CCD based curvature wavefront sensor for Adaptive Optics

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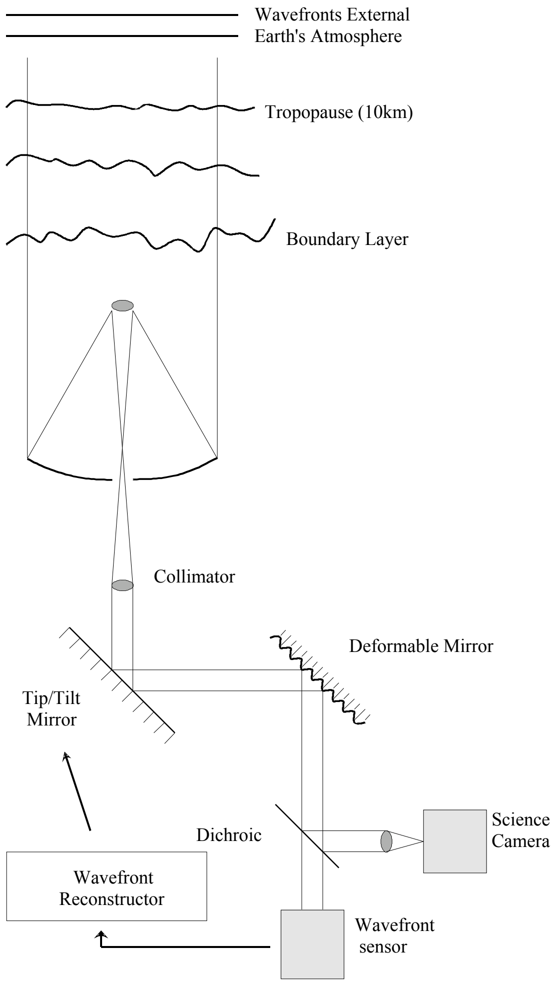
A simple adaptive optics system



- 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)

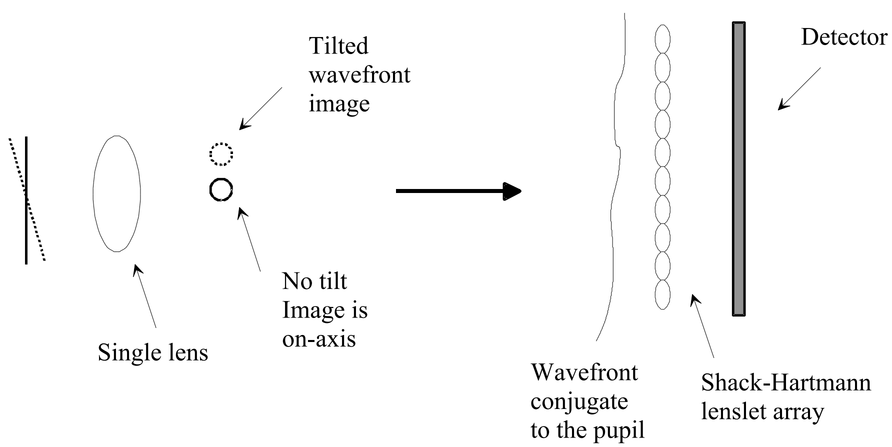
Basic requirements for wavefront sensors

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

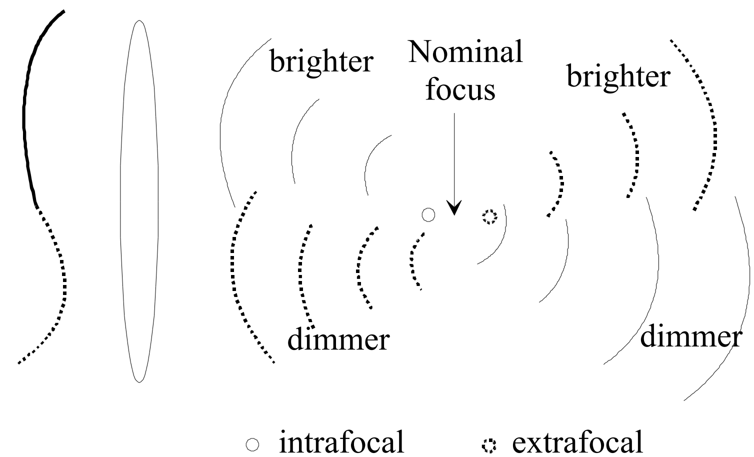
Limit of the wavefront sensor should only be photon noise!

Shack -Hartmann and curvature sensing

SHACK-HARTMANN WAVEFRONT SENSING



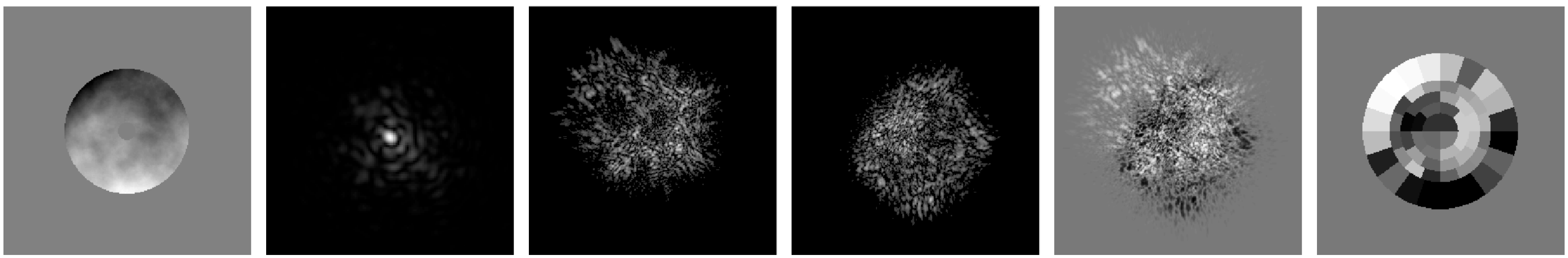
CURVATURE WAVEFRONT SENSING



Curvature wavefront sensing looks at intensity between pupil image and image plane. Curved wavefront comes to focus before and after nominal focal plane and thus is brighter or dimmer in out-of-focus image. Must sense on both sides of focus to calibrate scintillation.

Curvature sensing - Computer simulation of curvature wavefront sensing

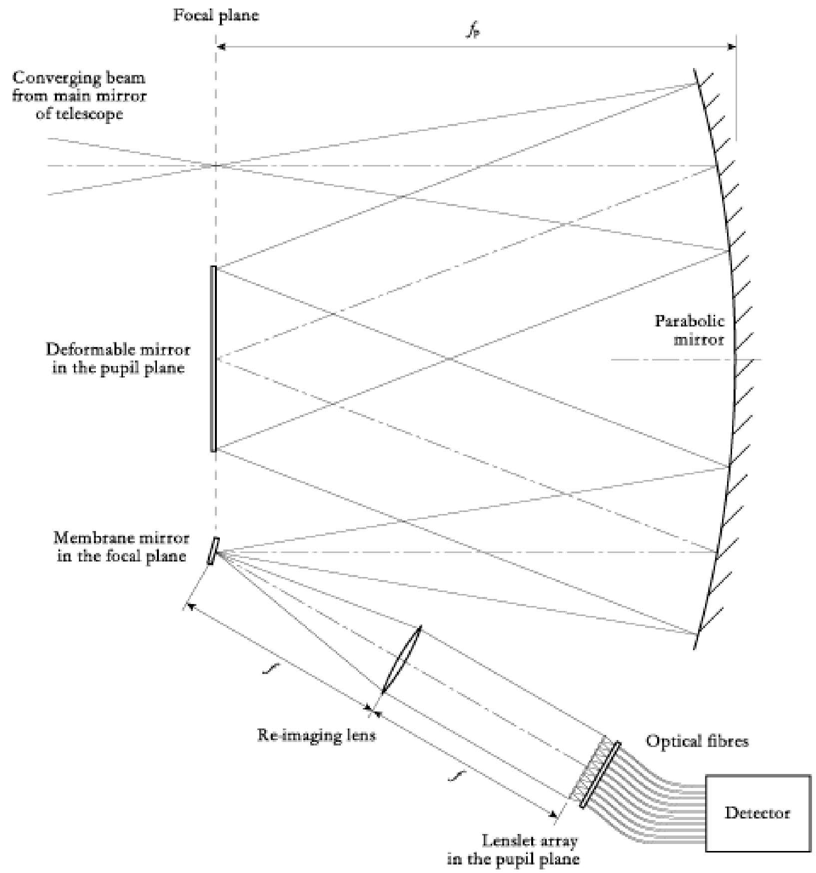
A realistic curvature signal is shown below, which presents a Kolmogorov atmospheric wavefront distortion, the infrared focal plane image, intrafocal and extrafocal images and the curvature signal.



