# CCD based curvature wavefront sensor for Adaptive Optics

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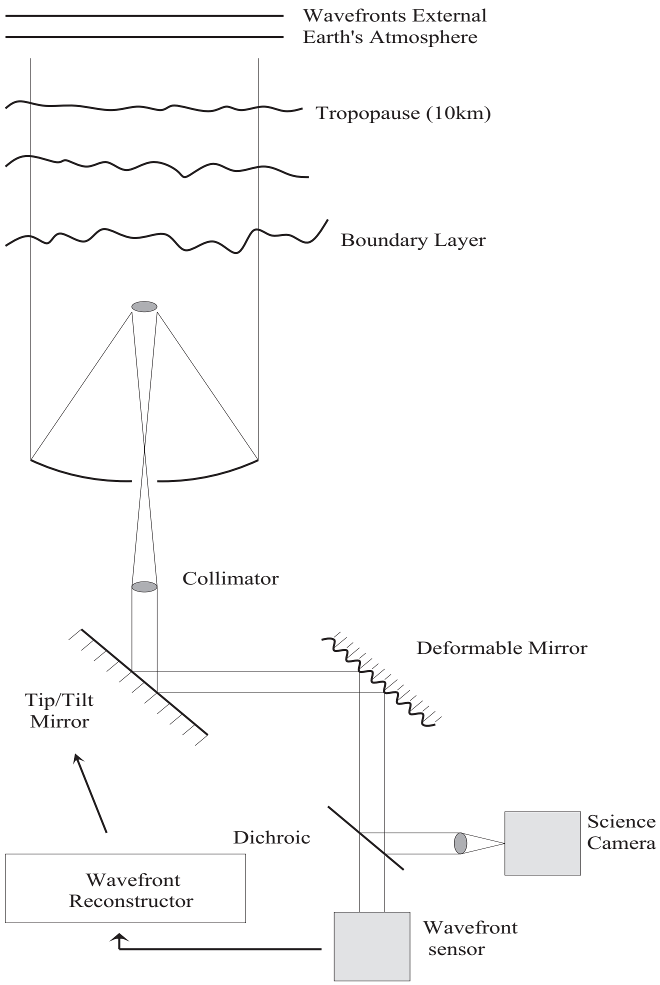
# Contents

# A simple adaptive optics system




- Most precious signal is the signal detected by the wavefront sensor.
  => Primary limit of performance is photon noise of the signal at the wavefront sensor.

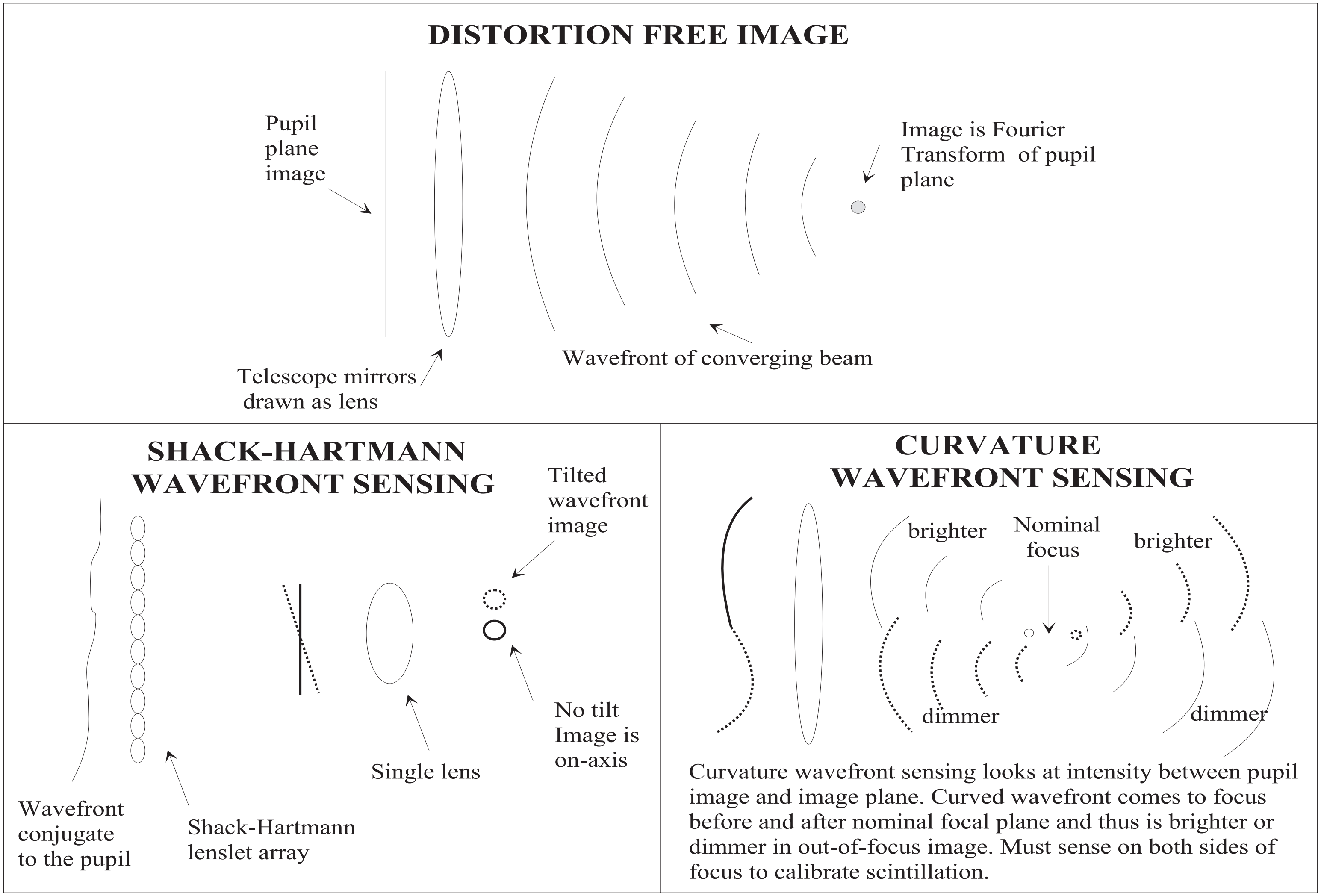
- Atmospheric distortions changes on timescales of 10 to 30 msec.
  => very short exposures needed (1 msec)

# Basic requirements for wavefront sensors

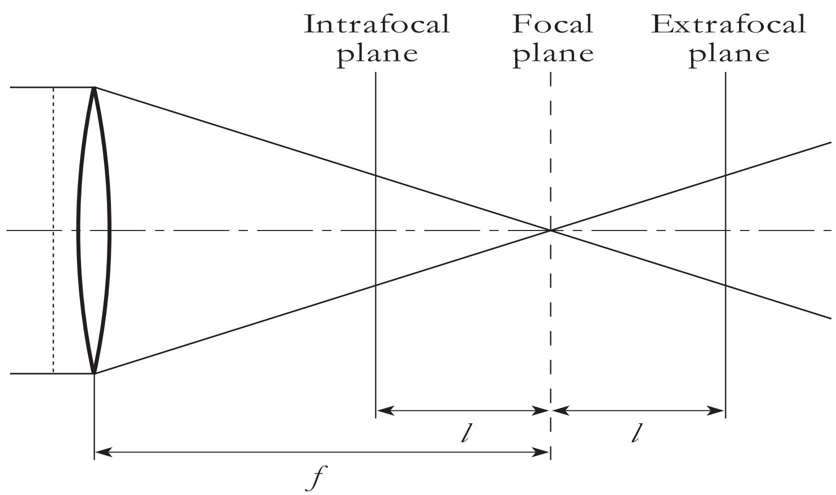
- High Quantum efficiency
- Low readout noise
- Ability to take very short exposures
- Fast readout must be possible
- Minimum phase lag (minimum delay)

*Limit of the wavefront sensor should only be photon noise!*

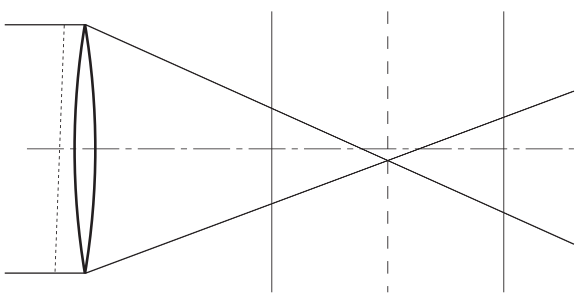
# Shack -Hartmann and curvature sensing

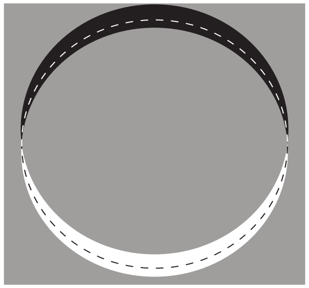


# Curvature sensing (1)




- A flat wavefront focused by a lens, showing the **intrafocal** and **extrafocal** image planes on either side of the focal plane.





- Propagation of a flat but tilted wavefront and the resulting curvature signal.
- Grey is a curvature signal of zero, white is positive and black is negative.
- The dashed line shows the outline of the pupil.

