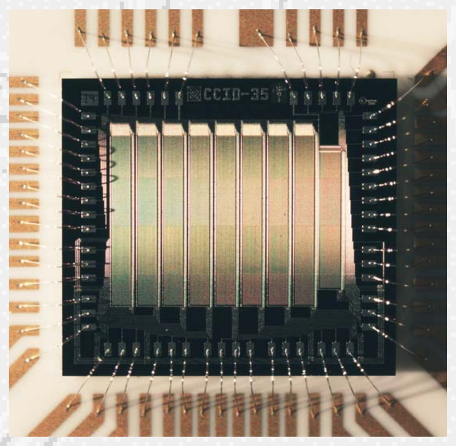

A CCD BASED CURVATURE WAVEFRONT SENSOR FOR ADAPTIVE OPTICS IN ASTRONOMY

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Advances in charge-coupled device (CCD) technology motivated an investigation of the use of a specially designed CCD as the wavefront sensor detector in a 60-element curvature AO system. A CCD has never been used before as the wavefront sensor in a low light level curvature adaptive optics system. A CCD can achieve nearly the same performance as APDs at a fraction of the cost and with reduced complexity for high order wavefront correction. Moreover the CCD has higher quantum efficiency and a greater dynamic range than APDs. A readout noise of less than 1.5 electrons at 4000 frames per second was achieved. A back-illuminated thinned version of this CCD can replace APDs as the best detector for high order curvature wavefront sensing.

Introduction

Curvature AO-systems have traditionally used avalanche photo diodes (APDs) as detectors. APDs are photon-counting devices that produce a pulse on their output whenever a photon is detected. APDs have no read-out noise and read-out is almost instantaneous. However, they have some serious drawbacks compared to charge-coupled devices (CCDs):

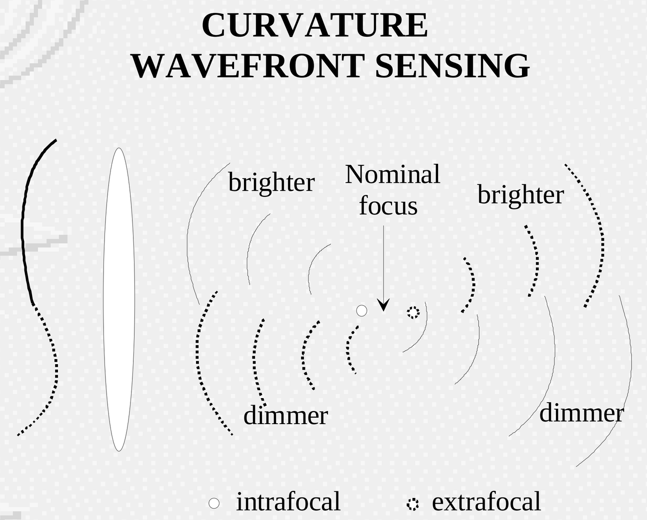
Small dynamic range. For the duration of the avalanche of electrons – typically around 40 ns – the APD is blind to any new photons arriving. This limits the dynamic range of the APD and calls for the use of neutral density filters to adapt the incident photon flux to the dynamic range of the APD. CCDs, on the other hand, have an enormous dynamic range and thus require no filters.

Low quantum efficiency. The quantum efficiency, which is the probability that an incident photon is detected, is lower for APDs than for CCDs. APDs typically have a peak quantum efficiency of 70% at 700nm, while the same number for CCDs is over 90%.

High dark current. APDs generate dark current, or false photon counts, of 100 to 250 counts per second depending on the cost of the APDs, while a well-cooled CCD generates a negligible amount of dark current. The dark current affects the performance of the system when faint guide stars are used.

High cost. A 60-element AO-system using APDs is significantly more expensive than one using a CCD. The drawbacks of the CCDs are their read-out delay and read-out noise.

