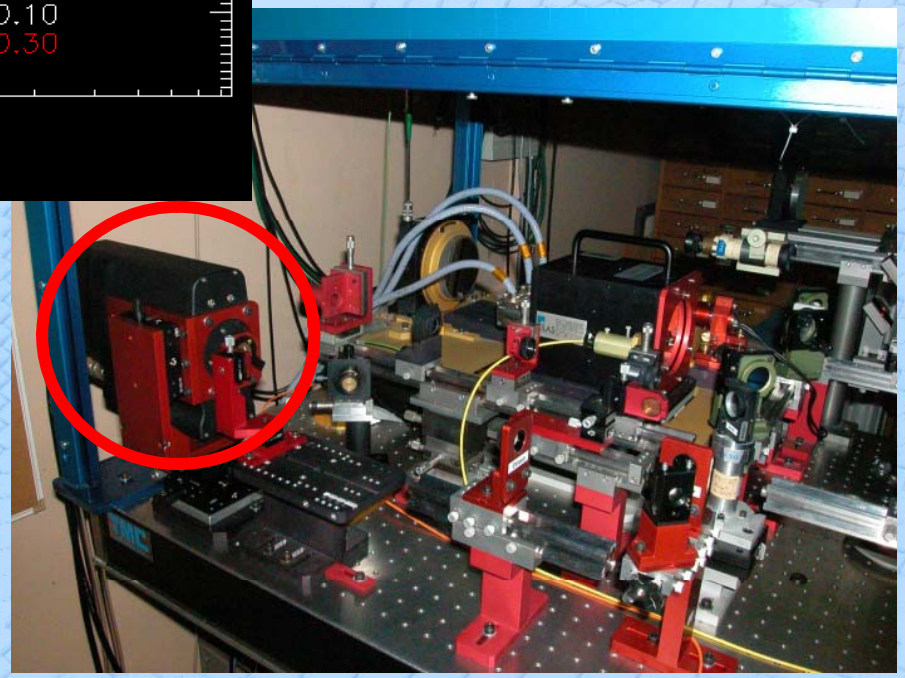
- Increase frame rate to 2,500 fps to extend use to E-ELT XAO (Extreme AO).

OCAM2 closed loop results at ONERA

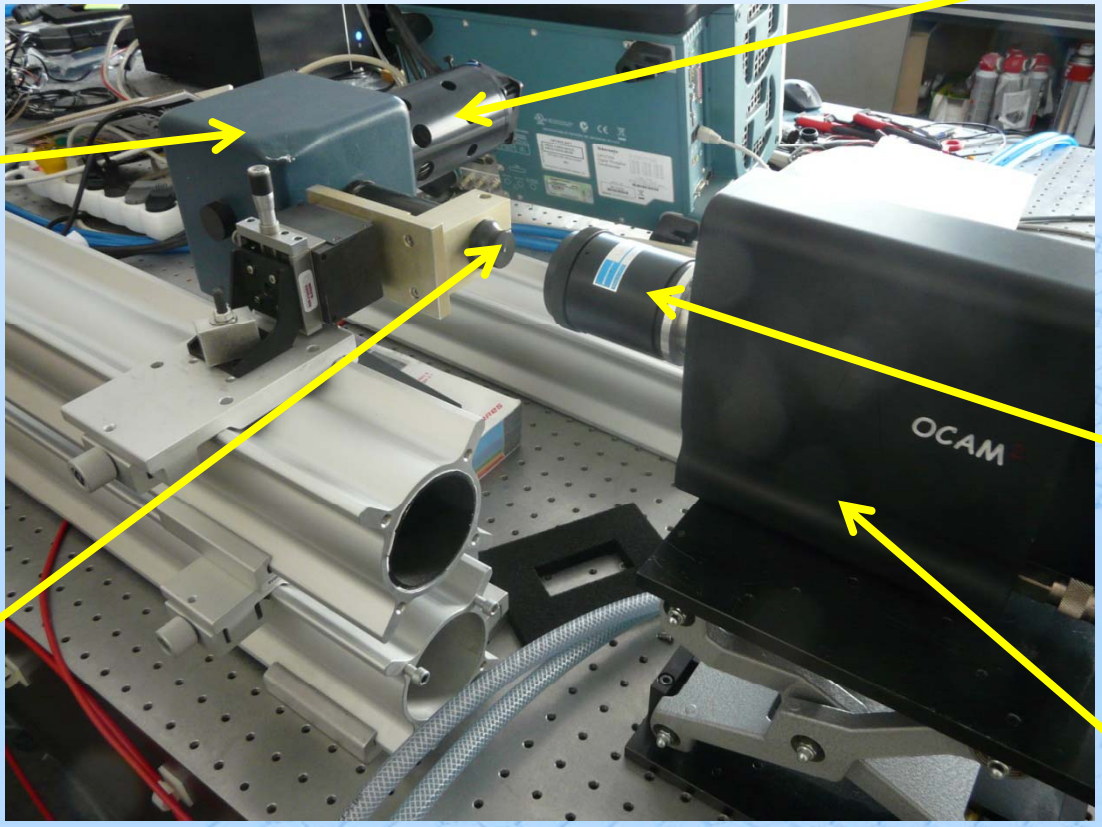


ONERA
THE FRENCH AEROSPACE LAB

Rejection transfer function of the AO loop system. Sampling frequency is 1503 Hz. Shakti RTC



Why multiplication gain ?



High stability
Tungsten lamp

Integrating
sphere

Diffraction
Limited
Relay lens

12 µm Pinhole

OCAM2

Centroiding with 5 photons…

Shack hartmann centroiding possible only with a few photons @ 1500 FPS

Central peak is only 5 photons/frame amplitude (mean value)
1503 FPS
Gain x 800
0.2 e noise

AO Detector needs for E-ELT

FP6

Low Order AO

Shack Hartmann Quad -Cell

Pyramid

Other WFS…

TipTilt Sensors

Guiding

Existing visible high performance detector (CCD220)