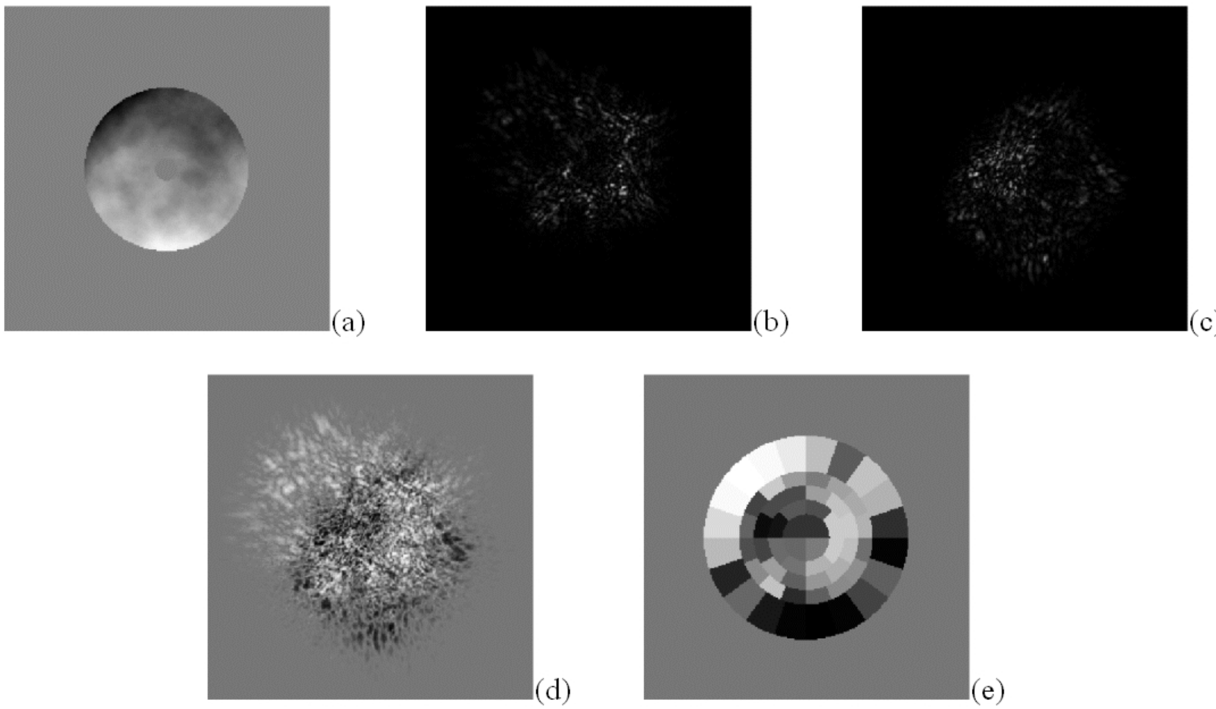
# Curvature sensing (2)

- The change in intensity from intrafocal to extrafocal planes is due to the curvature of the wavefront over the pupil and the tilt of the wavefront at the pupil edge.
- The usefulness of this signal for adaptive optics was first recognized by Francois Roddier (1987) and he first presented a system concept for wavefront sensing (Roddier, 1988).
- Using the vector *r* for the location *x,y* in a *z*-plane, $I_1$, $I_2$ for the intrafocal and extrafocal images, and *l* for the intra- and extrafocal distances, Roddier used the geometrical optics approximation to derive the curvature signal as,

$$S(r) = \frac{I_2(r) - I_1(-r)}{I_2(r) + I_1(-r)} = \frac{\lambda f(f-l)}{2\pi l}\left[\nabla^2\phi\left(\frac{fr}{l}\right) - \frac{\partial\phi}{\partial n}\left(\frac{fr}{l}\right)\delta_c\right]$$

- where *f* is the telescope focal length, is the derivative in the outward pointing radial direction and is a linear impulse function at the edge of the pupil (both at the outer edge of the primary and the inner edge due to secondary obscuration).
- The radial wavefront tilts provide the boundary conditions necessary to determine the phase from the curvature signal. Normally, in an operating curvature AO system, the phase is never computed as the Poisson equation is solved automatically by the bimorph mirror response function. Since tilt is only sensed at the pupil edge and the curvature signal is sensed over the entire pupil, this approach of sensing wavefront distortions is called **curvature wavefront sensing.**

# Curvature sensing - Computer simulation of curvature wavefront sensing




- AO loop open:

(a) wavefront distortion,

(b) intrafocal image,

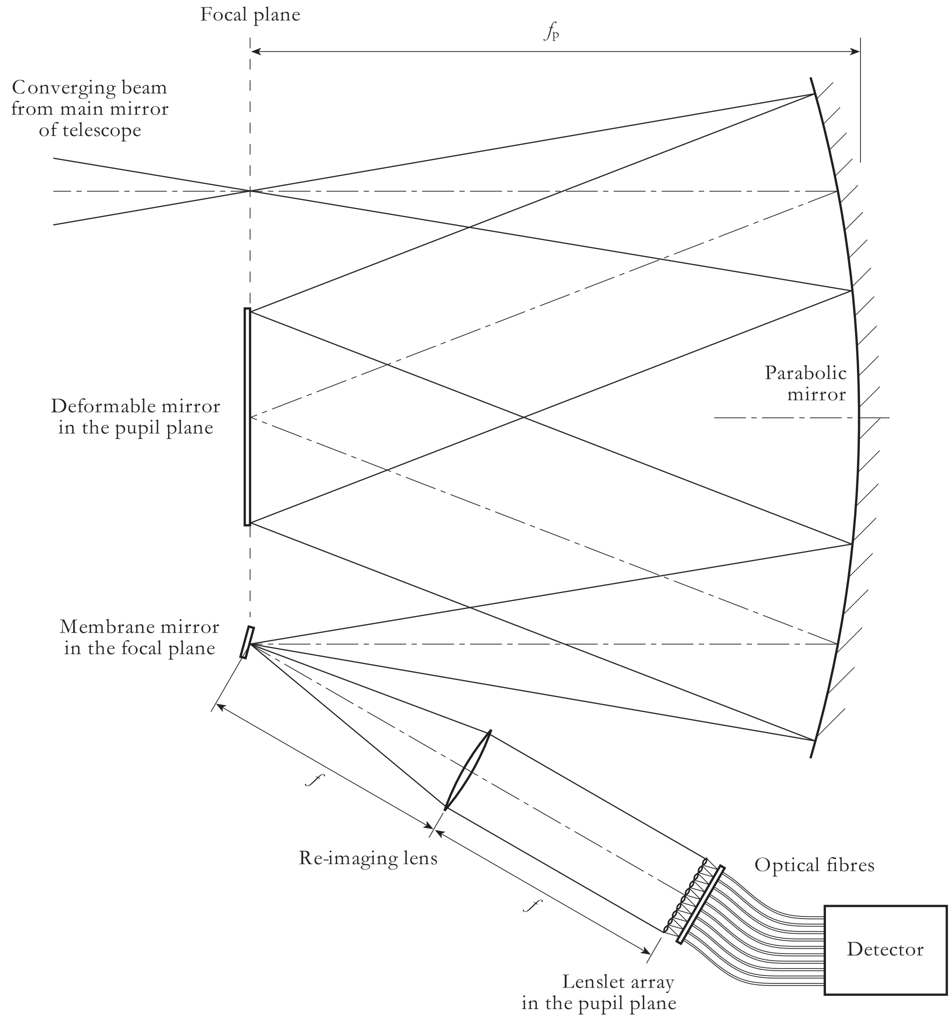
(c) extrafocal image

(d) curvature signal at high resolution,

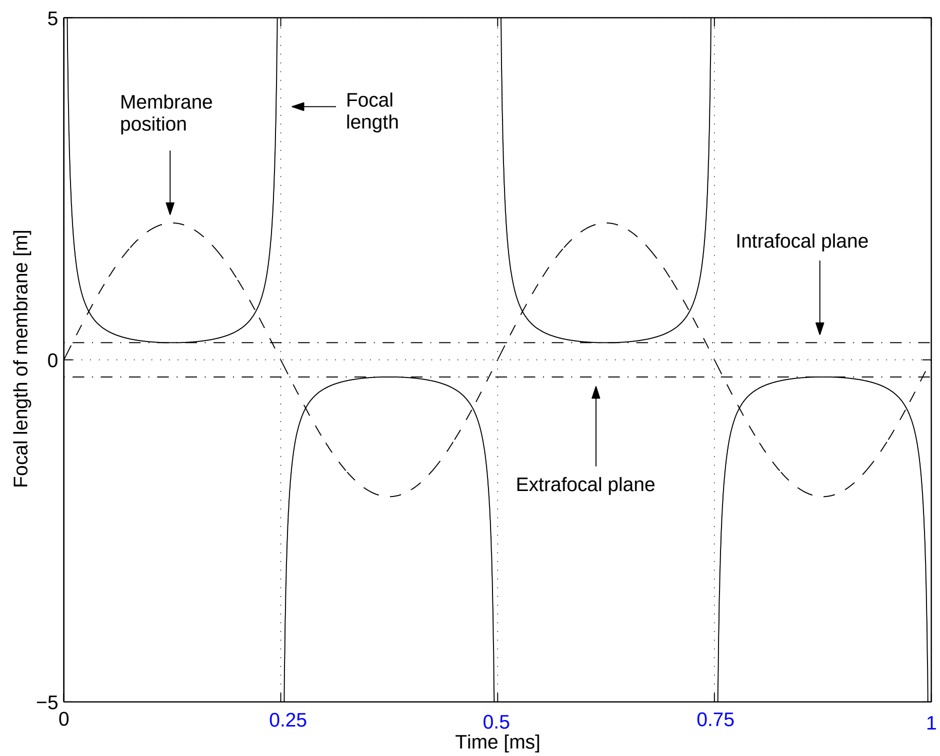
(e) curvature signal binned into 60 subapertures.

- Simulation parameters: 0.66 arc sec seeing (at 500 nm), sensing wavelength = 700 nm (monochromatic), infrared image wavelength = 2.2 µm, out of focus distance = 25 cm, telescope focal length = 400 m, telescope diameter = 8 m with 14% obscuration from 1.12 m diameter secondary. Photon noise has not been simulated – all signals are “infinite” light level.

# Implementation - AO curvature wavefront sensor

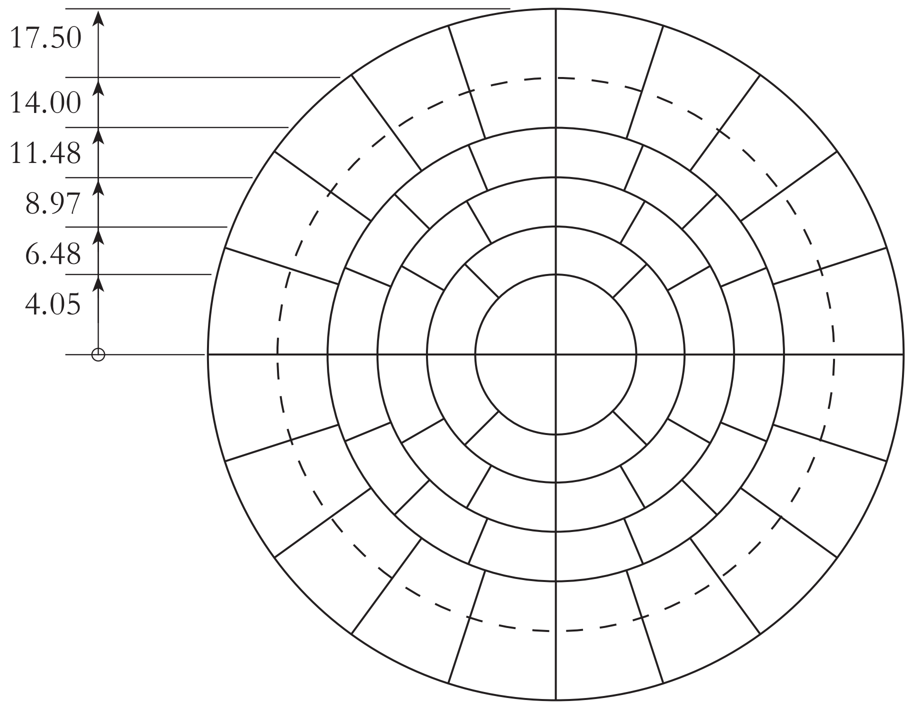


# Membrane function




- Membrane amplitude (dashed line) and membrane focal length (solid line) as a function of time for a 2 kHz membrane frequency with the minimum focal length set to 25 cm. Typical parameters for a membrane are: $d = 10$ mm, $f_{min} = 25$ cm, $A = 100$ µm. It is amazing what an oscillation of a small mirror by the width of a human hair can do!

