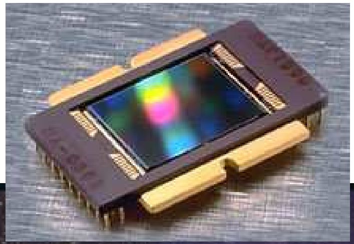
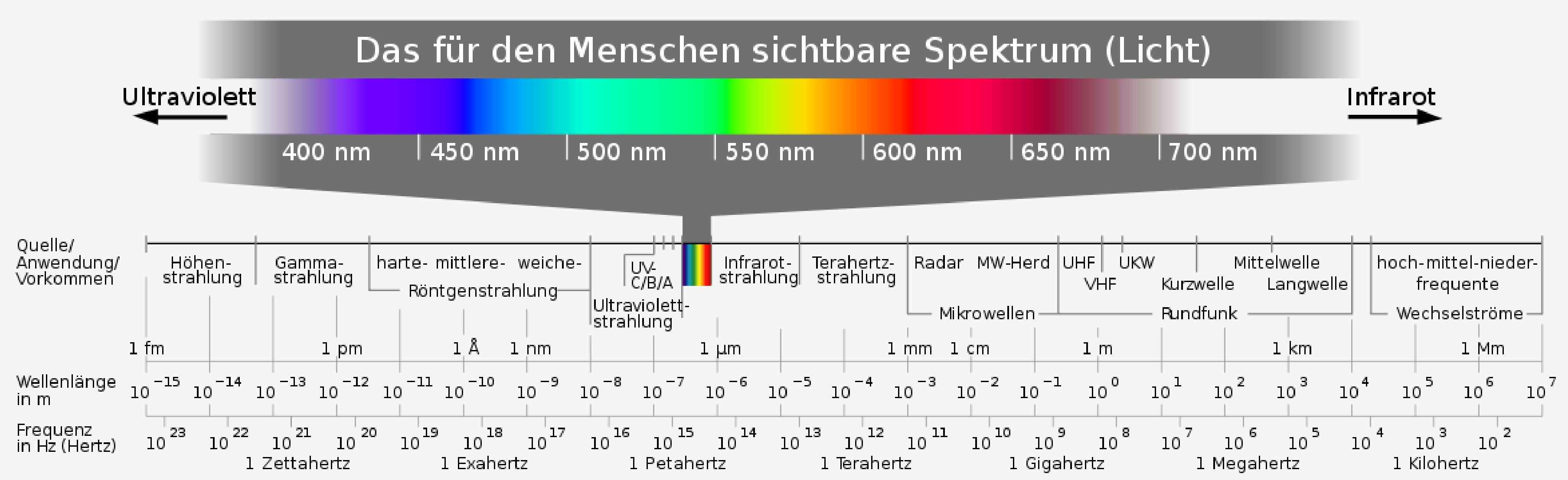
Astrofotografie mit CCD-Sensoren

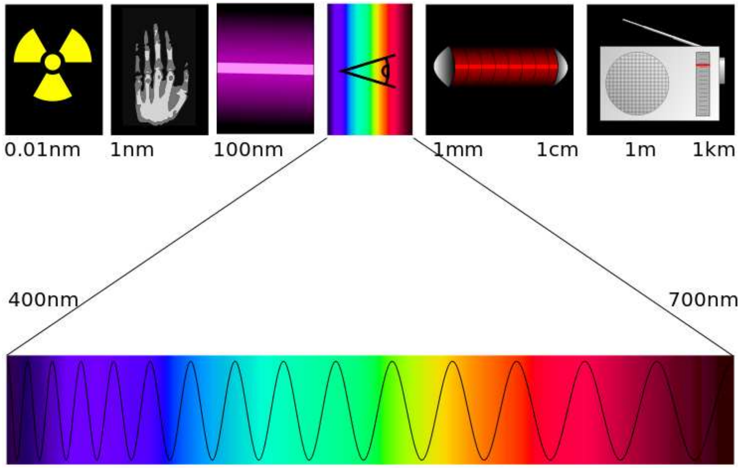


**Prof.(FH) DI Dr.
Michael Steinbatz**
(m.steinbatz@fh-wels.at)

Dezember 2014

Licht:


Das für den Menschen sichtbare Spektrum (Licht)
Ultraviolett
Infrarot
400 nm
450 nm
500 nm
550 nm
600 nm
650 nm
700 nm
Quelle/ Anwendung/ Vorkommen
Höhen-strahlung
Gamma-strahlung
harte- mittlere- weiche-
Röntgenstrahlung
UV-C/B/A
Ultraviolett-strahlung
Infrarot-strahlung
Terahertz-strahlung
Radar
MW-Herd
Mikrowellen
UHF
VHF
UKW
Kurzwelle
Mittelwelle
Langwelle
Rundfunk
hoch-mittel-nieder-frequente
Wechselströme
1 fm
1 pm
1 Å
1 nm
1 µm
1 mm
1 cm
1 m
1 km
1 Mm
Wellenlänge in m
Frequenz in Hz (Hertz)
1 Zettahertz
1 Exahertz
1 Petahertz
1 Terahertz
1 Gigahertz
1 Megahertz
1 Kilohertz


0.01nm
1nm
100nm
1mm
1cm
1m
1km
400nm
700nm

Optik:

Geometrische Optik:

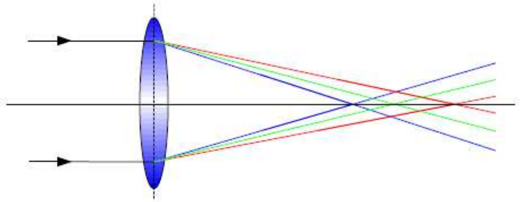


Figure 15: Longitudinal Chromatic Aberration

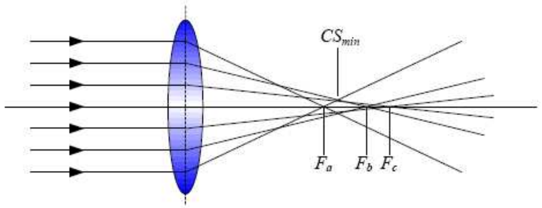


Figure 16: Spherical Aberration

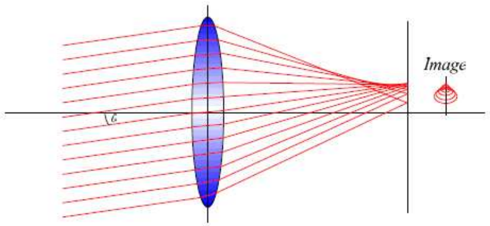


Figure 20: Coma

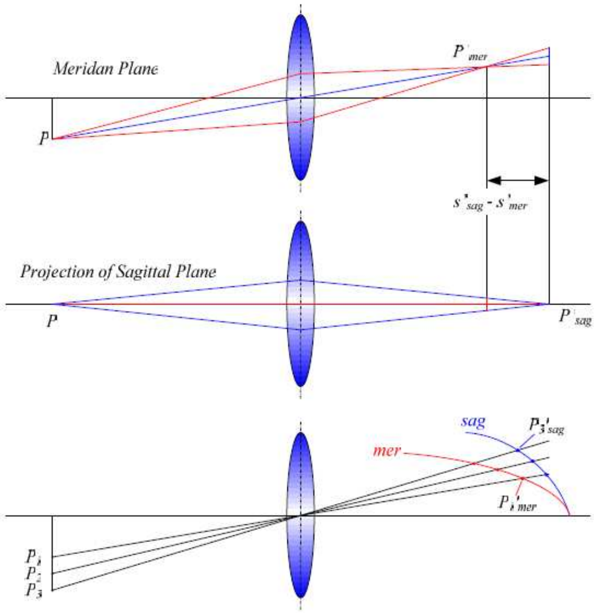
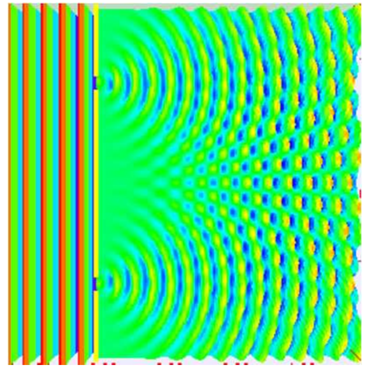
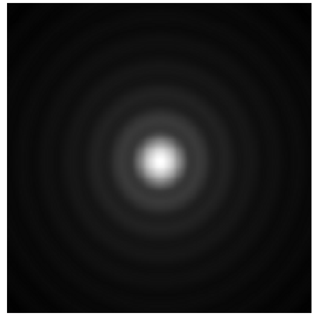


Figure 19: Astigmatism

Wellen Optik:





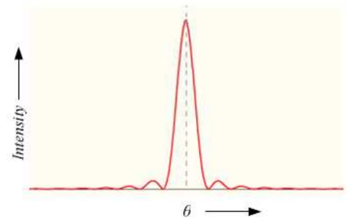
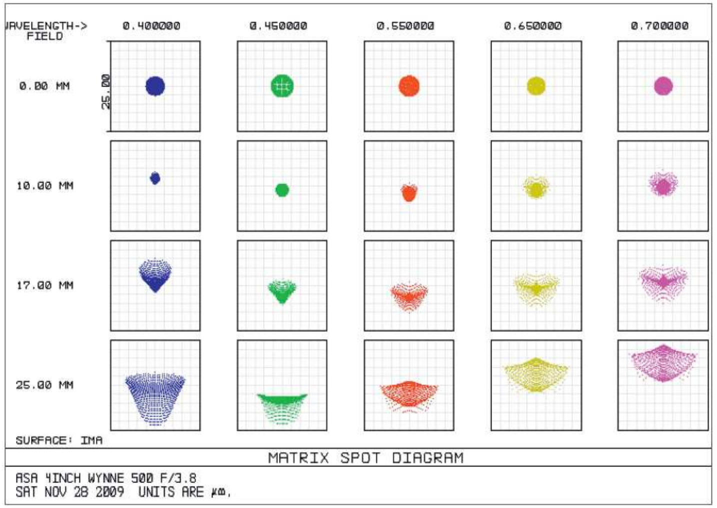


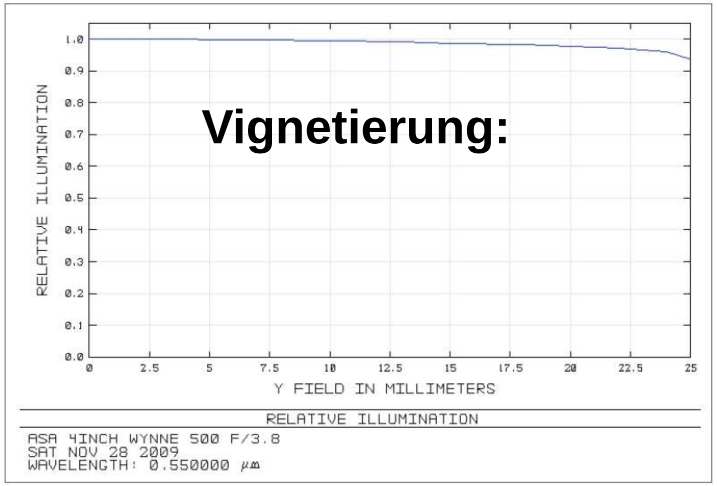
Figure 23: Diffraction Pattern

Optik:

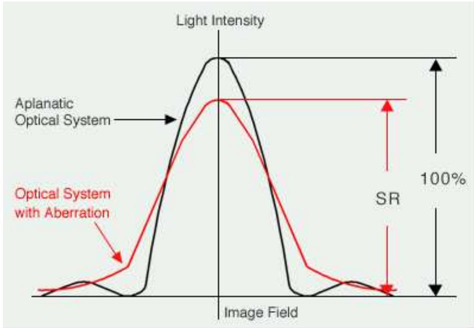
Spotdiagramme:



Vignetierung:

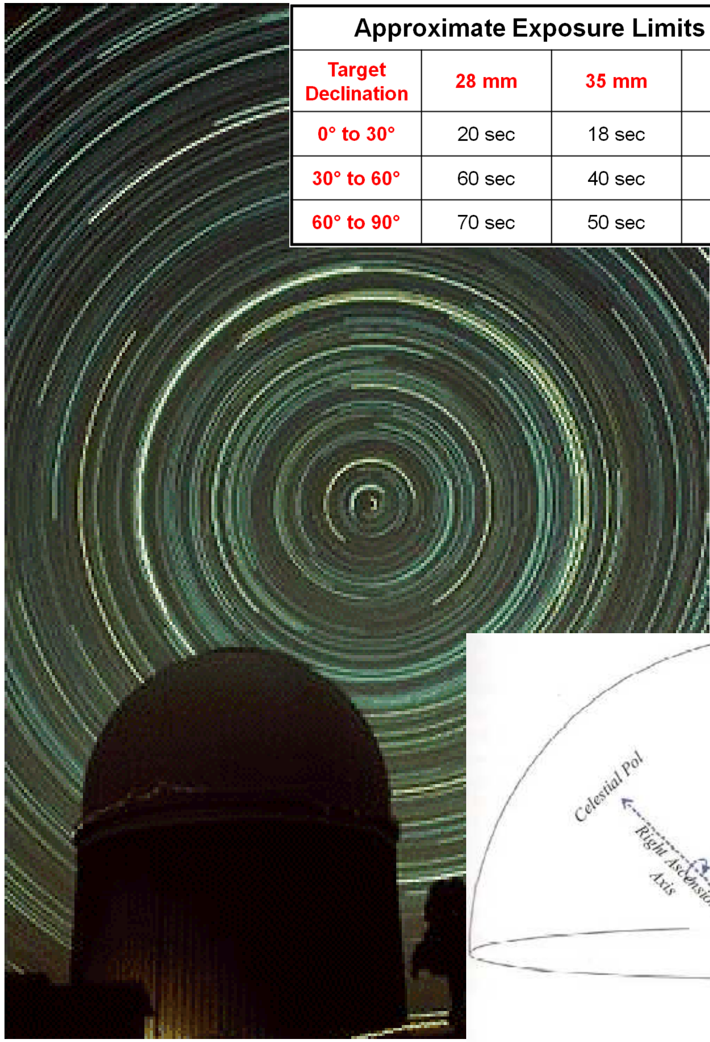


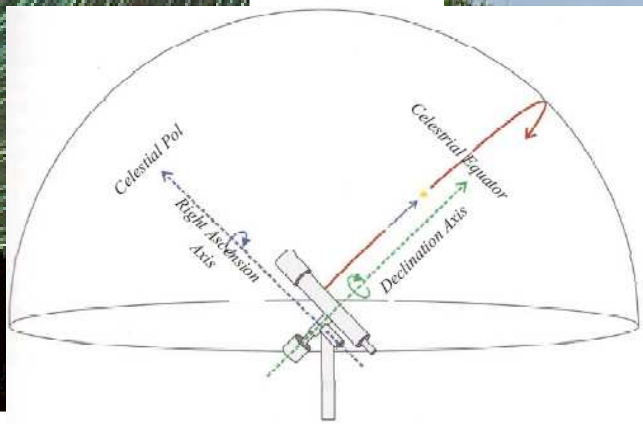
Strehl Ratio:

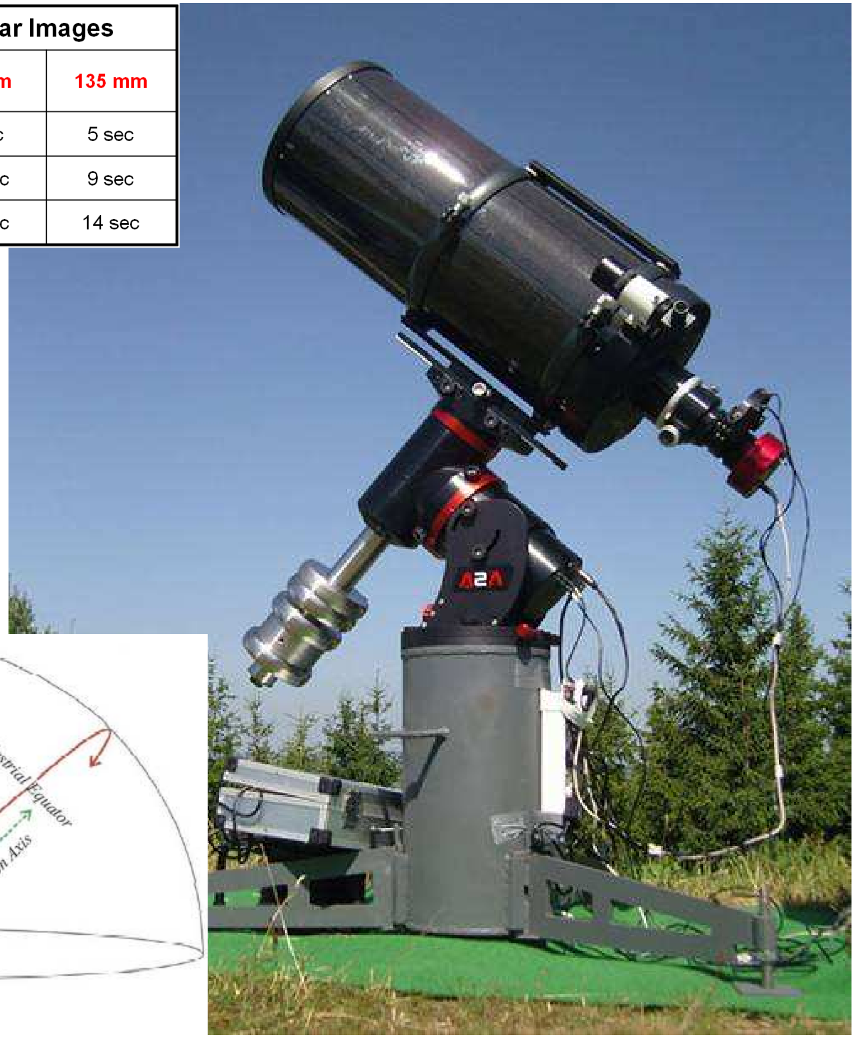


Nachführung:

Approximate Exposure Limits for Trail-Free Star Images					
Target Declination	28 mm	35 mm	50 mm	85 mm	135 mm
0° to 30°	20 sec	18 sec	13 sec	8 sec	5 sec
30° to 60°	60 sec	40 sec	25 sec	15 sec	9 sec
60° to 90°	70 sec	50 sec	40 sec	24 sec	14 sec

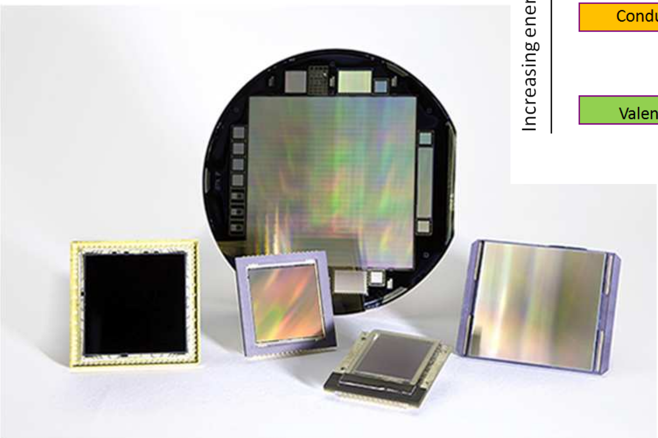


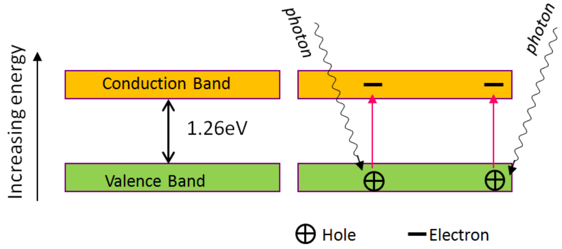


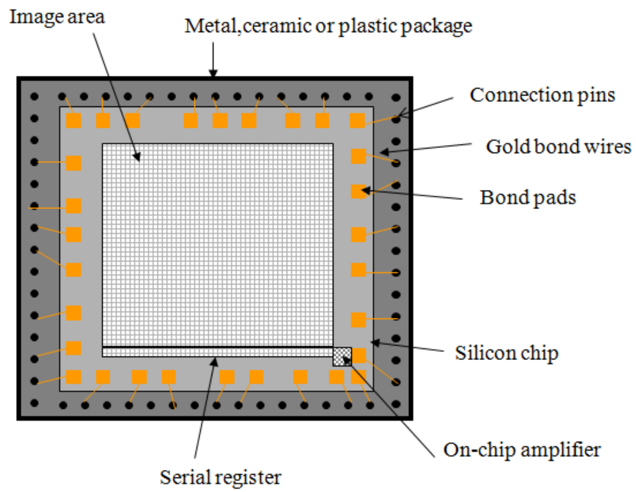


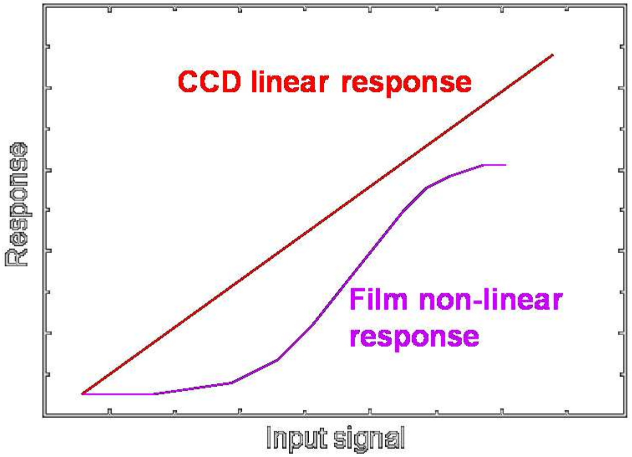
Klassische Photographie:

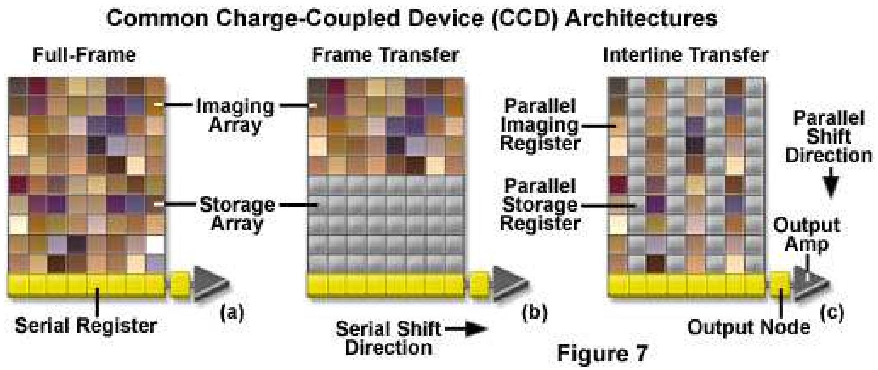
CCD-Sensor – Charge Coupled Device:



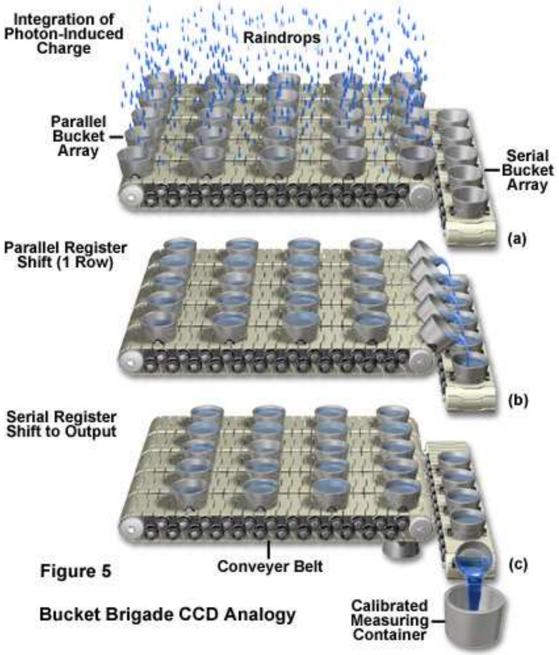


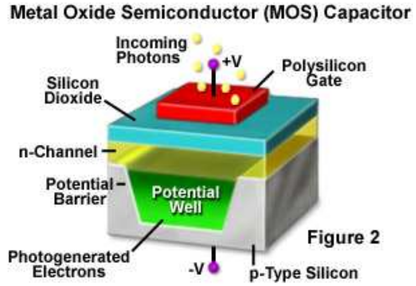


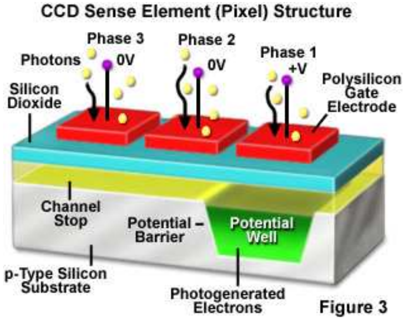


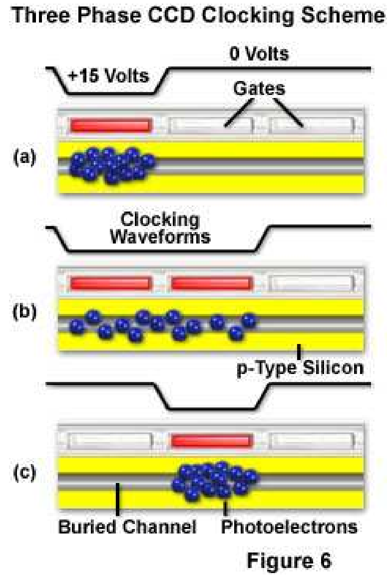


Aufbau und Funktion von CCDs:



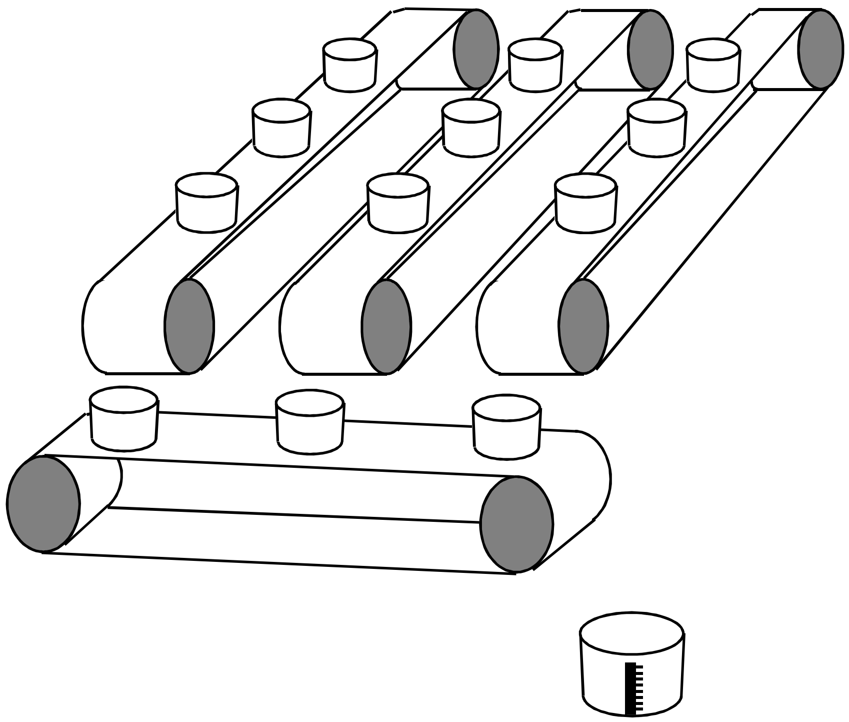






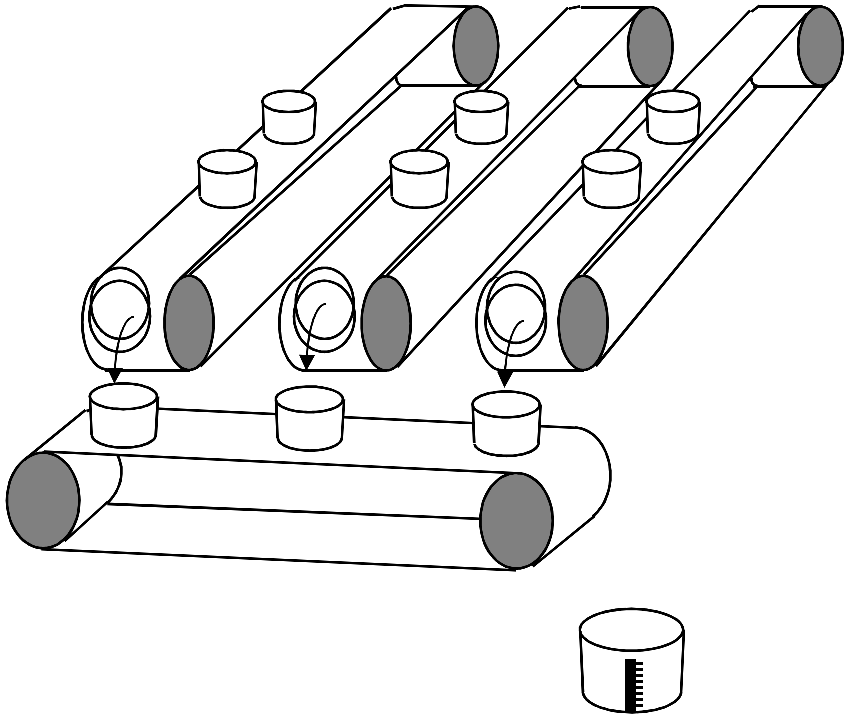
Auslesen von CCDs:

Exposure finished, buckets now contain samples of rain.



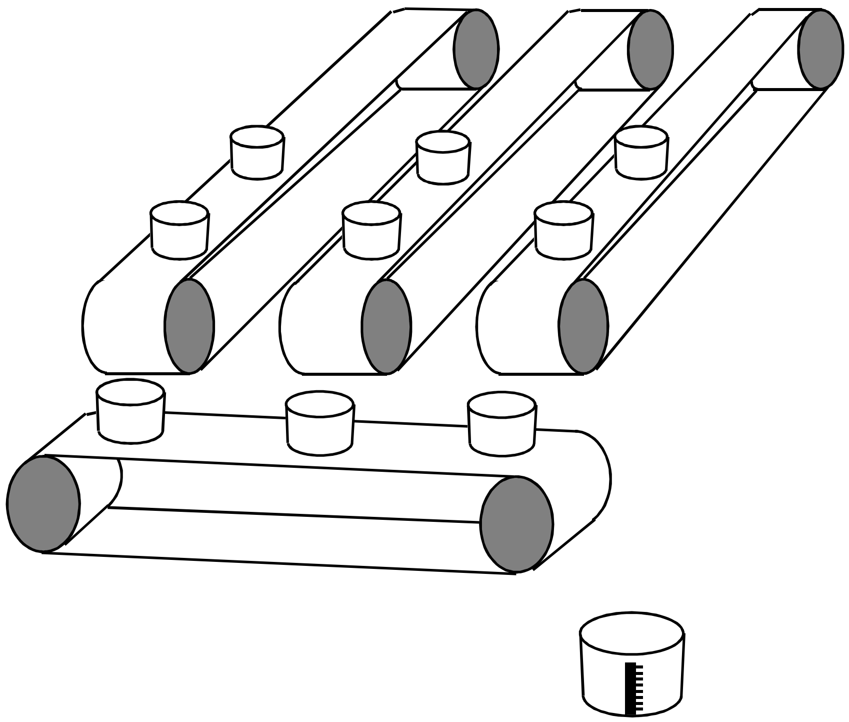
Auslesen von CCDs:

Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.



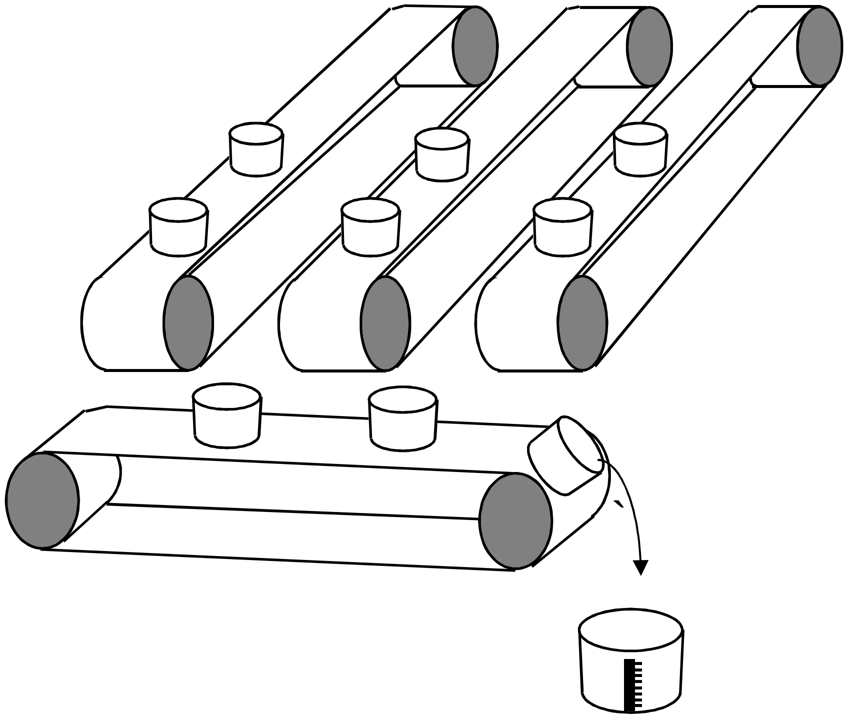
Auslesen von CCDs:

Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the measuring cylinder .



Auslesen von CCDs:

After each bucket has been measured, the measuring cylinder is emptied , ready for the next bucket load.



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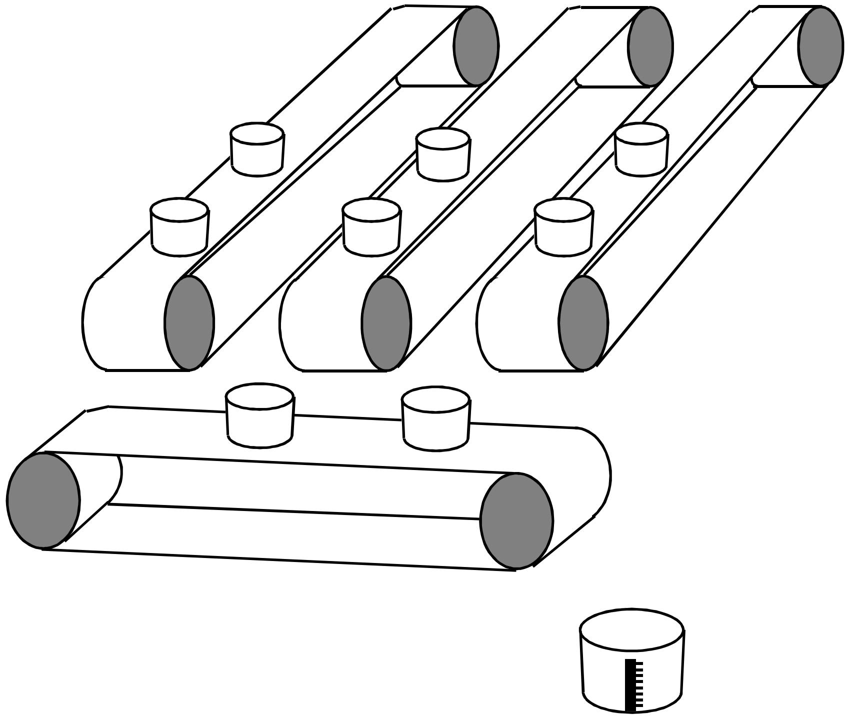

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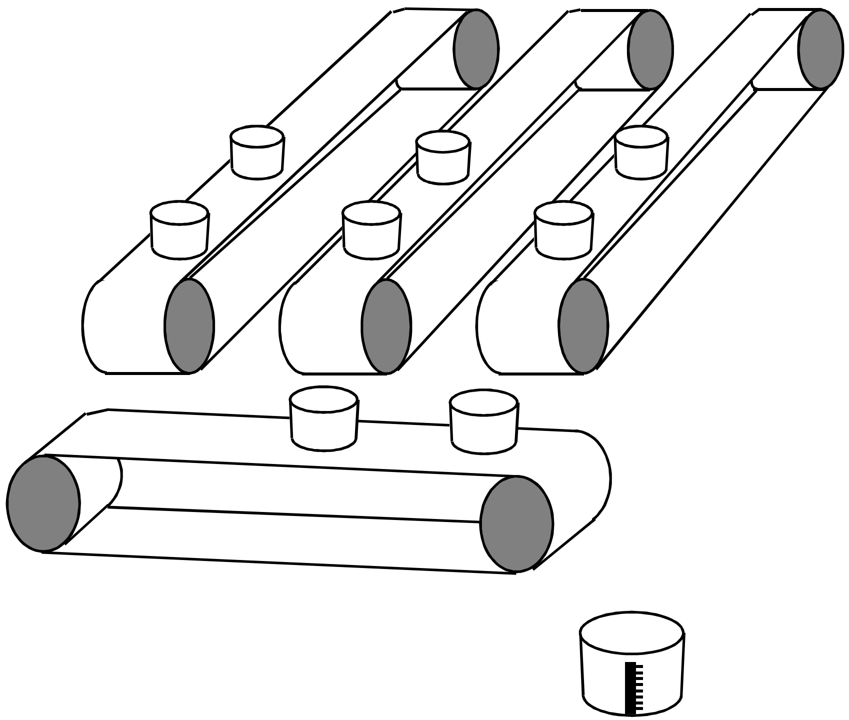

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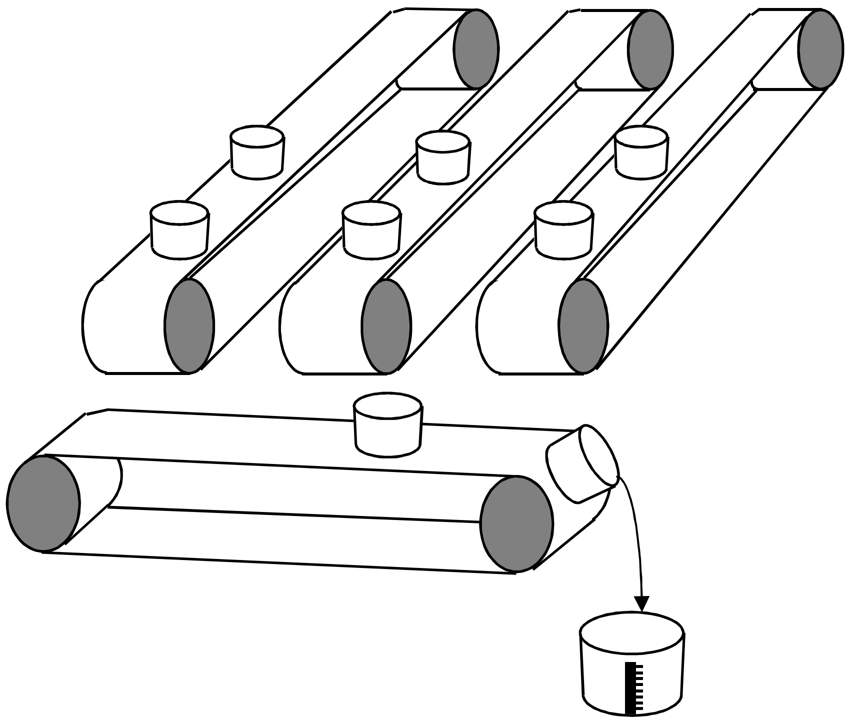

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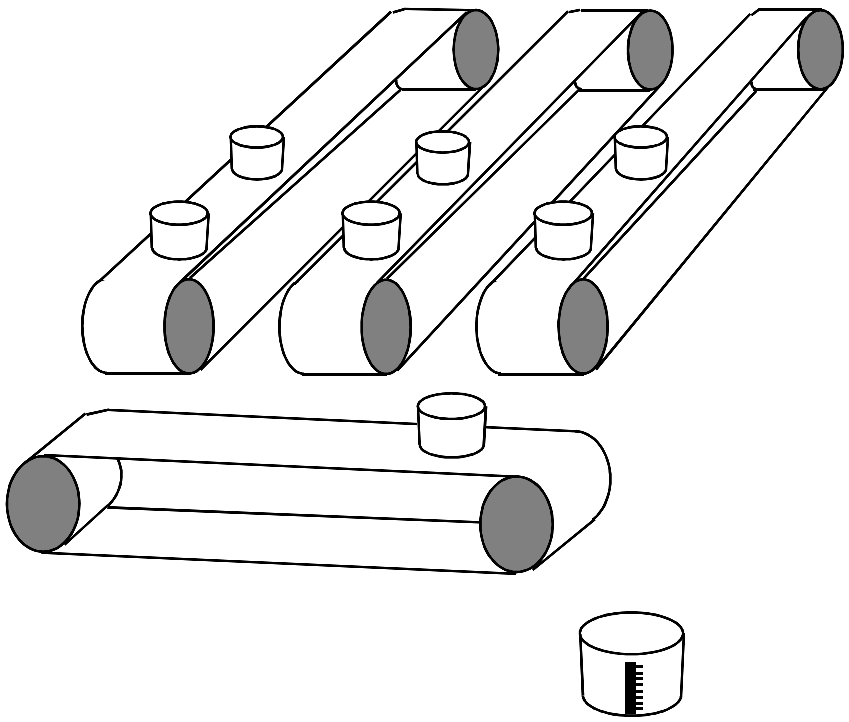

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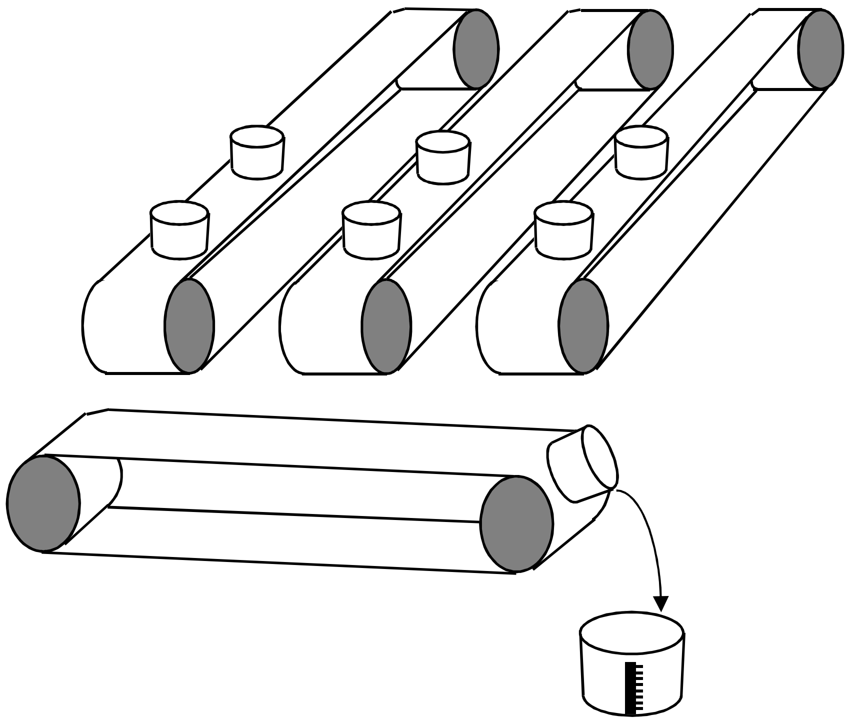

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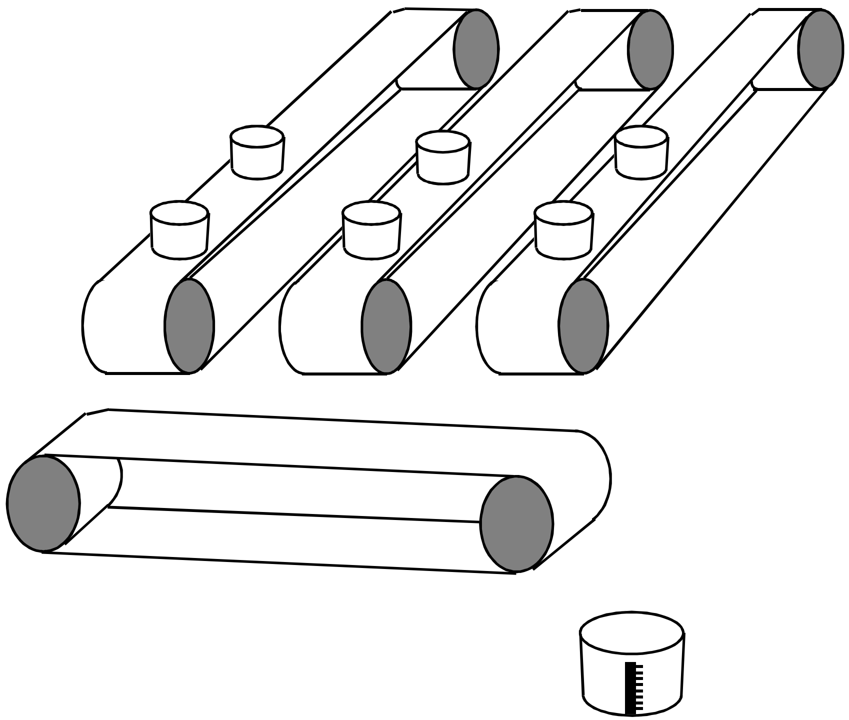
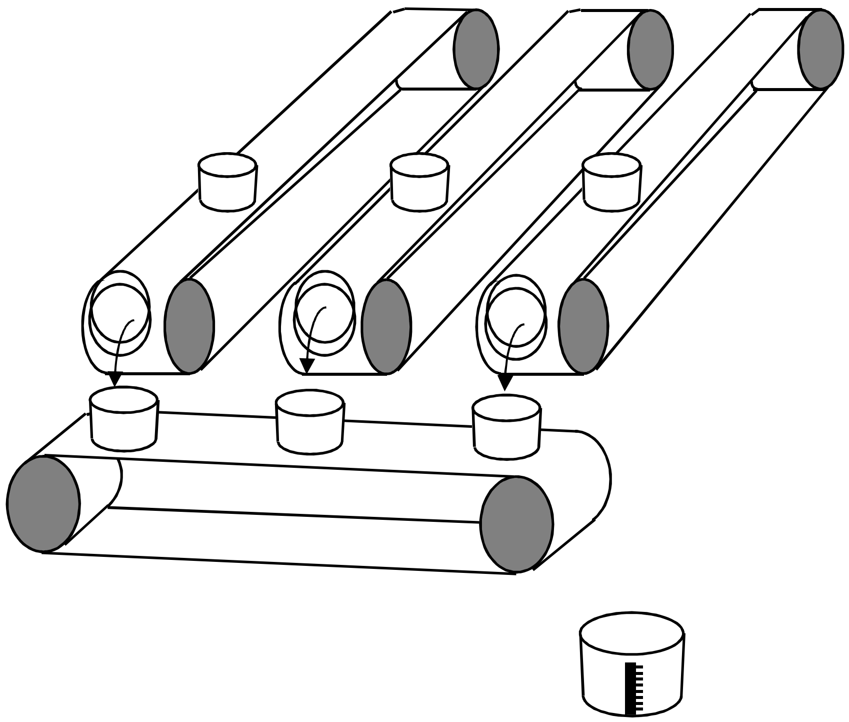


Auslesen von CCDs:

A new set of empty buckets is set up on the horizontal conveyor and the process is repeated.