IR WFS

IR TipTilt sensors

Extreme AO

2.5 kHz ultra low-noise detector
✓ possibly reuse CCD220

NGS - Natural Guide Star

NGS Ground Layer AO

NGS Single Conjugate AO

LGS - Laser Guide Star

LGS Multi-Conjugate AO

Multi-Object AO

Laser Tomography AO

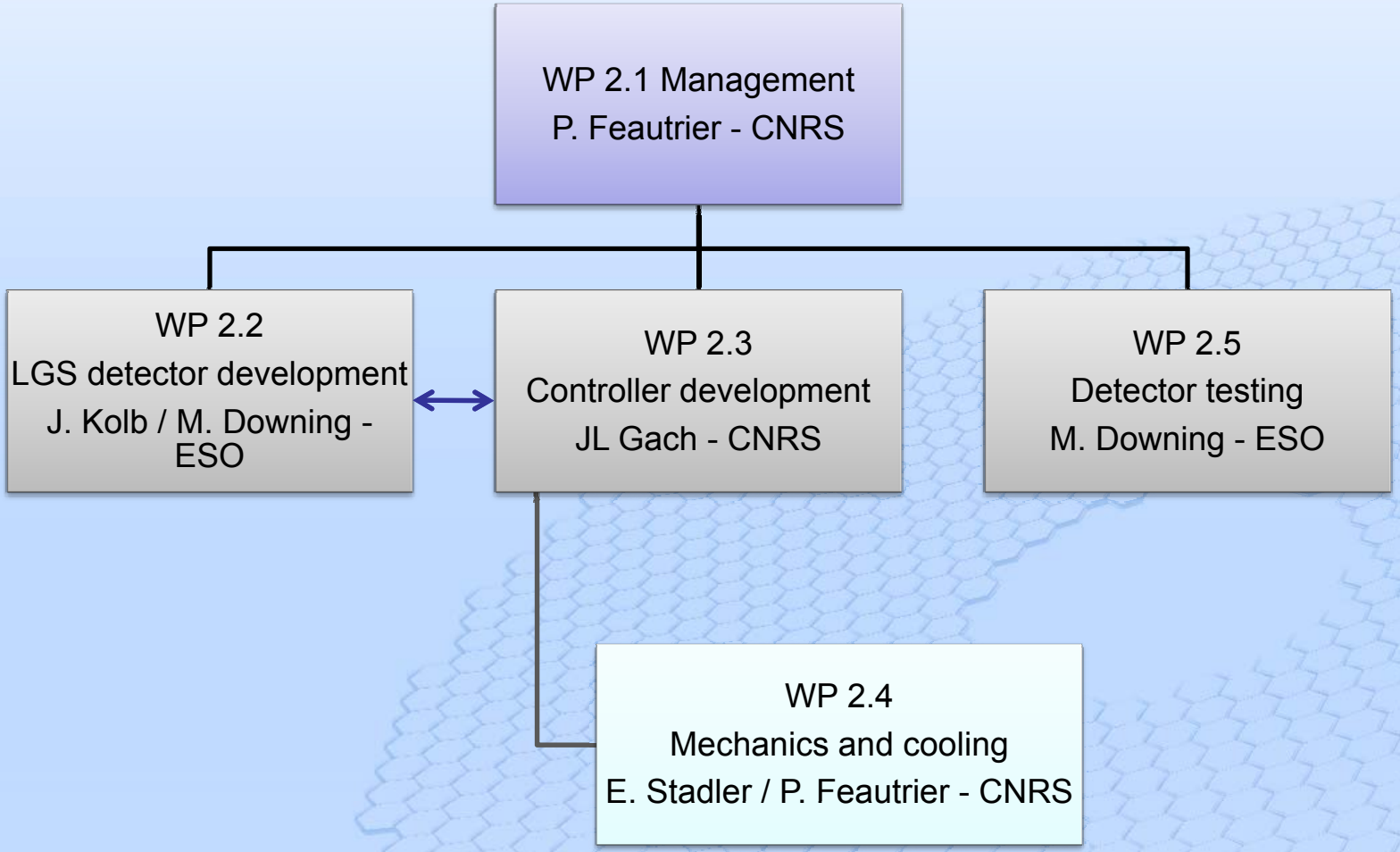
LGS Ground Layer AO

Large Visible AO WFS Detector

WP2's organisation in FP7-1

Deliverables
2.5.1: LGS detector test report at Optical wavelengths

On time



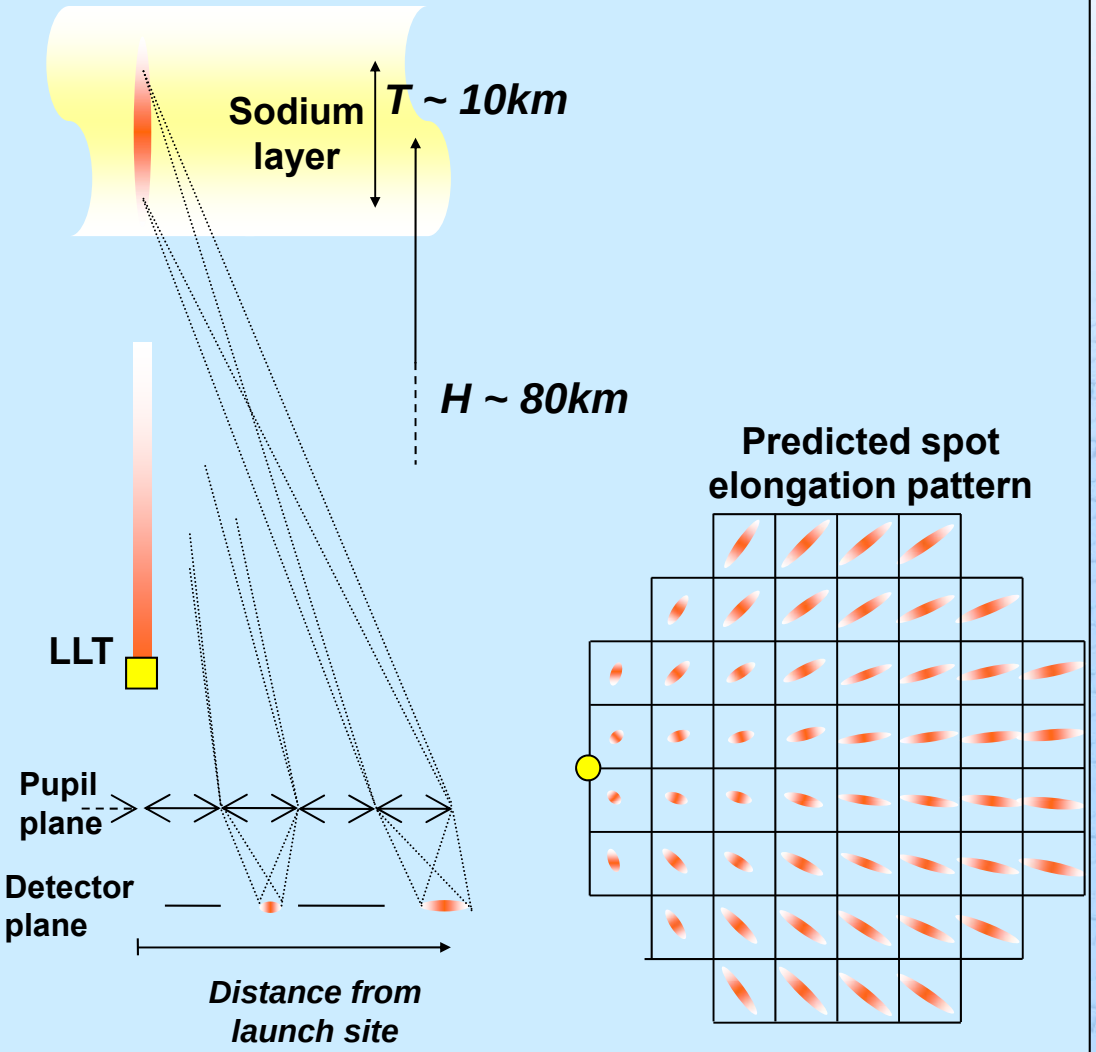
Large Visible AO WFS Detector needed to sample the spot elongation