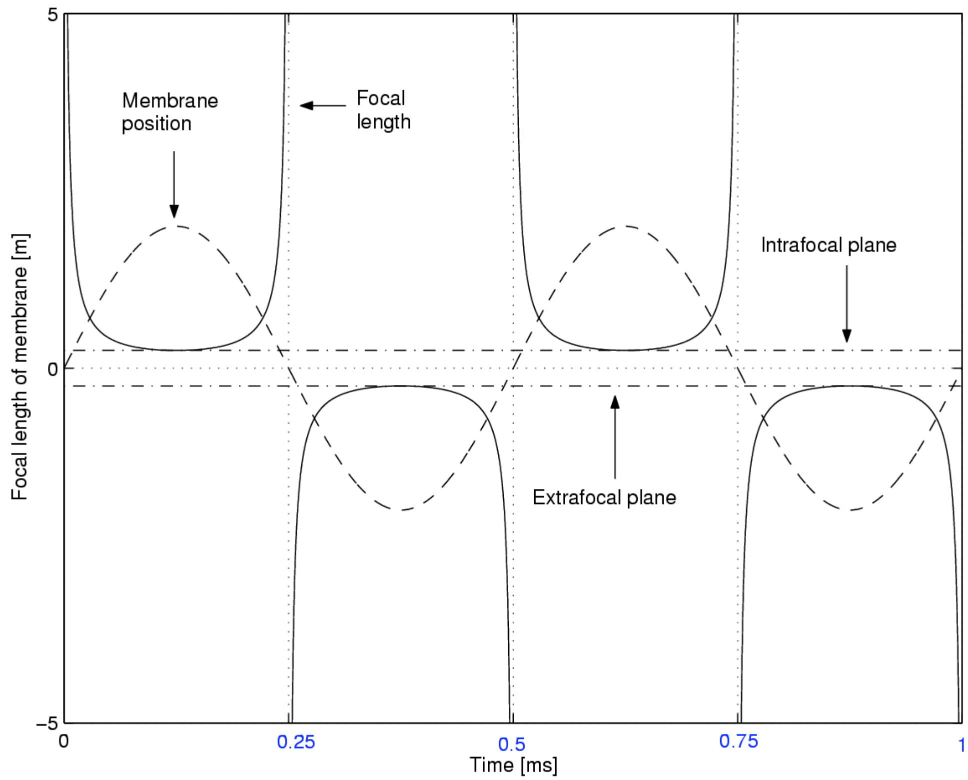
wavefront distortion | *infrared focal plane image* | *intrafocal image* | *extrafocal image* | *curvature signal at high resolution* | *curvature signal binned into 60 subapertures*

Simulation parameters: 0.66 arcsec 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

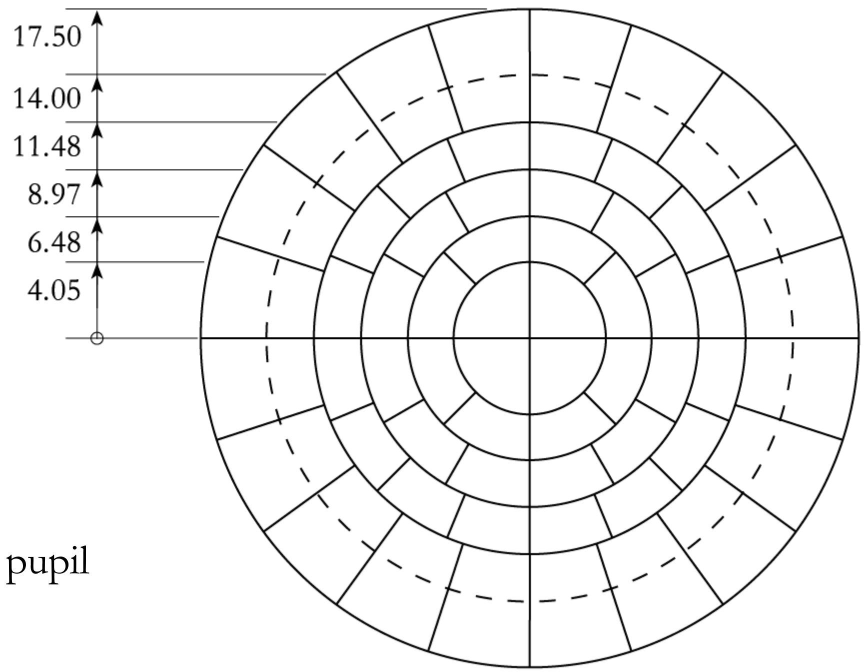


Membrane function



- 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



The dashed circle

shows the outline of the pupil

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

CCD design - design considerations

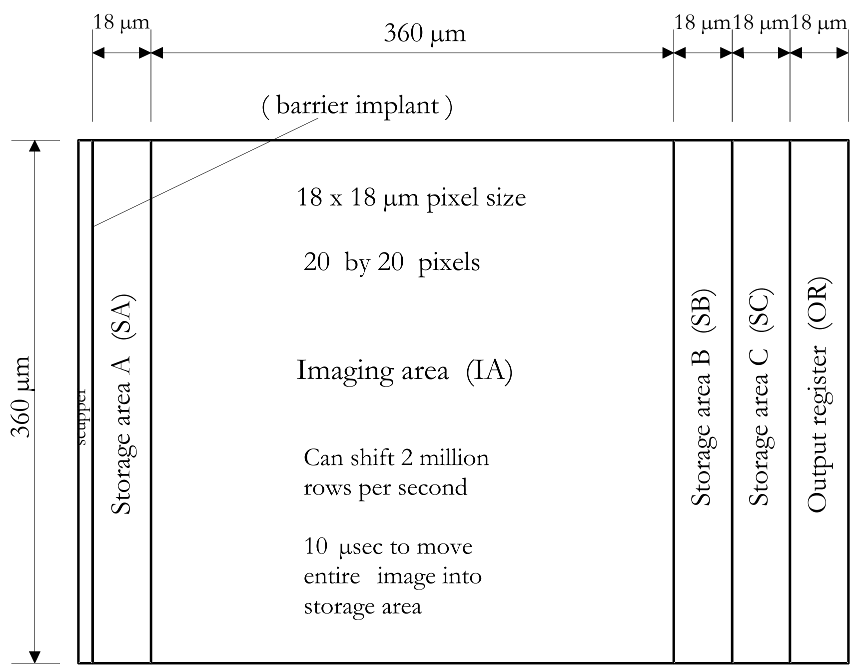
- 60 integration areas
- Very short exposure times (250 µsec) with "long" integration times (1 to 20 msec, 2 to 40 membrane cycles)
- Ability to switch between half-cycle integrations within 10 µses
- Lowest possible noise: 2 electrons maximum, < 1 electron desired (including all sources – dark current,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

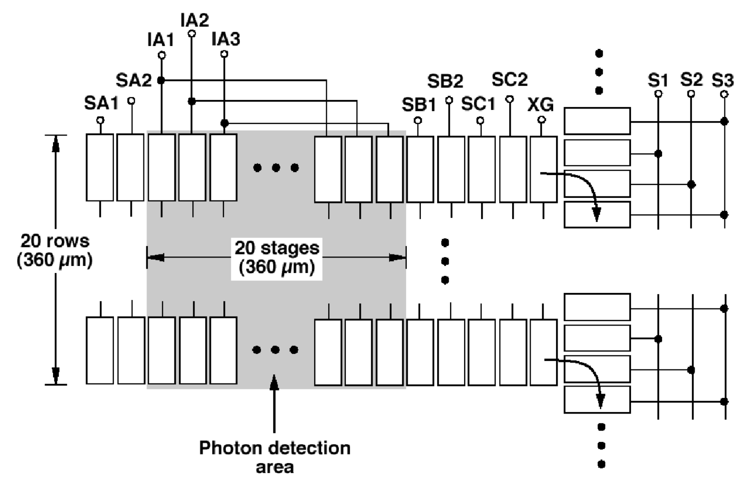
The key to making a CCD work in this application is on-chip integration. In order to fulfill the requirements, we have utilized the following design options:

- 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.