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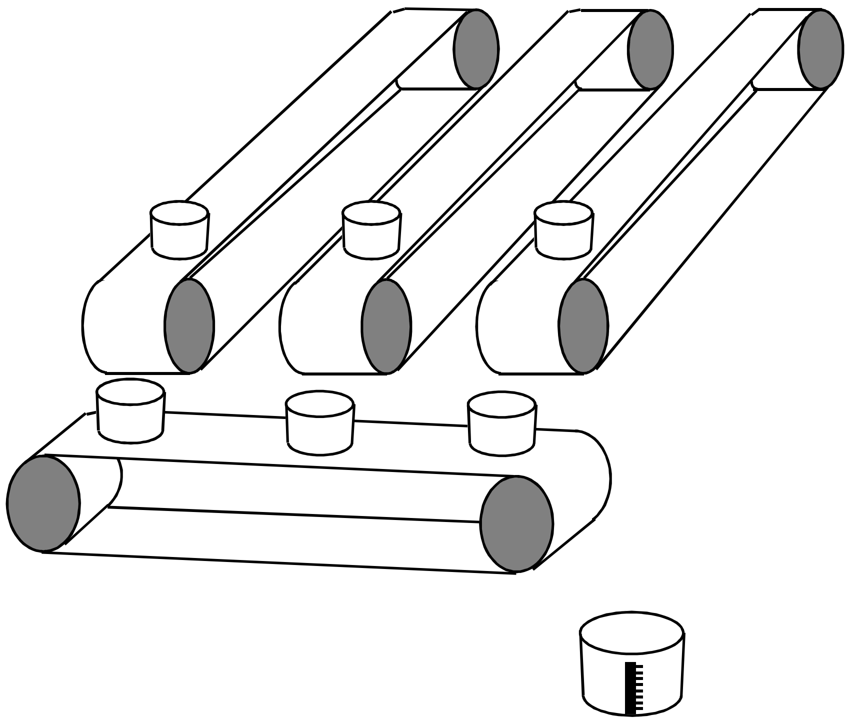
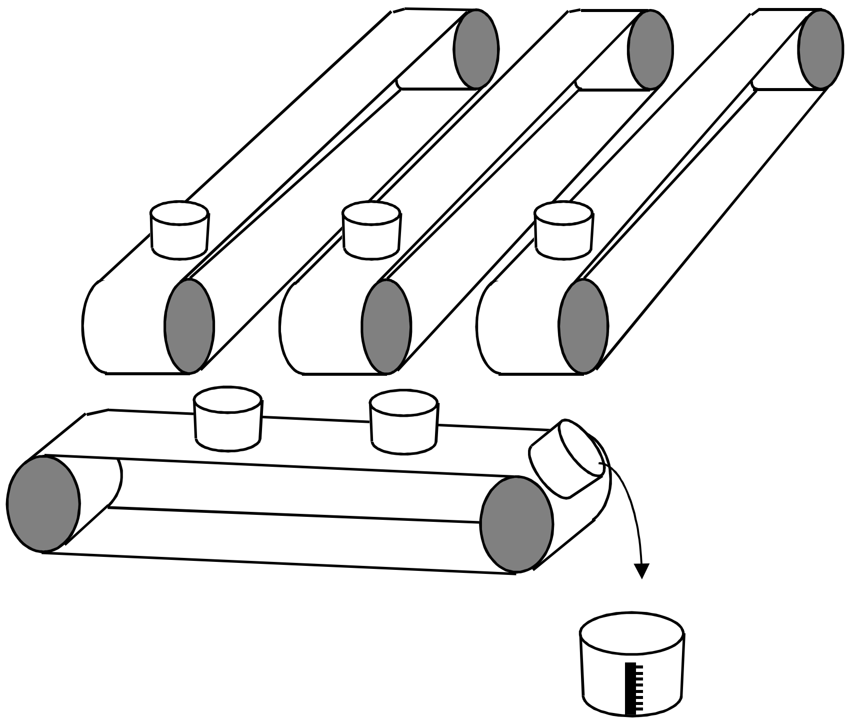


Auslesen von CCDs:



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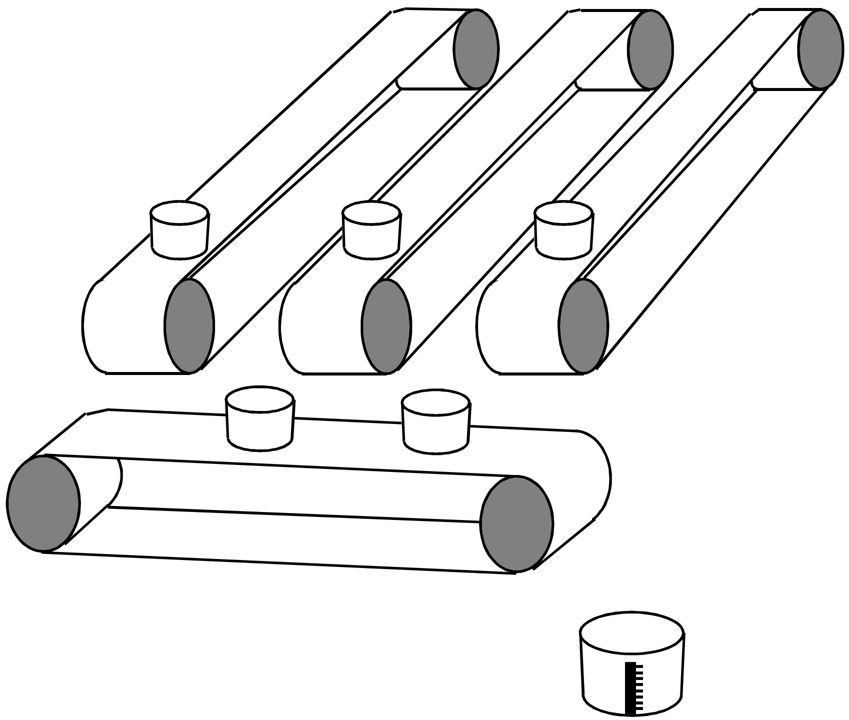

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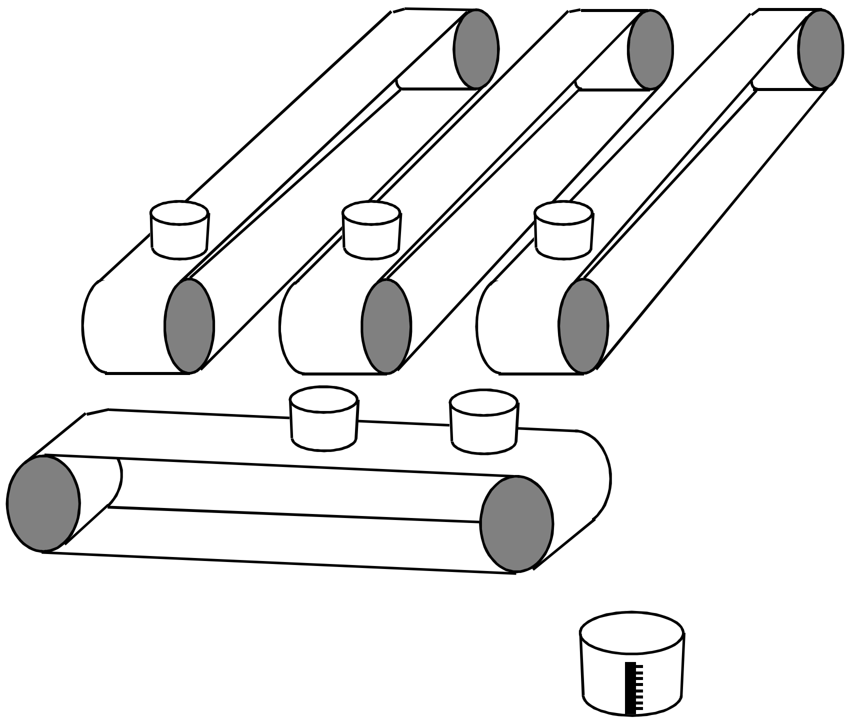

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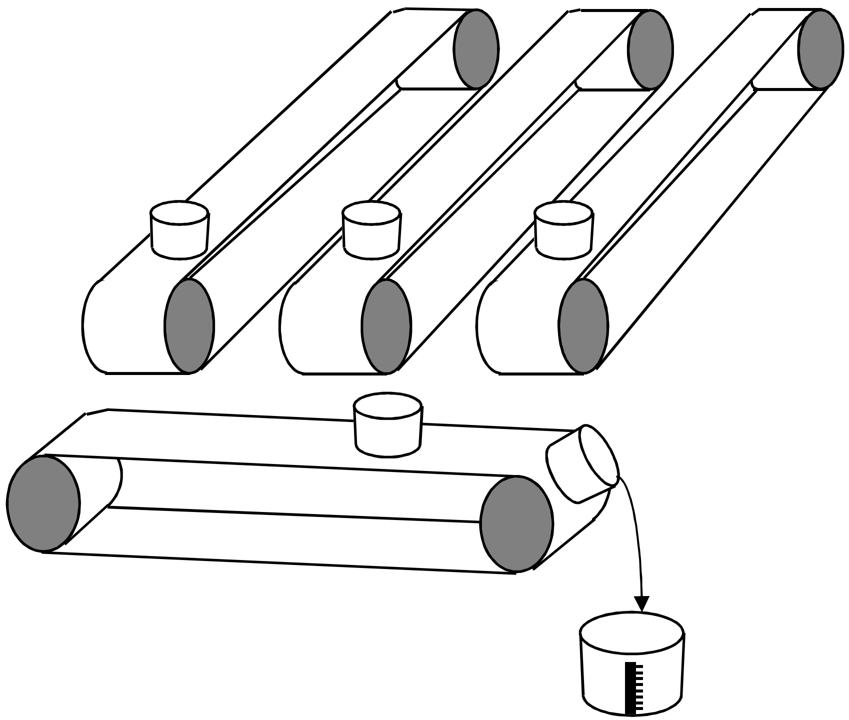

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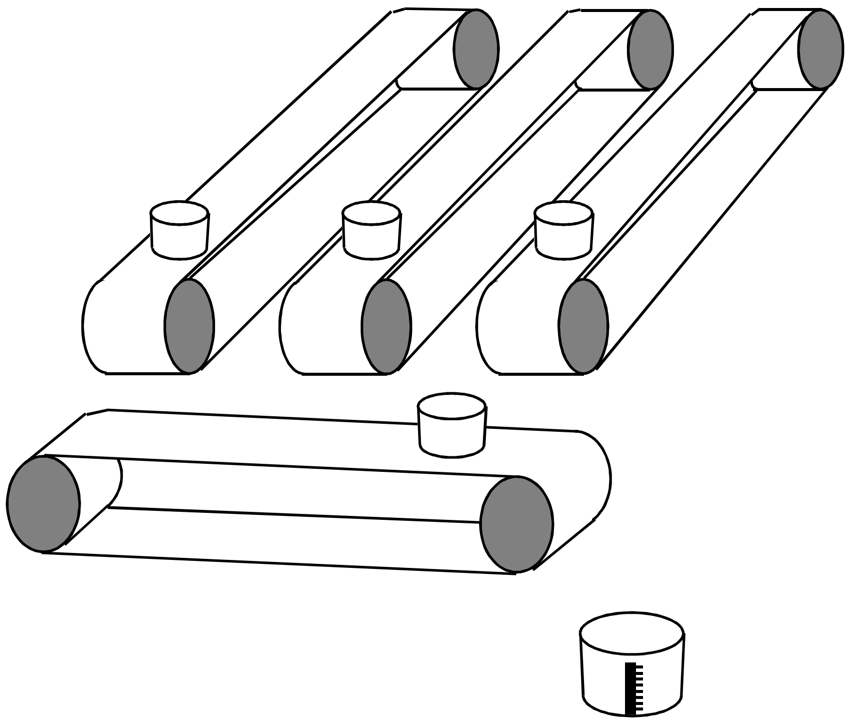

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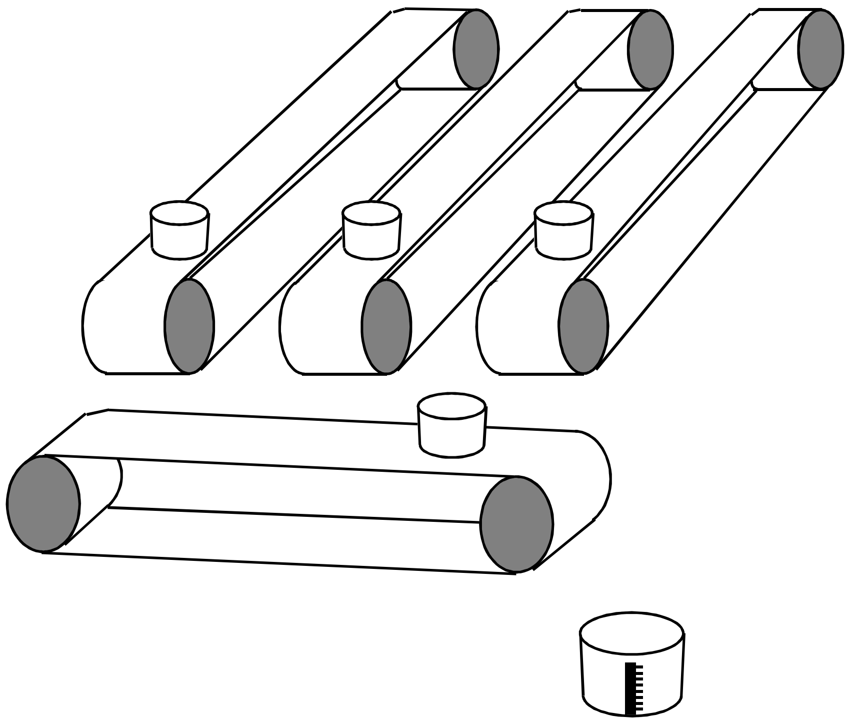

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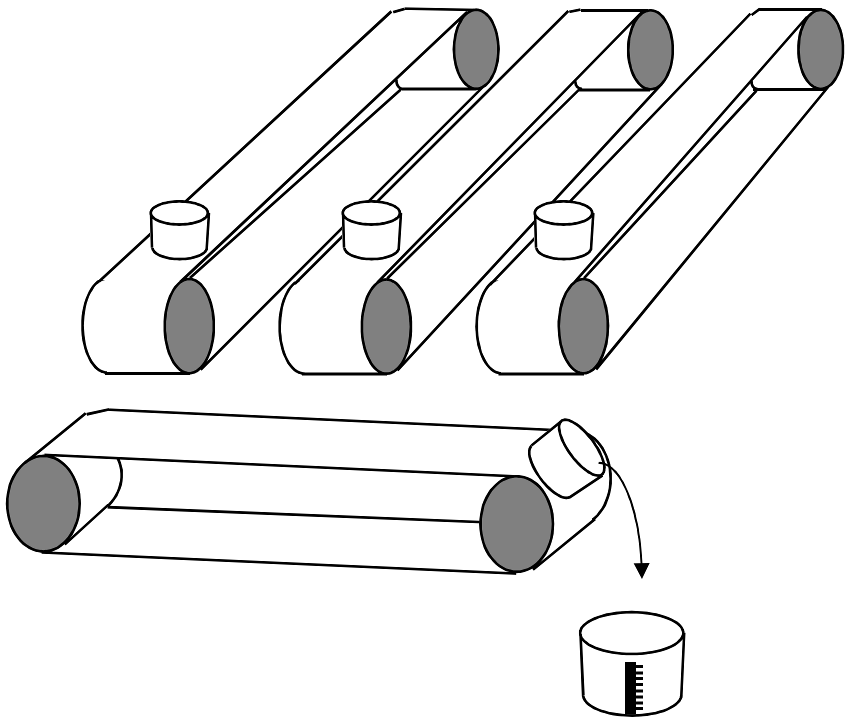

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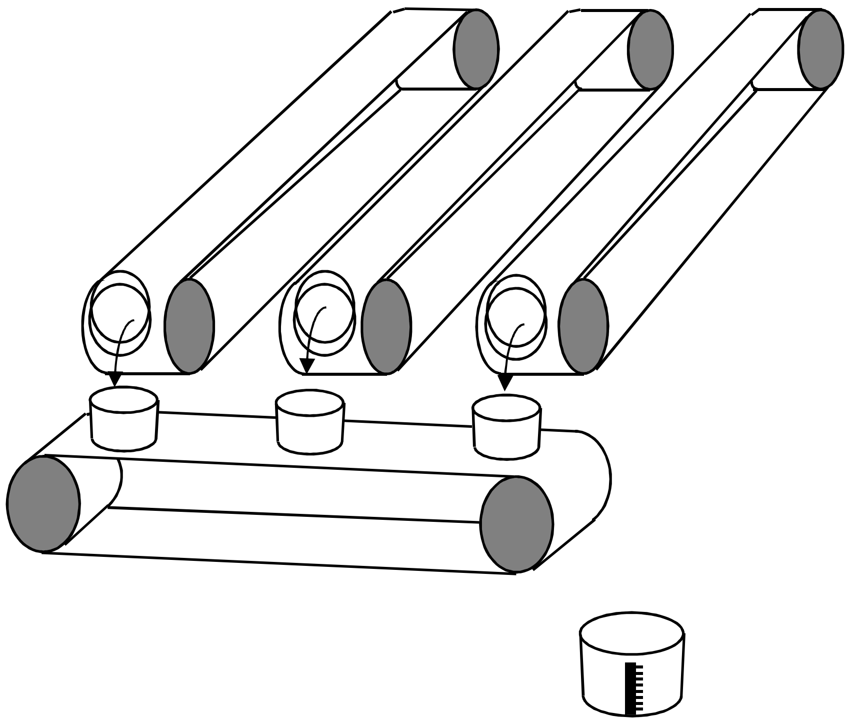

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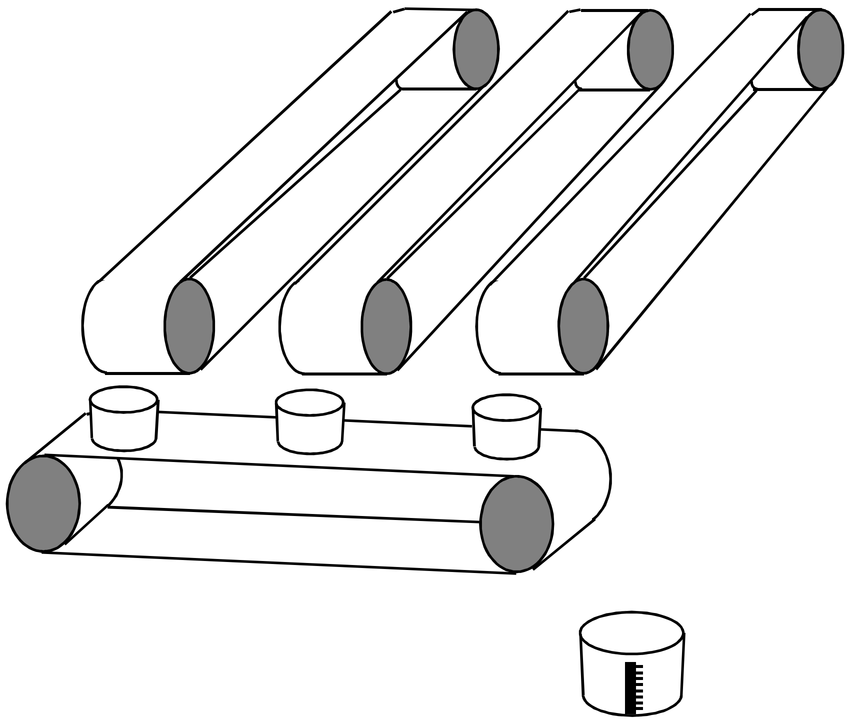

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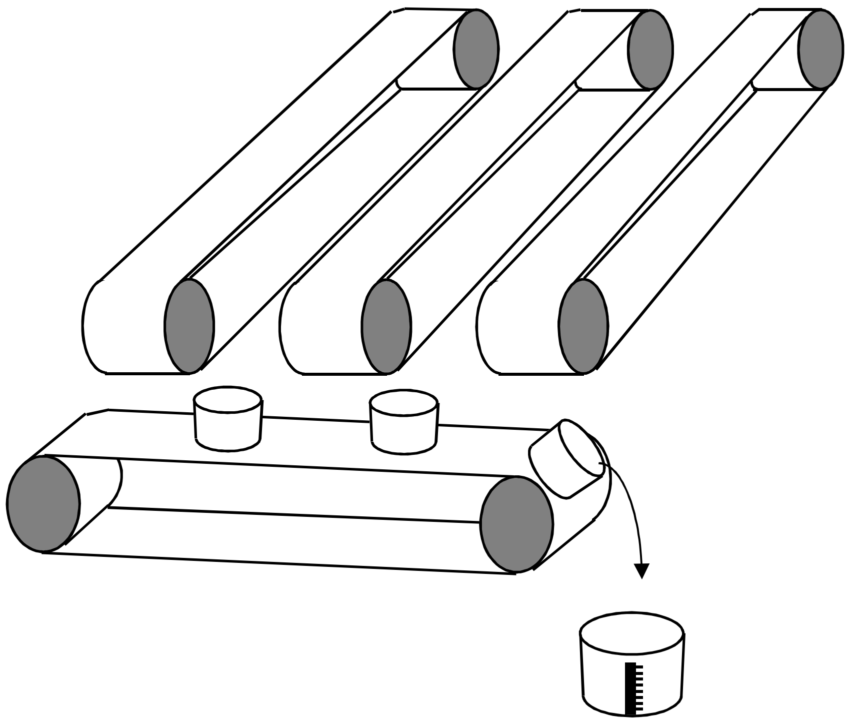

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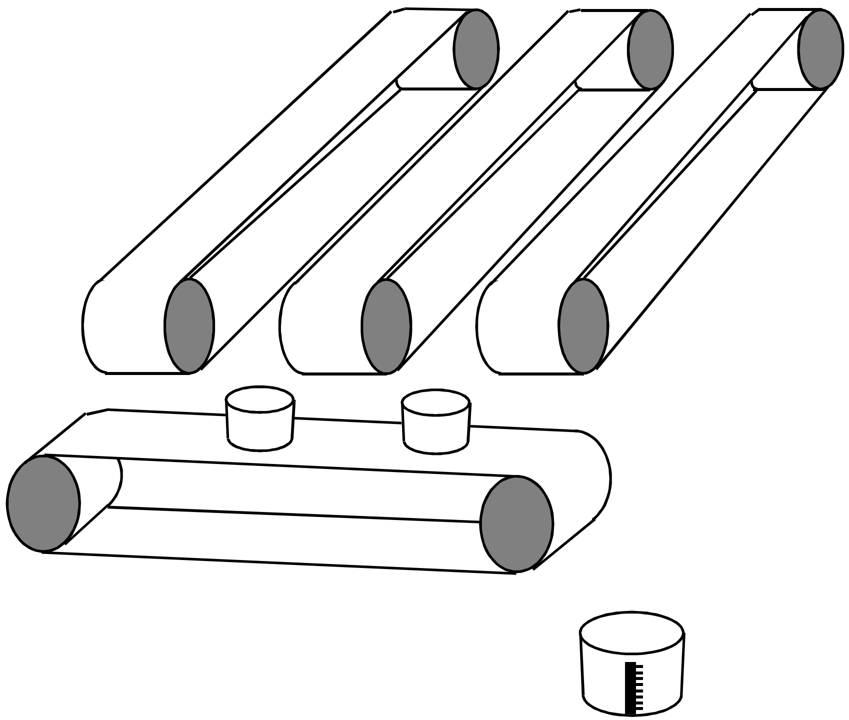

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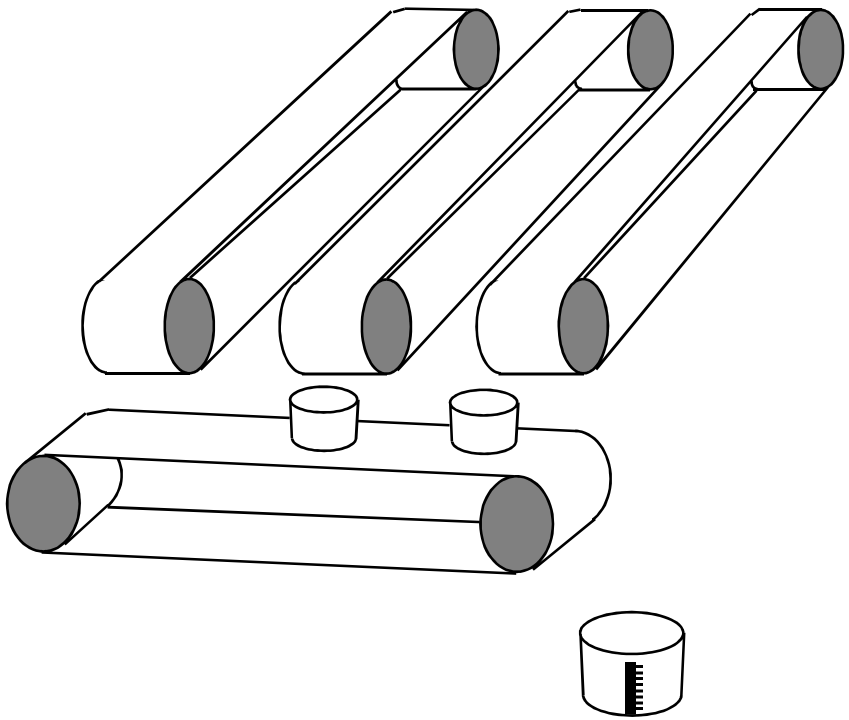