Sodium Laser Guide Stars

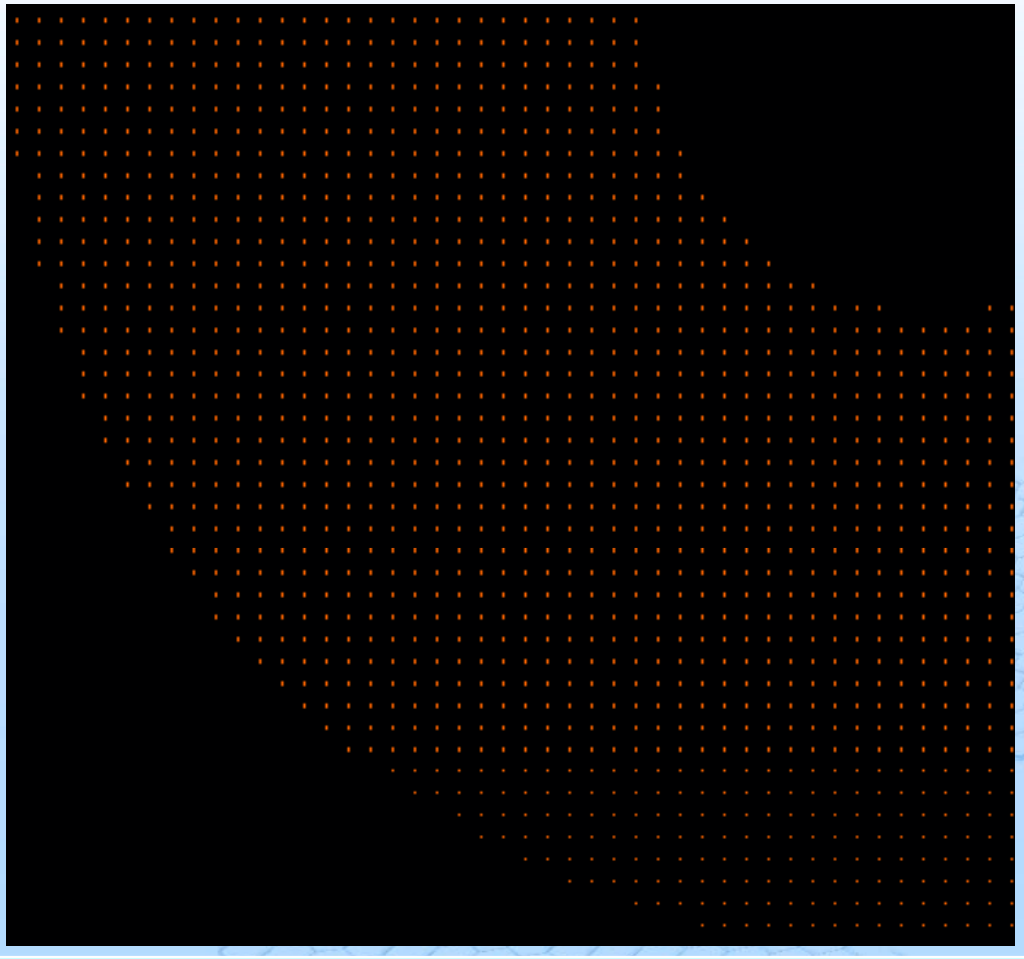
- Frame rate ~**1 kframe/sec**

→ 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

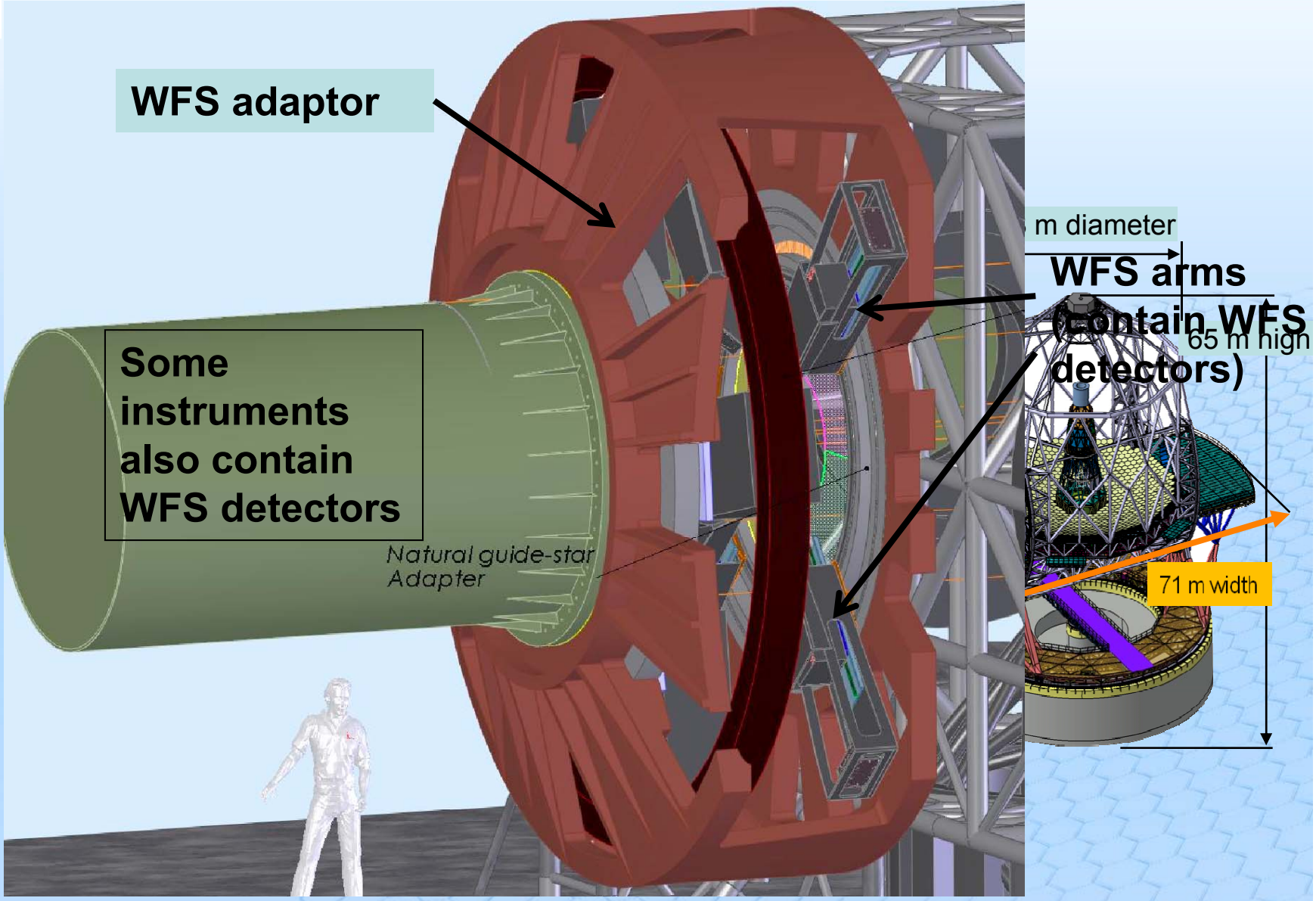


¼ WFS image



- Natural Guide Star: **84x84** sub-apertures of **8x8** pixels → NGSD
- Laser Guide Star: **84x84** sub-apertures of **20x20** pixels → LGSD

Location of Wavefront sensors on the E-ELT



Large Visible AO WFS Detector

Top Level Requirements

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 to simplify the optical design
Wavelength	460-950nm (NGS) 589nm (LGS)	
QE	**> 80 %**	High
Frame Rate	**700 fps**	Fast, low latency; up to 1000fps with reduce performance
RON	**< 3 e- rms**	Low read noise
Storage Capacity	< 4000e-/pixel	Expect few photons
Cosmetics	< 0.1% bad pixels	Good; very few bad sub-apertures

Ease of use/compact size:

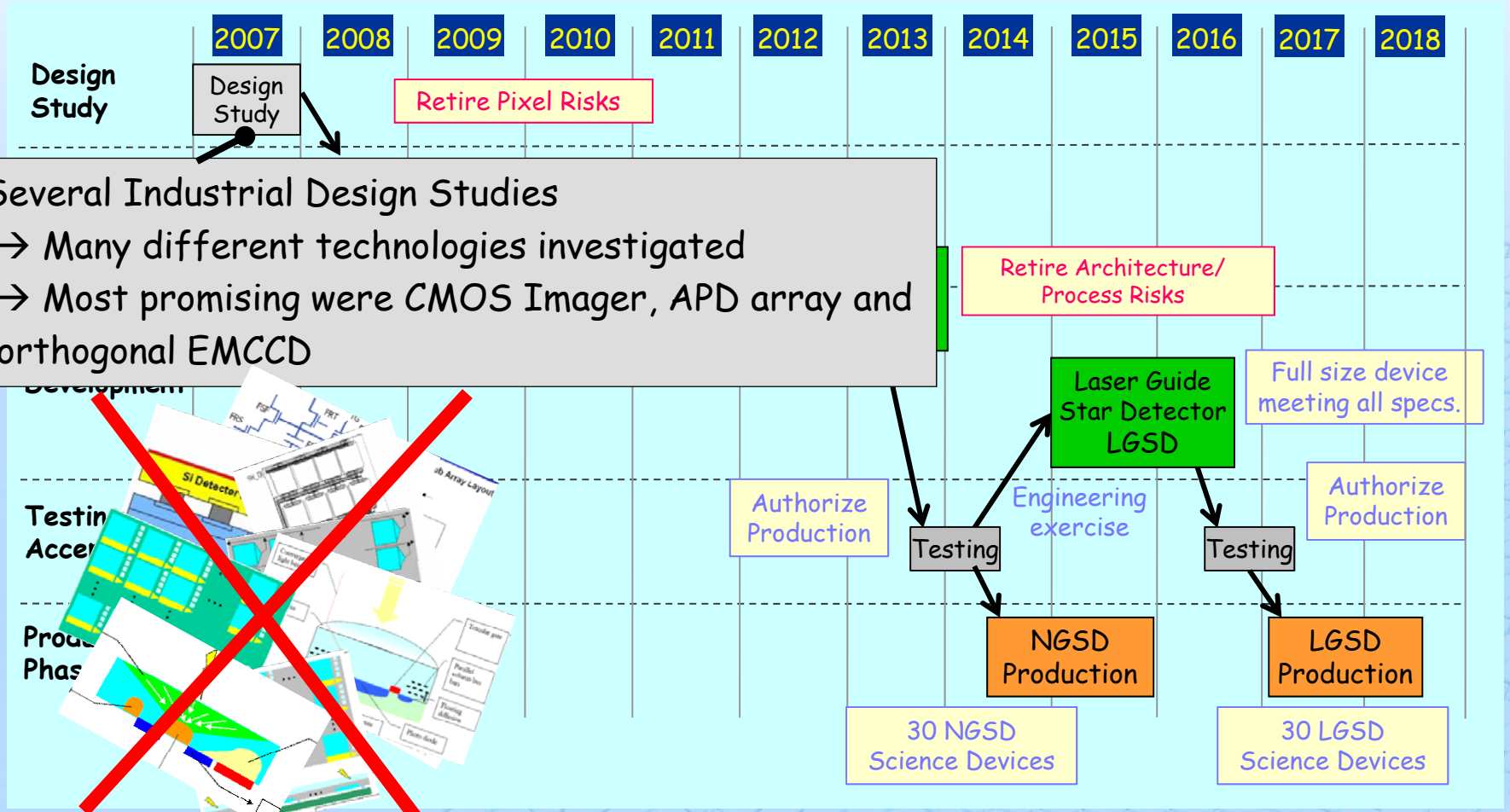
→ low pin count; goal < 200 pins

→ integral Peltier – low power < 5W

→ integrated read-out electronics - digital I/F preferred

ELT WFS DETECTOR

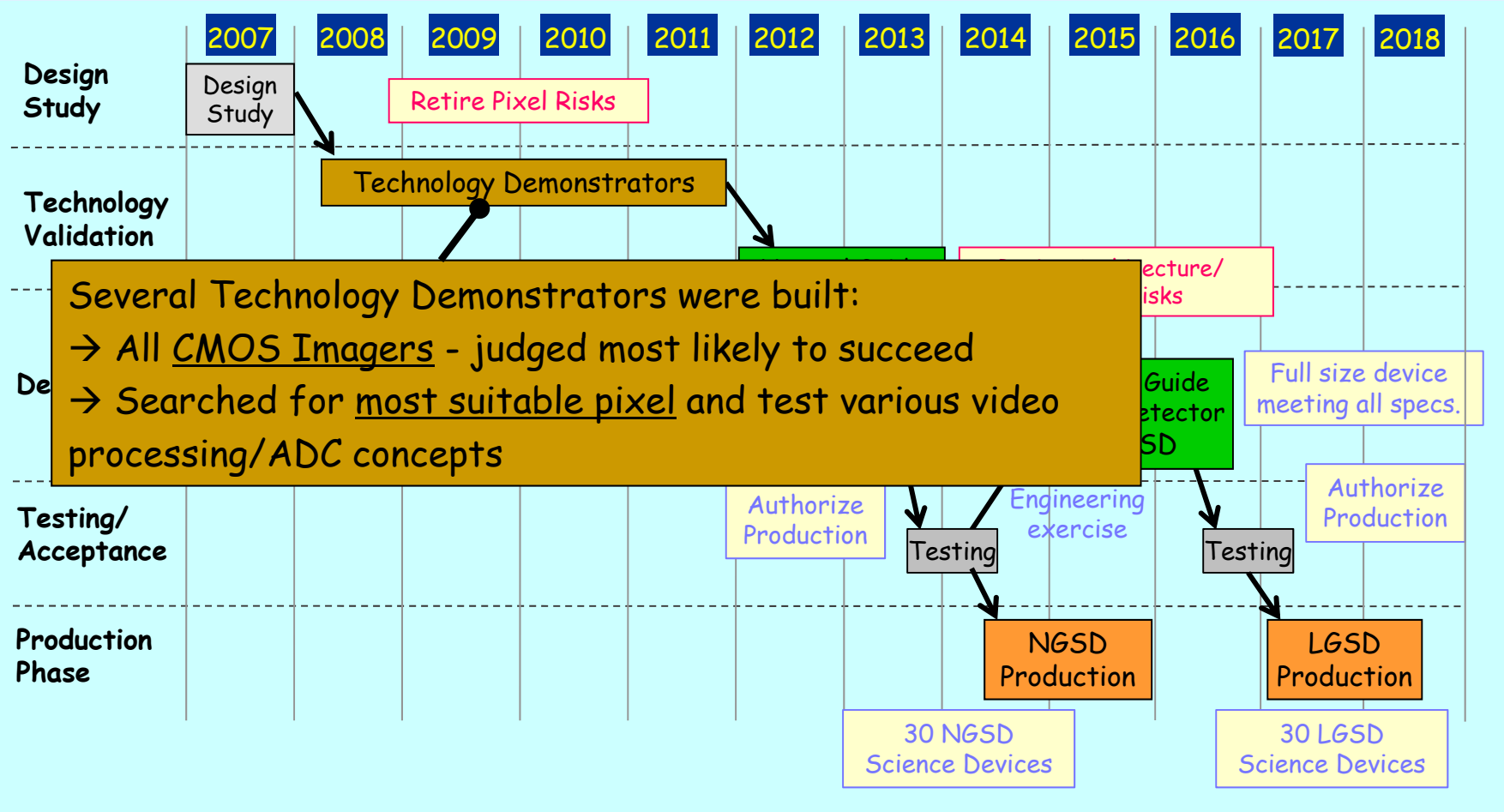
Multi-phase plan to progressively retire risk



Several Industrial Design Studies
→ Many different technologies investigated
→ Most promising were CMOS Imager, APD array and orthogonal EMCCD

ELT WFS DETECTOR

Multi-phase plan to progressively retire risk



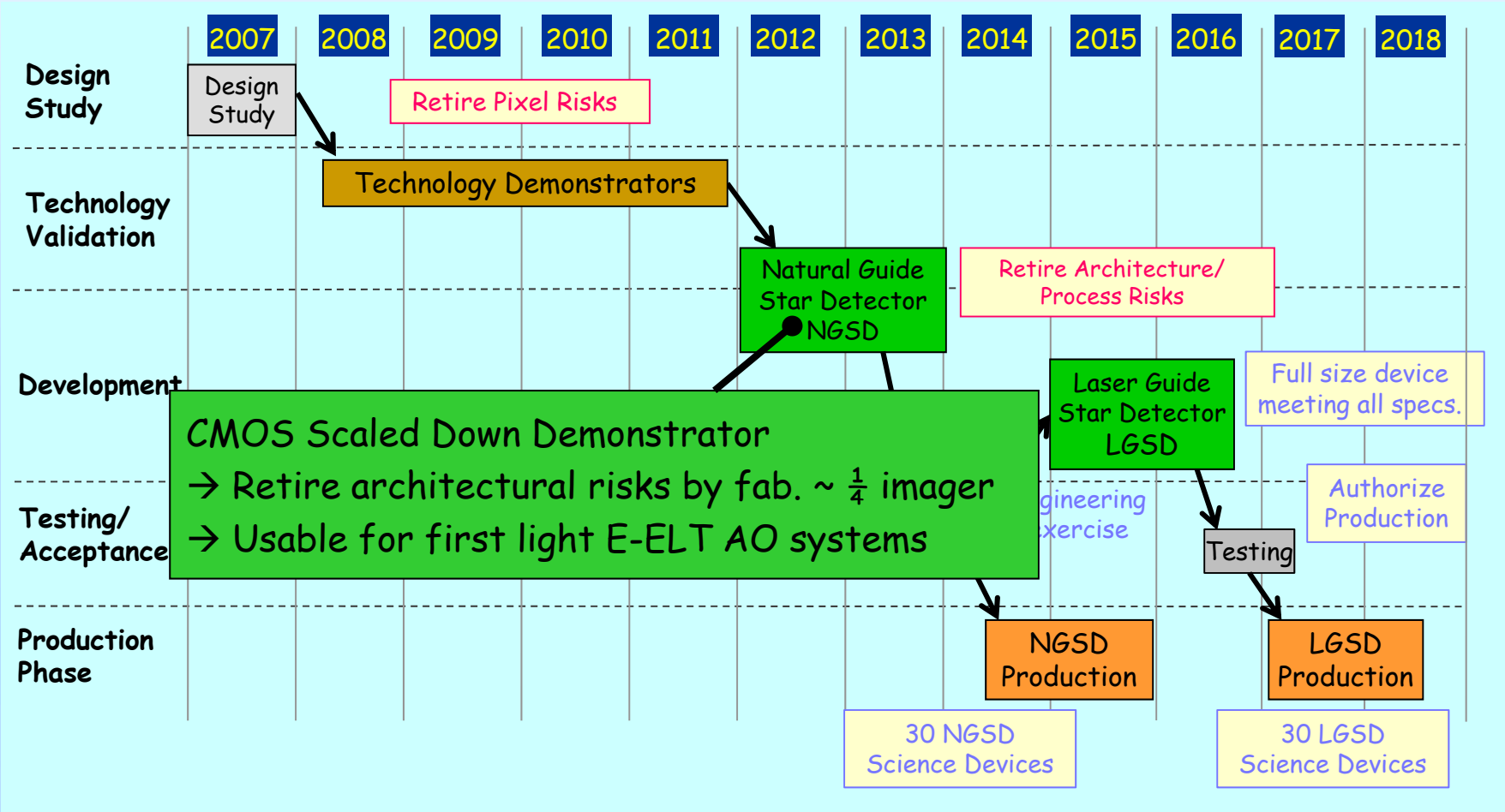
Several Technology Demonstrators were built:

→ All CMOS Imagers - judged most likely to succeed

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

ELT WFS DETECTOR

Multi-phase plan to progressively retire risk

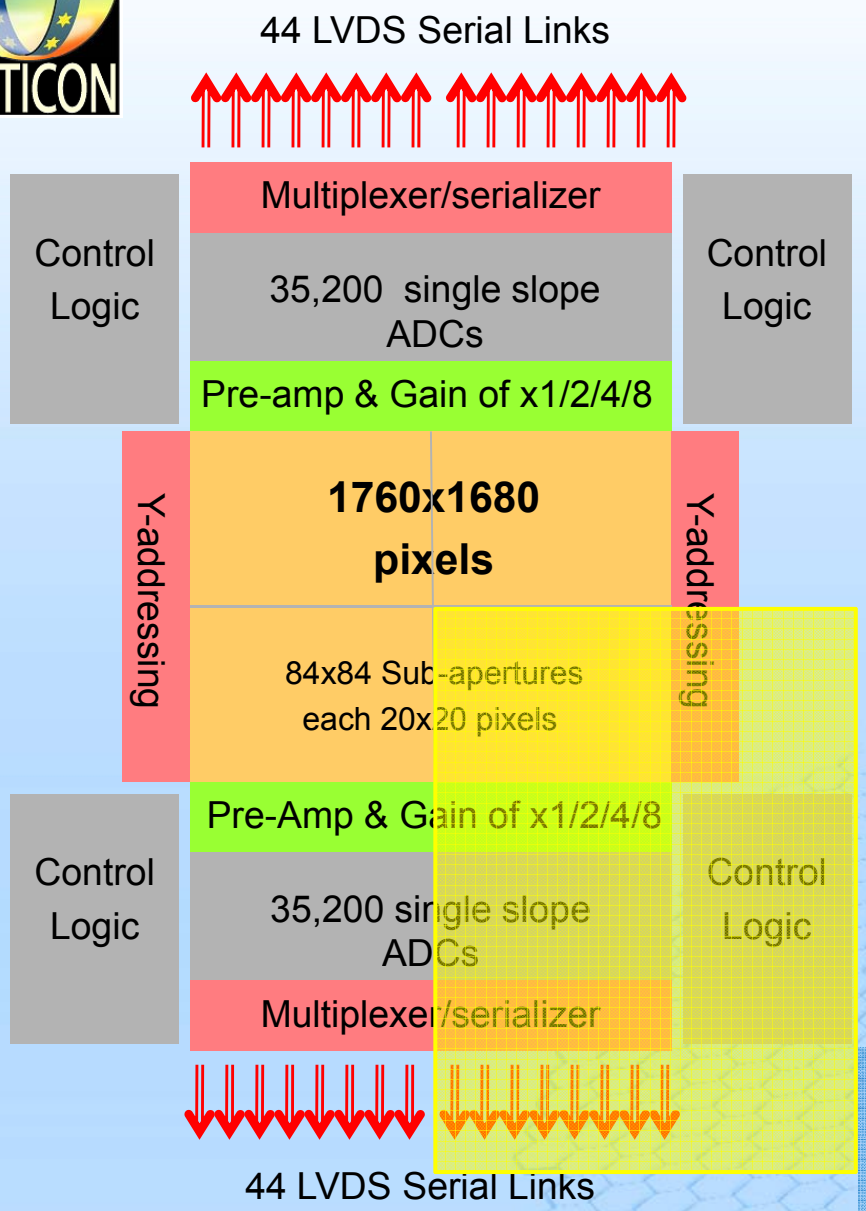


Specifications of the LGSD

Physical characteristics

Pixel array (reference pixels either side)	1760x1680 (880x840 pixels in NGSD) - 5x6cm requiring stitched design (max. reticle 25.5x32.5mm)
Technology	Thinned backside illuminated CMOS 0.18µm
Pixel pitch	24µm
Pixel topology	4T pinned photodiode pixel
Array architecture	84x84 time coherent “sub arrays” of 20x20 (8x8 NGSD) pixels - LGSD image area size of 4x4cm
Shutter	Rolling shutter in chunks of 20 rows → synchronous detection within a sub-array.

Block Diagram of Full Size Device; LGSD



Highly integrated

- All analog processing on-chip:
  - programmable gain of x1/2/4/8 on the fly,
  - correlated double sampling (CDS),
  - Single slope 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 LVDS serial interface to outside world
  - Simple digital interface
  - 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 → non-stitched

Specifications of the LGSD
Read out

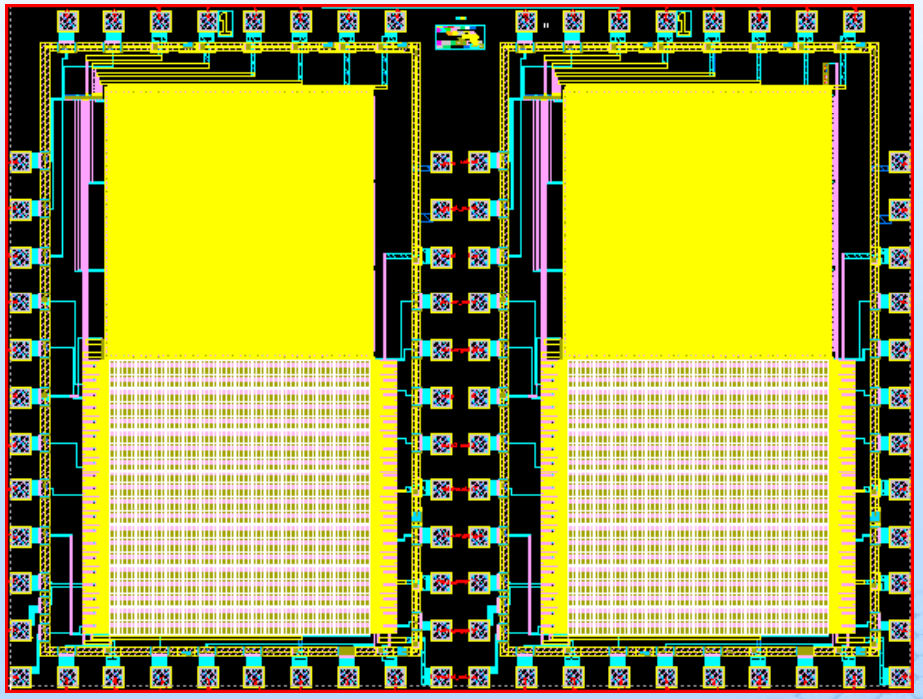
Number of rows read in parallel	40 (20 in NGSD) rows in parallel
Number of ADC's	40x1760 (20x880 in NGSD) at 9/10 bits
Number of parallel LVDS channels	88 (22 in NGSD)
Serial LVDS channel bit rate	210 Mb/s baseline, up to 420 Mb/s (desired)
Frame rate	700 fps up to 1000 fps with degraded performance 2 to 3 Gpixel/s = 20 to 30 Gb/s over 88 parallel LVDS channels
Power dissipation	< 5W , including the 88 LVDS drivers

Specifications of the LGSD
Performance

Pixel full well Q_{FW}	> 4000 e-
Linearity to full well	< 5%
Read noise including ADC	< 3.0 e^-_{RMS}
Dark Current	< 0.5 e-/pixel/frame
QE	> 90% over the visible range → BackSide Illumination (BSI)
Point Spread Function	< 0.8 pixel FWHM

Thought critical and need to validate

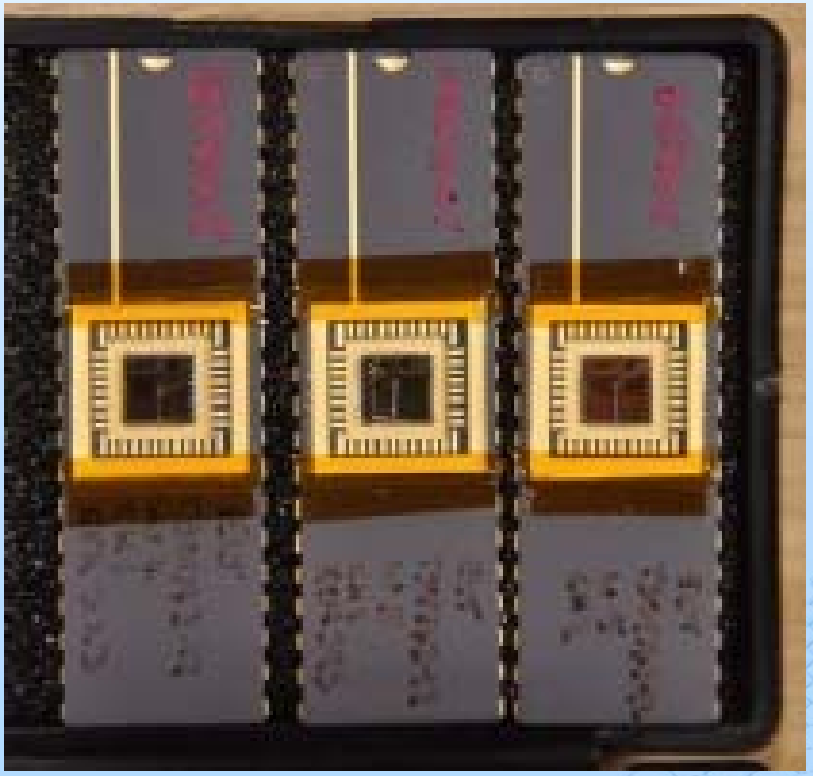
Technology Validator - TVP



In a nutshell:

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

TVP - All key performances validated

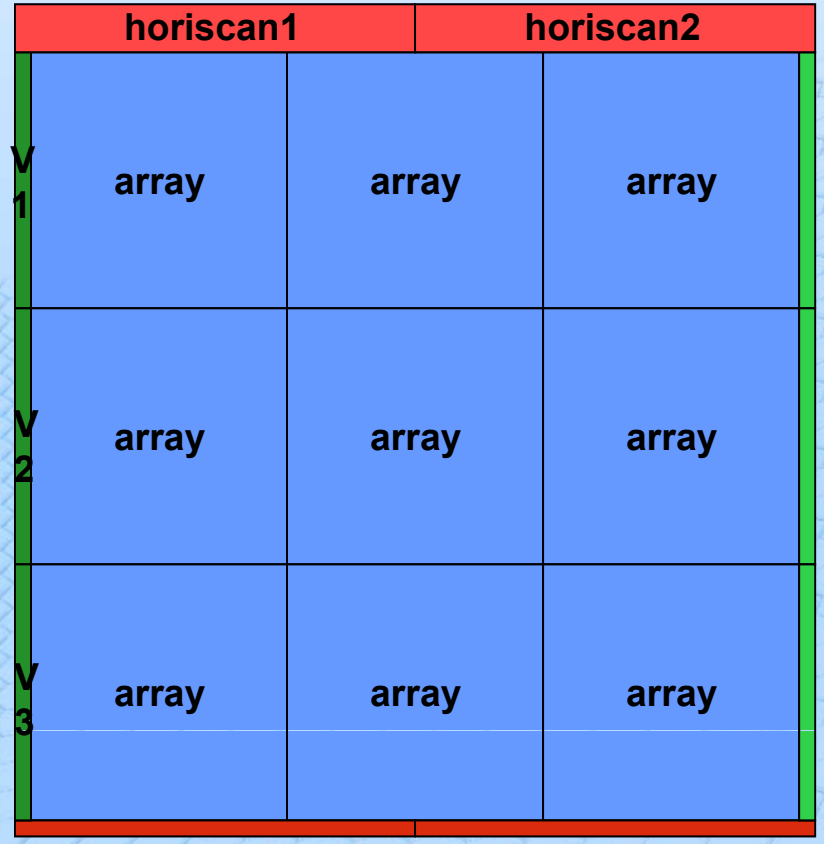


- All key performances validated
  - ✓ < 3.0e-$_{RMS}$
  - ✓ Full well > 4000 e-
  - ✓ Conversion gains > 100 µV/e-
  - ✓ Image Lag < 0.1 %
  - ✓ <u>Best pixel and implant levels</u> fed into the NGSD phase.
  - ✓ Column ramp ADCs
- Not tested in TVP:
  - ? Massive parallelism
  - ? Array of LVDS serial IO
  - ? Back Side Thinning & Back Side Illumination