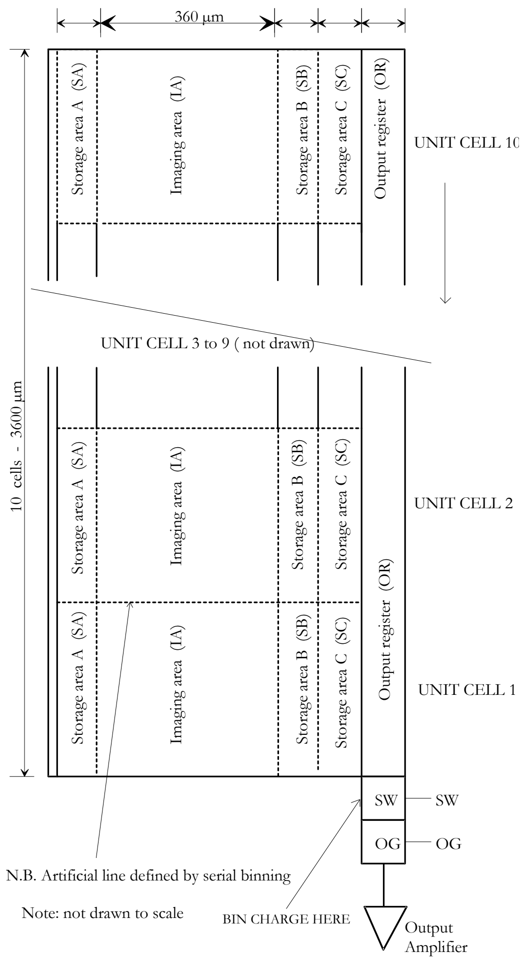
CCD design -unit cell

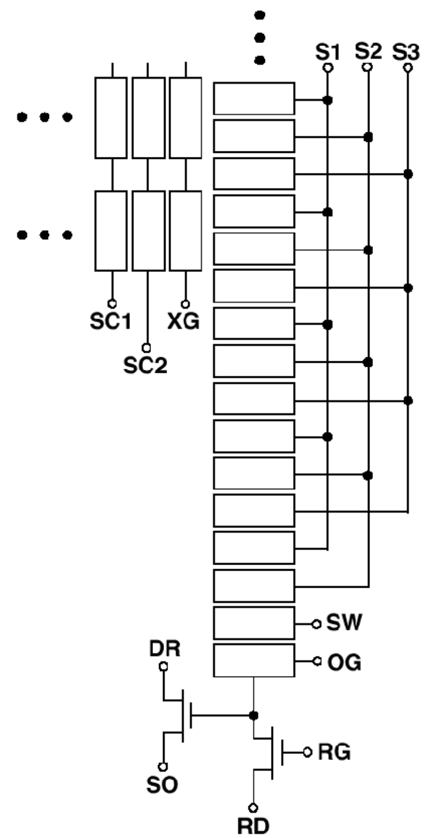
UNIT CELL OVERVIEW



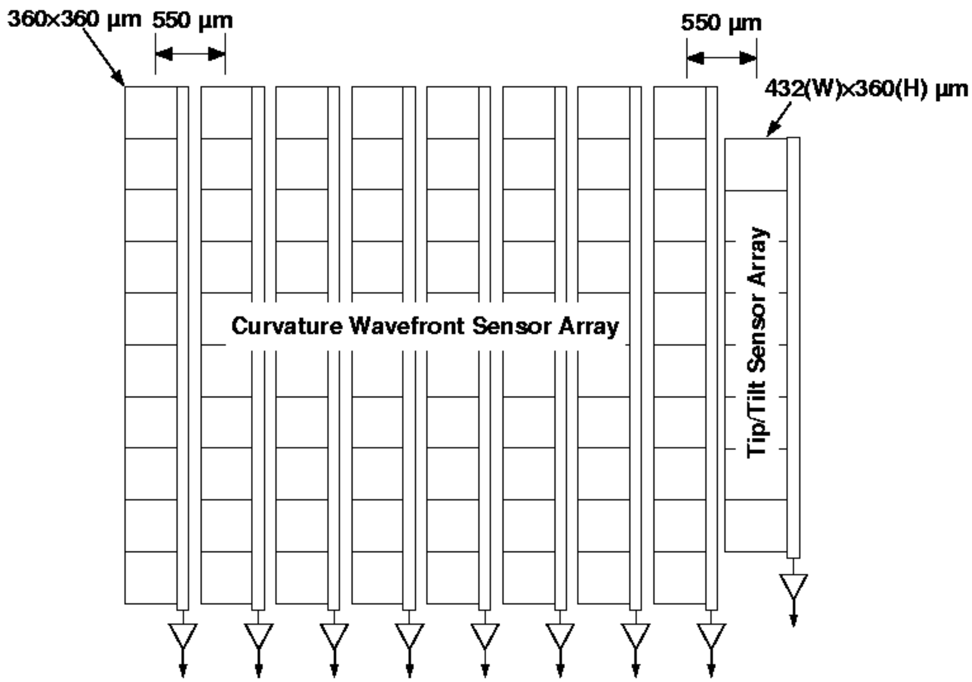


CCD design -unit column



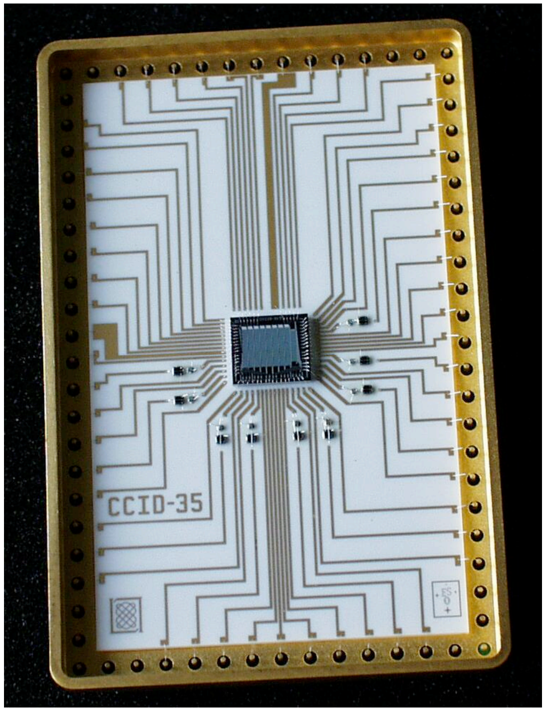


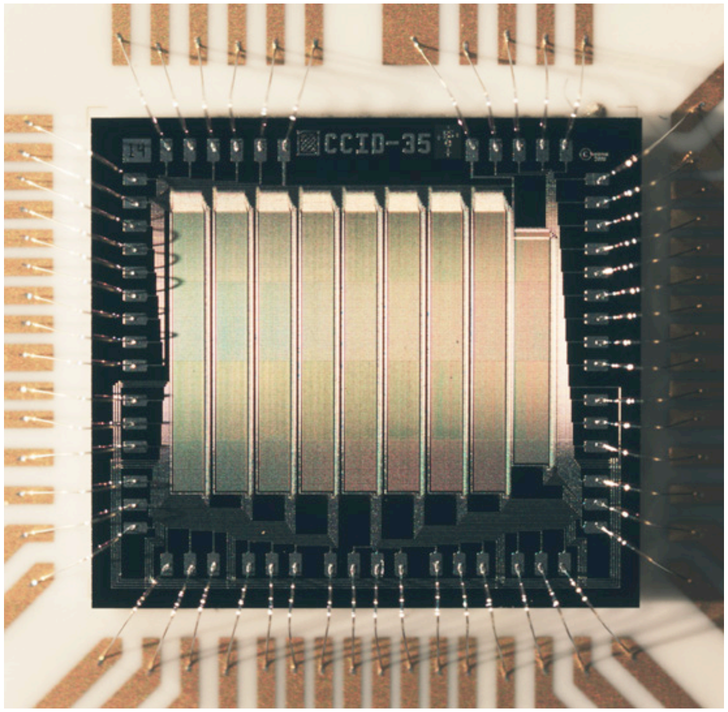
CCD design -CCD array



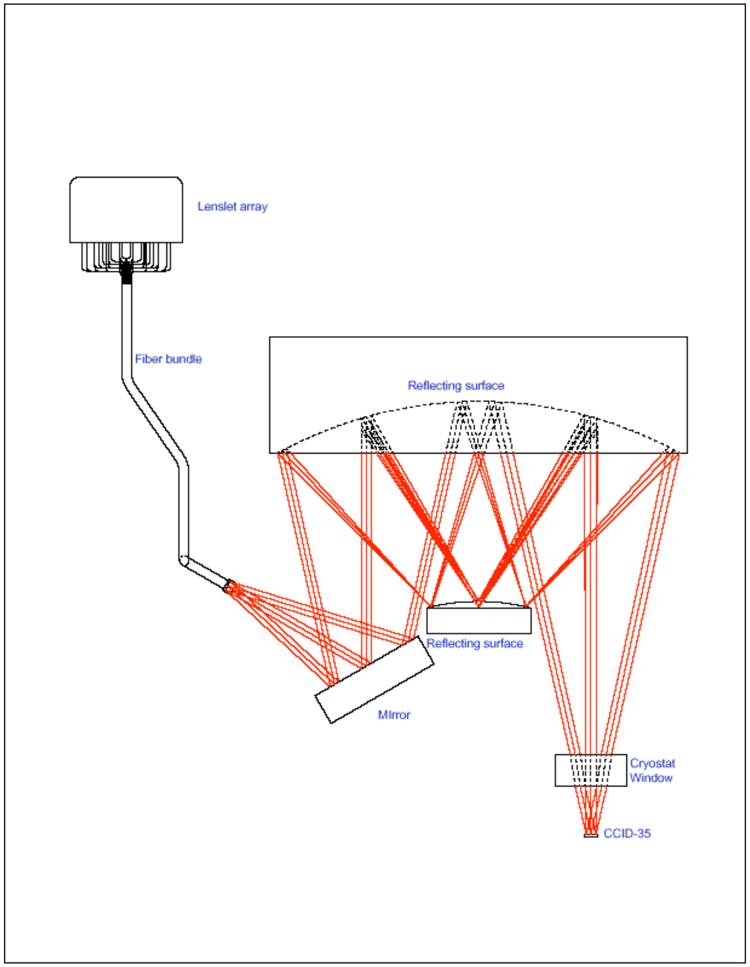
- Curvature wavefront sensor array.
- The design consists of 80 unit cells. Ten unit cells are combined into a unit column.
- Each of these unit columns has an amplifier at the "bottom" end of the serial register.
- One the right side of the device is the tip/tilt sensor.

ESO / MIT/LL CCID-35





Laboratory system design - Relay optics

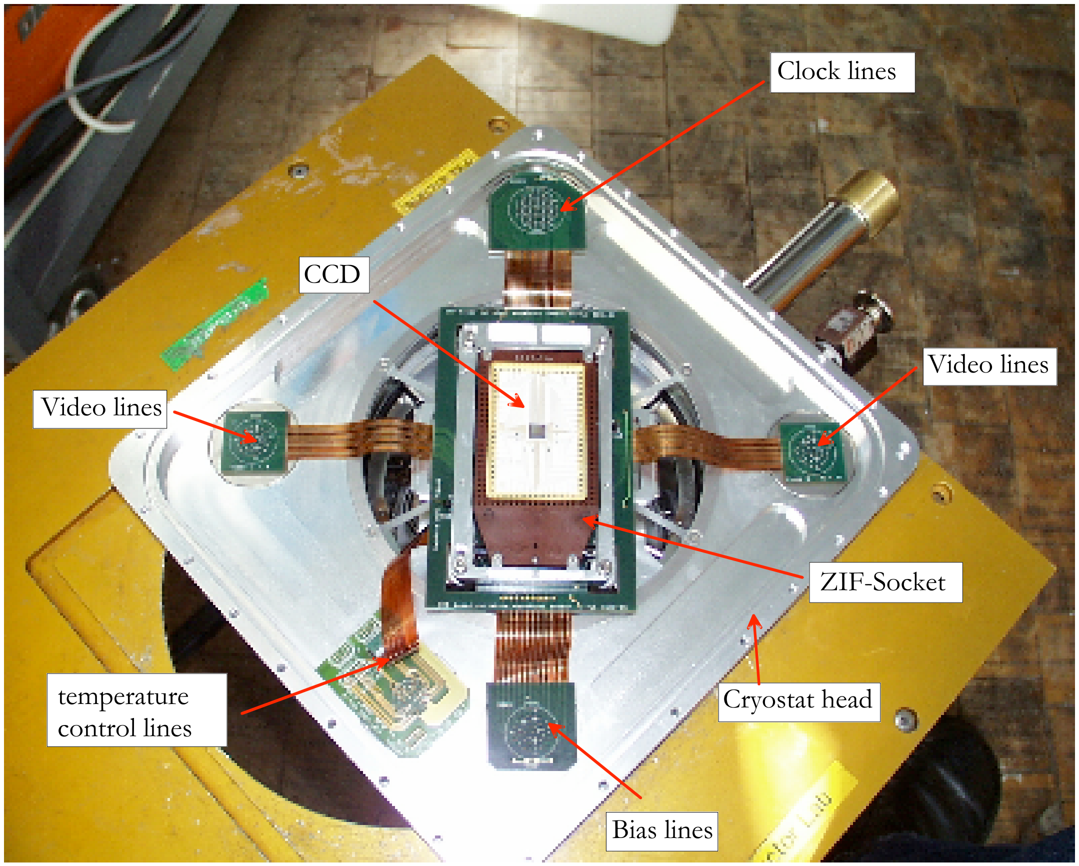


- An Offner Relay design consisting of two spherical, reflecting surfaces is used to re-image the light of the fibers 1:1 onto the superpixels