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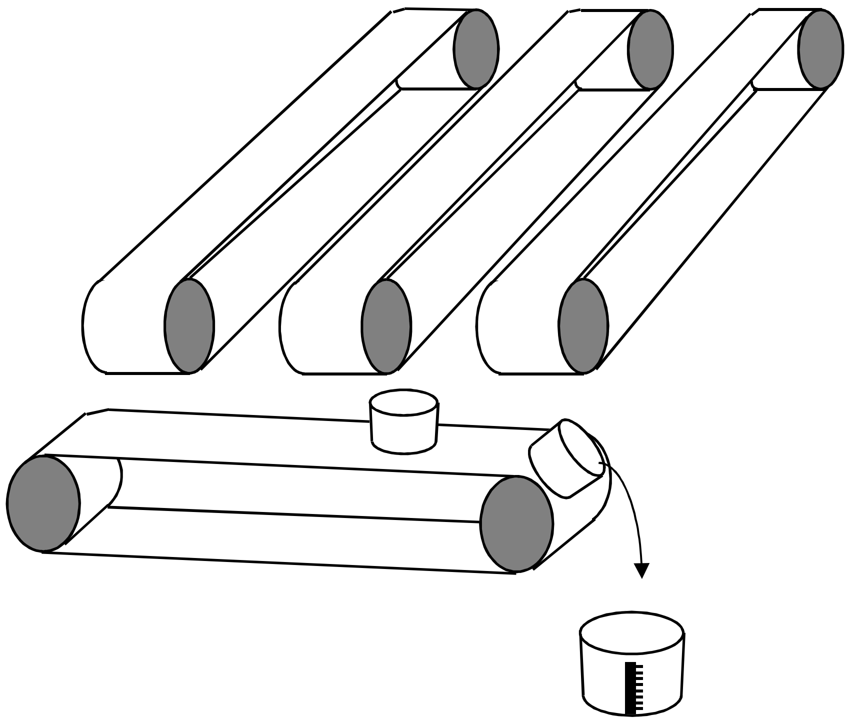

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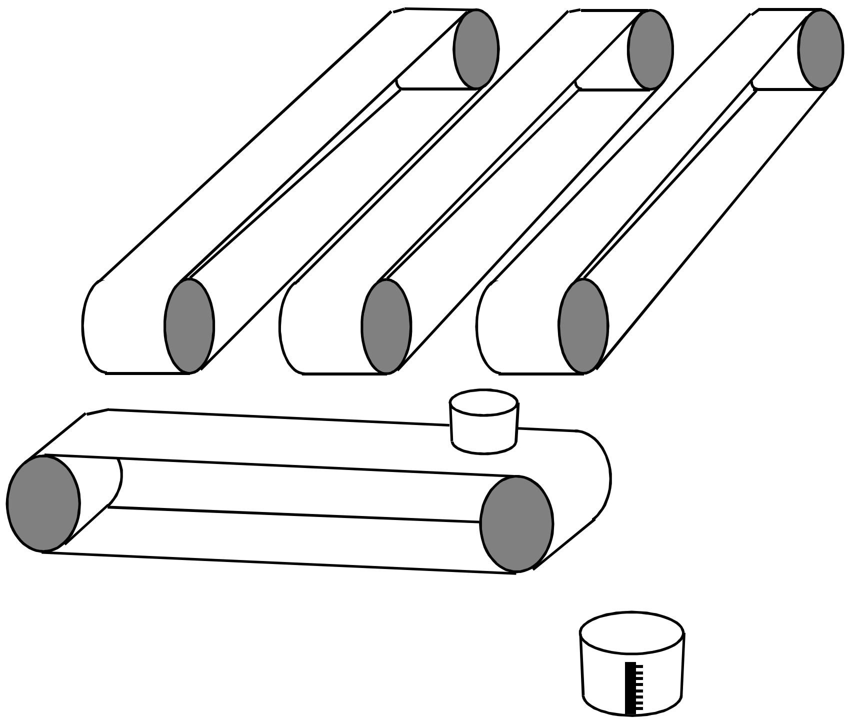

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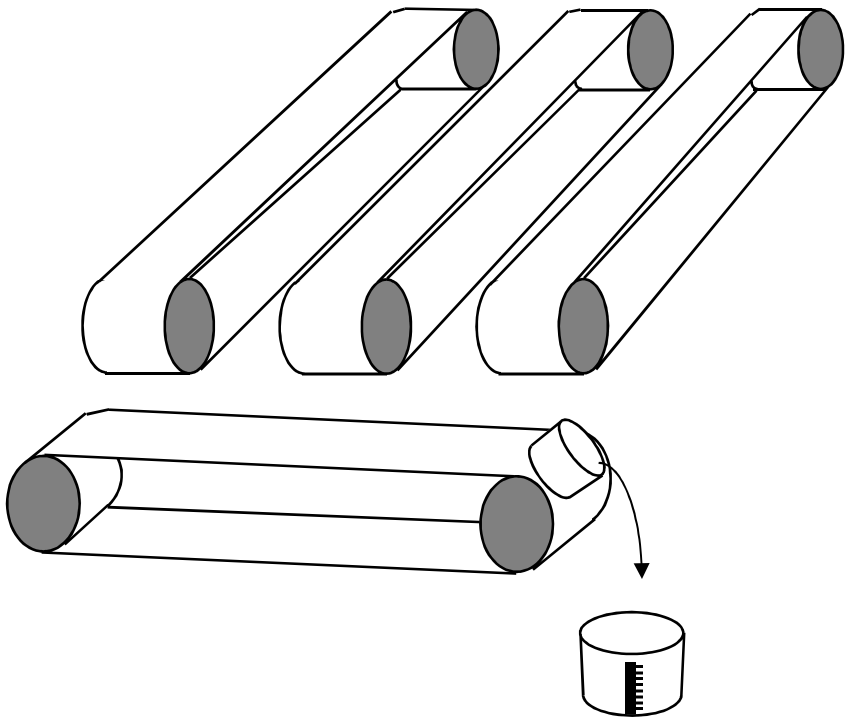
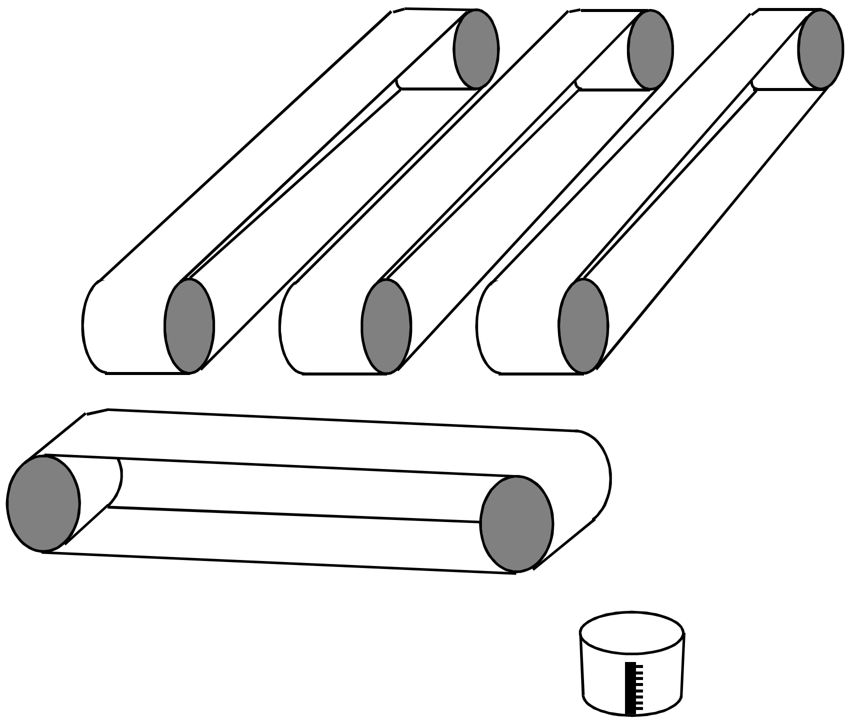


Auslesen von CCDs:

Eventually all the buckets have been measured, the CCD has been read out.



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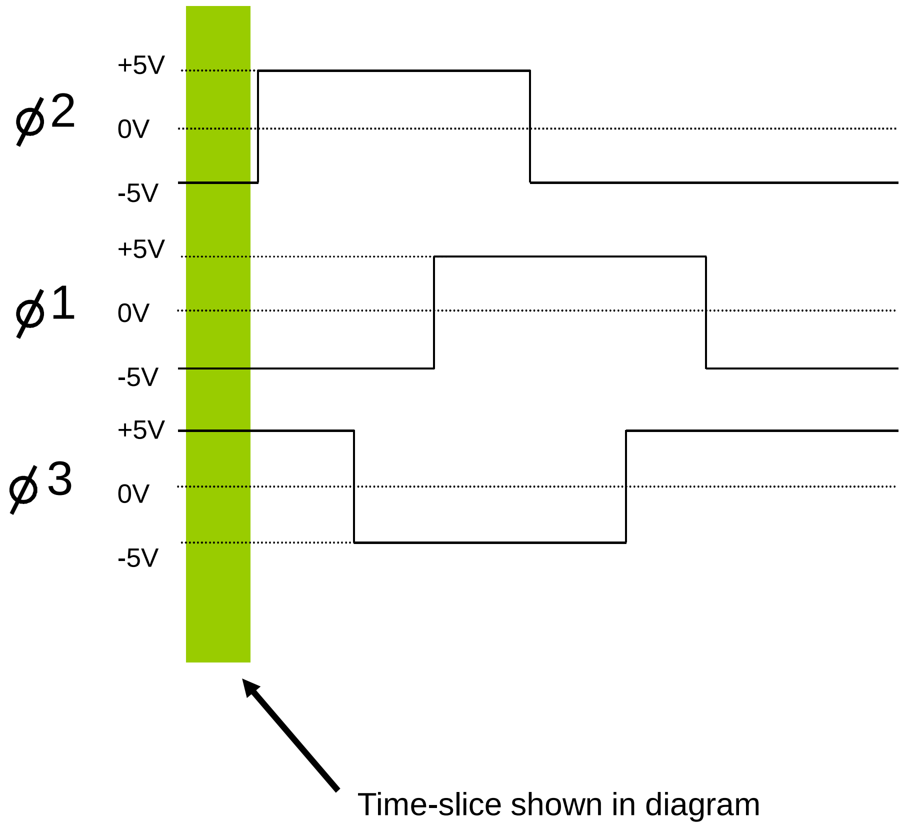

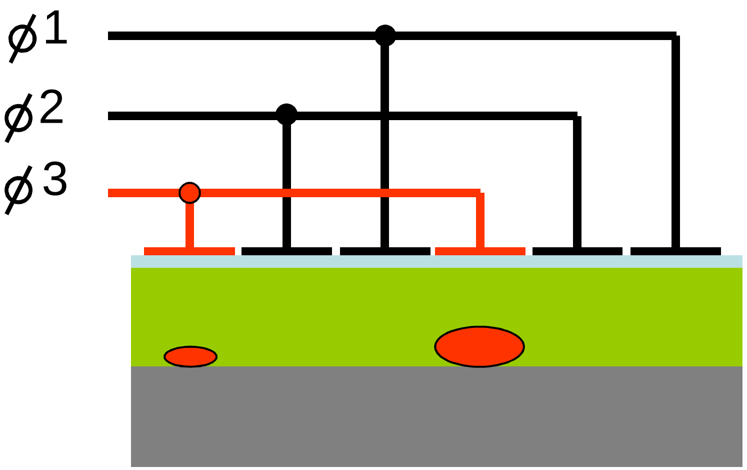

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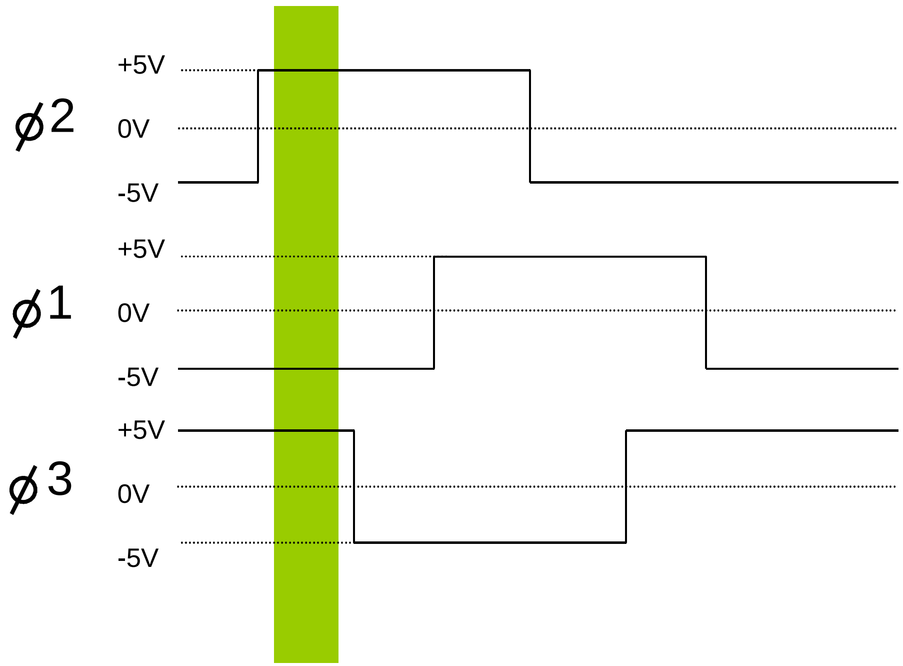

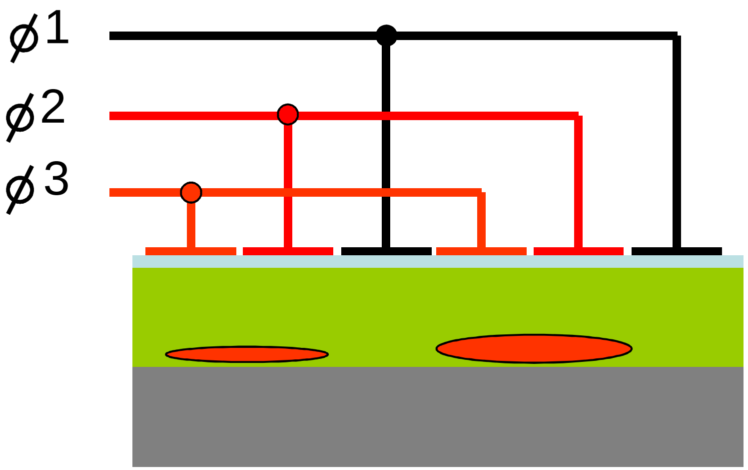

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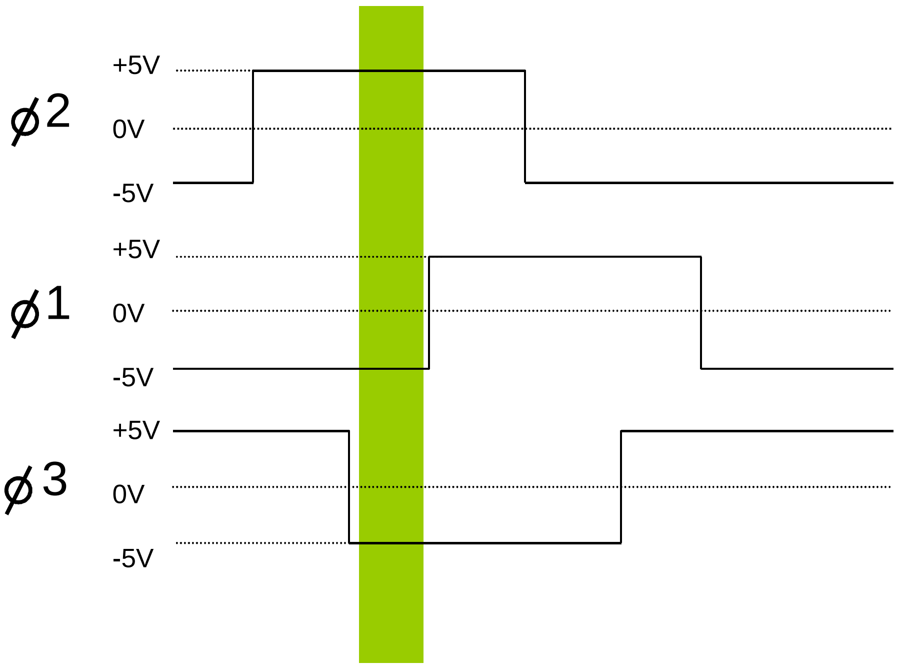

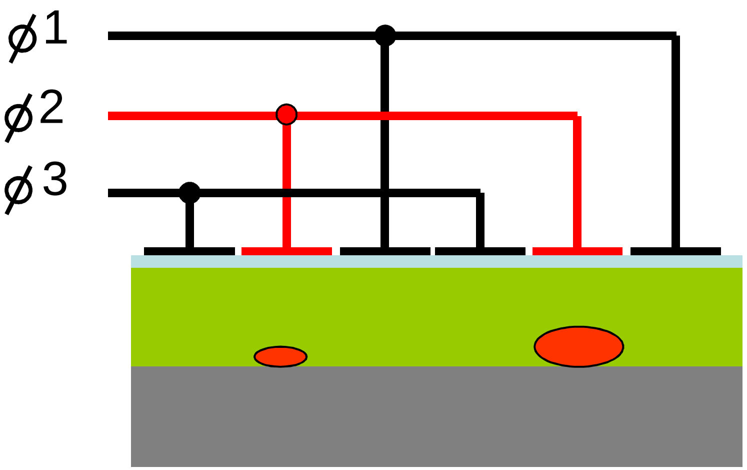

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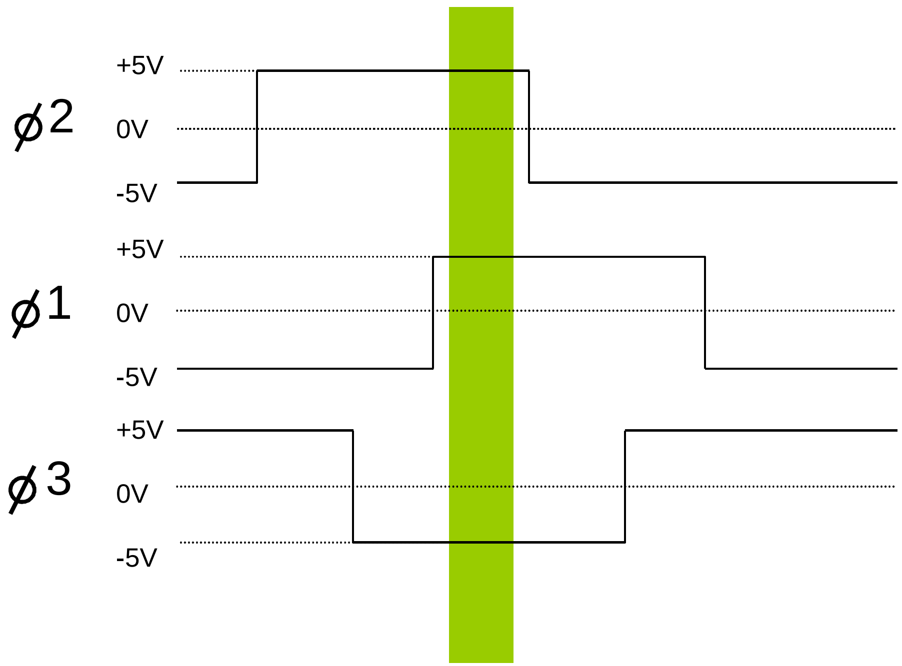

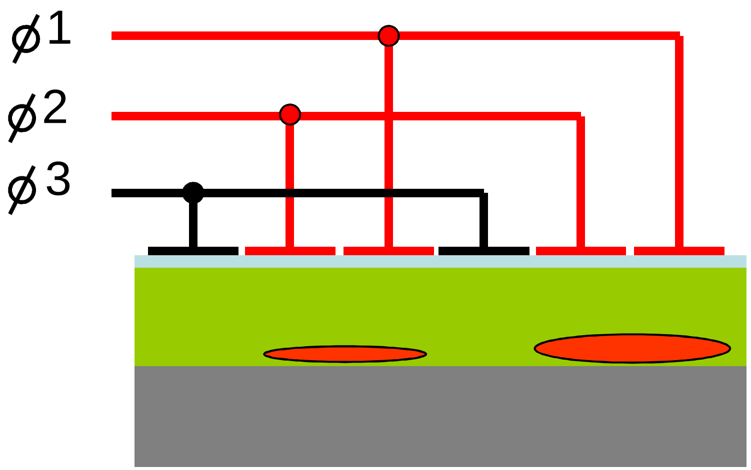

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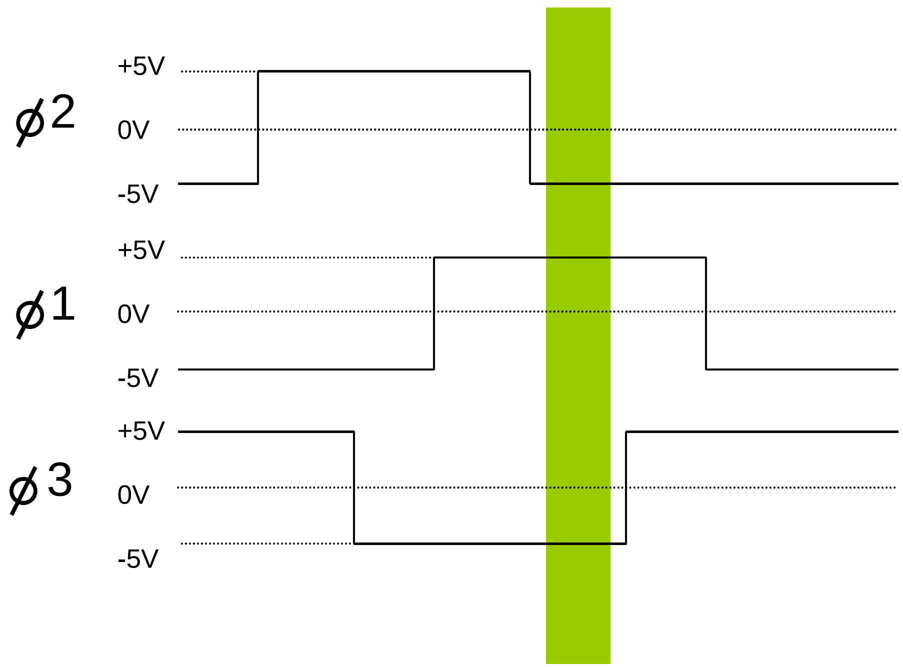
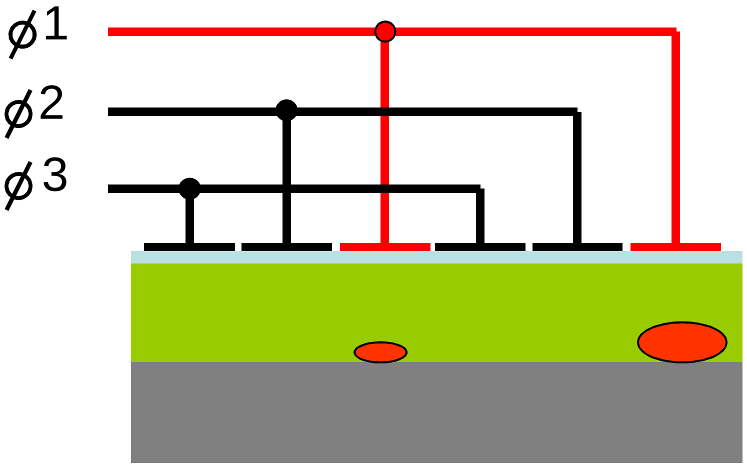
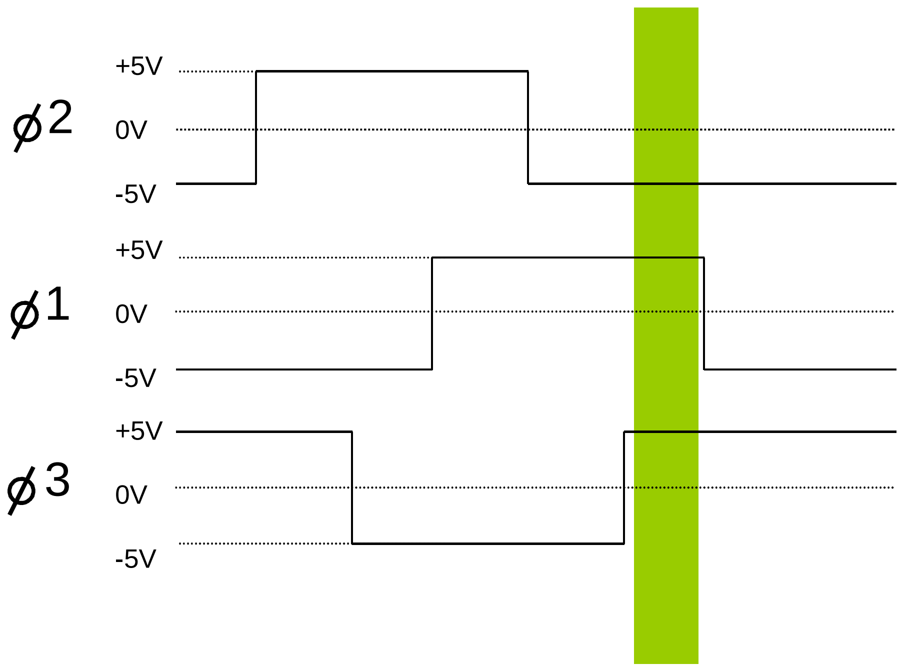
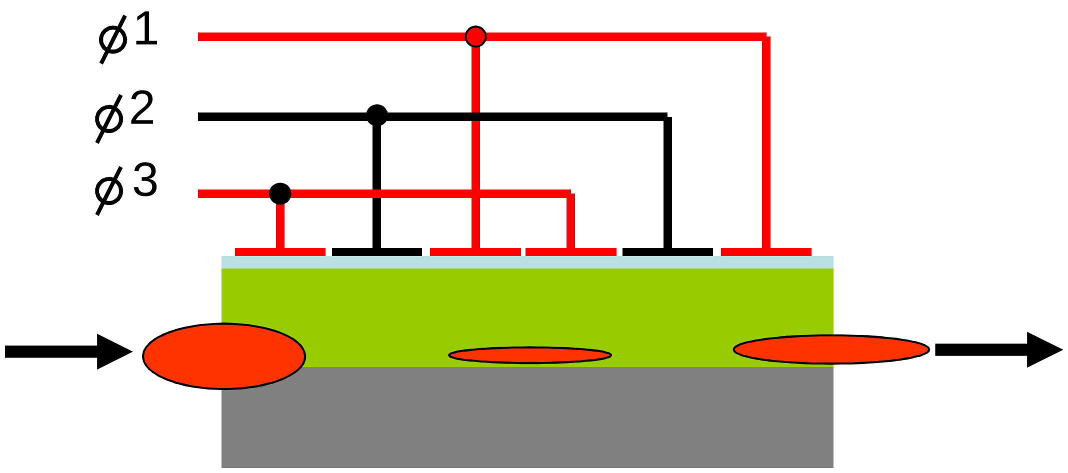