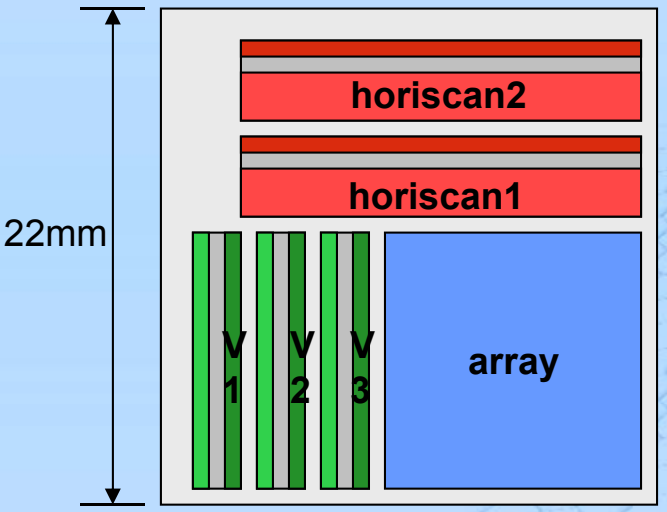
Stitching Enables Large Sensor Arrays (LGSD)

- The small feature size of modern CMOS processes limits the maximum area that can be exposed in one step (so-called “reticle”) to about 22 mm.
- However, larger chips can produced by breaking up the design into smaller sub-blocks that fit into the reticle.
- Sub-blocks are exposed one after another
- Some blocks are used multiple times
- Ultimate limit is given by wafer size