- 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

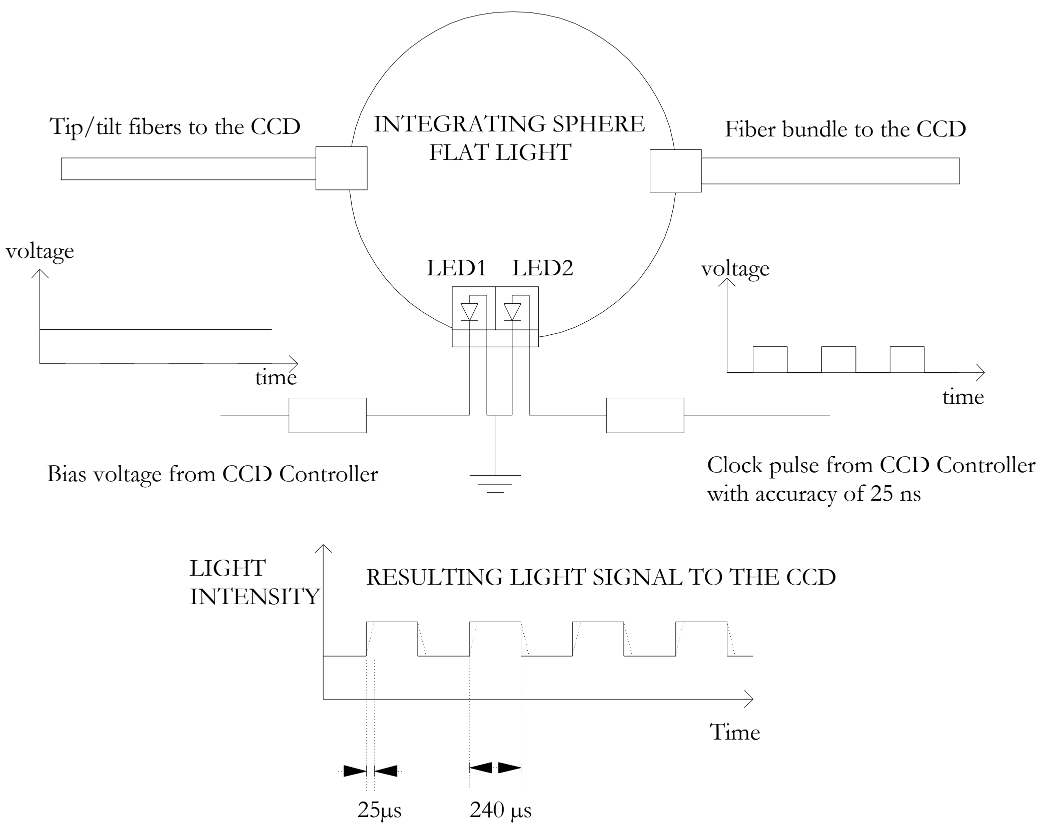
Laboratory system design - Detector board

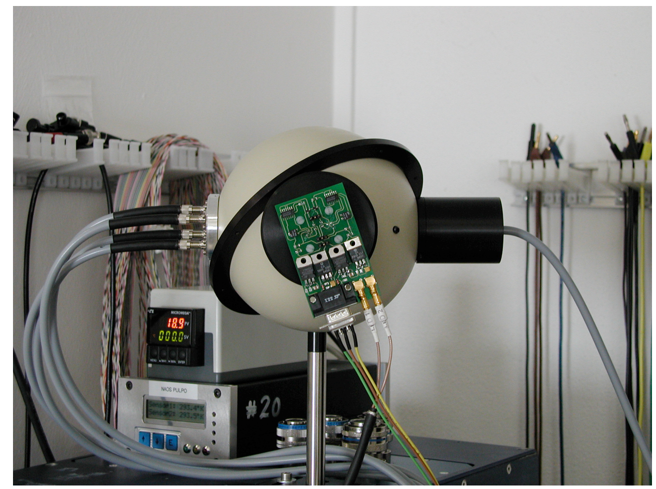


- Detector board important for low noise performance
- No connectors inside the cryostat
- No active electronics inside the cryostat

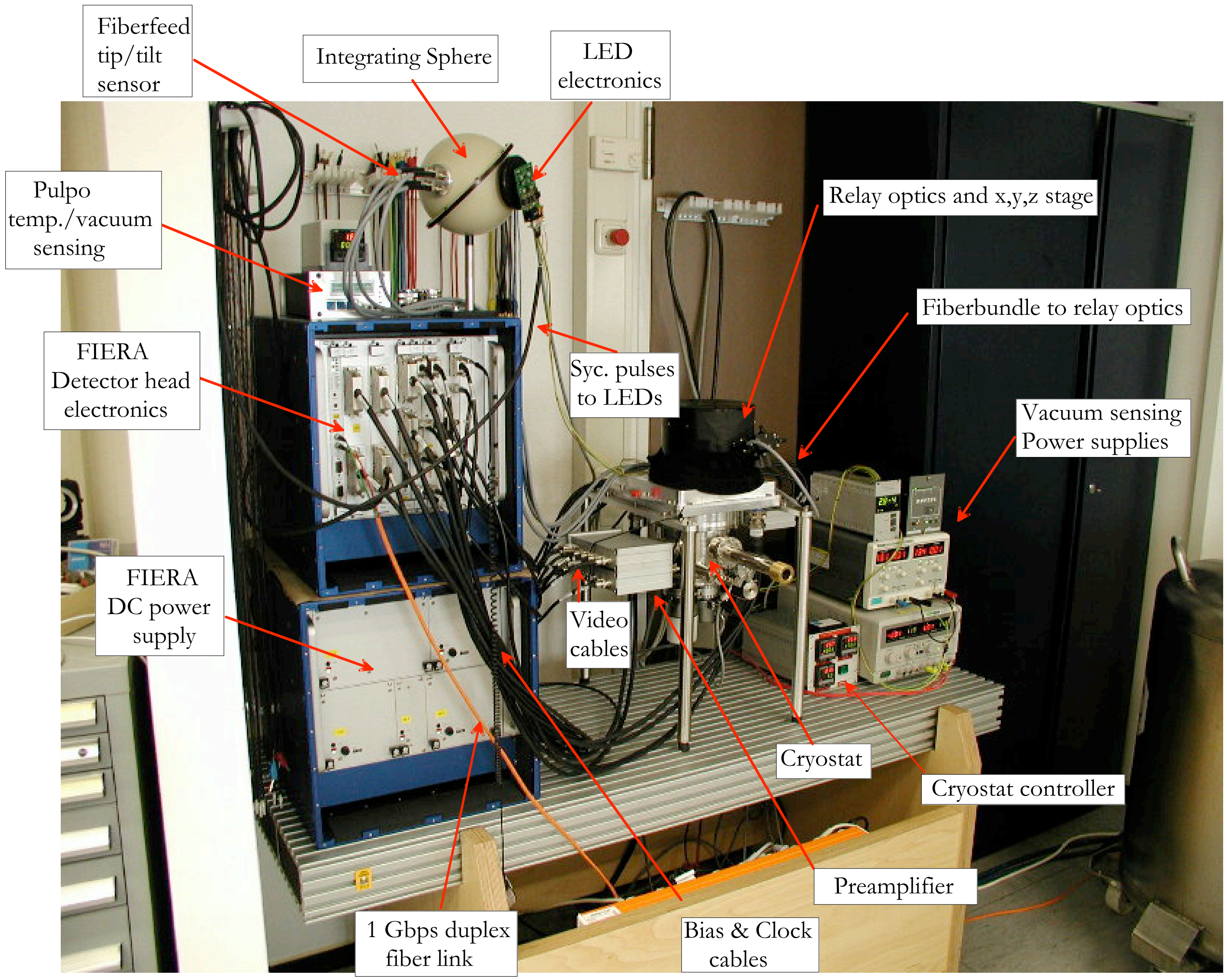
Laboratory system design - Fiber Feed and Simulation setup