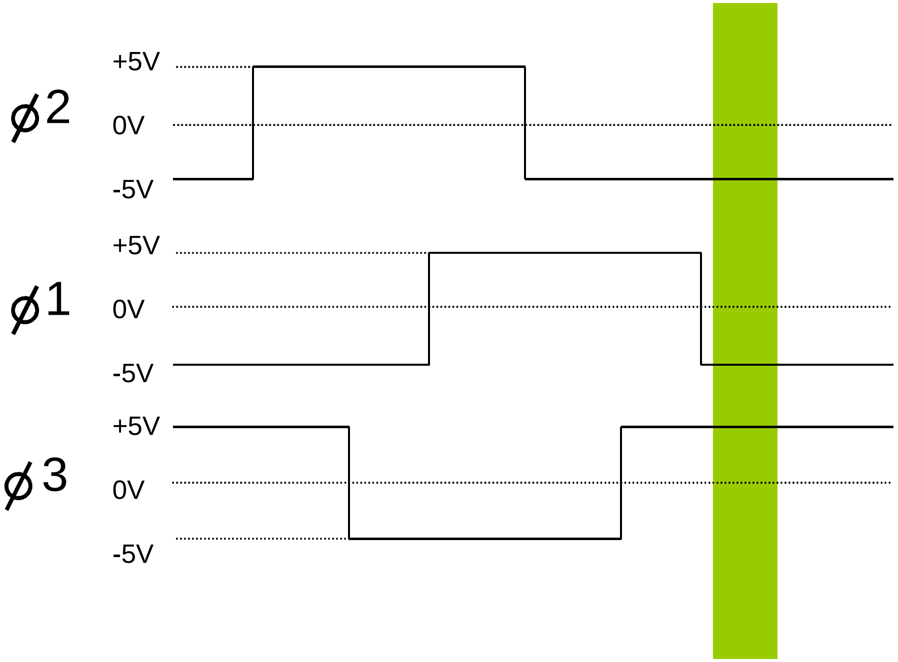
Auslesen von CCDs:

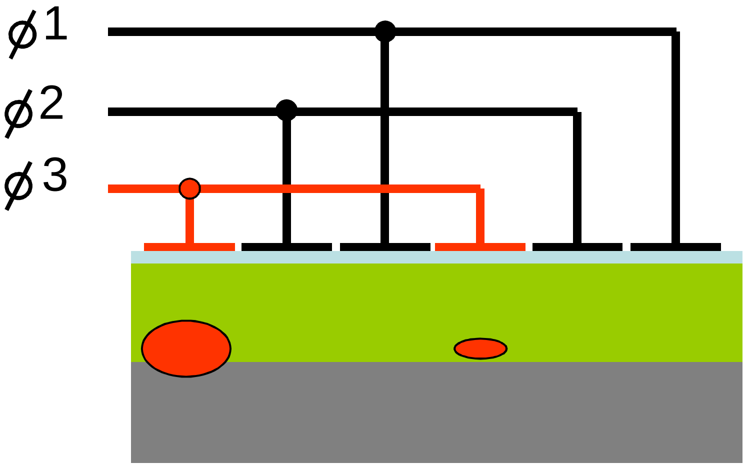
Charge packet from subsequent pixel enters from left as first pixel exits to the right.





Auslesen von CCDs:

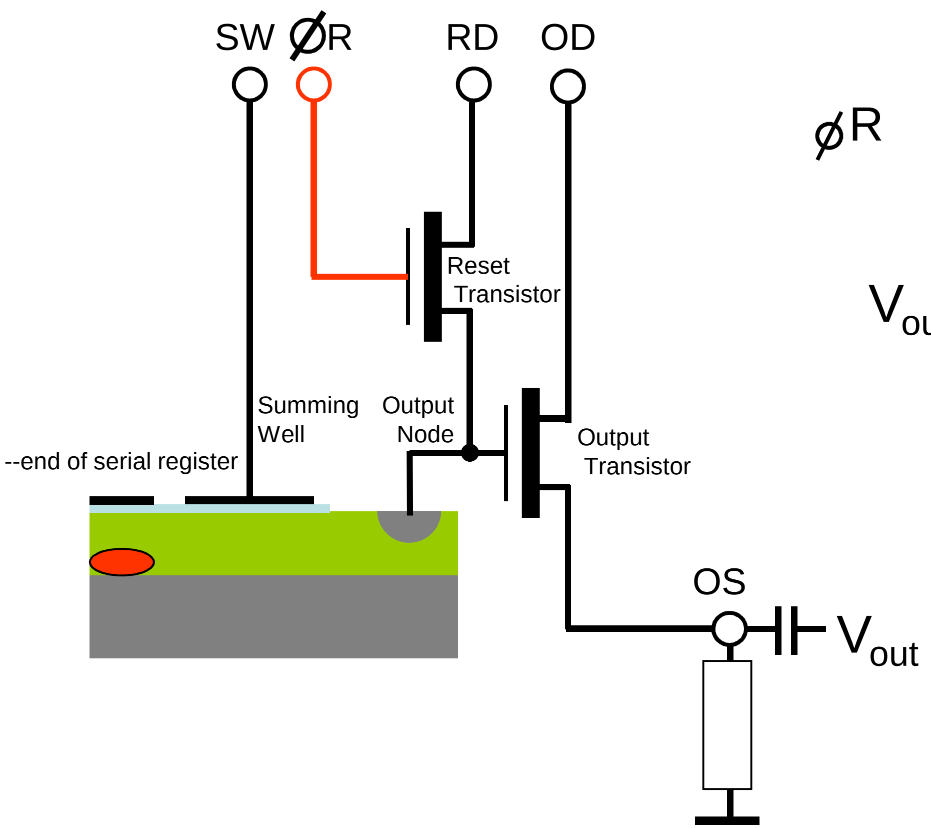


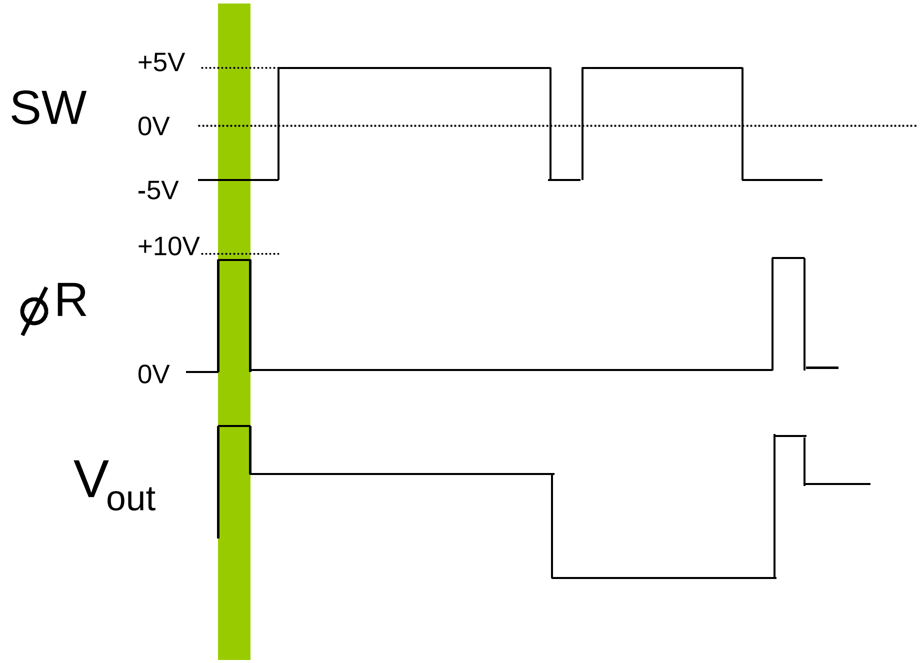


Auslesen von CCDs:

The on-chip amplifier measures each charge packet as it pops out the end of the serial register.

RD and OD are held at constant voltages



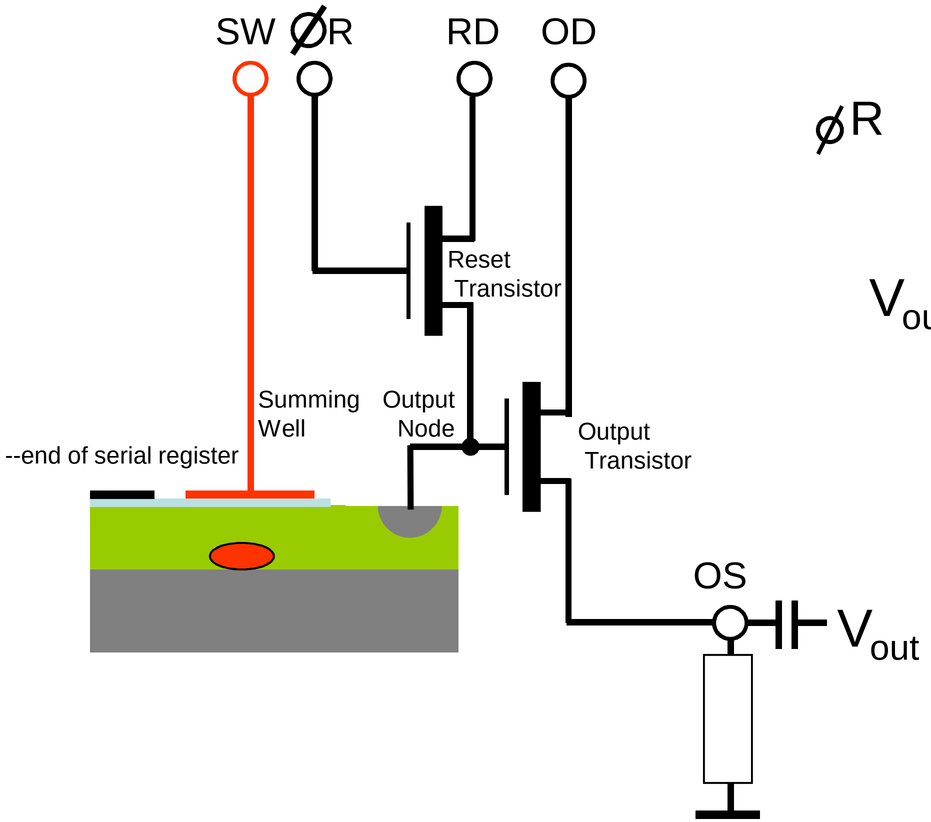


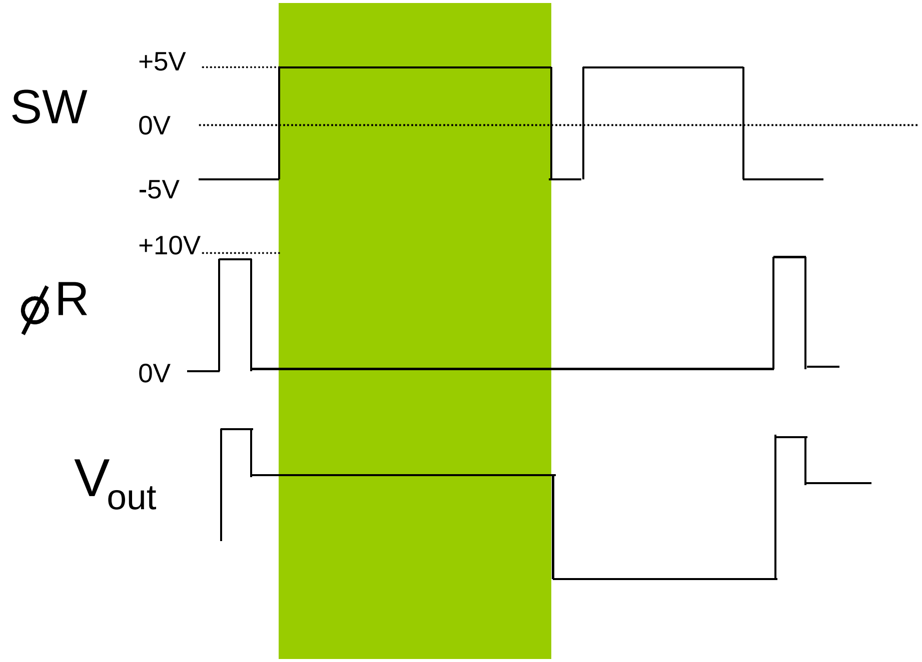
(The graphs above show the signal waveforms)

The measurement process begins with a reset of the ‘reset node’. This removes the charge remaining from the previous pixel. The reset node is in fact a tiny capacitance (< 0.1pF)

Auslesen von CCDs:

The charge is then transferred onto the Summing Well. V_{out} is now at the 'Reference level'

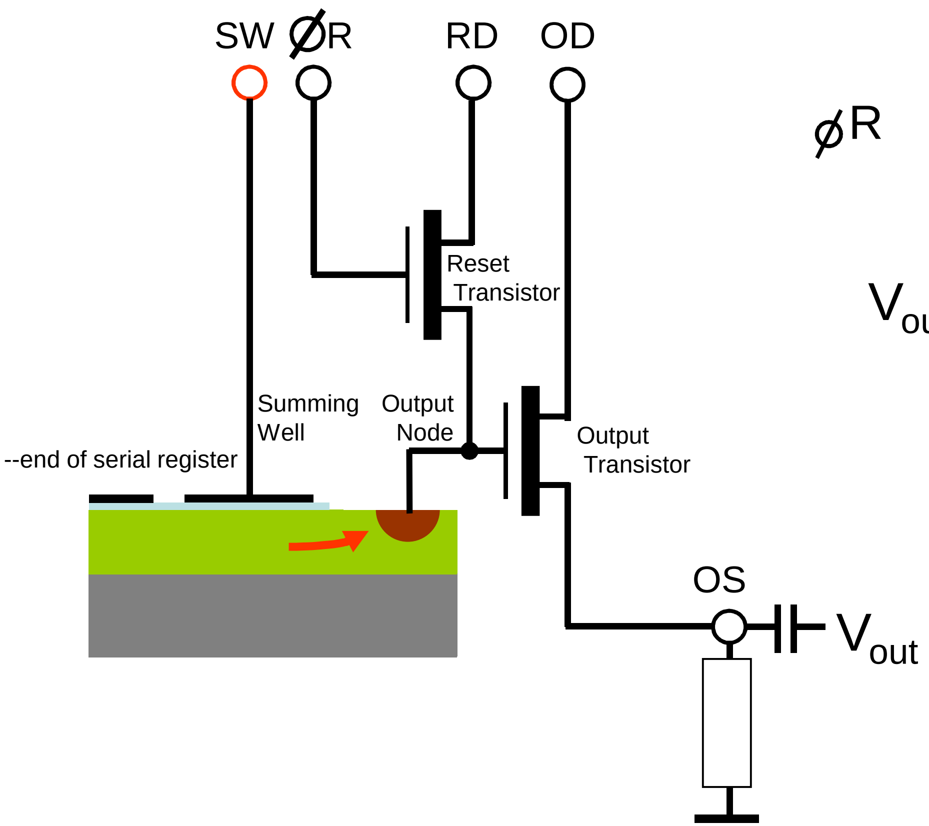


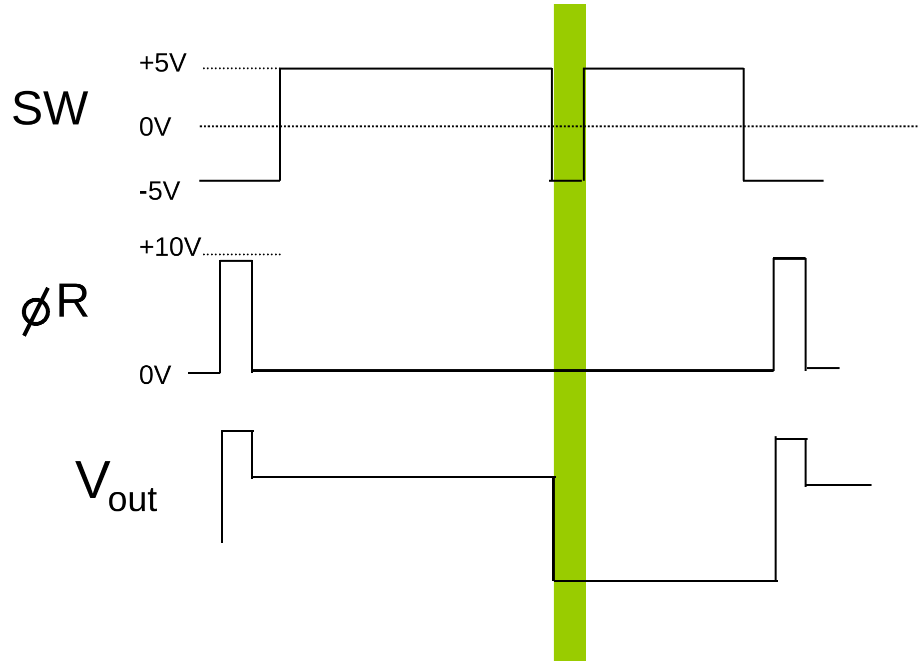


There is now a wait of up to a few tens of microseconds while external circuitry measures this 'reference' level.

Auslesen von CCDs:

The charge is then transferred onto the output node. V_{out} now steps down to the 'Signal level'

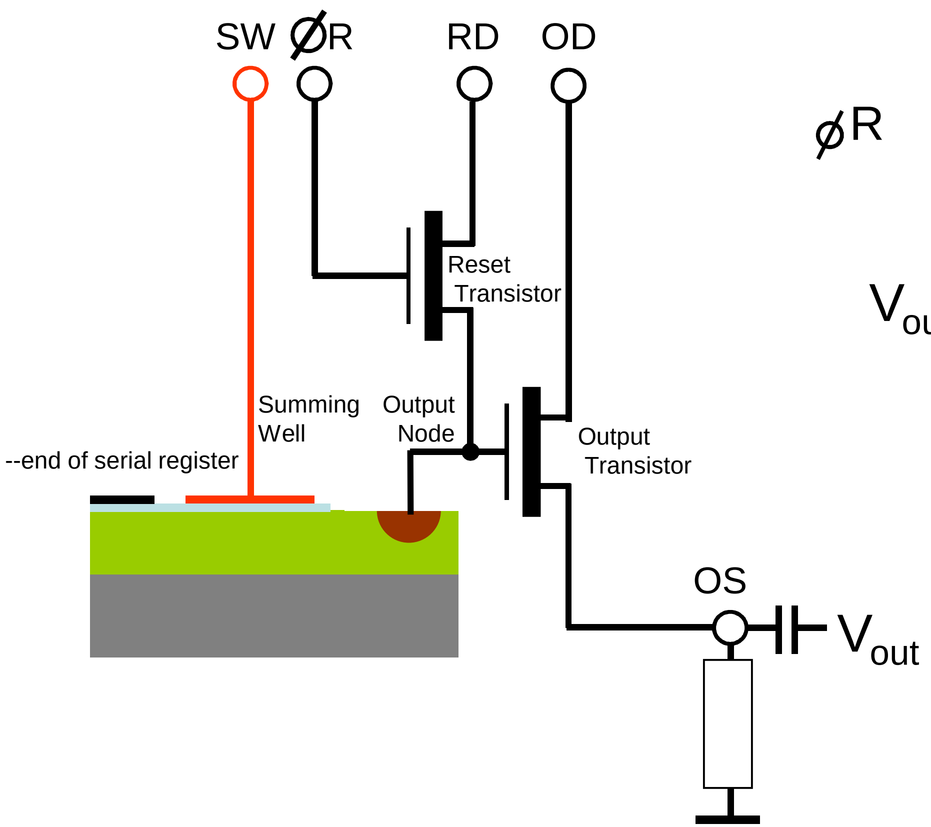


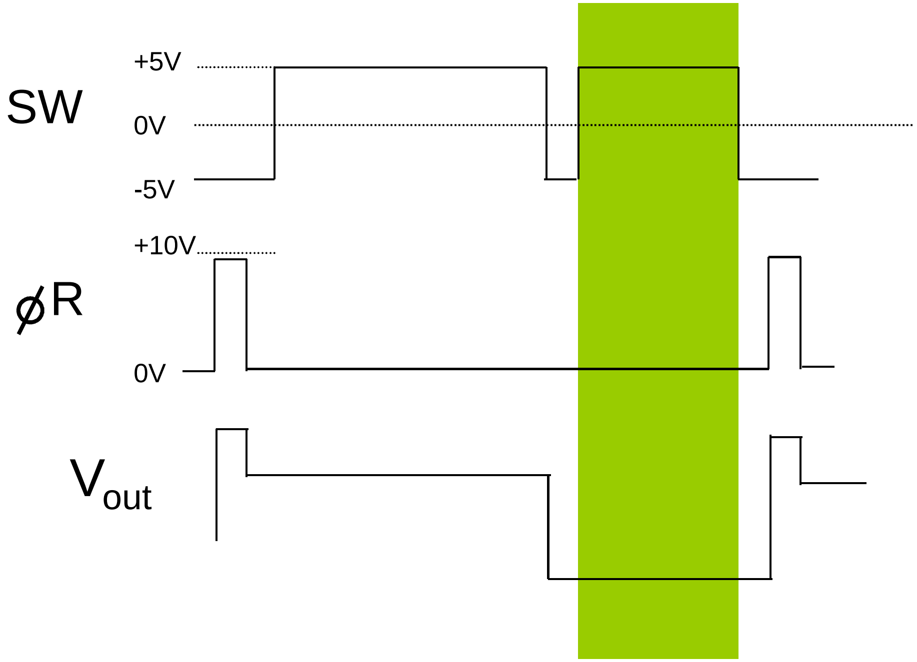


This action is known as the 'charge dump'
The voltage step in V_{out} is as much as several µV for each electron contained in the charge packet.