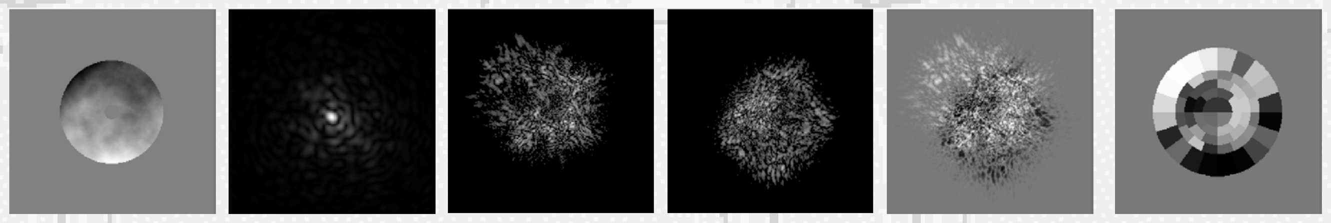
Curvature sensing - How does it work?



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.

A curvature wavefront sensor measures the intensity *I1* in an intrafocal plane and the intensity *I2* in an extrafocal plane and compares these intensities to determine the curvature of the wavefront. The normalised difference, $(I1-I2)/(I1+I2)$, is used to reconstruct the wavefront. An oscillating membrane mirror is used to modulate the location of the plane being imaged on a single detector. During one half-cycle of the membrane motion, the detector records the intrafocal distribution of light, and during the other half-cycle it records the extrafocal distribution.

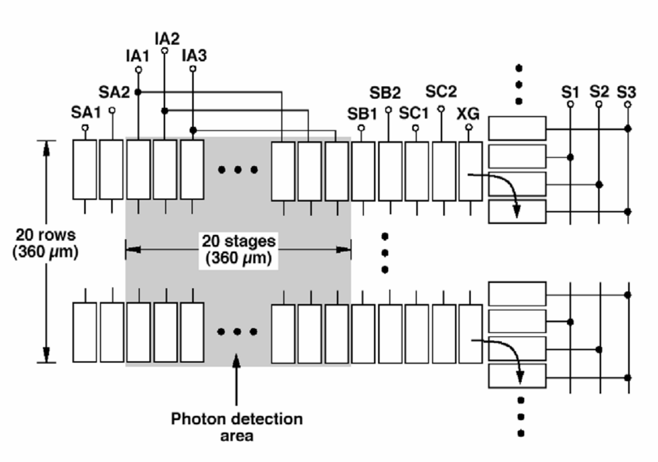
A realistic curvature signal is shown below, which presents a Kolmogorov atmospheric wavefront distortion, the infrared focal plane image, intrafocal and extrafocal images and the curvature signal.



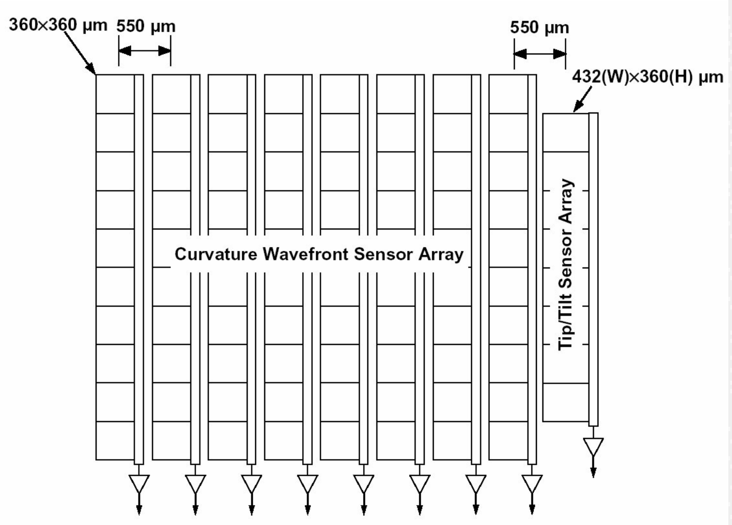
wavefront distortion — *infrared focal plane image* — *intrafocal image* — *extrafocal image* — *curvature signal at high resolution* — *curvature signal binned into 60 subapertures*

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.