TESTSETUP TO SIMULATE THE MEMBRANE MOVEMENT



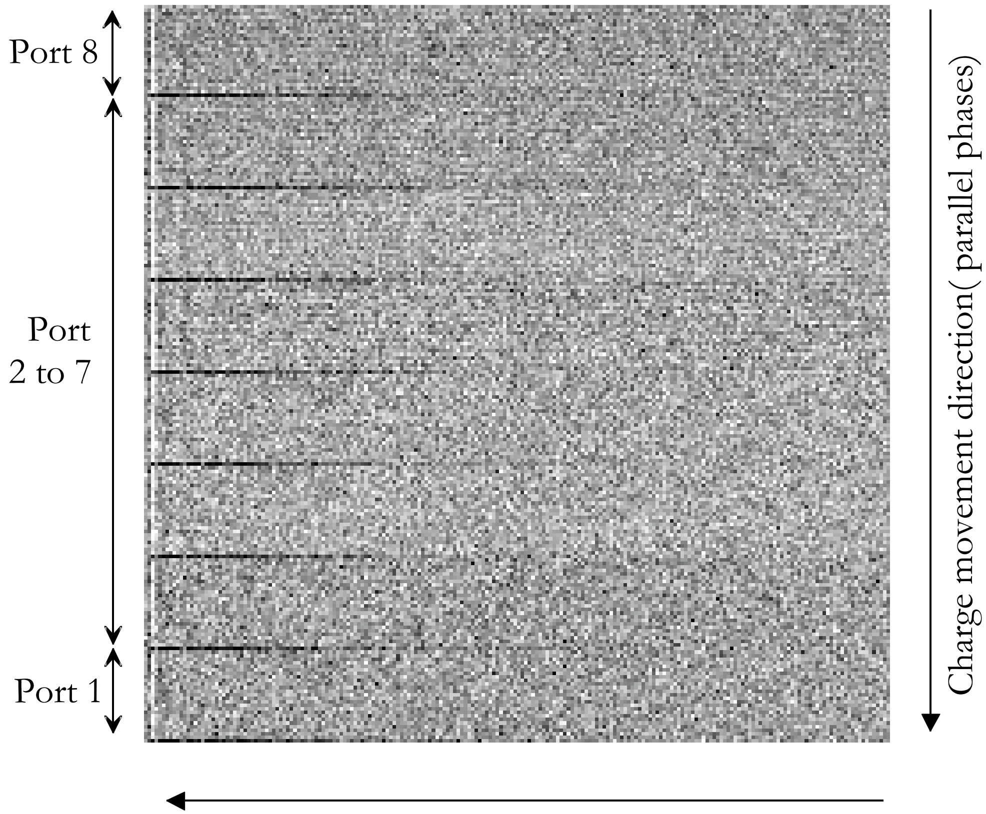


Laboratory system design - Picture of the lab system



Results - CCD readout modes

CCD image (0 second exposure) in unbinned mode



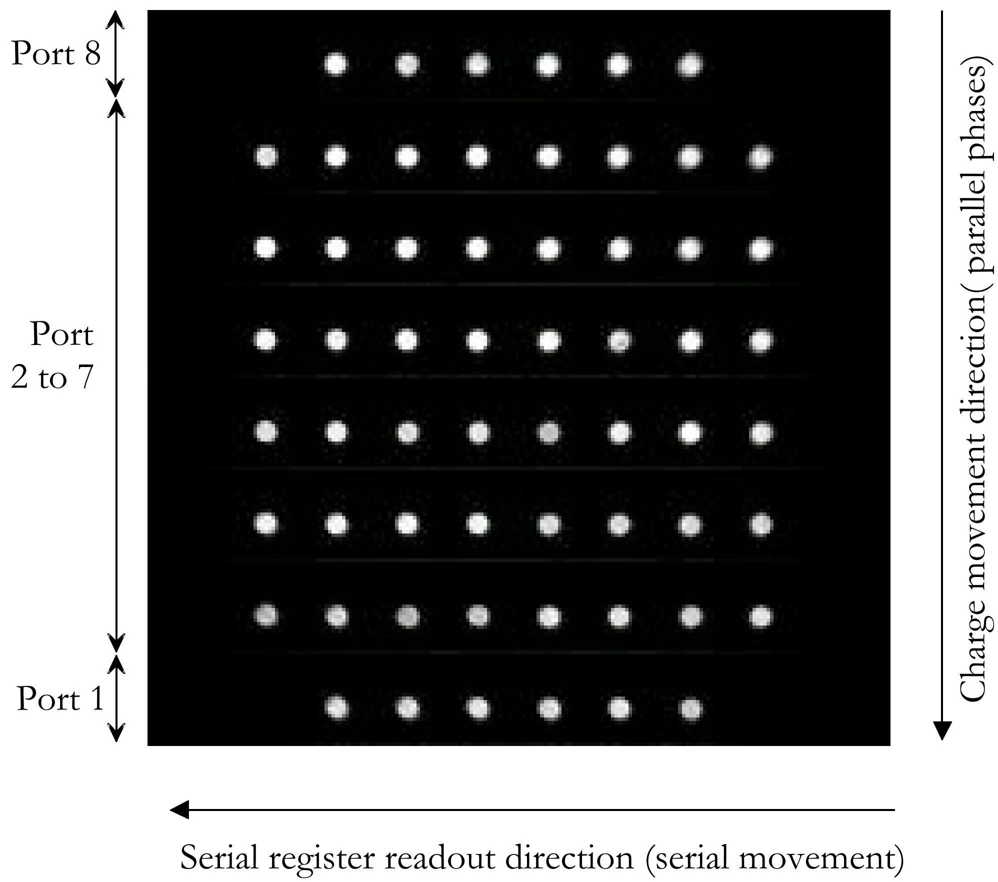
Serial register readout direction (serial movement)

This images shows a dark frame of the CCID-35 in unbinned mode.

Per readout port 20 image + 4 overscan pixels are read out in the vertical direction and 200 image pixels + 10 overscan pixels in the horizontal direction.

Note that the serial registers are in horizontal direction in this image.

CCD image in unbinned mode showing the 60 fiber spots

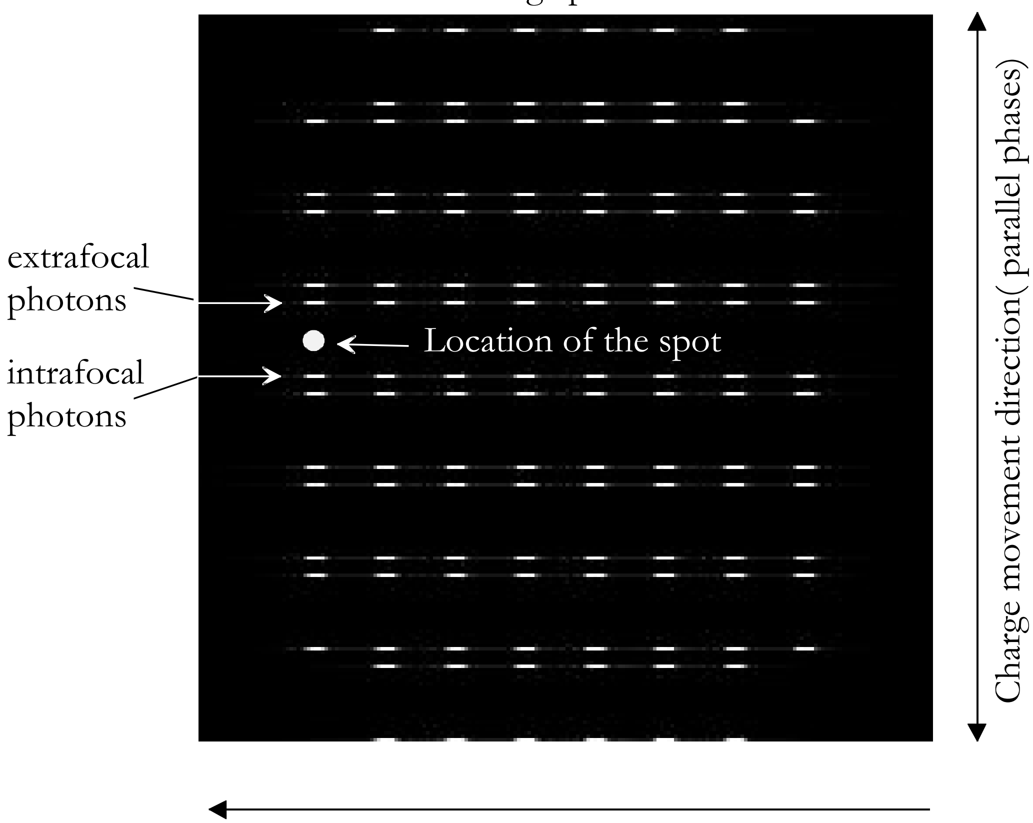


This images shows an exposure frame of the CCID-35 in unbinned mode showing the 60 fiberspots

Per readout port 20 image + 4 overscan pixels are read out in the vertical direction and 200 image pixels + 10 overscan pixels in the horizontal direction.

Note that the serial registers are in horizontal direction in this image.

CCD image in unbinned mode showing photons stored in the storage pixels SA and SB

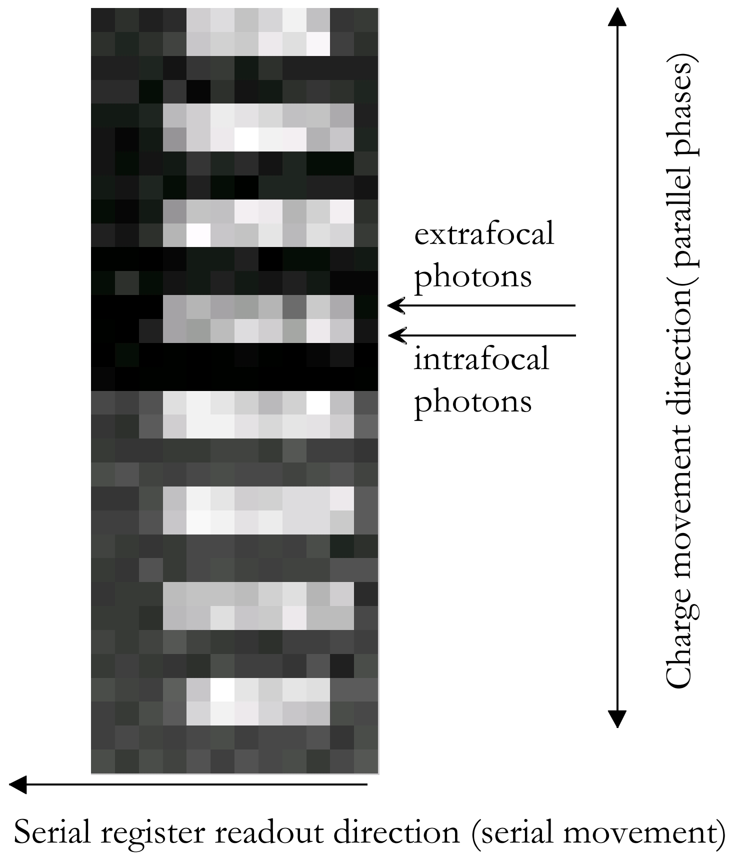


This images shows an CCID-35 image with charge collected during extrafocal and intrafocal periods of 10 cycles and stored in storage pixels SA and SB

Note that this requires charge movement up and down in vertical direction.