Auslesen von CCDs:

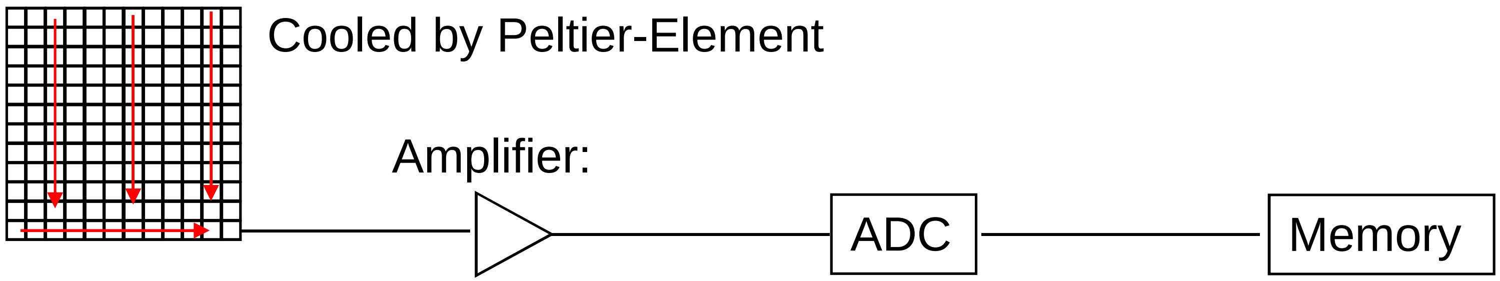
V_{out} is now sampled by external circuitry for up to a few tens of microseconds.

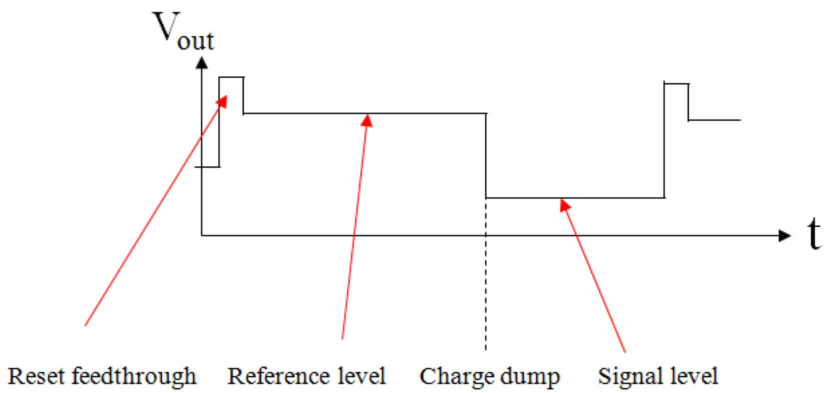




The sample level - reference level will be proportional to the size of the input charge packet.

Auslesen von CCDs:





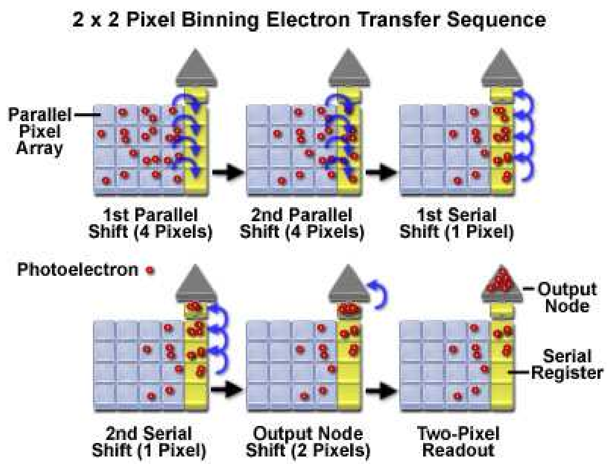
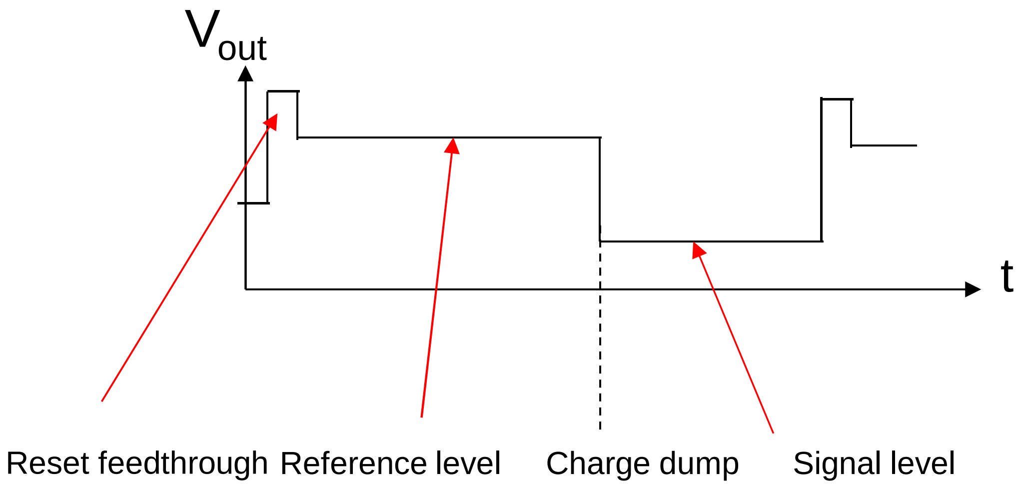


Figure 9

Auslesen von CCDs – Correlated Double Sampling:

The video waveform output by a CCD is at a fairly low level : every photo-electron in a pixel charge packet will produce a few micro-volts of signal. Additionally, the waveform is complex and precise timing is required to make sure that the correct parts are amplified and measured.

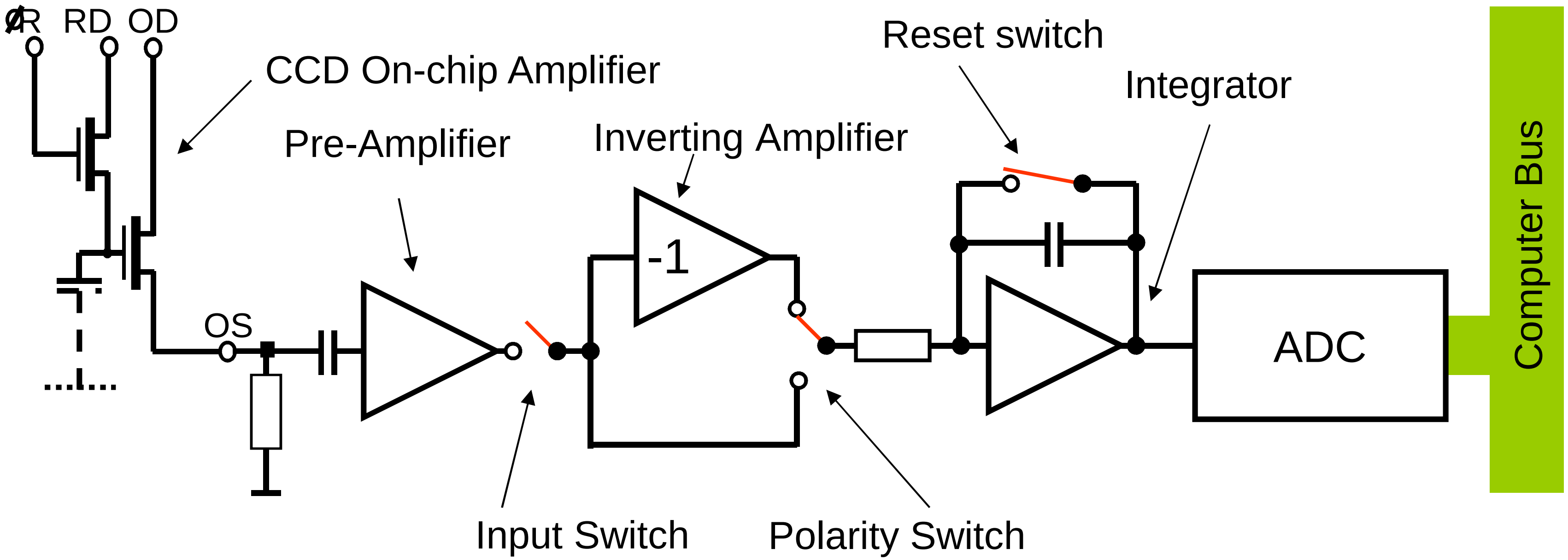
The CCD video waveform , as introduced in Activity 1, is shown below for the period of one pixel measurement



The video processor must measure , without introducing any additional noise, the Reference level and the Signal level. The first is then subtracted from the second to yield the output signal voltage proportional to the number of photo-electrons in the pixel under measurement. The best way to perform this processing is to use a ‘Correlated Double Sampler’ or CDS.

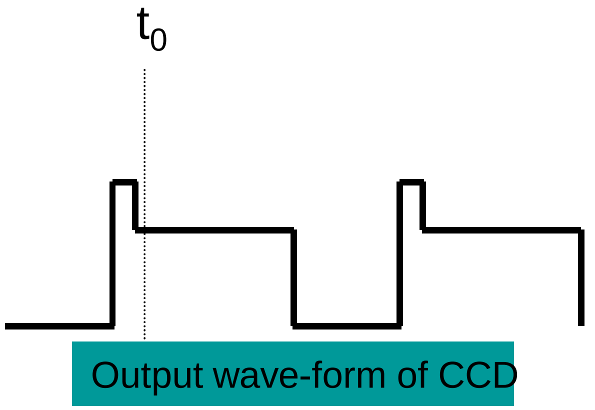
Auslesen von CCDs – Correlated Double Sampling:

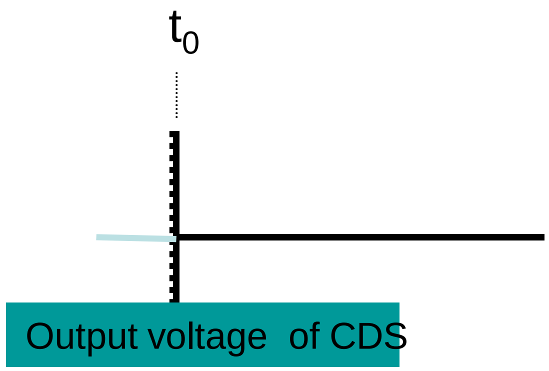
The CDS design is shown schematically below. The CDS processes the video waveform and outputs a digital number proportional to the size of the charge packet contained in the pixel being read. There should only be a short cable length between CCD and CDS to minimise noise.The CDS minimises the read noise of the CCD by eliminating 'reset noise'. The CDS contains a high speed analogue processor containing computer controlled switches. Its output feeds into an Analogue to Digital Converter (ADC).

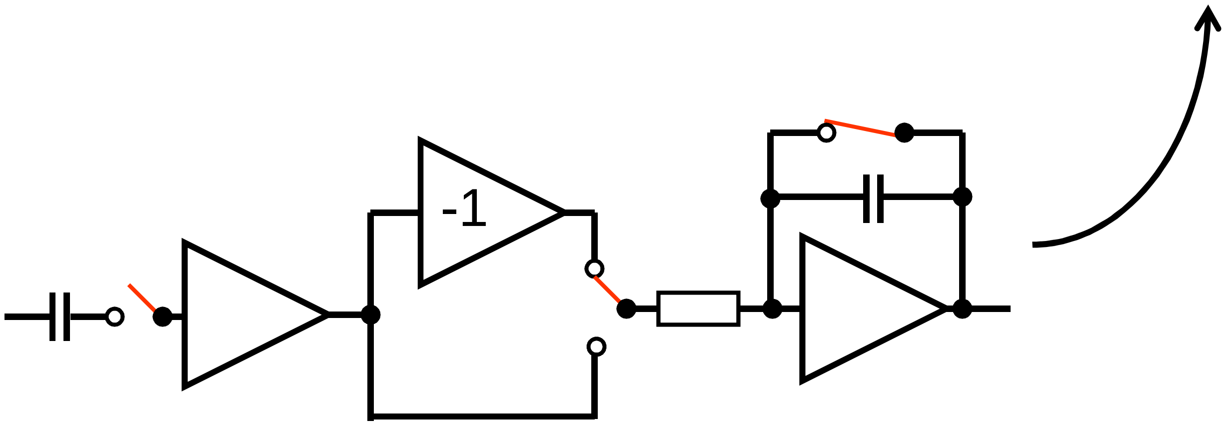


Auslesen von CCDs – Correlated Double Sampling:

The CDS starts work once the pixel charge packet is in the CCD summing well and the CCD reset pulse has just finished. At point t_0 the CCD wave-form is still affected by the reset pulse and so the CDS remains disconnected from the CCD to prevent this disturbing the video processor.

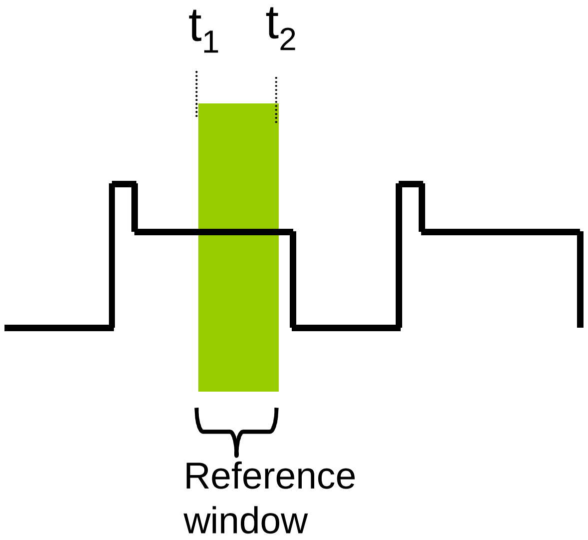


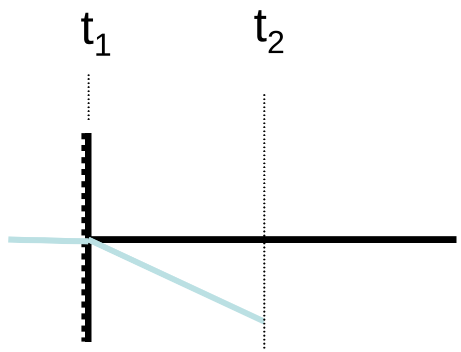


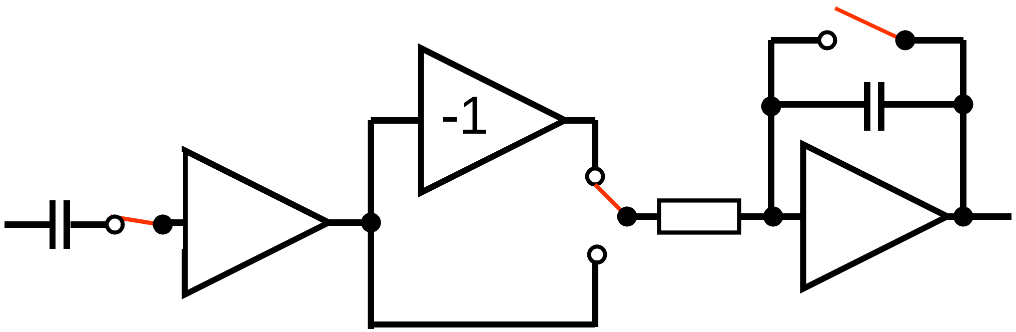


Auslesen von CCDs – Correlated Double Sampling:

Between t_1 and t_2 the CDS is connected and the 'Reference ' part of the waveform is sampled. Simultaneously the integrator reset switch is opened and the output starts to ramp down linearly.

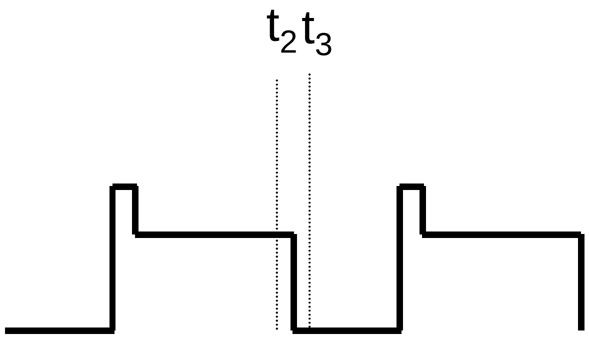


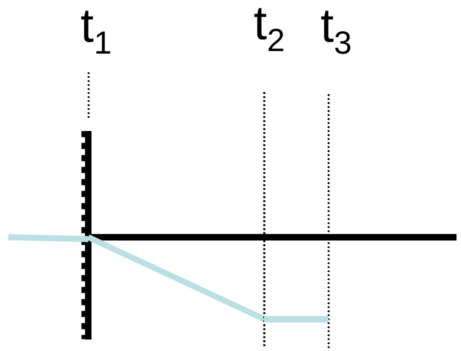


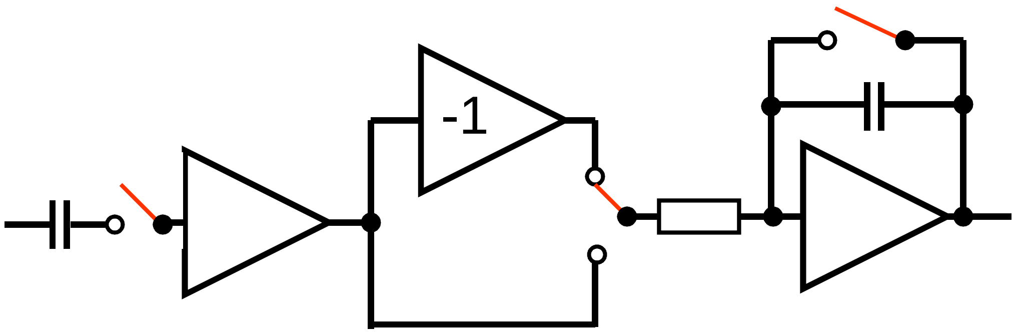


Auslesen von CCDs – Correlated Double Sampling:

Between t_2 and t_3 the 'charge dump' occurs in the CCD. The CCD output steps negatively by an amount proportional to the charge contained in the pixel. During this time the CDS is disconnected.

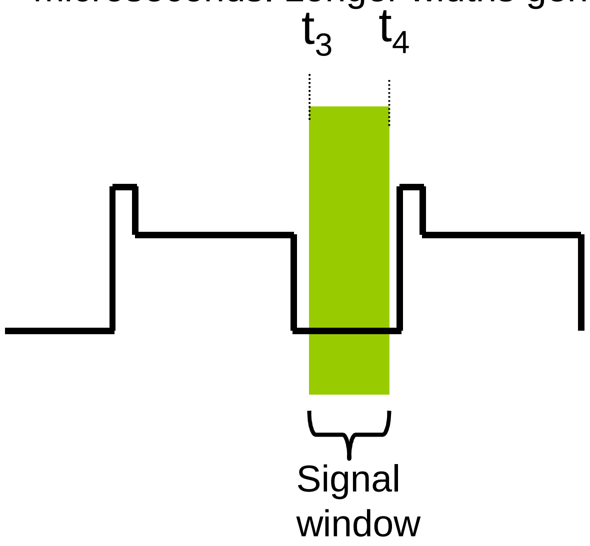


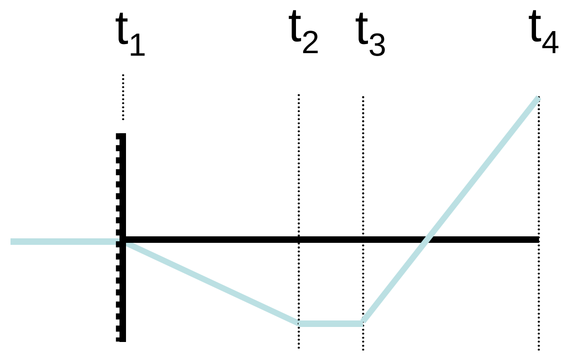


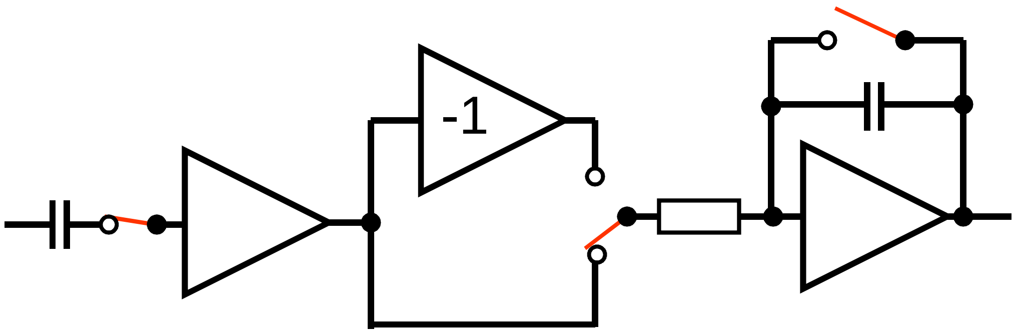


Auslesen von CCDs – Correlated Double Sampling:

Between t_3 and t_4 the CDS is reconnected and the ‘signal’ part of the wave-form is sampled. The input to the integrator is also ‘polarity switched’ so that the CDS output starts to ramp-*up* linearly. The width of the signal and sample windows must be the same. For Scientific CCDs this can be anything between 1 and 20 microseconds. Longer widths generally give lower noise but of course increase the read-out time.

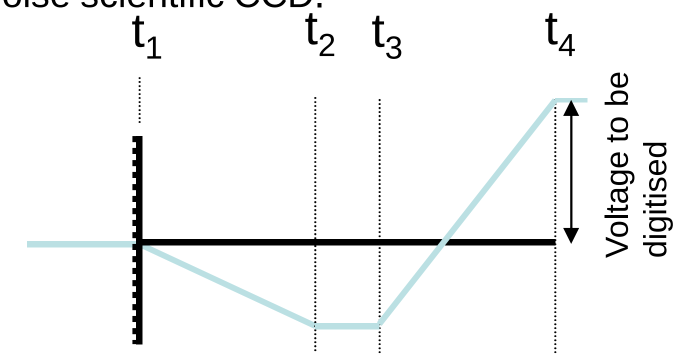




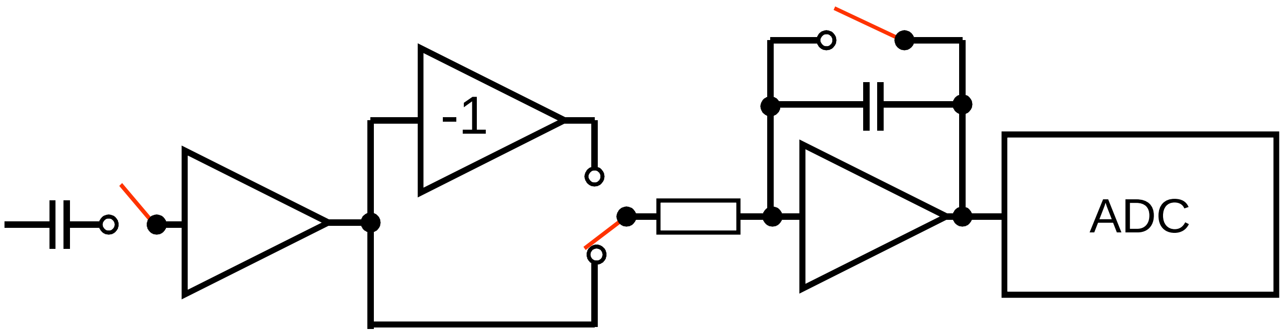


Auslesen von CCDs – Correlated Double Sampling:

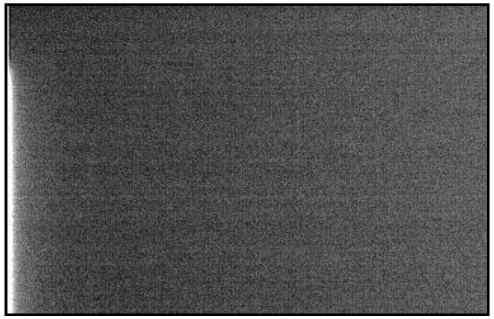
The CDS is then once again disconnected and its output digitised by the ADC. This number , typically a 16 bit number (with a value between 0 and 65535) is then stored in the computer memory. The CDS then starts the whole process again on the next pixel. The integrator output is first zeroed by closing the reset switch. To process each pixel can take between a fraction of a microsecond for a TV rate CCD and several tens of microseconds for a low noise scientific CCD.