Architecture of the curvature CCD

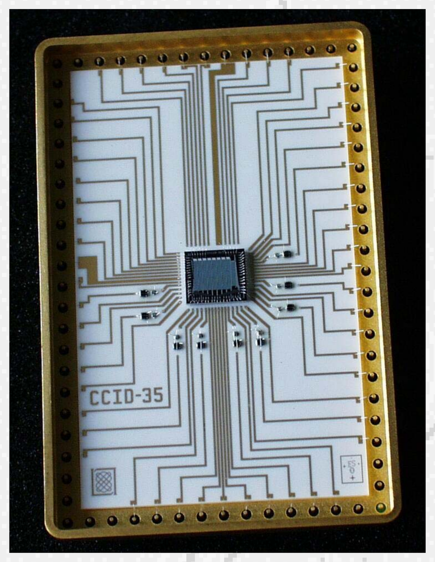


Functional drawing of a unit cell, with an integration area made of 20 x 20 pixels, each 18 µm square. These unit cells form an imaging area (IA) of 360 by 360 µm for each subaperture. These pixels are binned by rows into the storage areas SA and SB. The storage areas are small compared to the imaging area, being only one pixel wide.



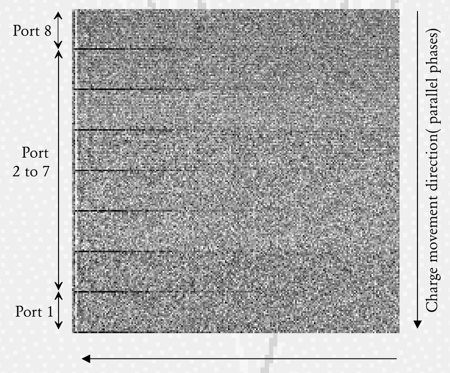
CCD design - curvature wavefront sensor array. The design consists of 80 unit cells. Ten unit cells are combined into a unit column. Each of these unit columns has an amplifier at the "bottom" end of the serial register. On the right side of the device is the tip/tilt sensor.

Functionality of the curvature CCD



- 80 integration areas.
- High quantum efficiency (peak greater 80%).
- Very short exposure times (250 µsec) with "long" integration times (1 to 20 msec, 2 to 40 cycles of a 2 kHz membrane).
- Ability to switch between half-cycle integrations within 10 µsec.
- Ability to store half-cycle frames on-chip while integrating other half-cycle frames.
- Read out of all pixels within 250 µsec.
- Use of superpixels, i.e. bin on-chip, to loosen alignment tolerances.
- Use of multiple readout ports to have slower readout rates and lower readout noise.

CCD image (0 second exposure) in unbinned mode

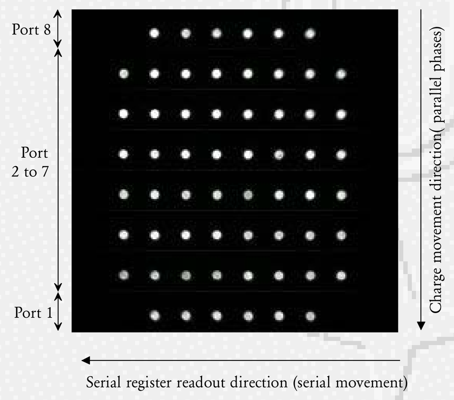


This images shows a dark frame of the CCID-35 in unbinned mode.

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

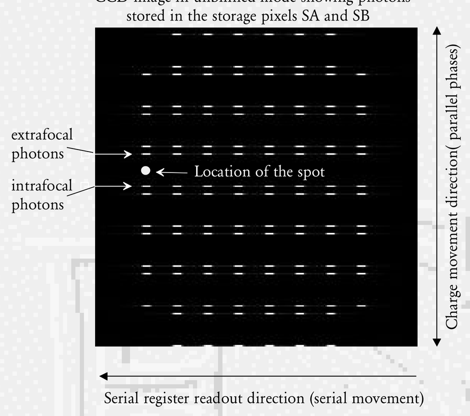


This images shows an exposure frame of the CCID-35 in unbinned mode showing the 60 fiberspots

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

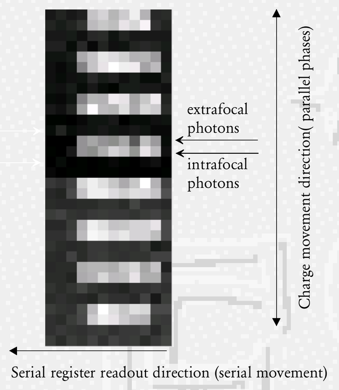


This images shows an CCID-35 image with charge collected during extrafocal and intrafocal periods of 10 cycles and stored in storage pixels SA and SB

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.