# Subaperature geometry




- Subaperture geometry for ESO's 60 element curvature AO systems

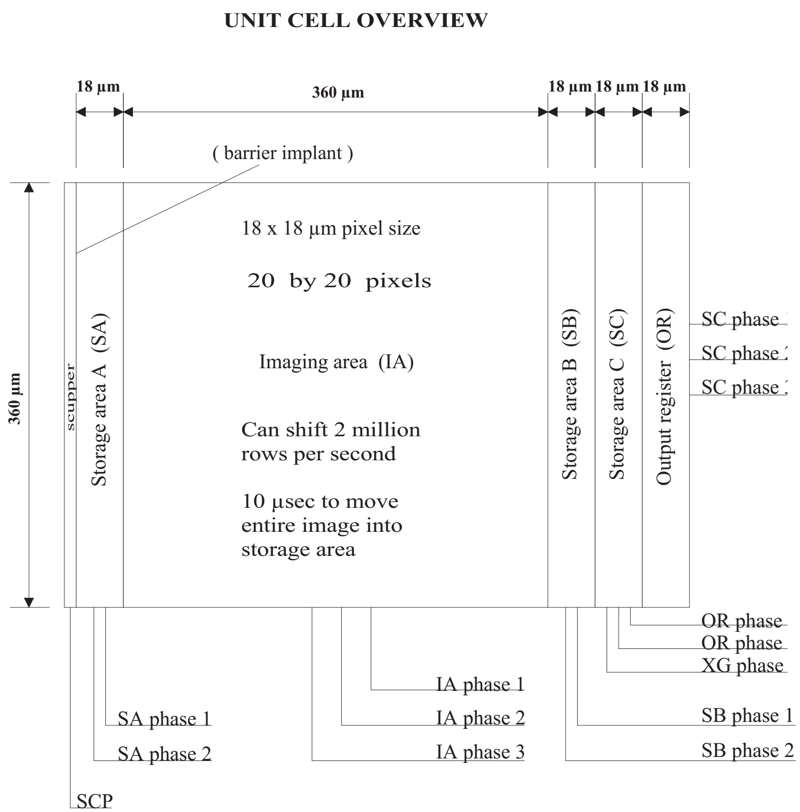
# CCD design - design considerations

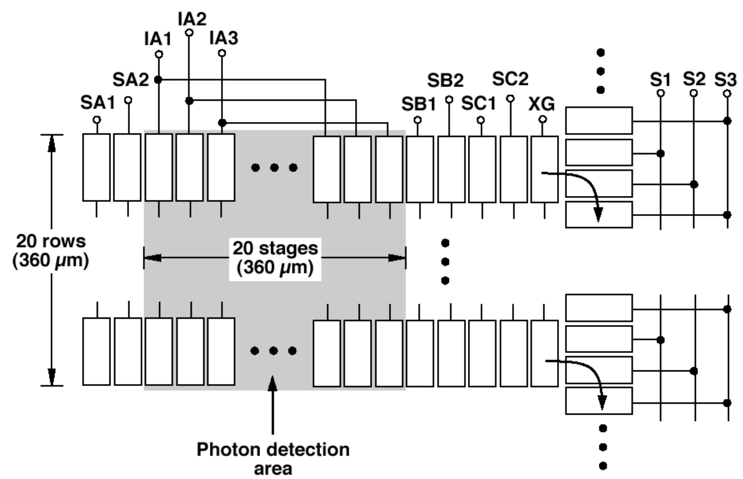
- 60 integration areas
- Very short exposure times (250 µsec) with "long" integration times (1 to 20 msec, 2 to 40 membrane cycles)
- Ability to switch between half-cycle integrations within 10 µses
- Lowest possible noise: 2 electrons maximum, < 1 electron desired (including all sources – dark current, readout noise, etc.)
- Ability to store half-cycle frames on-chip while integrating other half-cycle frames.

The key to making a CCD work in this application is on-chip integration. In order to fulfill the requirements, we have utilized the following design options:

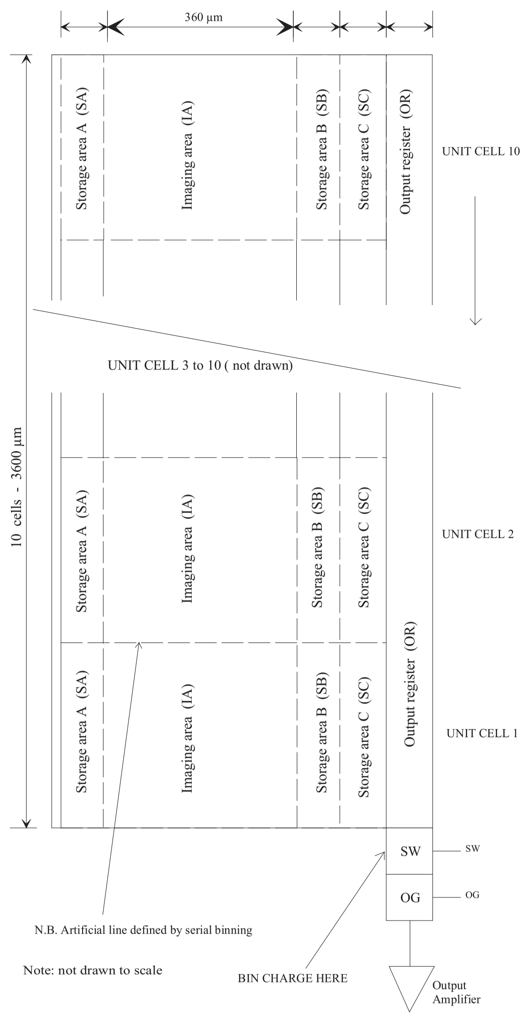
- Use superpixels, i.e. bin on-chip, to loosen alignment tolerances
- Layout pixels on a grid to lower risk (keep it simple!), using fibers to feed from the lenslet array to the CCD, as is done with APD modules
- Use multiple readout ports to have slower readout rates and lower readout noise.