The type of CDS is called a ‘dual slope integrator’.
A simpler type of CDS known as a ‘clamp and sample’ only samples the waveform once for each pixel.
It works well at higher pixel rates but is noisier than the dual slope integrator at lower pixel rates.



Dark Current:

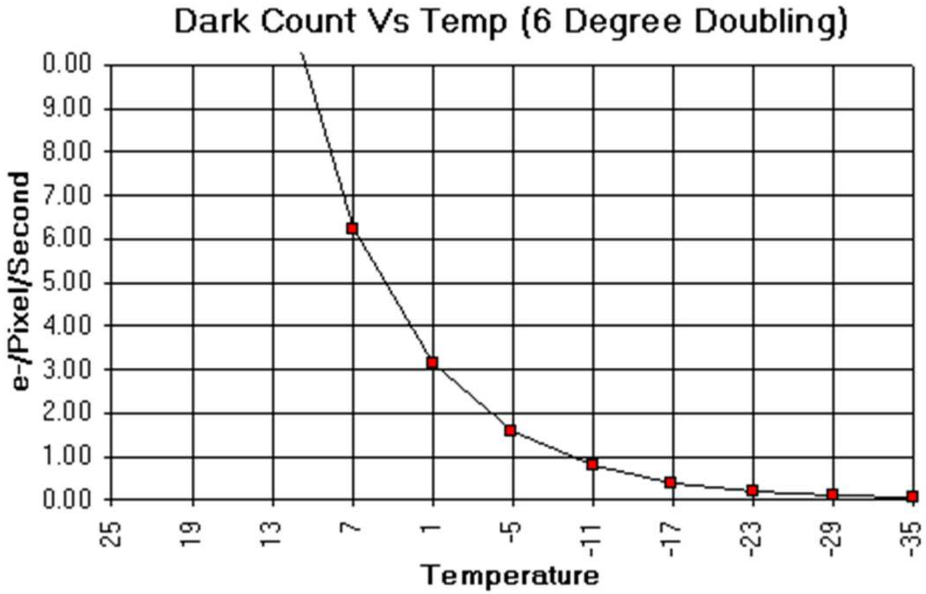


The finite temperature of the CCD leads to the production of thermally induced electrons in the silicon
Dark current increases linearly with time

A function of the temperature of the CCD

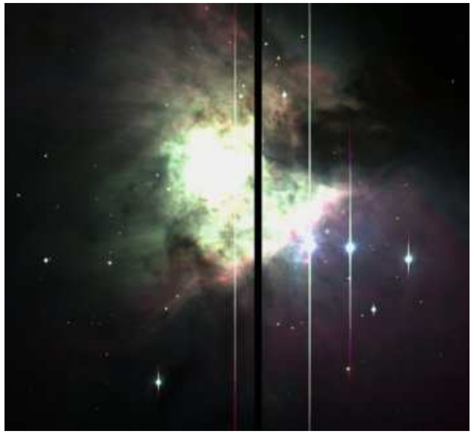
CCDs cooled to reduce thermal noise

Dark current can be removed with careful calibration (dark frames)



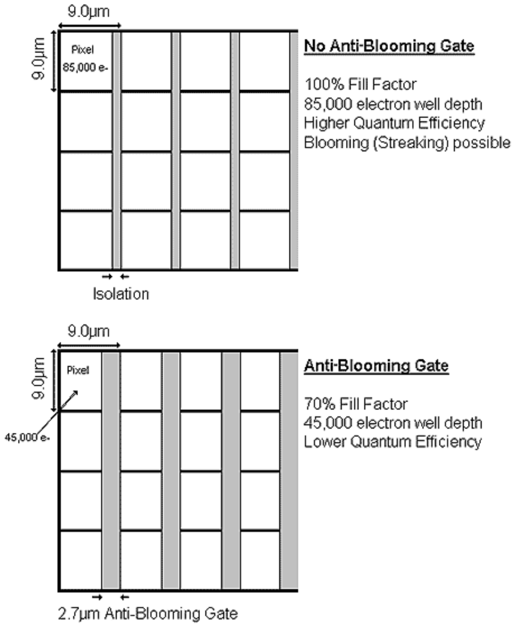
Saturation / Blooming-Effekt:

What if a pixel's potential well "fills up" with electrons? The physical size of the pixel determines how much charge it can hold. Larger pixels can hold more charge.

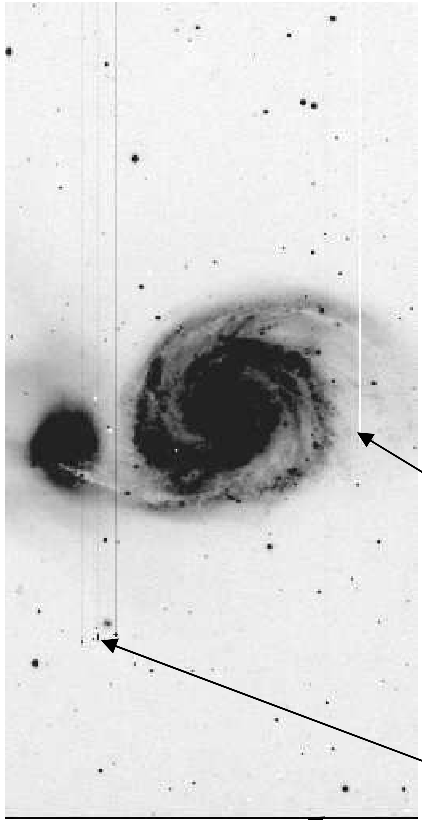


Pixels are saturated when their potential wells are full.
Electrons "bleed" along columns into nearby pixels
As a CCD pixel nears saturation, the response of the pixel becomes non-linear.

The data number read out from a saturated pixel cannot exceed the largest number allowed by the "analog to digital converter" that converts the voltage to a digital signal (typically 16 bit, or 65,536).



Kosmetische Defekte:



CCDs:

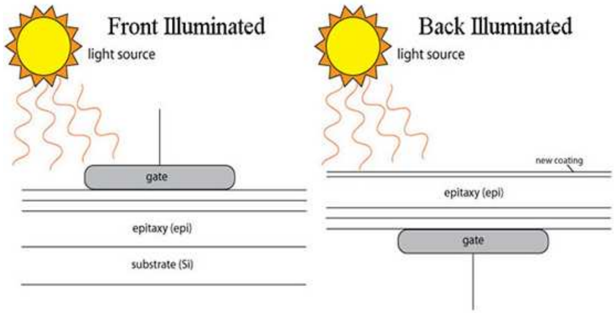
- *small, compact, rugged, stable, low-power devices*
- *excellent, near-perfect sensitivity over a wide range in wavelengths*
- *wide dynamic range (from low to high light levels)*
- *no image distortion (pixel fixed by construction)*
- *easily connected to computer*

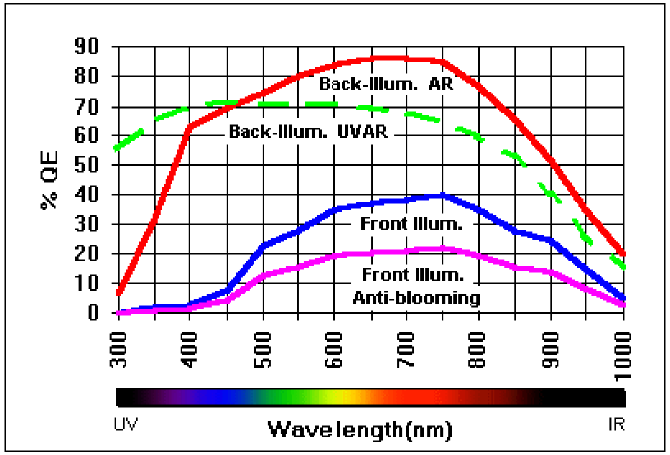
Dark column

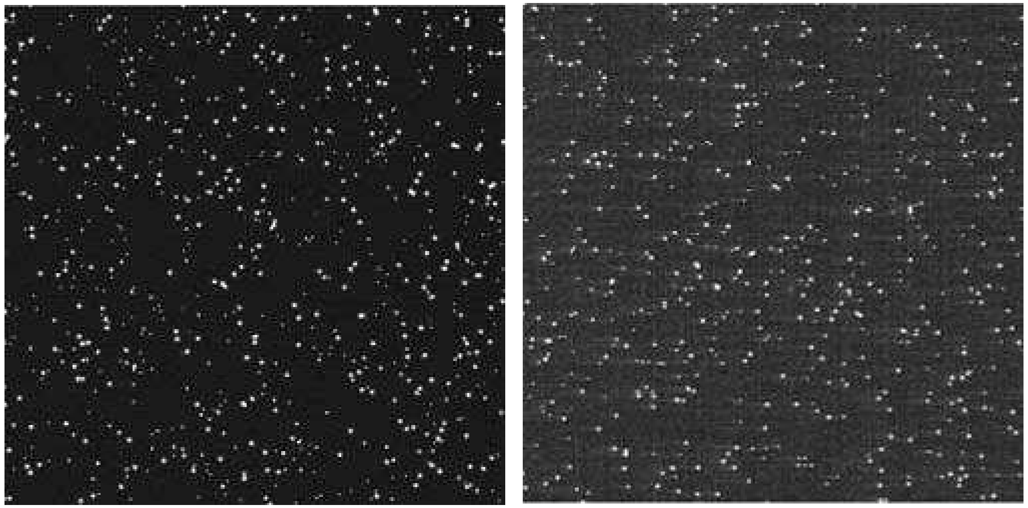
Hot spots and bright columns

Bright first image row caused by incorrect operation of signal processing electronics.

Quanteneffizienz & Charge Transfer Effizienz:







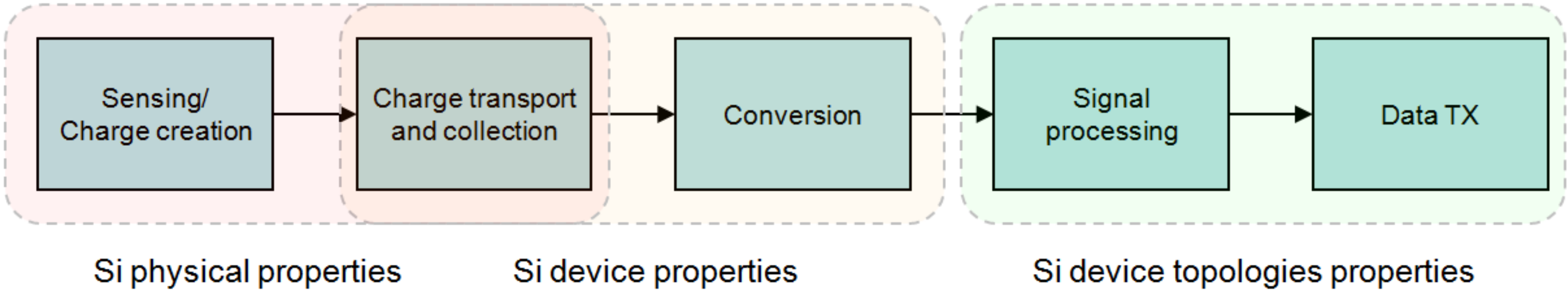
good CTE
99,9999%

bad CTE

original image

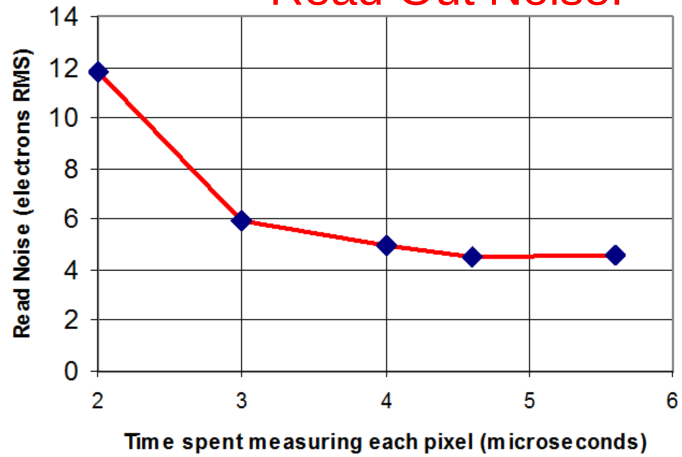
after *n* transfers

Dynamic Range:

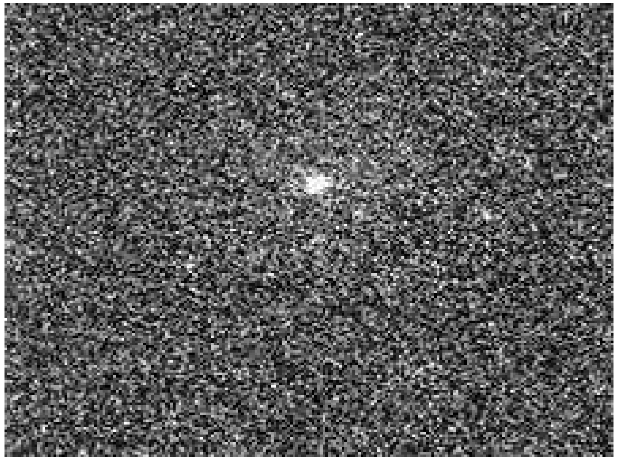


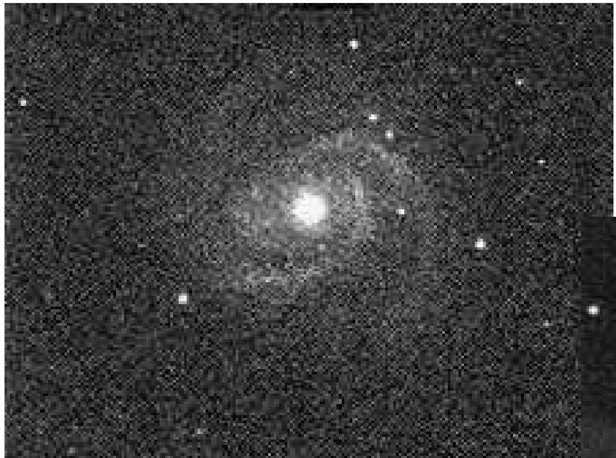
$$\text{Dynamic Range} = \frac{\text{Full Well Capacity}}{\text{Read Noise}} : 1$$

Read Out Noise:



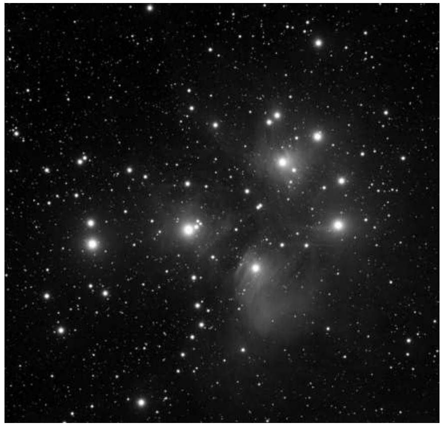
S/N-Ratio:

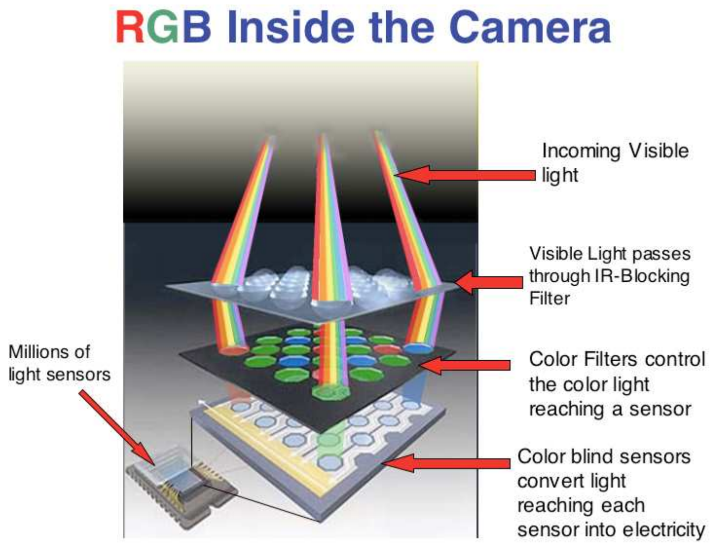


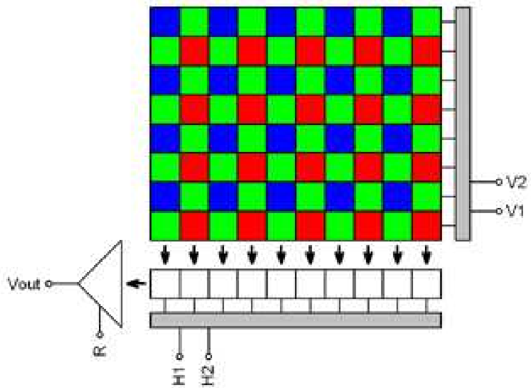


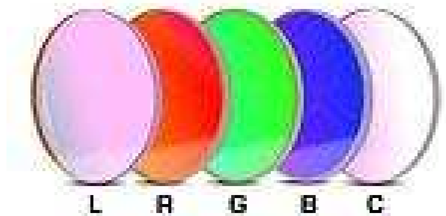
- 1, 10, 100 and 1000 sec exposures of M100
- S/N ratio improves with exposure time
- Readout noise dominates in the shortest exposure
- Photon noise in the sky dominates for the longest exposure

Monochrom- und Farb-CCDs:

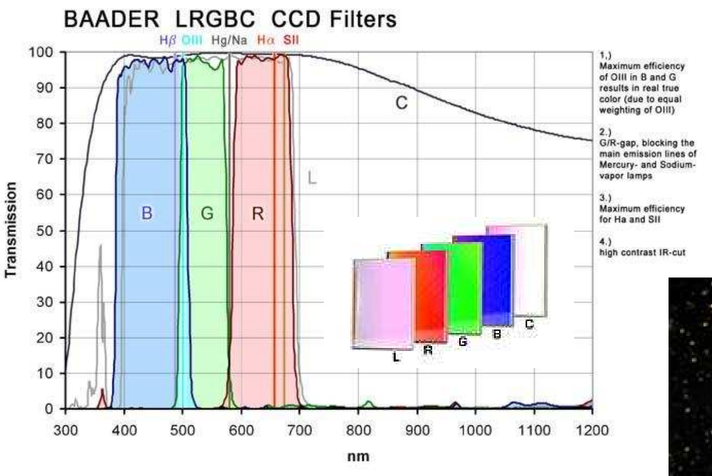


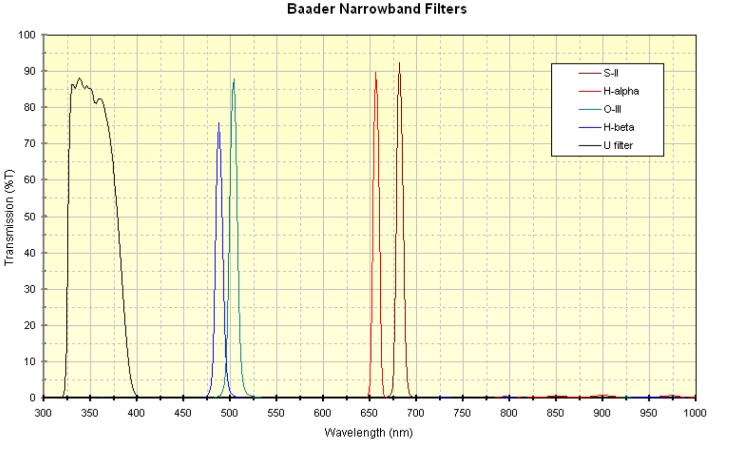


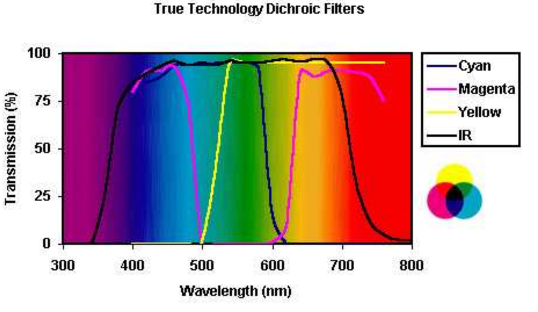




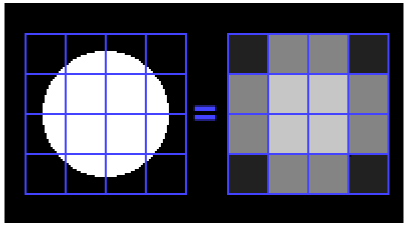
(L)RGB, CMY & Schmalband-Filter:

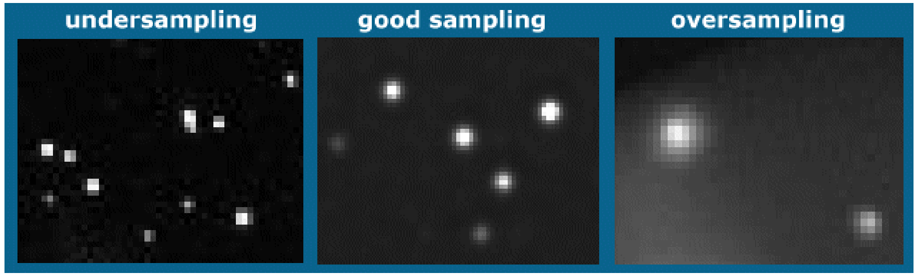




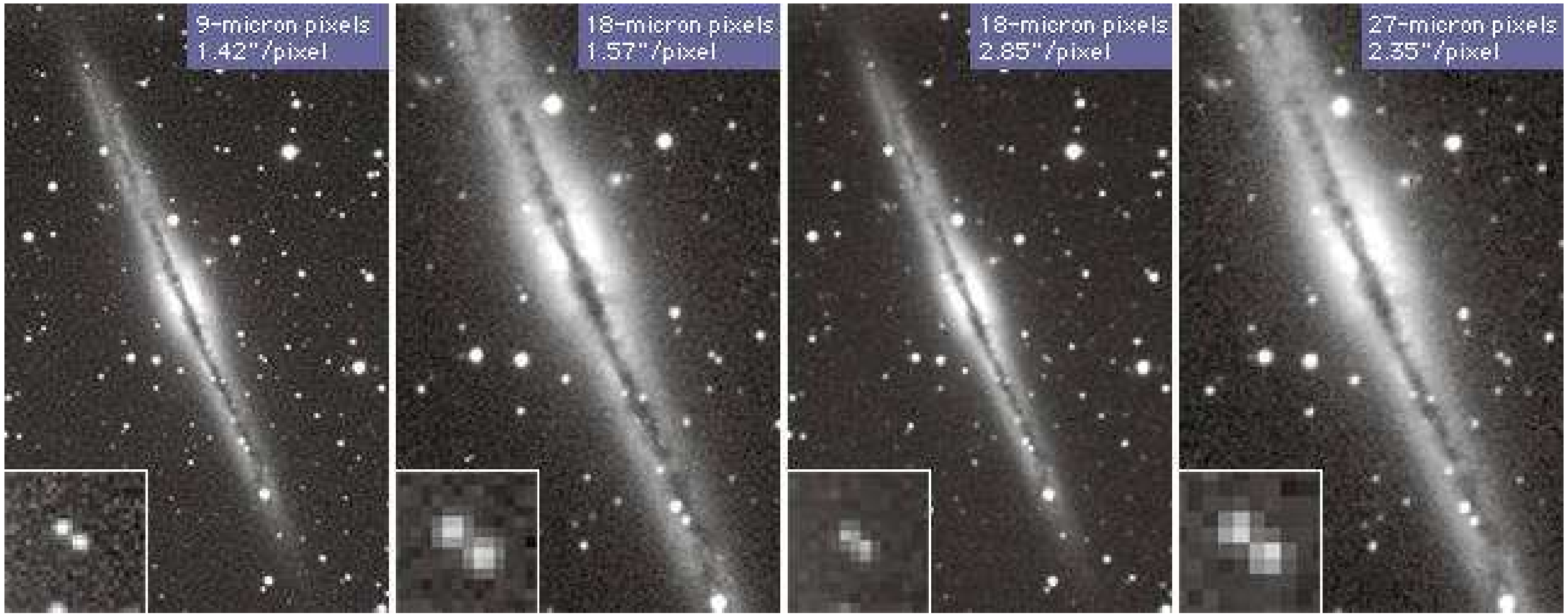


Sampling – Field of View (FOV):