CCD performance compared to APDs

A common measure used to quantify the performance of an AO-system is the *Strehl ratio* of the corrected point spread function (PSF). To compare the performance of the CCD and APDs, a computer model of the atmosphere, telescope and AO-system was developed in MatLab. 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

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*

CCD achieves nearly the same performance as APDs

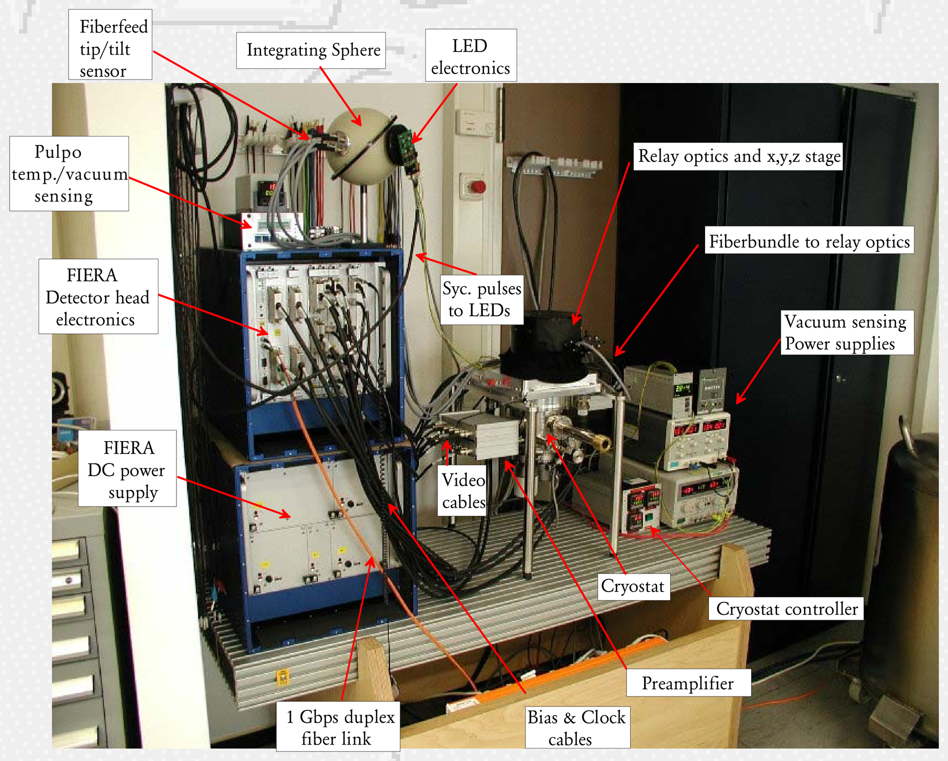
- **Thinned versions have the potential to work as well as APDs with reduced cost and reduced complexity**
- **No neutral density filters needed (simpler)**
- **The CCD provides a much greater integration area per subaperture (360 µm by 360 µm)**
- **CCD has a higher quantum efficiency than APDs**
- **CCD has a greater dynamic range than APDs (factor 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**