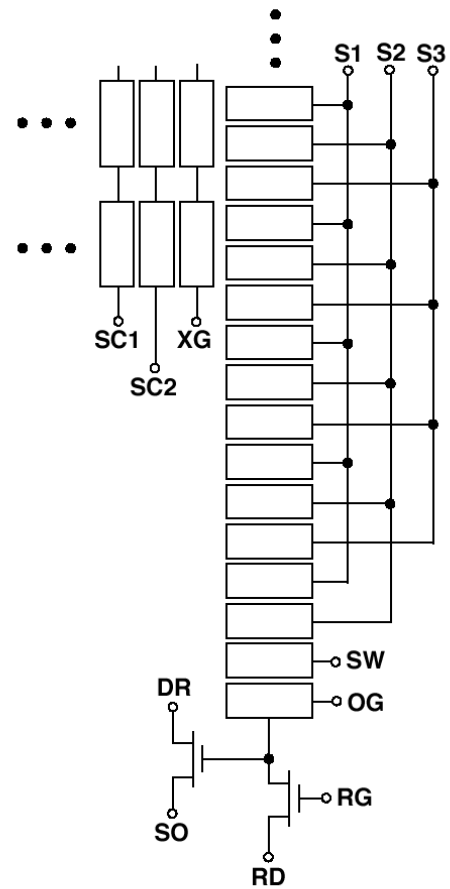
# CCD design -unit cell



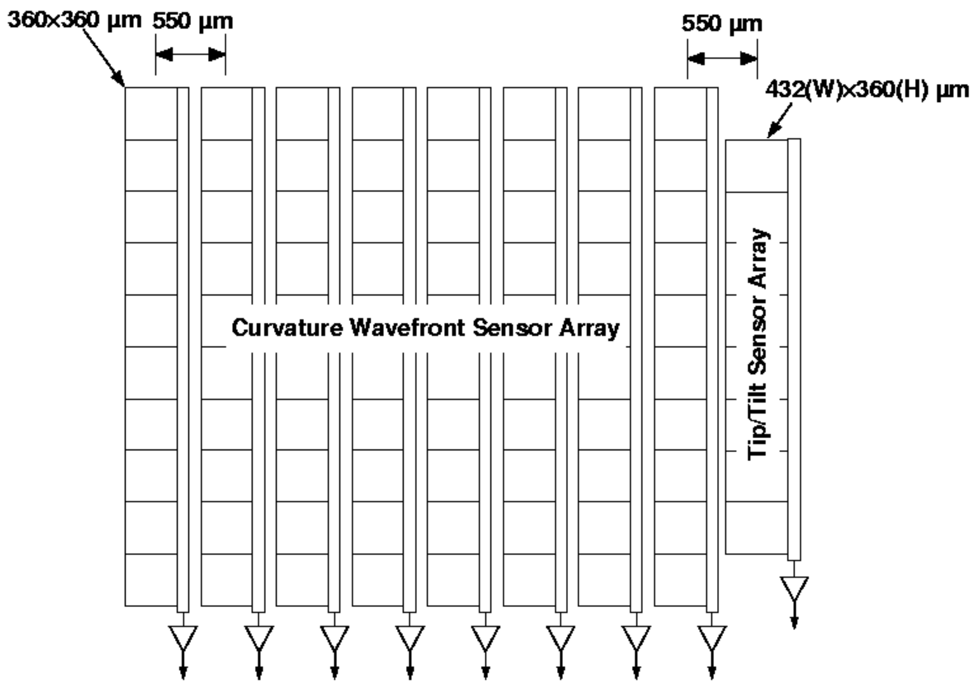



# CCD design -unit column



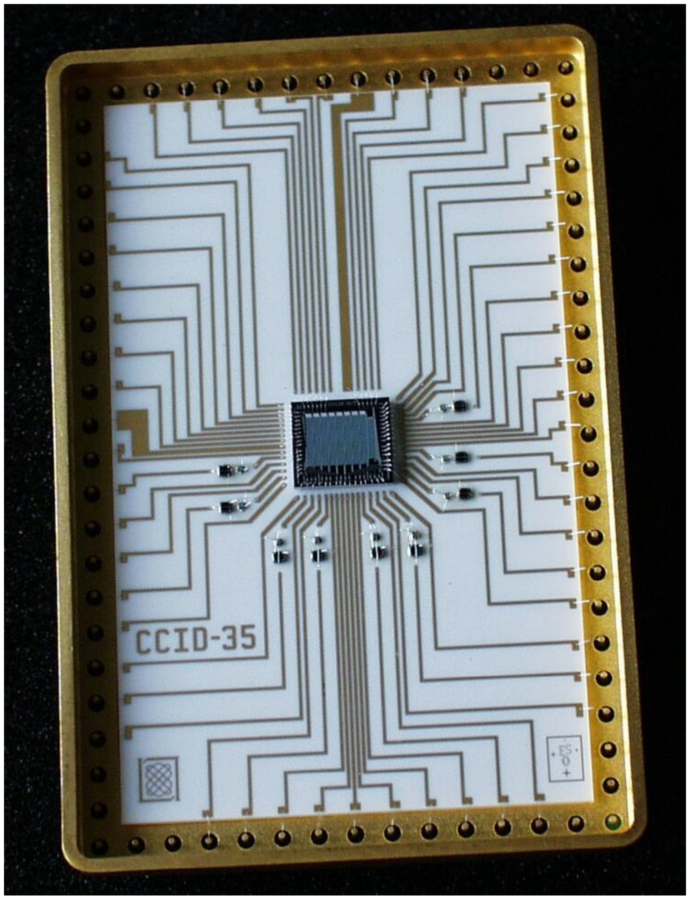



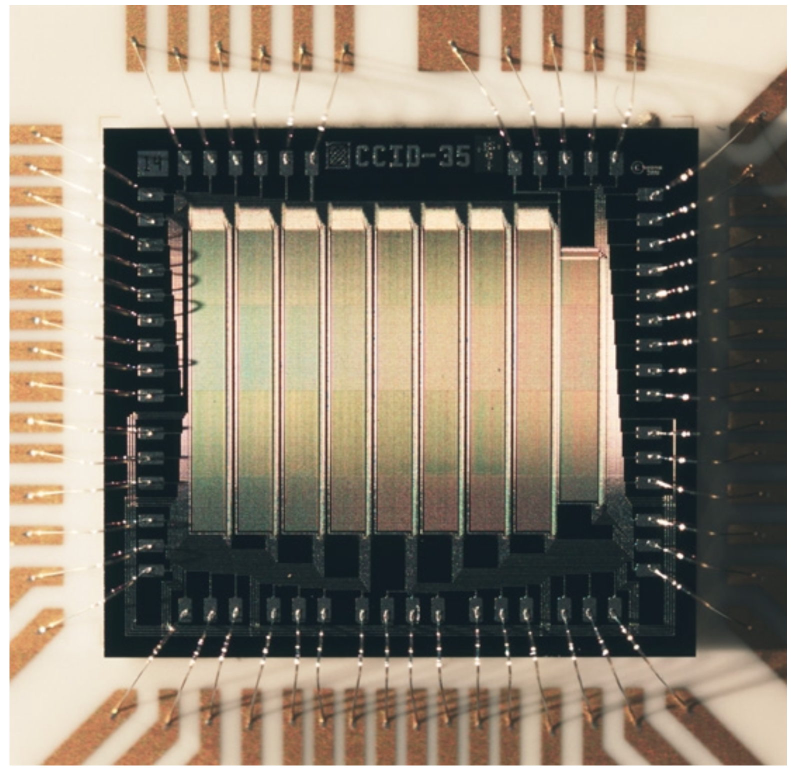
# CCD design -CCD array




- Curvature wavefront sensor array.
- The design consists of 80 unit cells. Ten unit cells are combined into a unit column.
- Each of these unit columns has an amplifier at the "bottom" end of the serial register.
- One the right side of the device is the tip/tilt sensor.

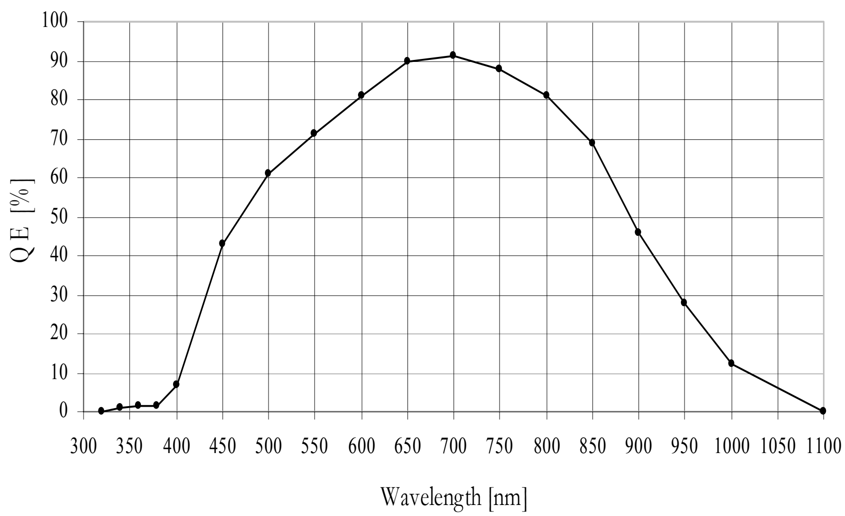
# ESO / MIT/LL CCID-35



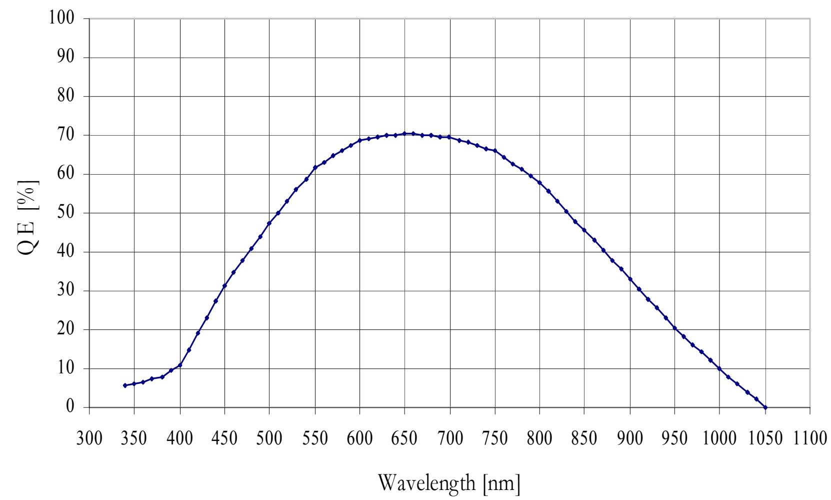



# Expected QE for the thinned CCD (versus APD)

Expected quantum efficiency of the CCID-35 for curvature wavefront sensing




Measured quantum efficiency of an EG&G APD module

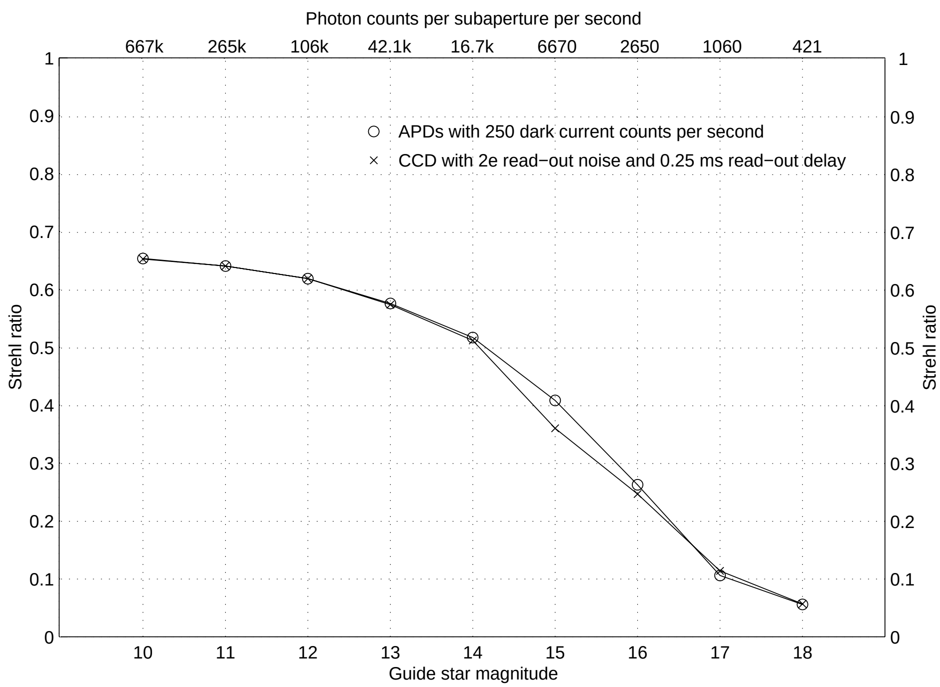



• High Quantum efficiency (peak > 90%)

+ the ability to store charge while reading and integrating

• *Thinned versions of the CCD are expected by the end of 2001*

# System performance - Simulation results




*Strehl ratio in K-band for the different detectors.*

*Specifications of the detectors.*

| Property | APDs | CCD |
|---|---|---|
| Peak quantum efficiency | 70% | 80%* |
| Dark current [electrons/s] | 250 | 0 |
| Read-out noise [electrons RMS] | 0 | 2 |
| Read-out delay [µs] | 0 | 250 |

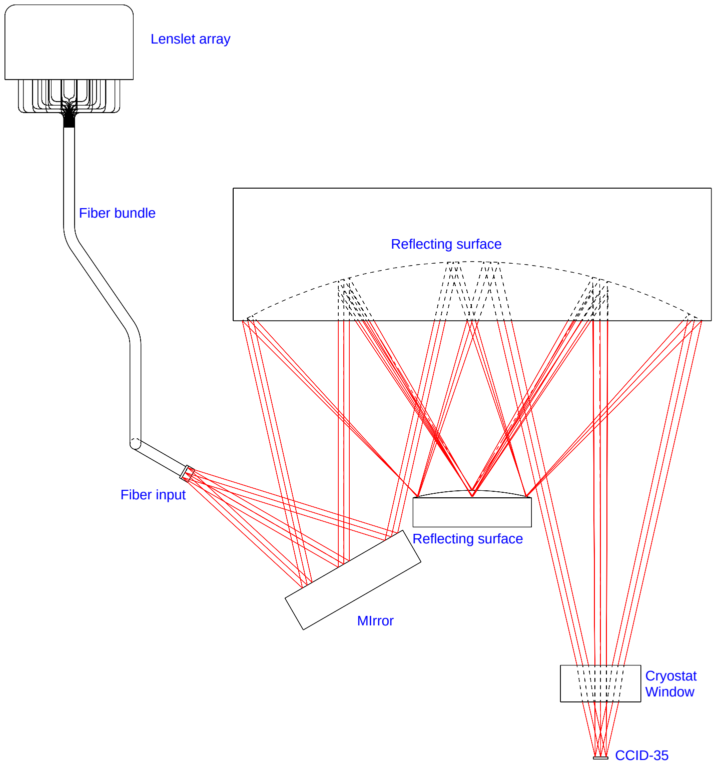
* includes light loss in the additional relay optics required for the CCD.