Note that the serial registers are in horizontal direction in this image.

CCD image in 20x20 binned mode showing photons
stored in the storage pixels SA and SB

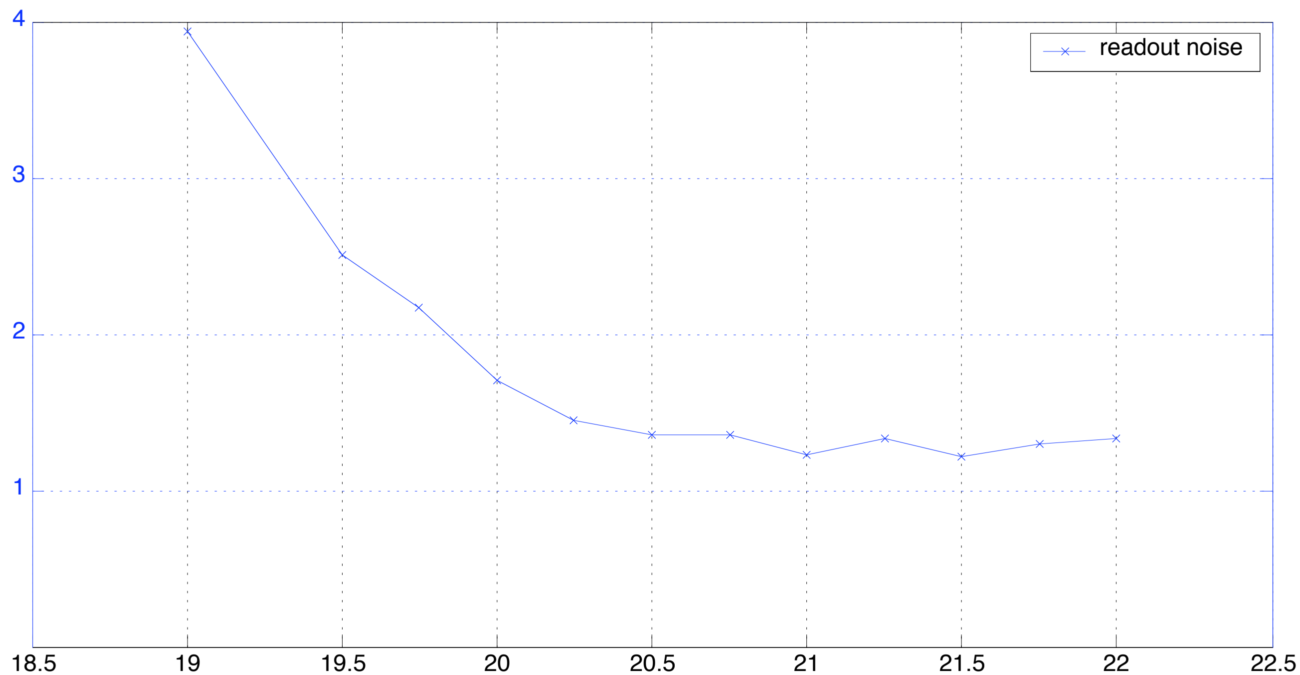


This images shows an CCID-35 image in curvature mode (20 x 20 binning). Charge is collected during extrafocal and intrafocal periods of 10 cycles and stored in storage pixels SA and SB and then read out.

Each superpixel reflects one subaperture in this mode. However, for better visualisation parallels are overscanned by two superpixels.

Note that this requires charge movement up and down in vertical direction.

Results - CCD readout noise performance

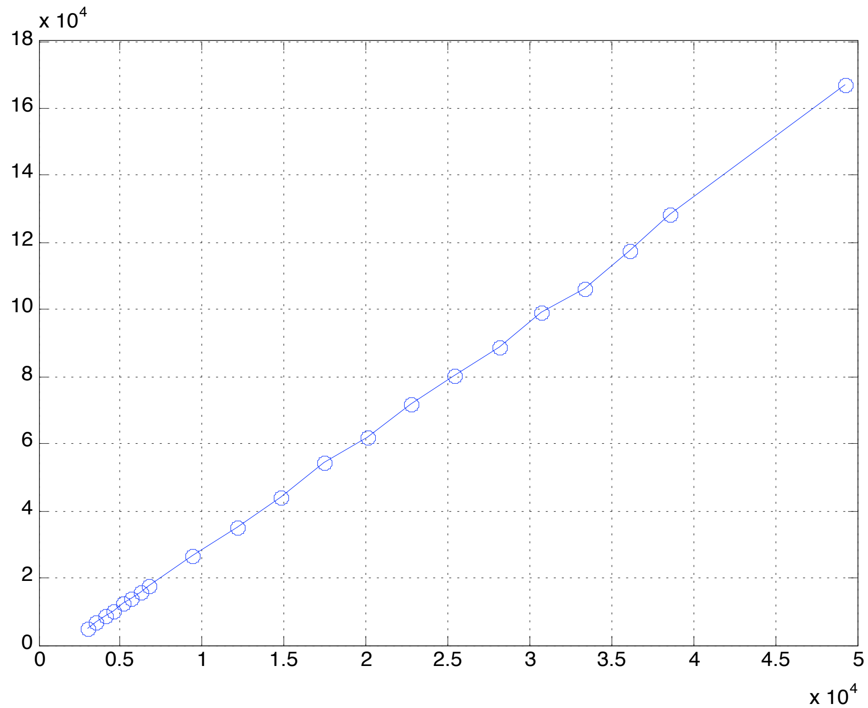


A readout noise of less than 1.5 electrons was achieved
for all readout ports including the tip/tilt sensor **at a readout speed of 4000 frames** per second.

With all pixels per readout port binned into 12 superpixels, it was possible to read the serial register relatively slowly at 50 kilopixels per second. The plot shows readout noise and conversion factor versus drainvoltage

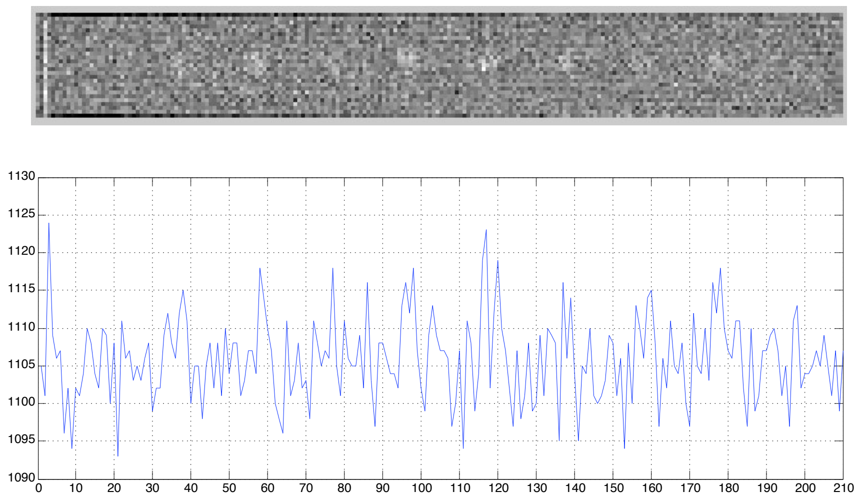
Results - Photon Transfer Curve

CCD output amplifier	*Readout noise (electrons)*	*Conversion factor (electrons/ADU)*
1	*1.42 ± 0.002*	*0.295 ± 0.007*
2	*1.38 ± 0.002*	*0.293 ± 0.005*
3	*1.42 ± 0.002*	*0.294 ± 0.005*
4	*1.42 ± 0.002*	*0.297 ± 0.004*
5	*1.31 ± 0.002*	*0.294 ± 0.005*
6	*1.43 ± 0.004*	*0.290 ± 0.005*
7	*1.28 ± 0.002*	*0.292 ± 0.004*
8	*1.23 ± 0.002*	*0.288 ± 0.005*
Tip/tilt sensor	*1.44 ± 0.003*	*0.299 ± 0.004*