Prototype system and CCD test results

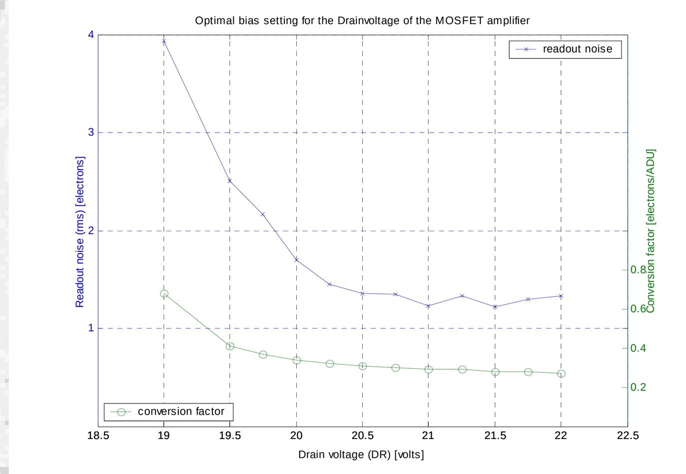
To test the performance and the functionality of the curvature CCD, a laboratory system has been built to allow independent testing without the need to interface to a full adaptive optics system.

- An integrating sphere and a stable light source were used to simulate the membrane movement and providing the light signal for CCD characterization.
- An Oeffner relay optics was designed (consisting of two spherical, reflecting surfaces) to re-image the light of the fibers 1:1 onto the superpixels) and a fiberfeed with 60 individual fibers plus 4 additional fibers for the tip/tilt sensor to feed the subapertures of the CCD with light.

Picture of the Laboratory detector system



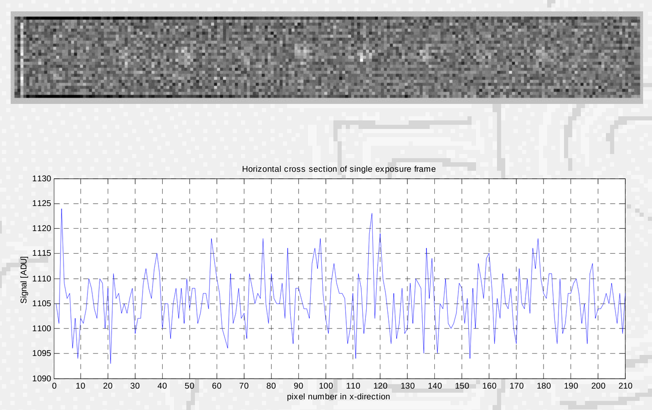
A readout noise of less than 1.5 electrons was achieved for all readout ports including the tip/tilt sensor at a readout speed of 4000 frames per second. With all pixels per per readout port binned into 12 superpixels, it was possible to read the serial register relatively slowly at 50 kilopixels per second. The plot shows readout noise and conversion factor versus drainvoltage



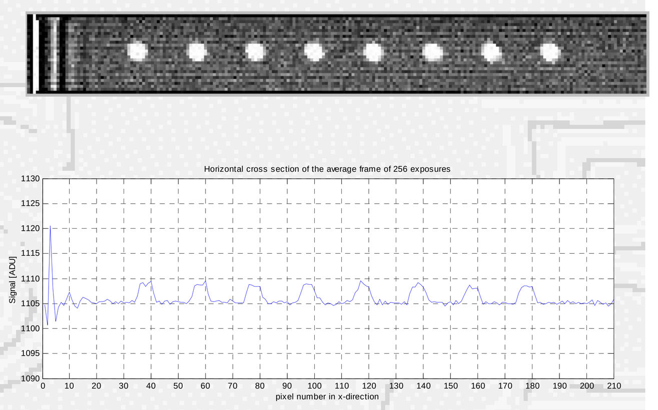
- **Vertical and horizontal CTE better than 0.99999 down to lowest light levels**
- **Residual non-linearity better than 0.5% / -0.5%. (peak to peak)**
- **Negligible amount of dark current at 197 Kelvin (0.25 electrons per subaperture at 50 Hz frame rate)**
- **Measured responsivity of the CCID-35: 14.2 µV/electron ± 5%.**
- **Very good cosmetic quality**

Low light level performance

To verify the capability of the CCID-35s 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.



CCD image with ~ 1 electron charge per pixel and a readout noise of 1.4 electrons and its horizontal cross section.



Average frame of 256 CCD image with ~1 electron charge per pixel and a readout noise of ~0.1 electrons and its horizontal cross section.