Measuring the integrated Strehl ratio in K-band achieved by the system for guide stars of magnitude 10 to 18, these curves are obtained.

The difference in performance between APDs and the CCD is only significant at magnitude 15 and 16 where the APDs perform better than the CCD by five and two percent Strehl respectively.

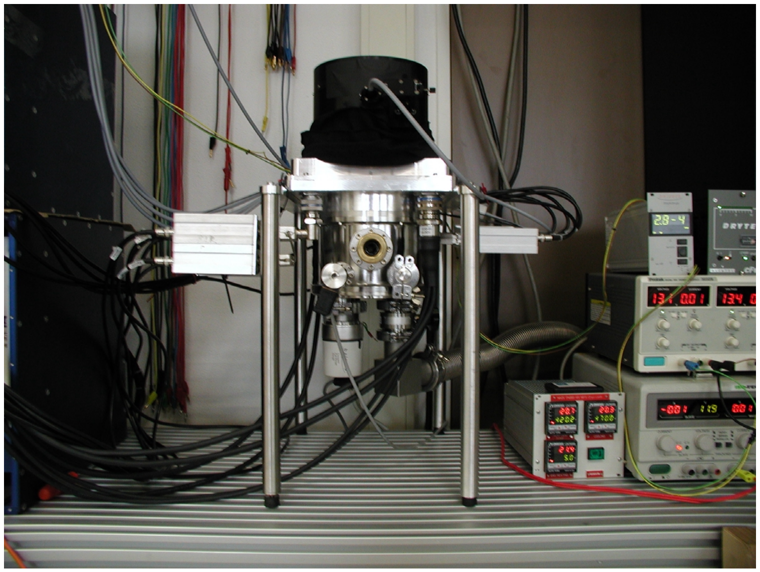
For all other magnitudes, the difference amounts to less than 0.6 percent Strehl.

# Laboratory system design - Relay optics



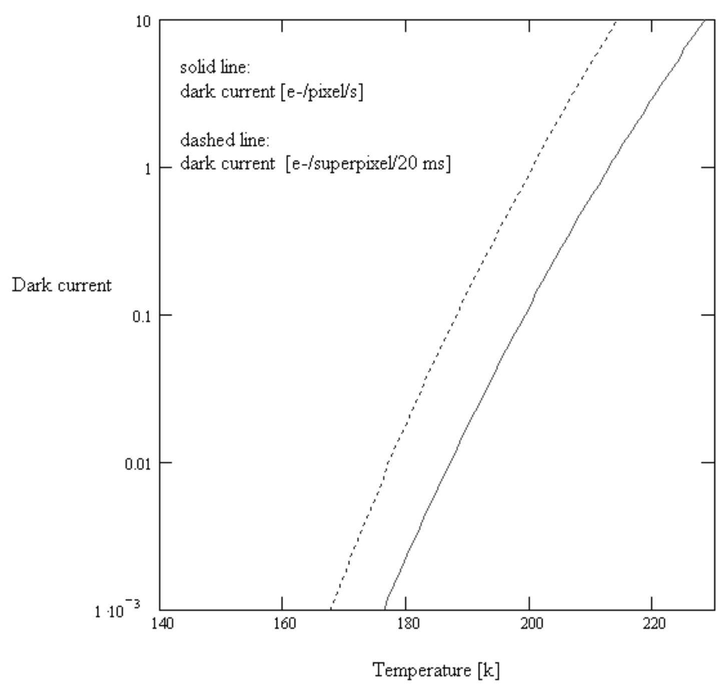

- An Offner Relay design consisting of two spherical, reflecting surfaces will be used to re-image the light of the fibers 1:1 onto the superpixels
- Optics has a maximum blur of 60 microns (100% encircled energy)
- Fiber is comparable to a 3 arcsec field of view in the VLT curvature AO system design

# Laboratory system design - Cryostat



*Cryostat design by J.L. Lizon*

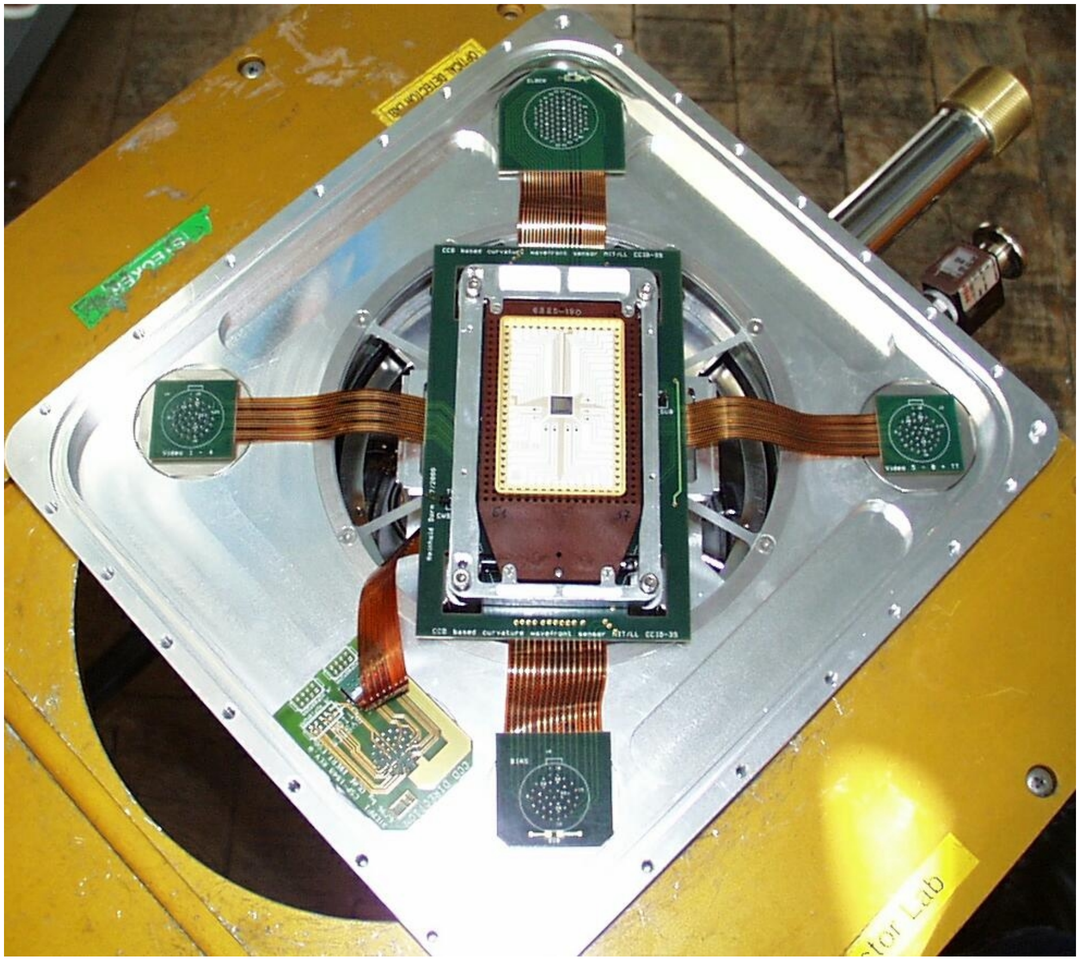
Calculated dark current for the MIT/LL CCID-35




•The CCD must be cooled to a temperature of 192 Kelvin or - 81°C to achieve a dark current of 0.25 electrons per superpixel at 50 Hz frame rate.

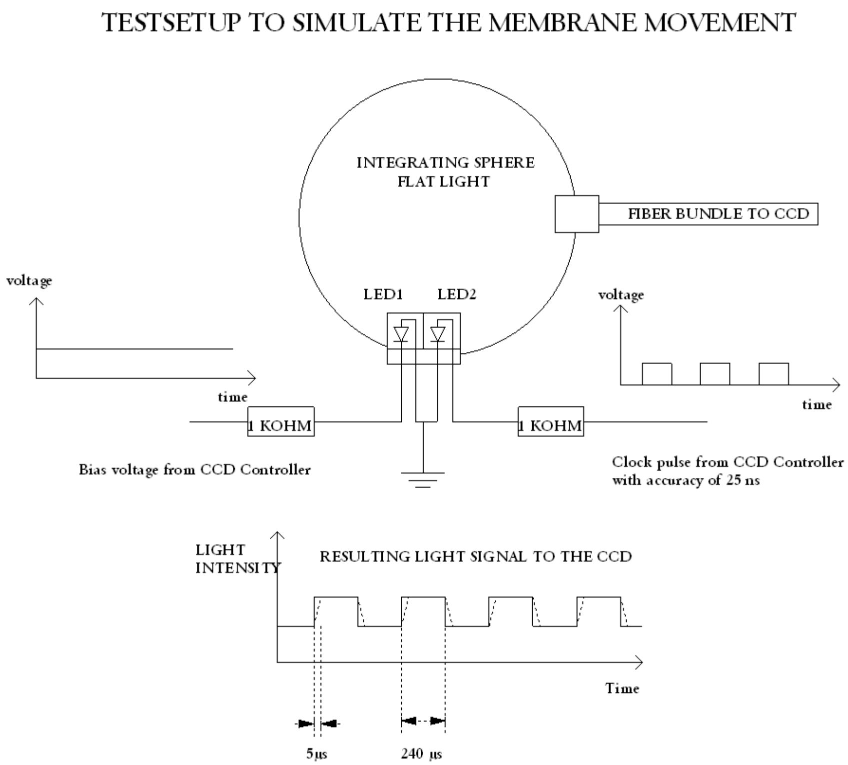
•Thus liquid nitrogen and a cryostat is used to cool the CCD.