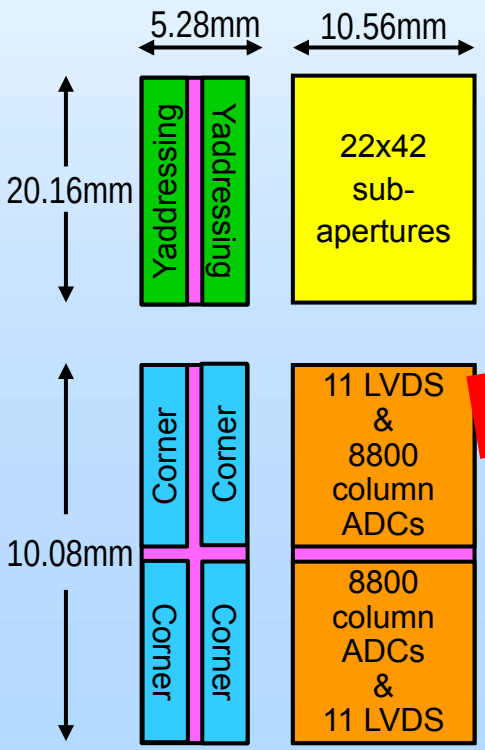
Stitched CMOS Sensor



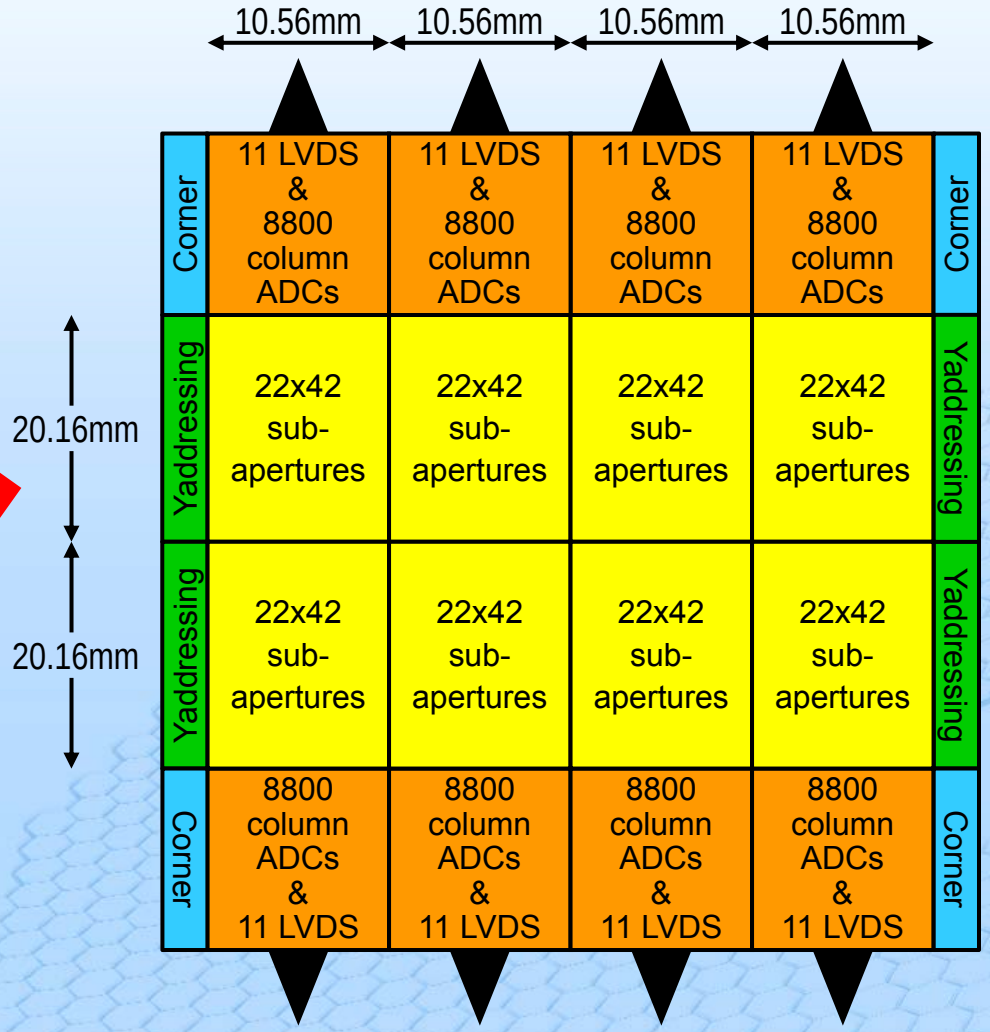
Reticle



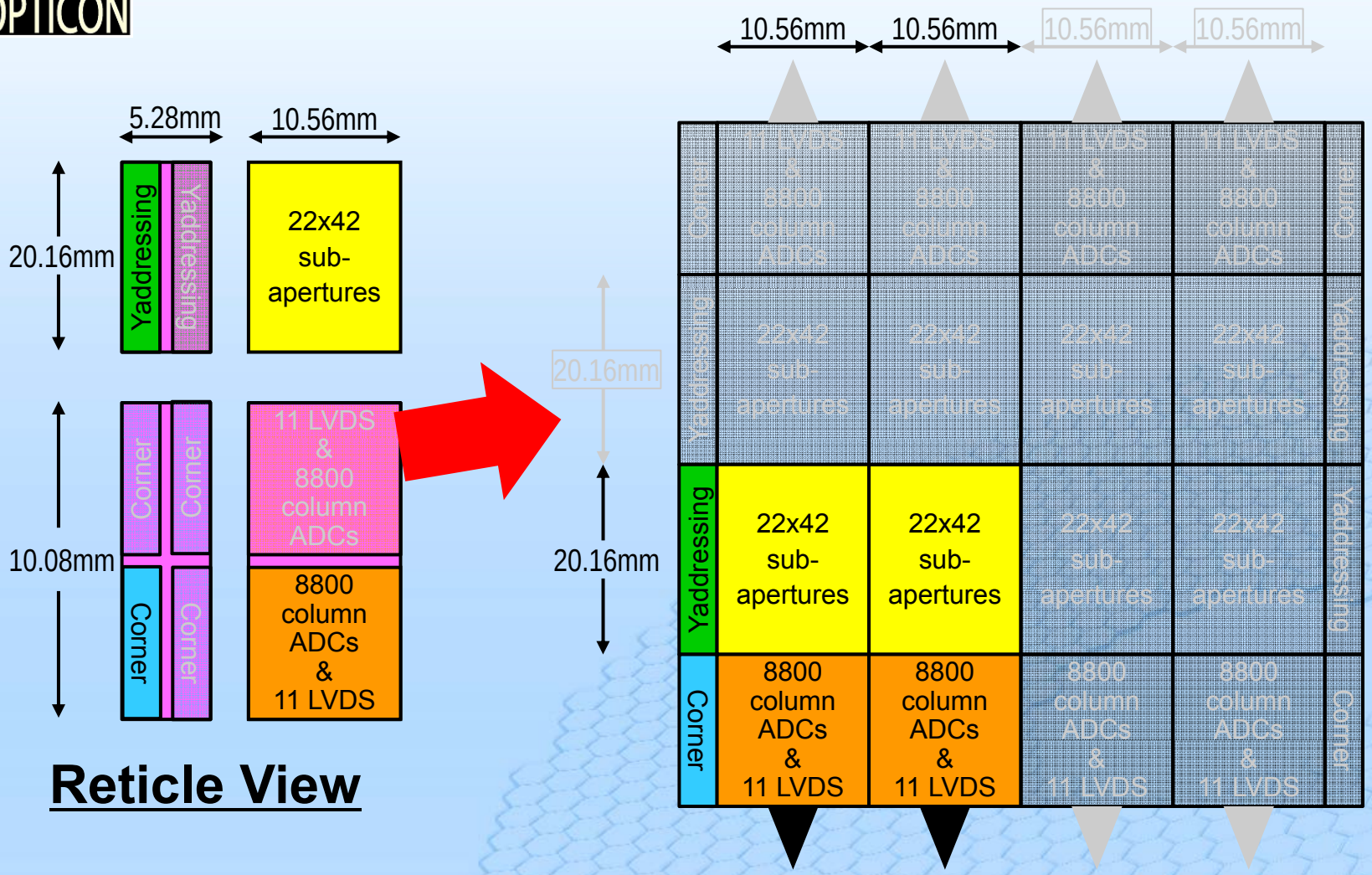
LGSD Tentative Stitching Plan



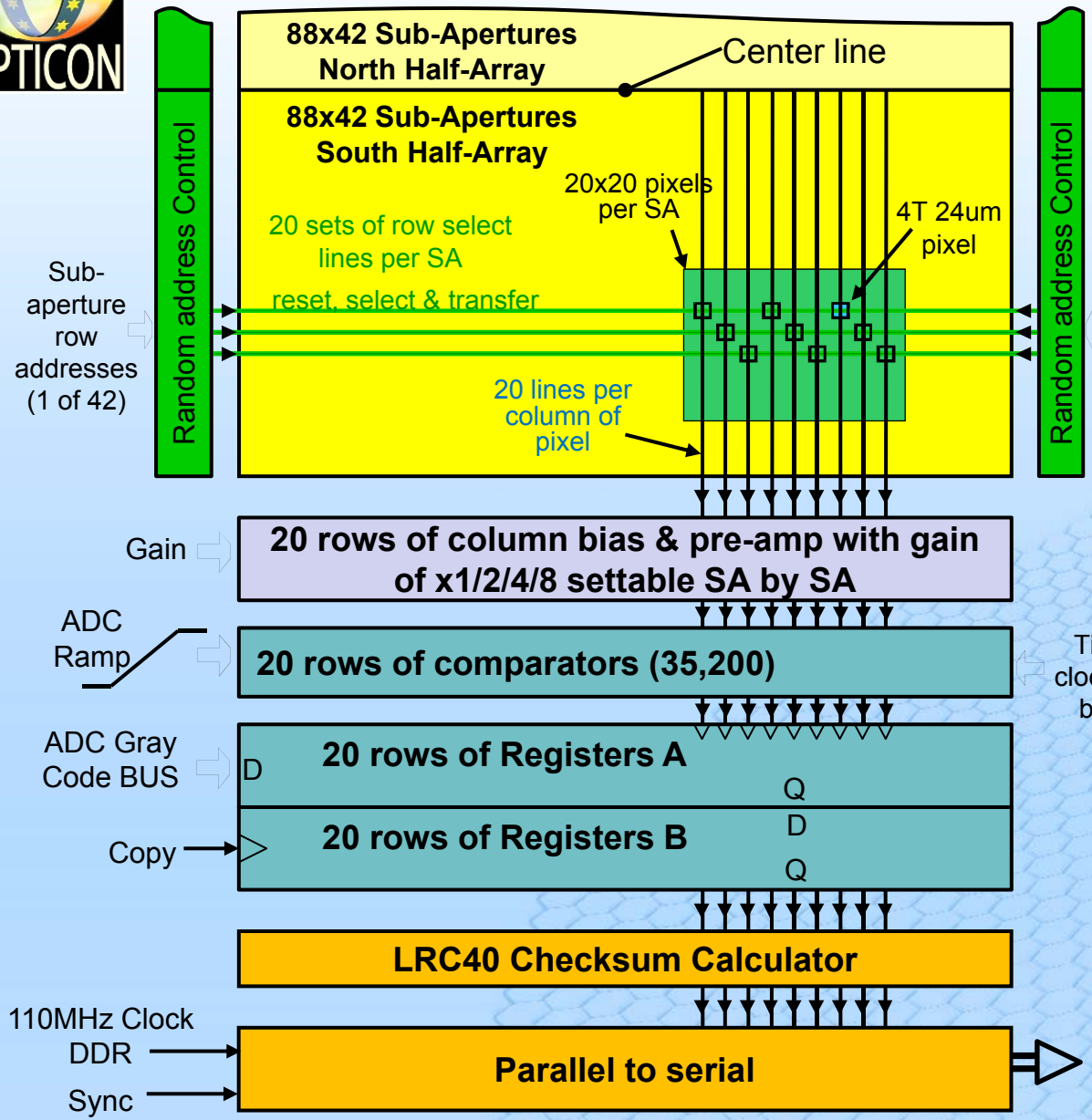
Reticle View

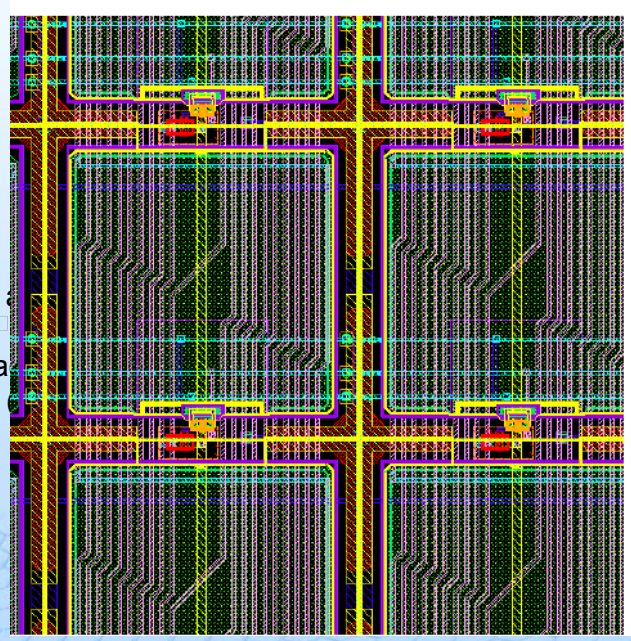


NGSD anticipates scaling to LGSD

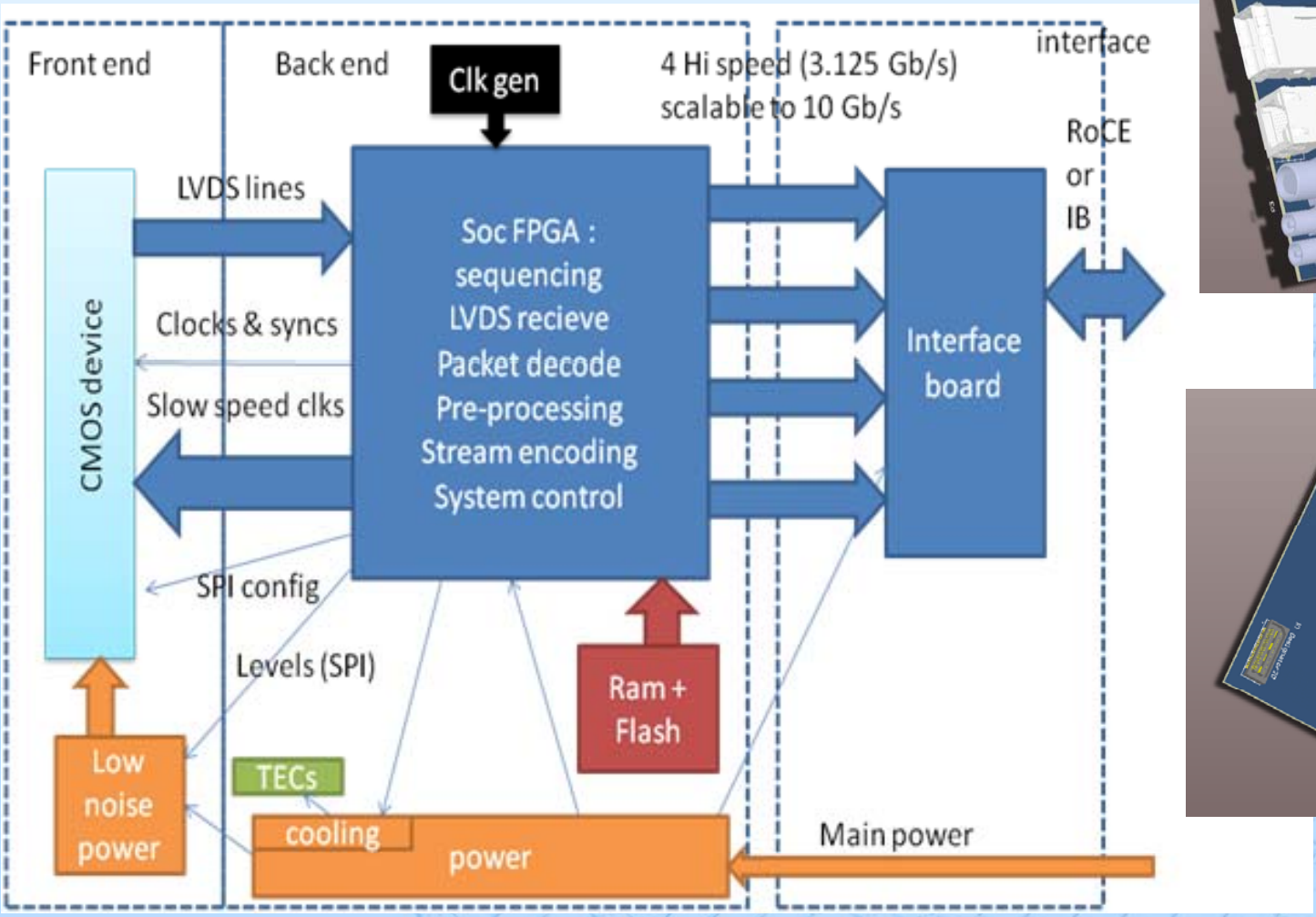


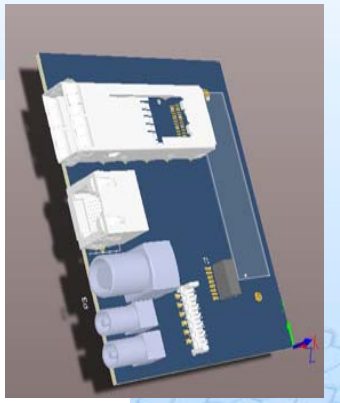
Read out

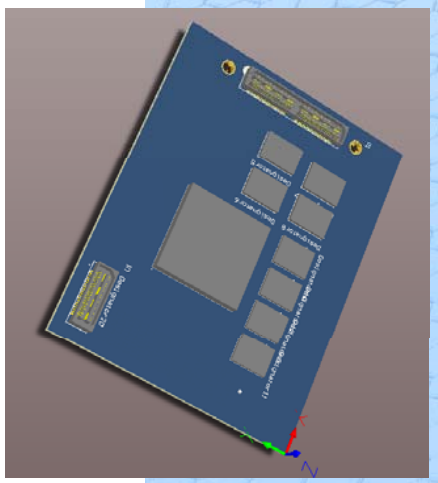

88x42 Sub-Apertures
North Half-Array
Center line
88x42 Sub-Apertures
South Half-Array
20x20 pixels
per SA
4T 24um
pixel
20 sets of row select
lines per SA
reset, select & transfer
Sub-
aperture
row
addresses
(1 of 42)
Random address Control
Random address Control
20 lines per
column of
pixel
Gain
20 rows of column bias & pre-amp with gain
of x1/2/4/8 settable SA by SA
ADC
Ramp
20 rows of comparators (35,200)
Timing,
clocks and
biases
ADC Gray
Code BUS
D
20 rows of Registers A