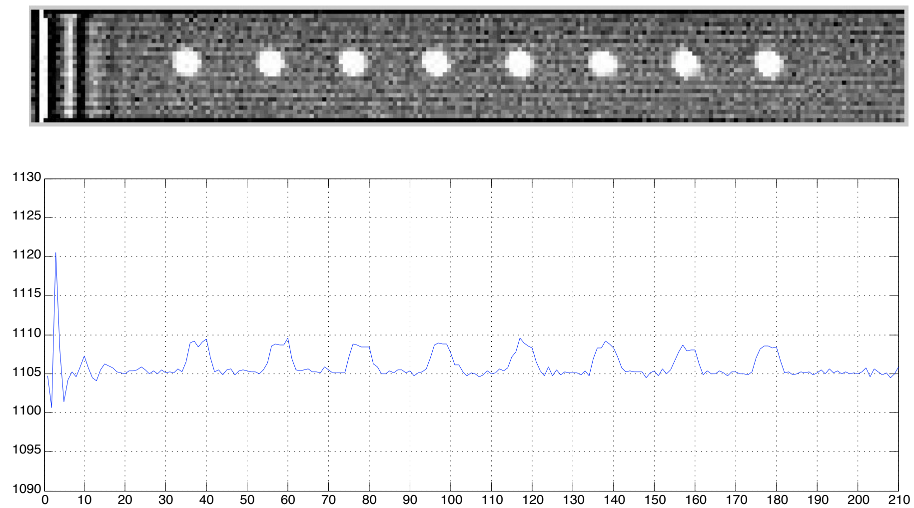


Results – low light level performance

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



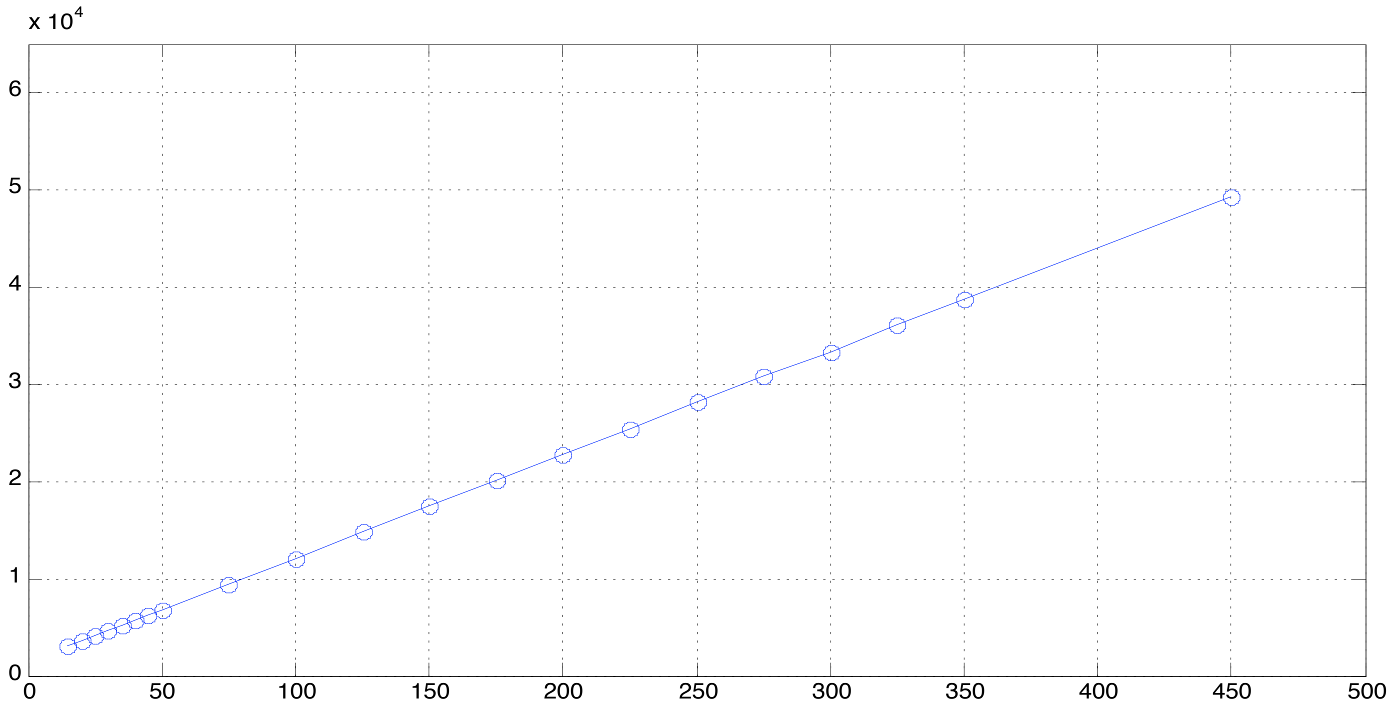
Sum of 256 exposures and then normalized



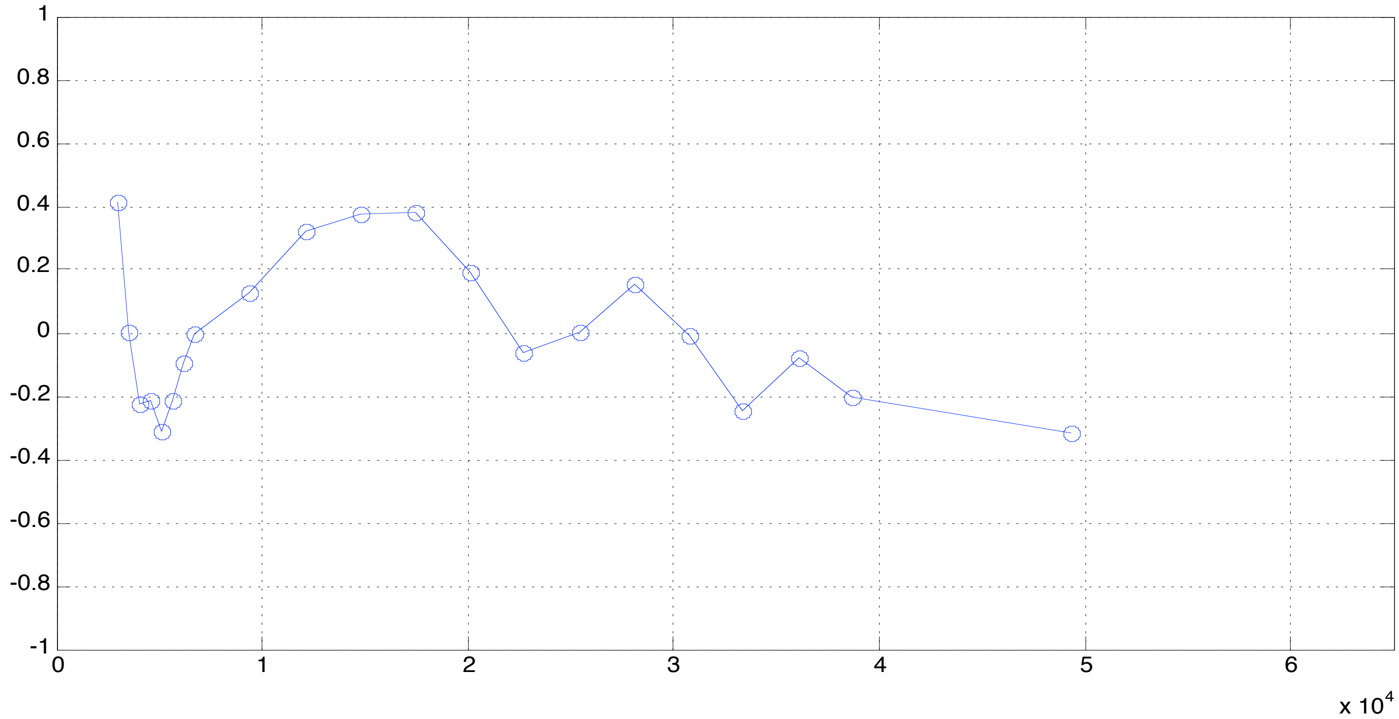
To verify the capability of the CCID-35 to move very small charge packets with high efficiency, the input illumination on the fiber entrance was turned down with neutral density filters to give a signal of ~1 electron per pixel per exposure. The signal produced in the fiber spots is almost not visible and embedded in the noisy trace of the readout noise. Hence 256 exposures with the same illumination level were summed up and normalized.

Results - CCD Linearity

Linearity curve up to full well @ 20000 electrons)



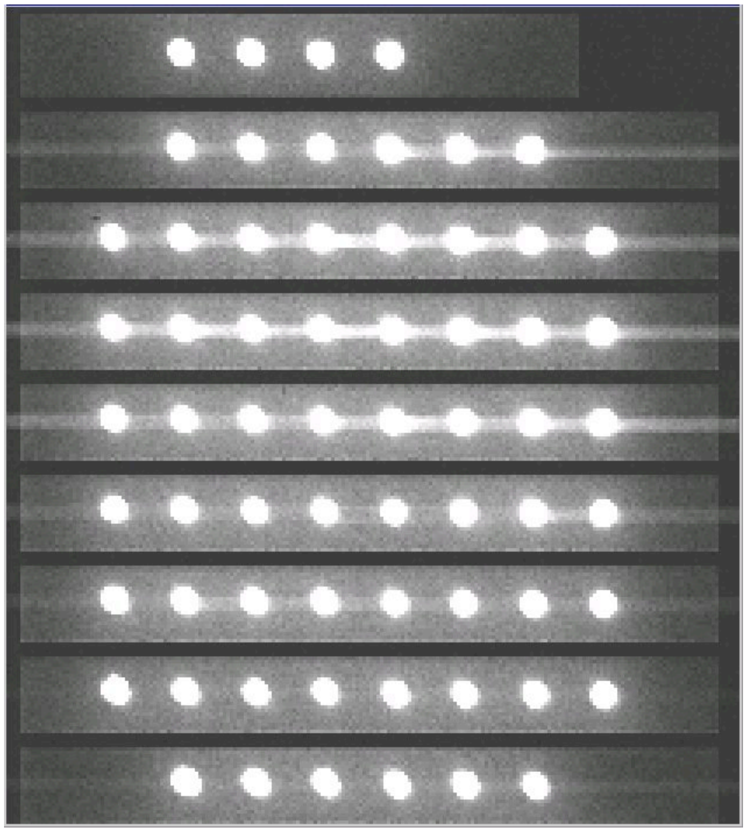
Results - Residual non Linearity curve



Residual non-linearity curve of the first output amplifier of the CCID-35.

The non-linearity (peak to peak) is 0.41% / -0.32%.