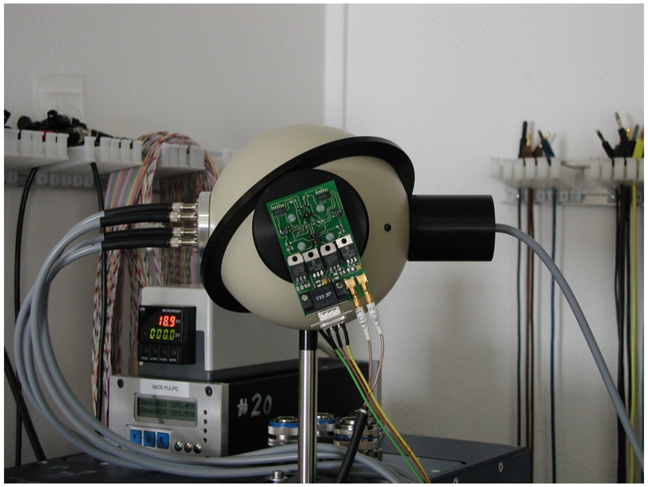
# Laboratory system design - Detector board



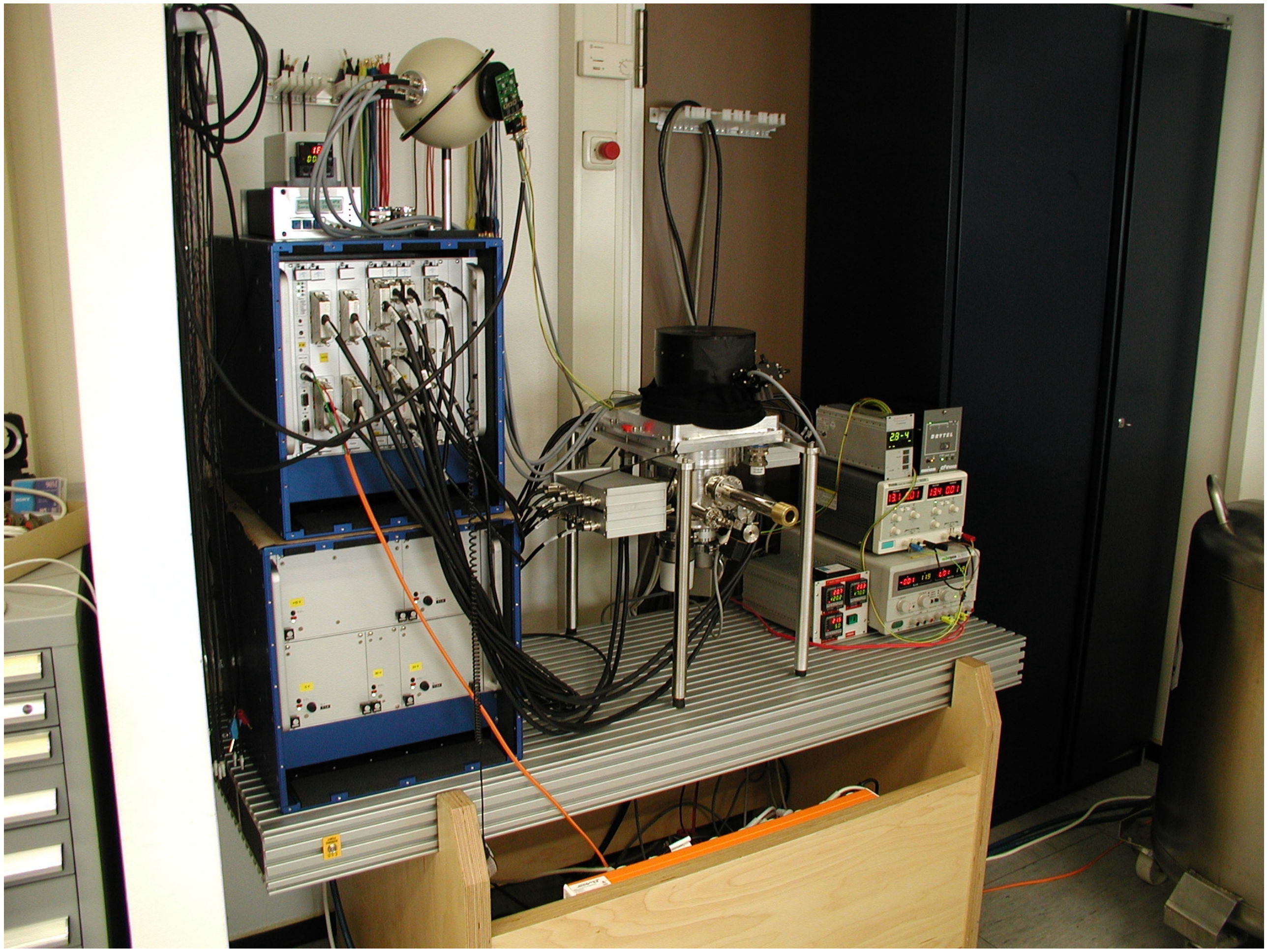
- Detector board important for low noise performance
- No connectors inside the cryostat
- No active electronics inside the cryostat