Q
D
20 rows of Registers B
Q
Copy
LRC40 Checksum Calculator
110MHz Clock
DDR
Sync
Parallel to serial
LVDS Outputs



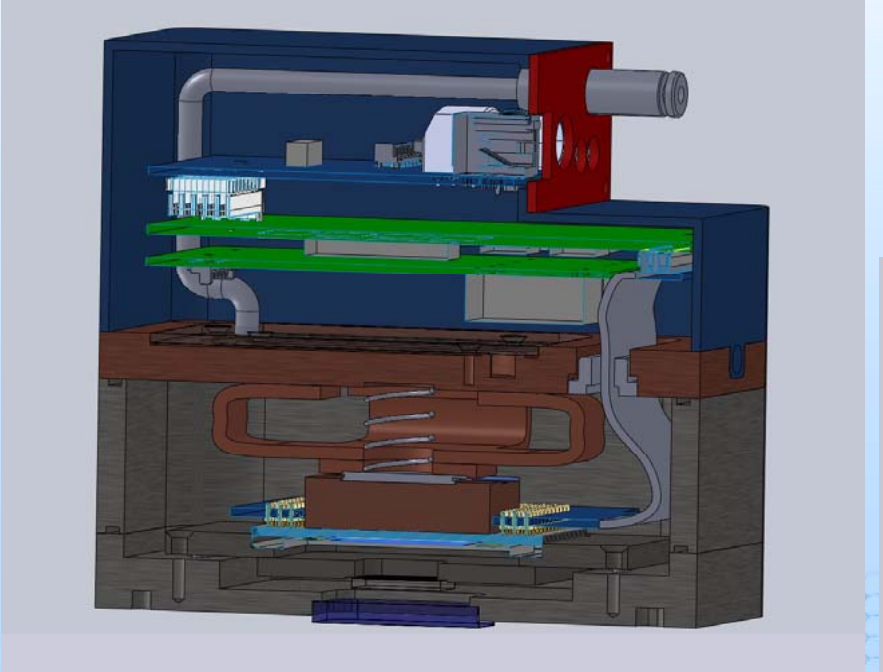
WP 2.3 Controller design

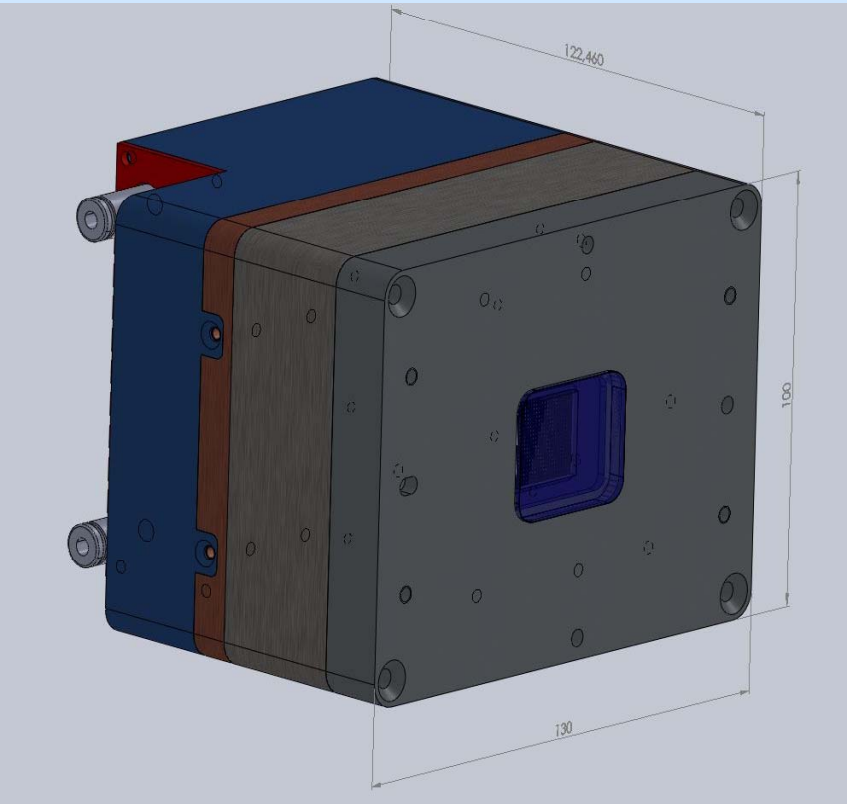






WP 2.4 Camera head design





Outreach

- Several SPIE papers: one in 2010, 2 invited talks at SPIE Amsterdam 2012 (AO and Detectors session)
- One refereed paper in PASP (2011)

Summary

- Preparation work for our next challenge, the E-ELT, is well advanced.
- 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 schematic design of the NGSD is complete and layout has started. Fabrication is scheduled for late autumn with devices available early next year.
- The controller design and camera head design is at preliminary design level (PDR) and need to be continued during next contract.
- Deliverable for EU will be delivered on time

2.5.1	LGS detector test report at Optical wavelengths	2.5	ESO	8	PP	46