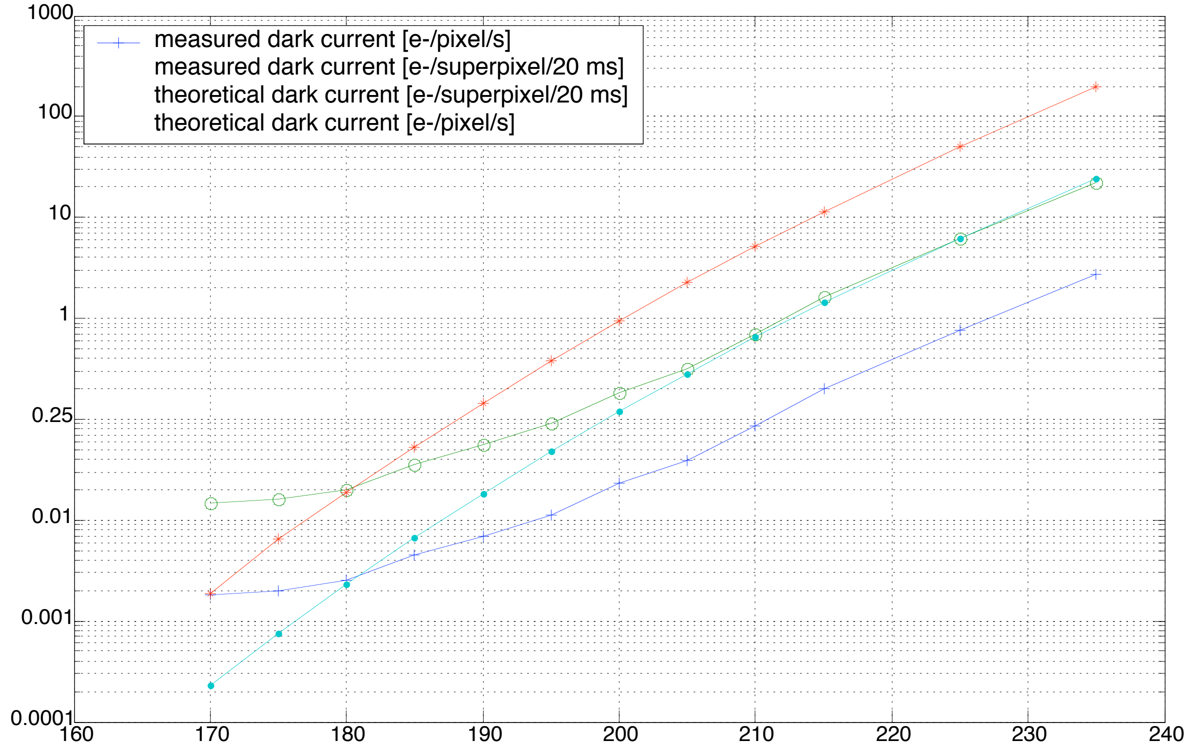
Full well capacity and dynamic range



CCID-35 image with on average 25,000 electrons per pixel in the spots exceeding the full well capacity of the serial register seen as deferred charge trails after bright pixels. The cause of this problem is currently not fully understood but it limits the use of the frontside versions of the CCD to signal levels of 20,000 electrons per pixel or less depending on the device.

With a full well capacity of 10,000 to 20,000 electrons the CCDs are still suited for the application.
Even with a full well capacity of 10,000 electrons the dynamic range of the curvature CCD is still higher by a factor of 100 compared to avalance photo diodes.

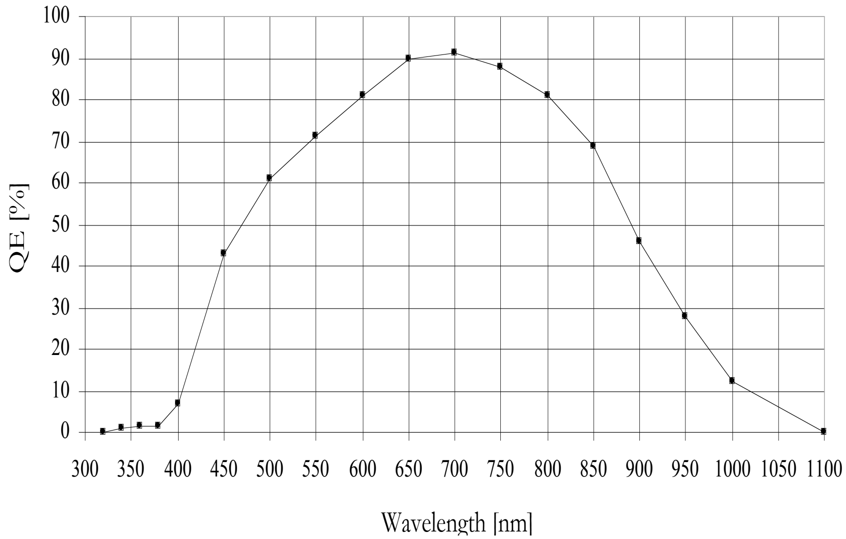
CCD results– Dark current



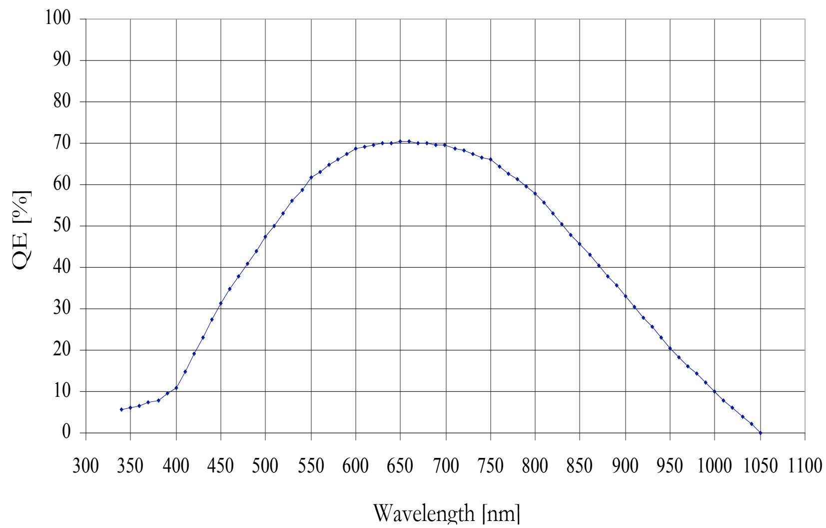
The CCD must be cooled to a temperature of **192 Kelvin or - 81°C** to achieve a dark current of 0.25 electrons per superpixel at 50 Hz frame rate. Thus liquid nitrogen and a cryostat is used to cool the CCD.

Expected QE for the thinned CCD (versus APD)

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

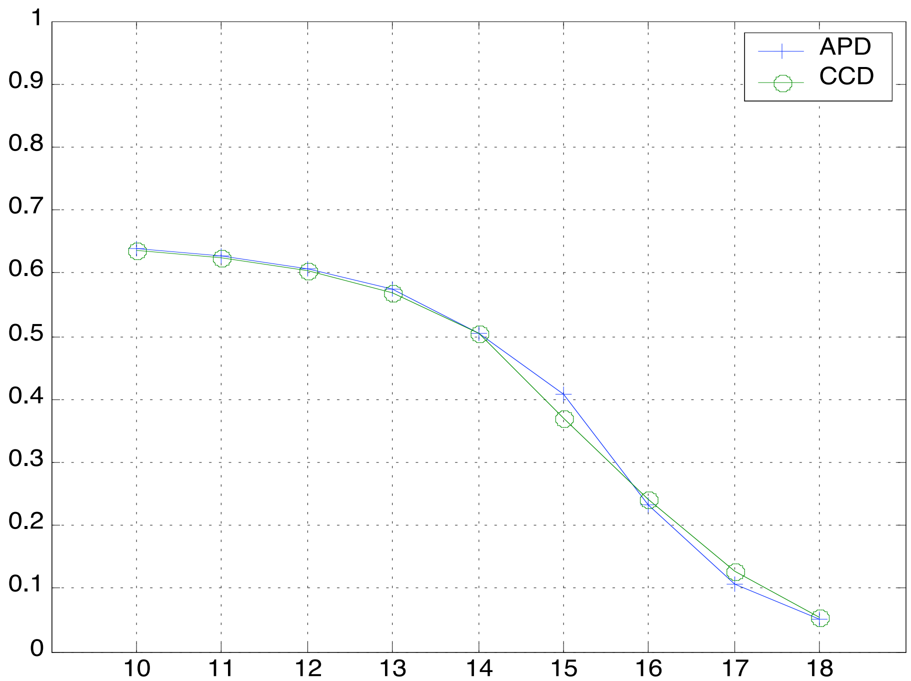


Measured quantum efficiency of an EG&G APD module



- **High Quantum efficiency (peak > 90%)+ the ability to store charge while reading and integrating**

System performance - Simulation results



Property	APD	CCD
Sky background magnitude	19.0	19.0
Field of view diameter	2"	2"
Quantum efficiency	70%	80%
Dark current [electrons/s]	250	0
Read-out noise [electrons RMS]	0	1.5
Read-out delay [µs]	0	250
Seeing [arcsec]	0.65	0.65

Using the computer model, the Strehl ratio in K-band was measured for guide stars of magnitude 10 to 18 and compared for the different detectors. The CCD performs as well as APDs over the entire range of magnitudes down to very faint guide stars at magnitude 18. The plot shows a small difference of the performance of the CCD of 3% at magnitude 15 compared to APDs

Conclusions

- CCD achieves nearly the same performance as APDs
- Thinned versions have the potential to work as well as APDs with reduced cost and reduced complexity
- No neutral density filters needed (simpler)
- The CCD provides a much greater integration area per subaperture (360 μm by 360 μm)
- CCD has a higher quantum efficiency than APDs
- CCD has a greater dynamic range than APDs (factor 100 to 1000)
- Readout noise of less than 1.5 electrons at 4000 frames/s has been demonstrated
- Curvature CCD combines high order curvature sensing with the possibility of separate tip/tilt sensing in one sensor