# Laboratory system design - Fiber Feed and Simulation setup

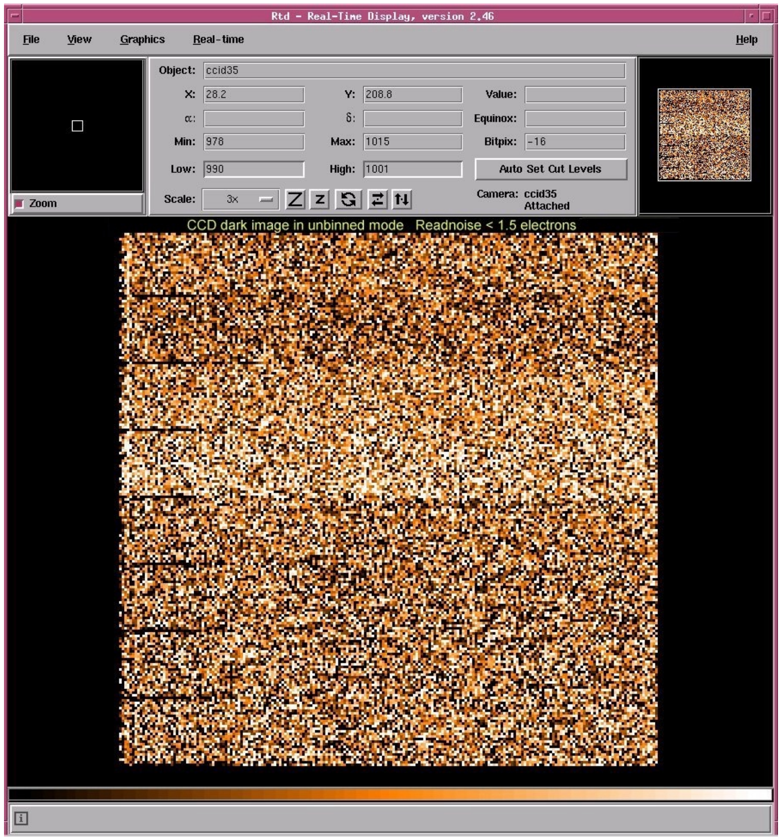


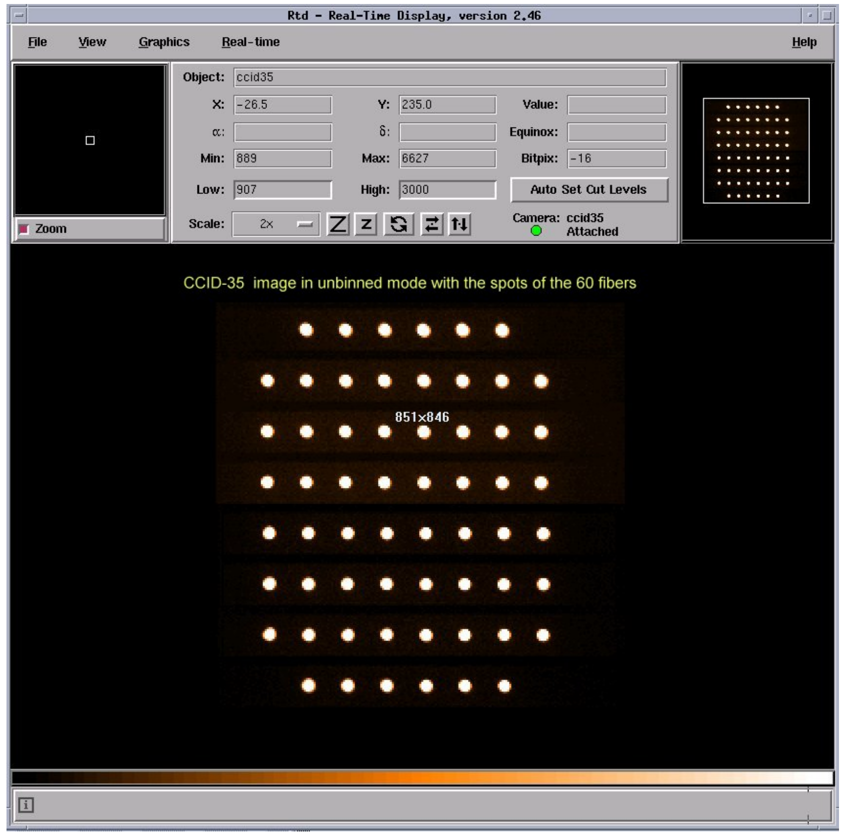



# Laboratory system design - Picture of the lab system

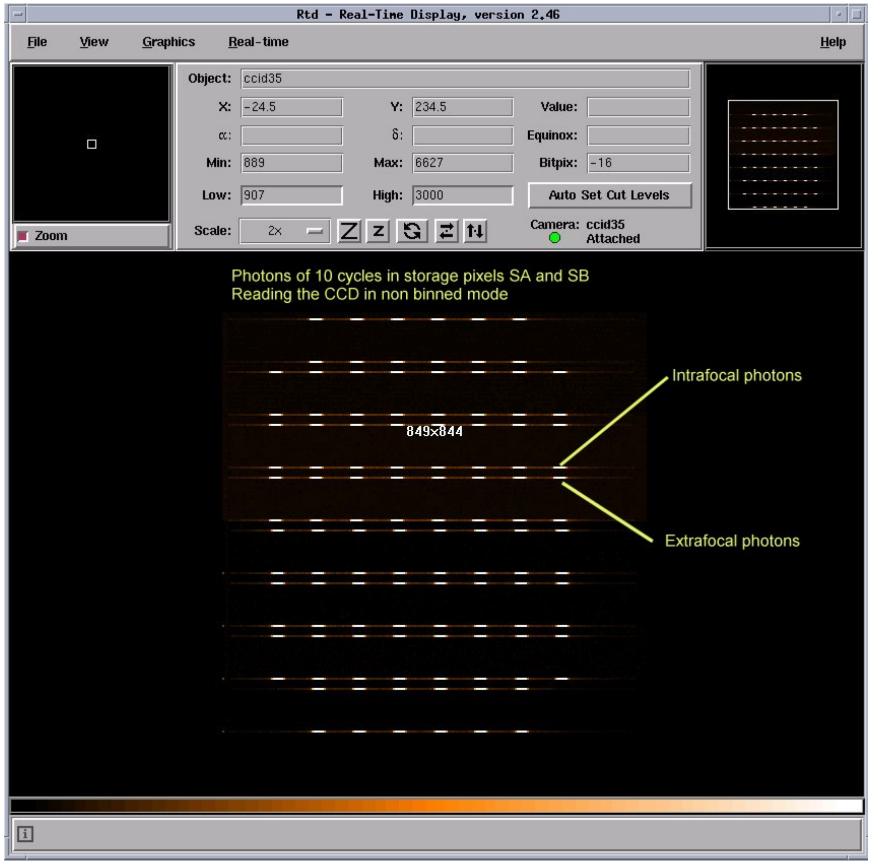


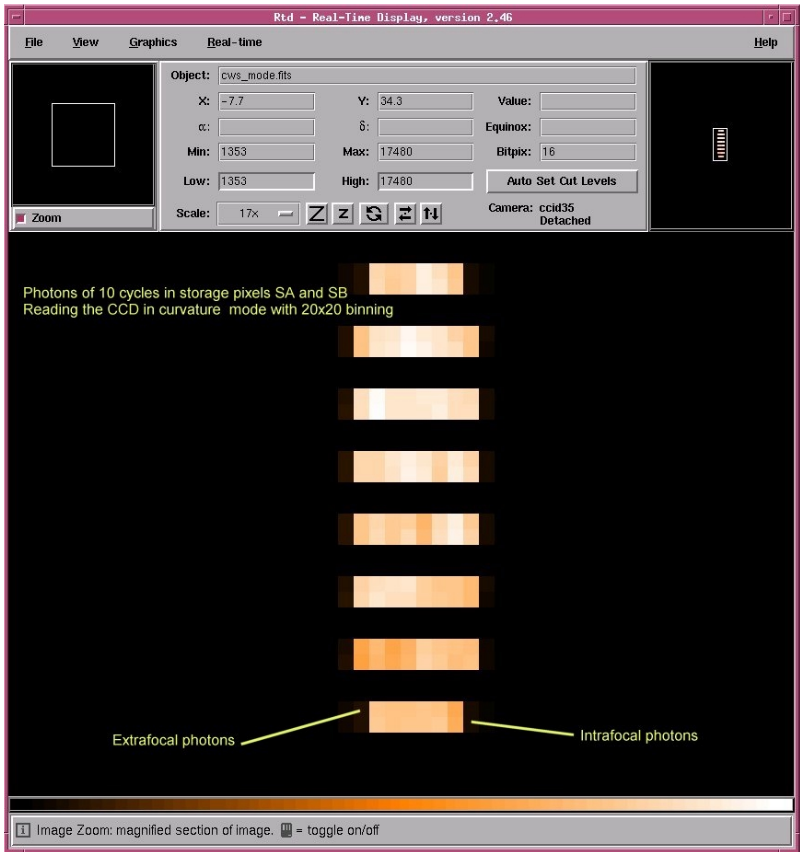
# Results - CCD readout modes



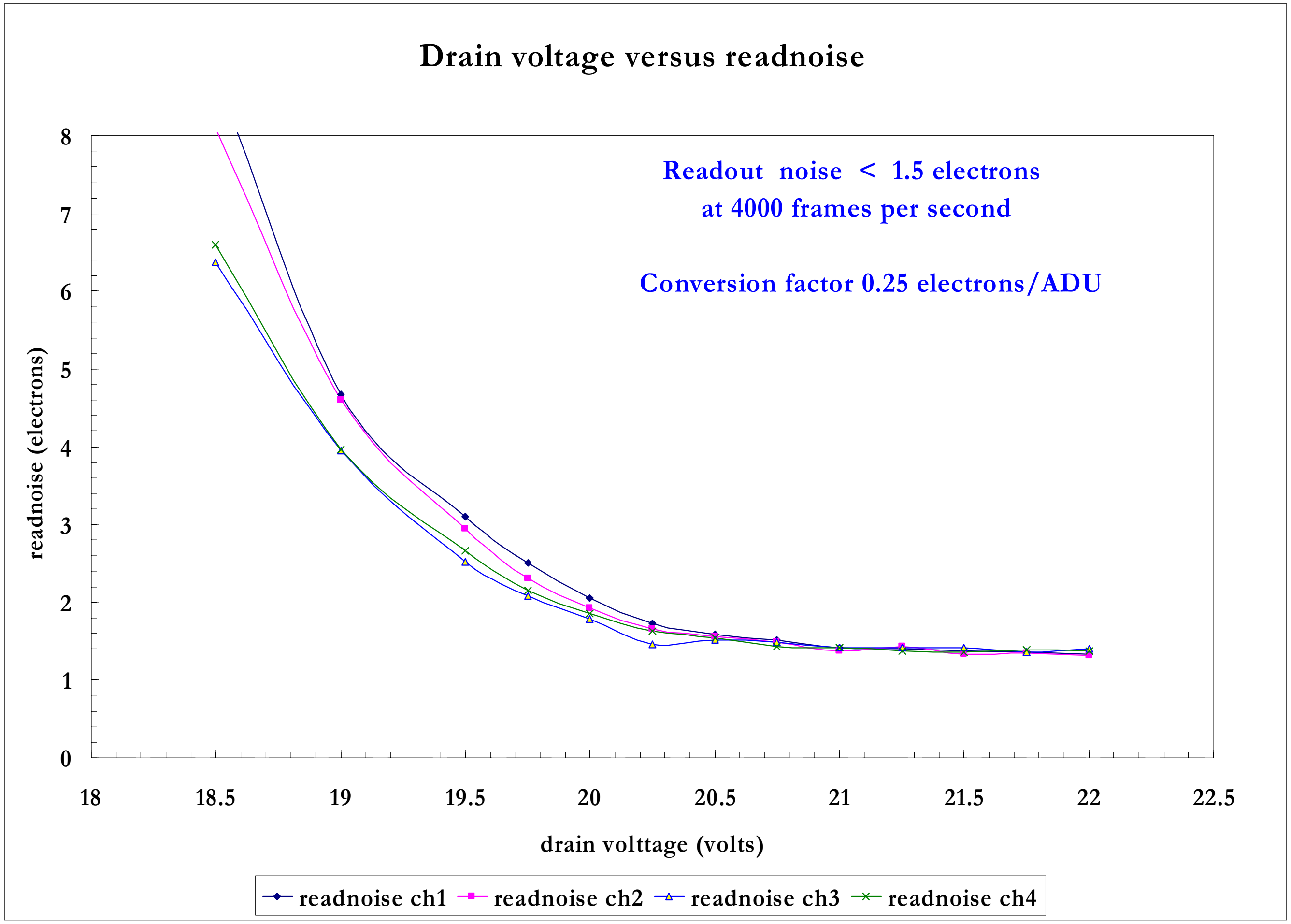



# Results - CCD readout modes

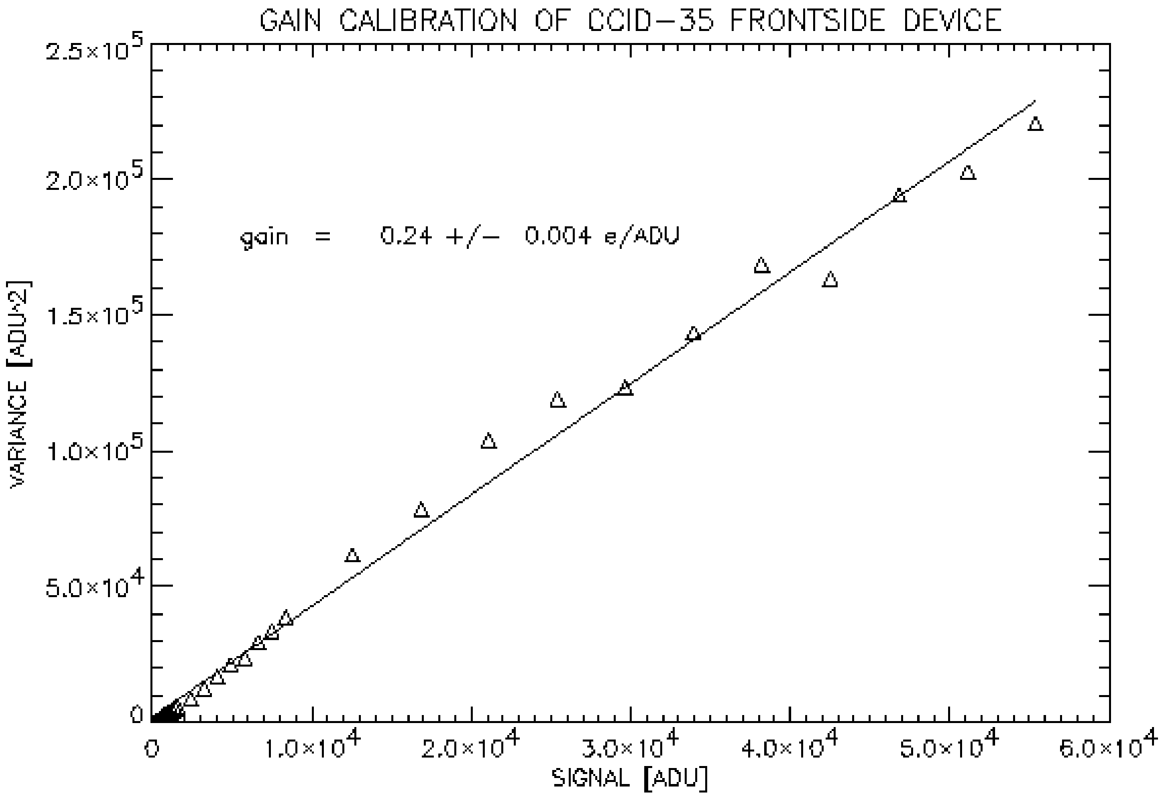


# Results - CCD readout noise performance

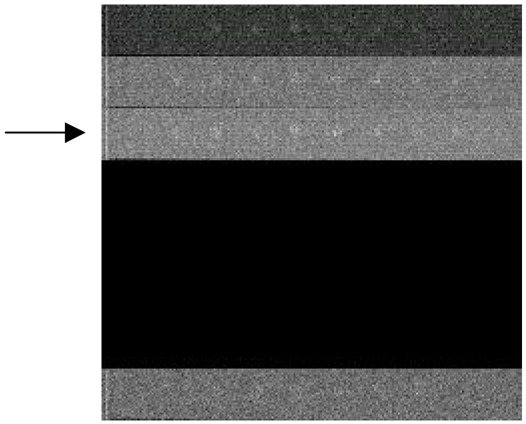


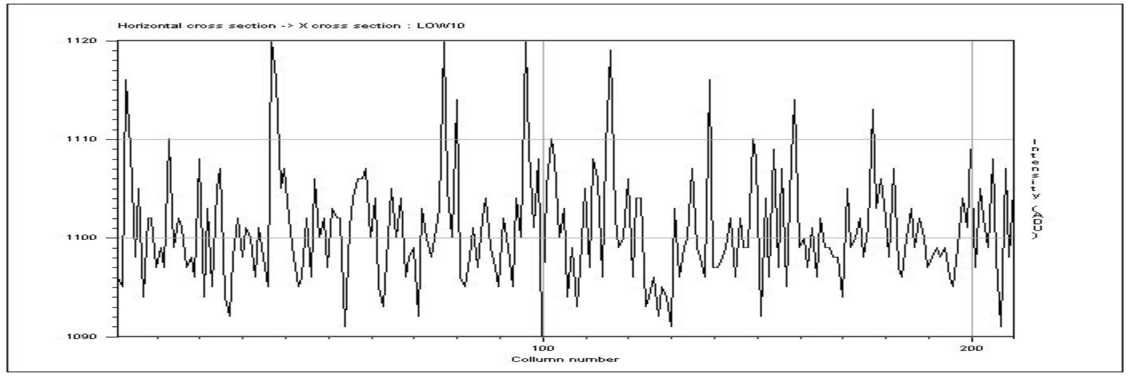
# Results - Photon Transfer Curve



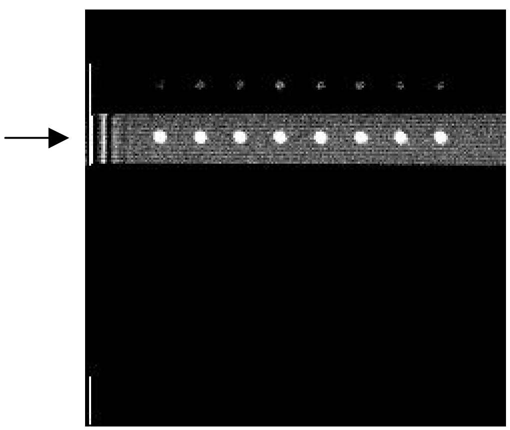
# Results - moving small charge packages

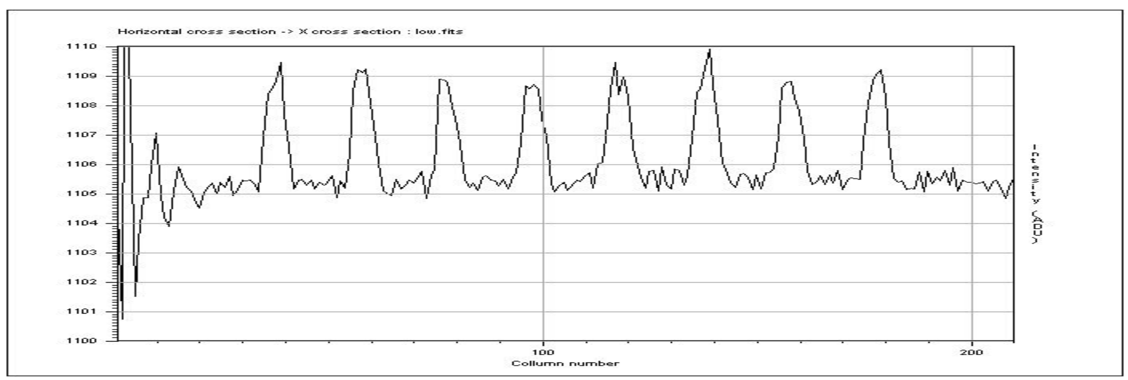
Single exposure ~ 1 electron/pixel (readout noise 1.3 electrons @ 50 kps)





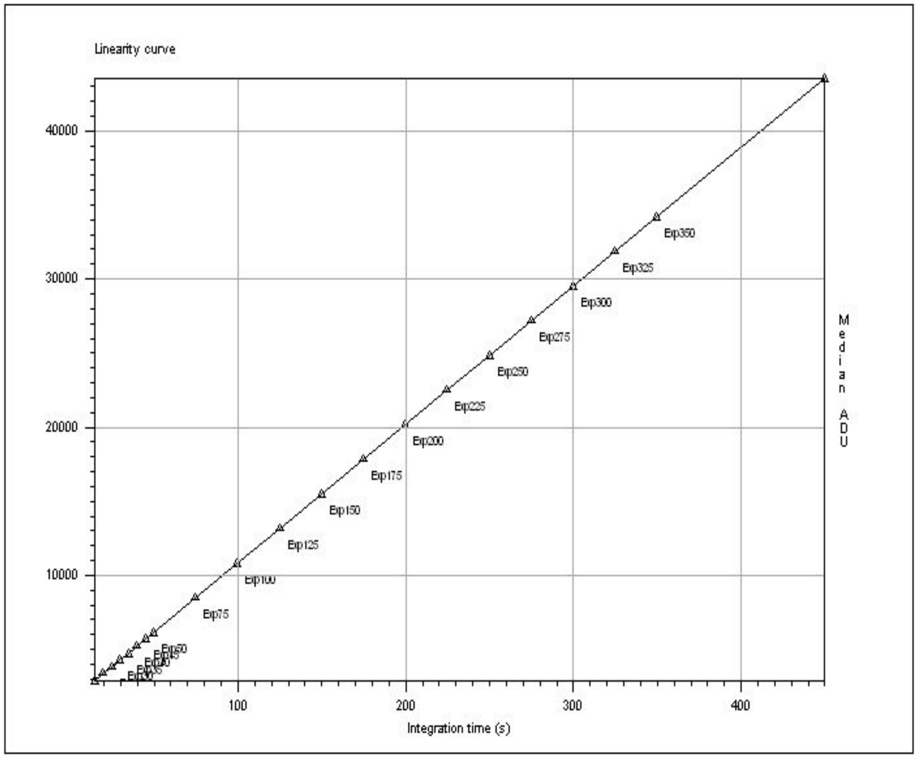

Sum of 256 exposures and then normalized



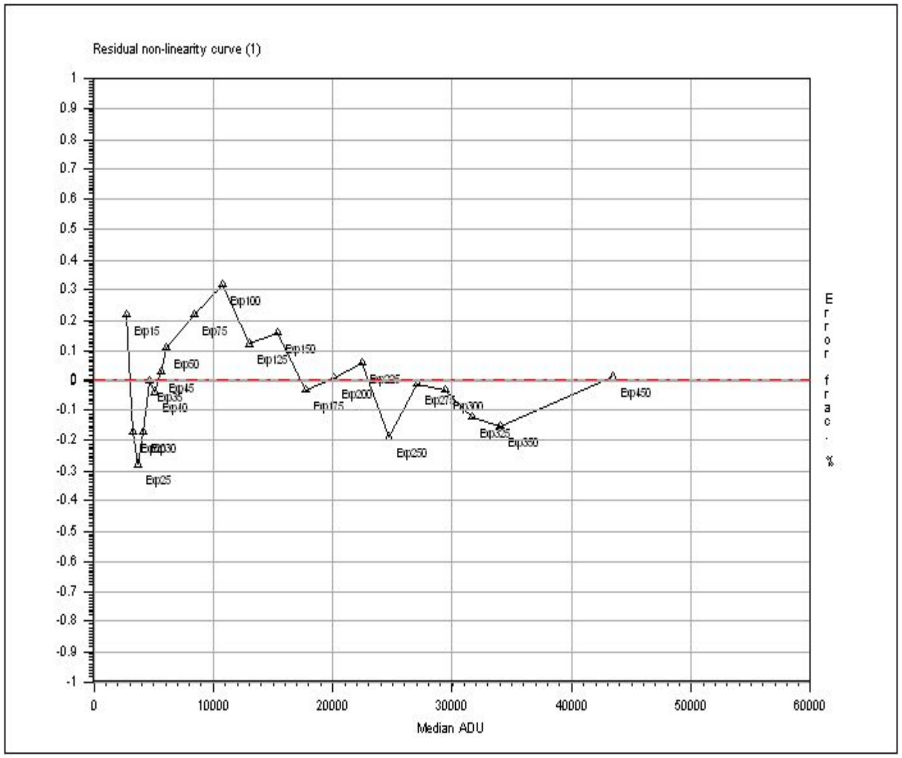


# Results - CCD Linearity

## Linearity curve up to full well @ 20000 electrons)




## Residual non Linearity curve



# From a prototype system to a science system

- Evaluation of the thinned versions of the CCD.

  *(Difference should only be higher QE for the thinned CCDs!)*
- Requires new PCB inside the Cryostat.
- FIERA DSP/control software adaptation.
- Synchronization of the readout modes with the membrane frequency.

  *(Hardware already foreseen in the new FIERA PCI - SLCU).*
- Interface to MACAO OS.
- Timing board /RTC interface board +software.

# Conclusions

- This CCD achieves nearly the same performance as APDs and thinned versions have the potential to work as well as APDs with reduced cost and reduced complexity (no neutral density filters needed, simpler).
- CCD has a higher quantum efficiency than APDs and greater dynamic range than APDs (factor 1000).
- A readout noise of less than 1.5 electrons at 4000 frames per second has been demonstrated.
- This research showed that detectors can be successfully designed for special purposes (instruments).
- Special lenslet array that images the pupil image directly onto the grid structure of the CCD is under investigation (hence no light loss due to relay optics or fibers).