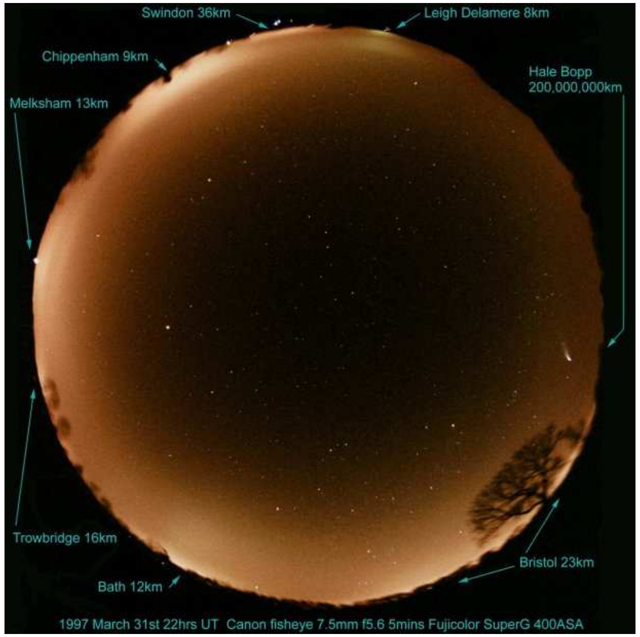


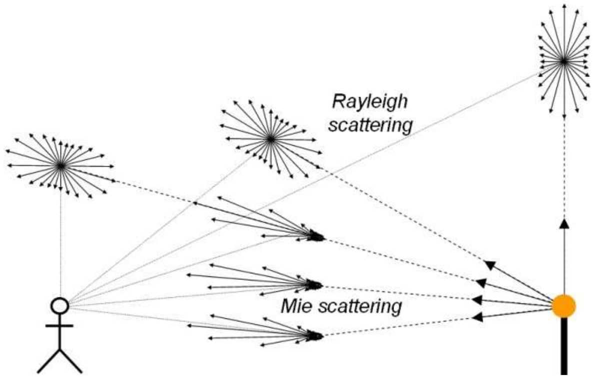


Auflösung [“] = 206 * Pixelgröße[µm] / Brennweite [mm]

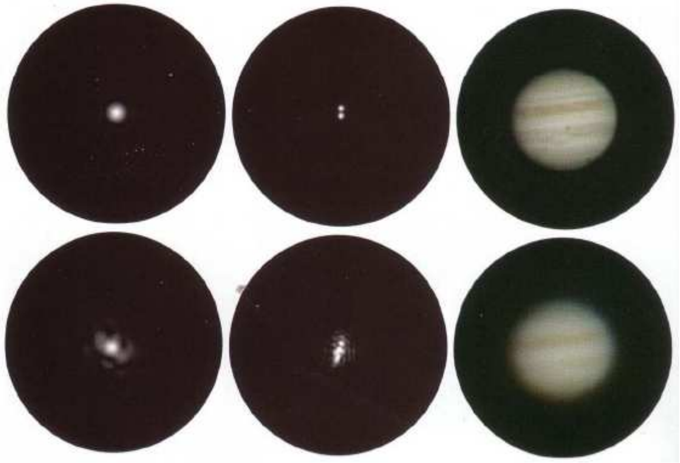


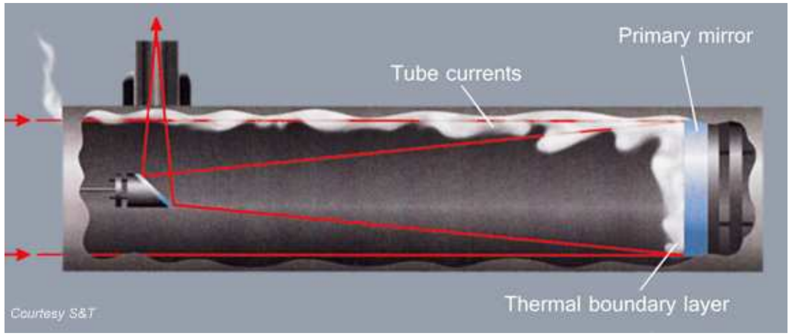
Sky Glow:

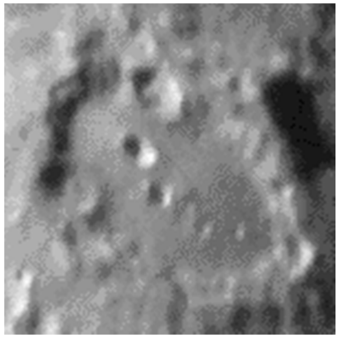

Swindon 36km
Leigh Delamere 8km
Chippenham 9km
Hale Bopp
200,000,000km
Melksham 13km
Trowbridge 16km
Bristol 23km
Bath 12km
1997 March 31st 22hrs UT Canon fisheye 7.5mm f5.6 5mins Fujicolor SuperG 400ASA


Rayleigh
scattering
Mie scattering

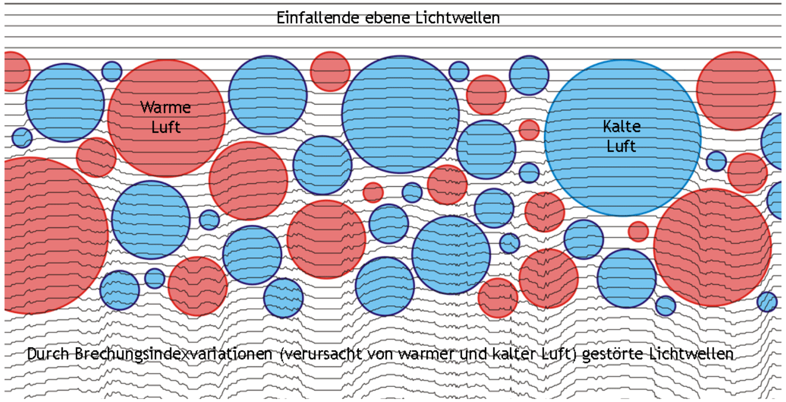
Seeing:



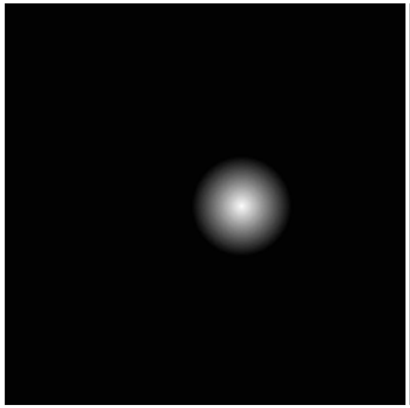


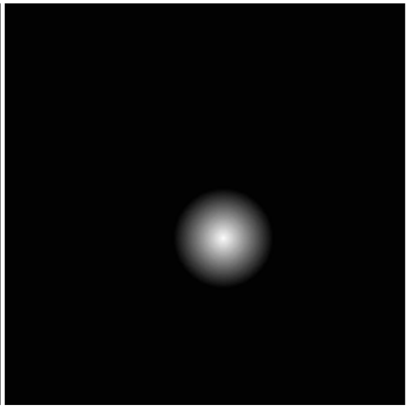


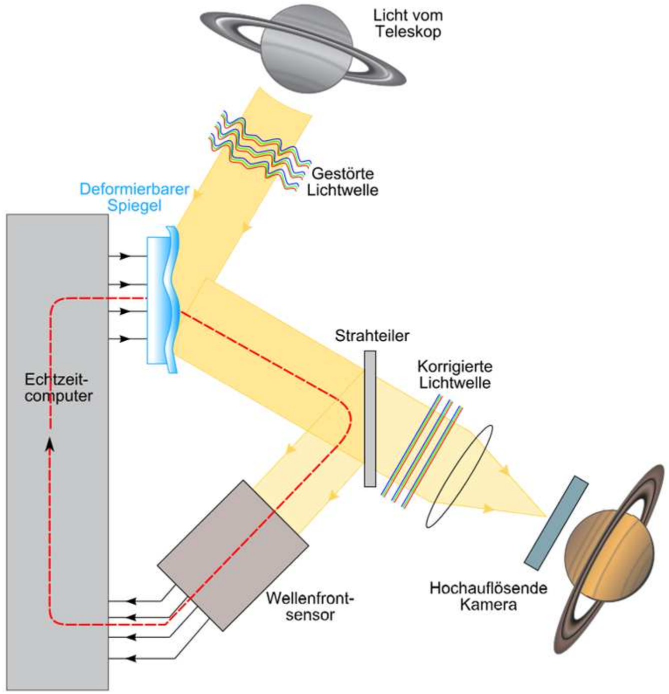
Das Kolmogorow-Turbulenzmodell

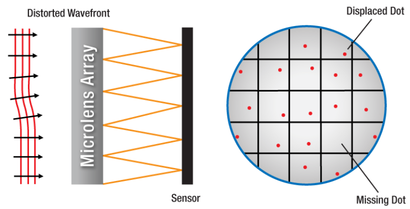


Aktive und Adaptive Optik:

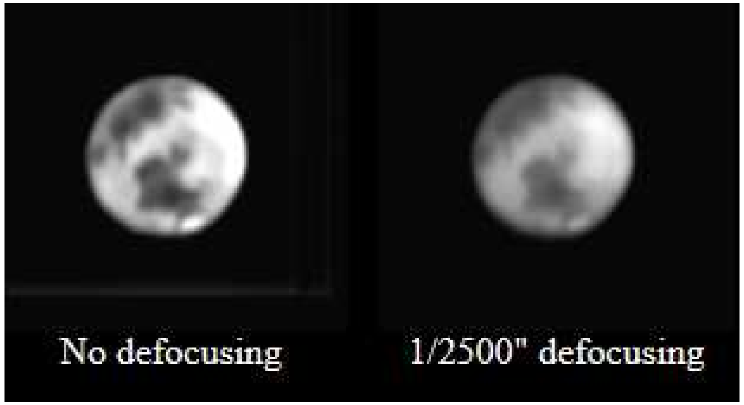




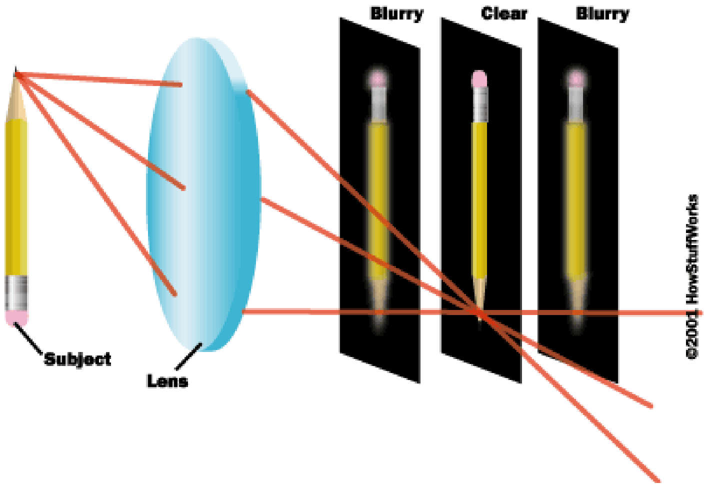


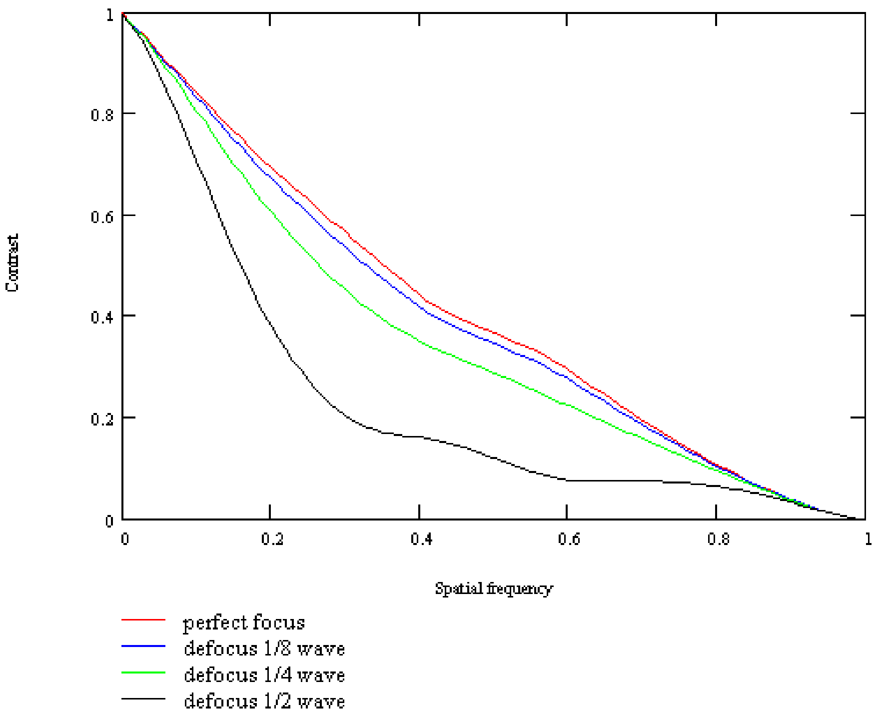


Fokussierung:



F/D	2	3	4	5	6	8	10	12	15	20	30
Tolerance ± mm	0.0025	0.005	0.01	0.015	0.02	0.04	0.06	0.09	0.13	0.24	0.54





Flat-Fields, Bias- and Dark- Frames:

master bias frame (B)

dark frame (D)

flat field (F)

raw image (R)

final image (I)

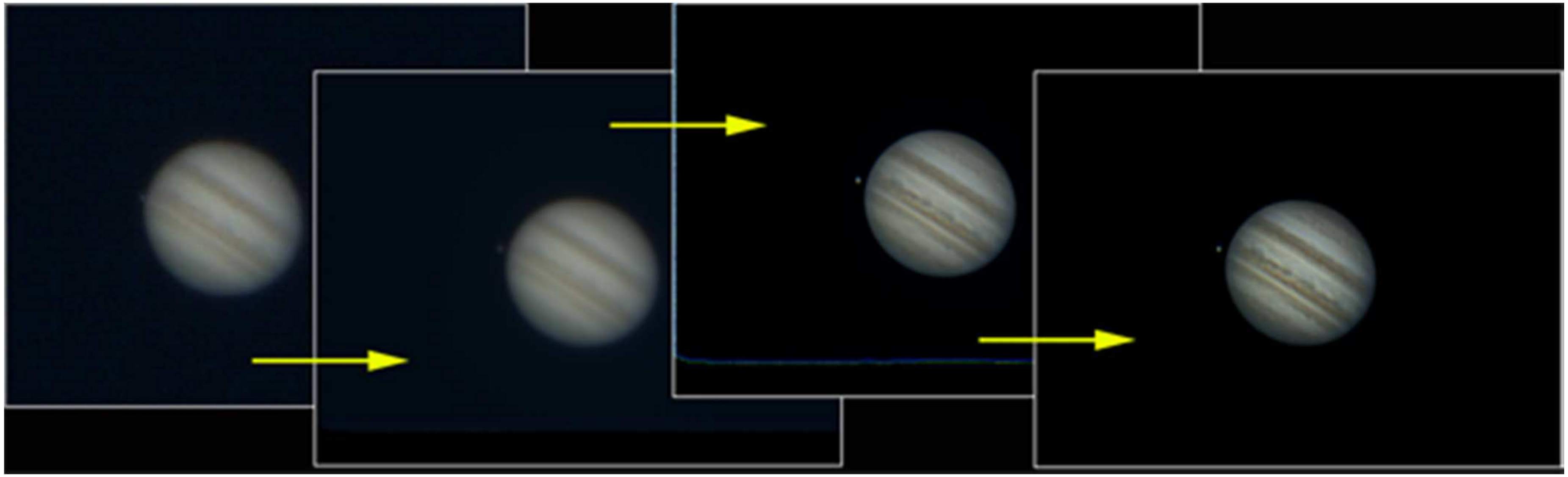
$$I = (R-D-B)/(F-D-B)$$

Dateiformate - Kompression:

.TIF 150 Kbytes

.JPG 34 KBytes

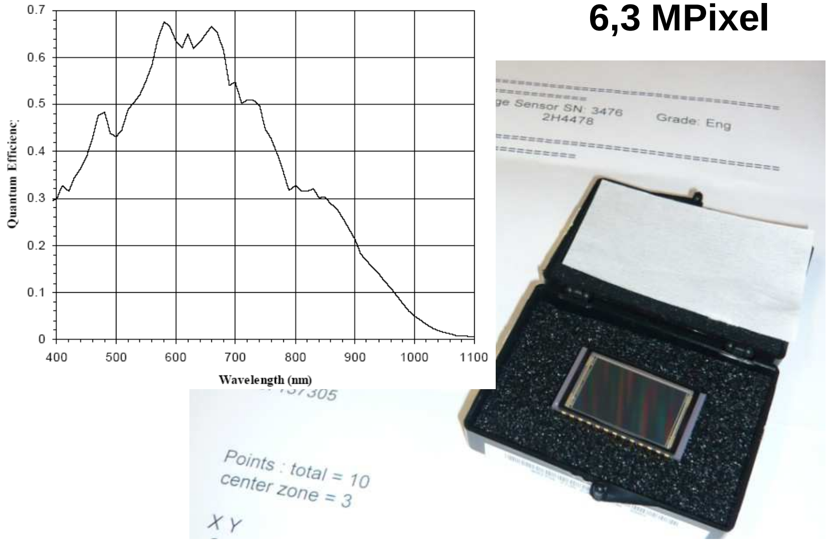
Image Stacking:



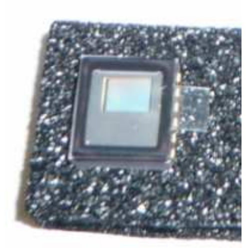
Gekühlte CCDs, DSLR und Webcams:

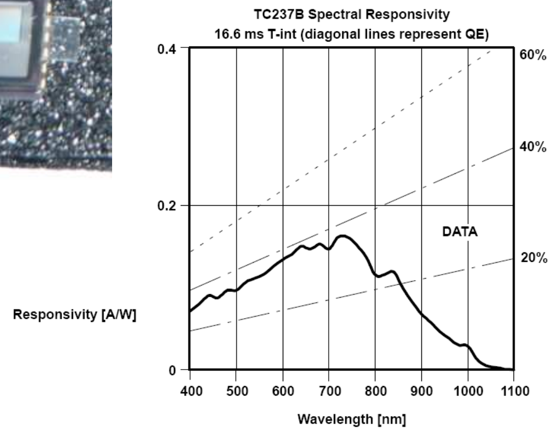
Target-Sensoren für eigene Entwicklung:

KODAK KAF6303E
6,3 MPixel

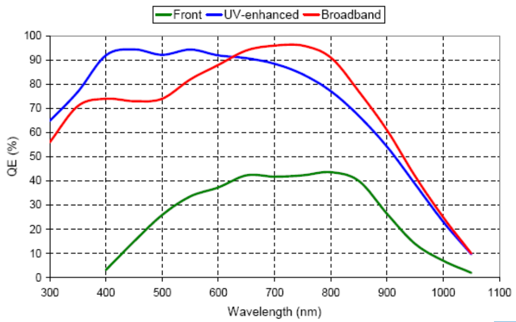


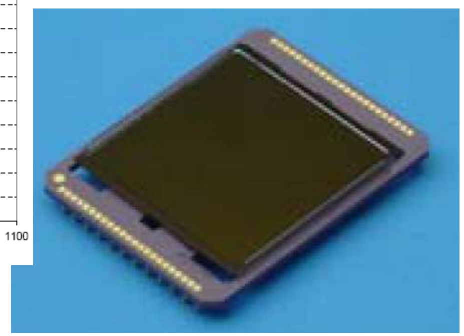
Texas Instruments TC237
0,3 MPixel (VGA)





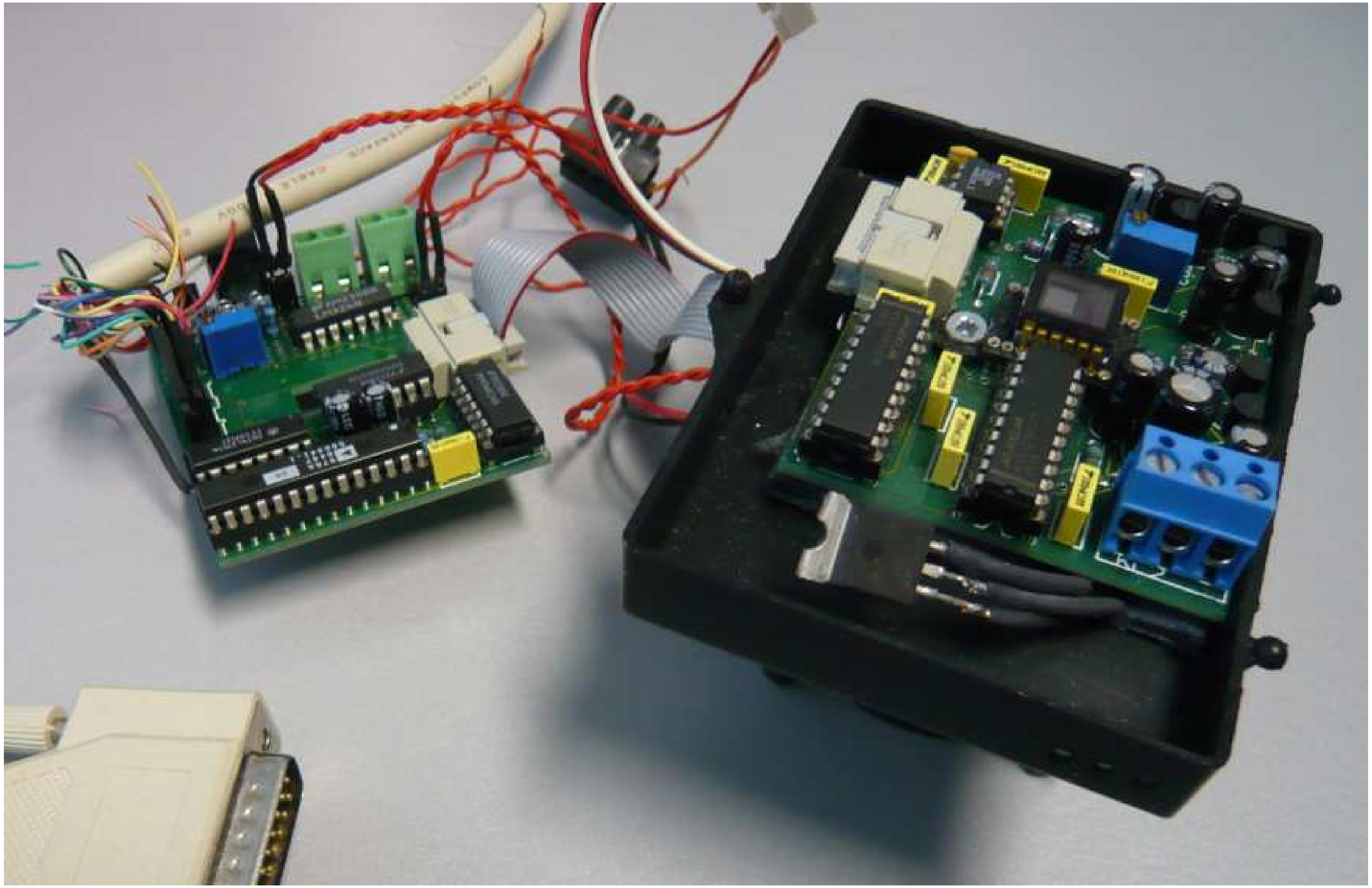
SONY ICX-285AL
1,4 MPixel



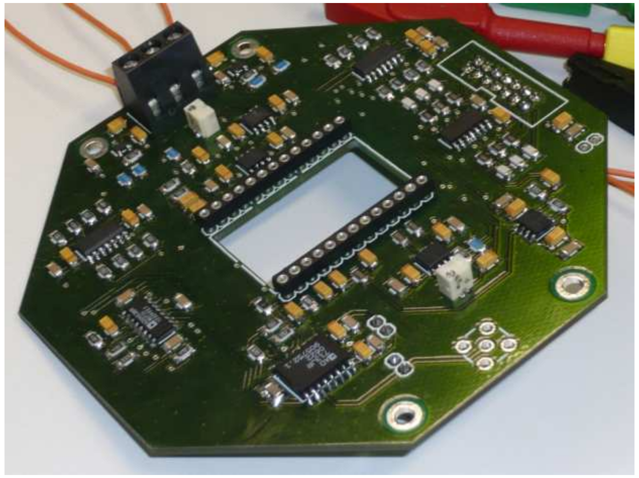


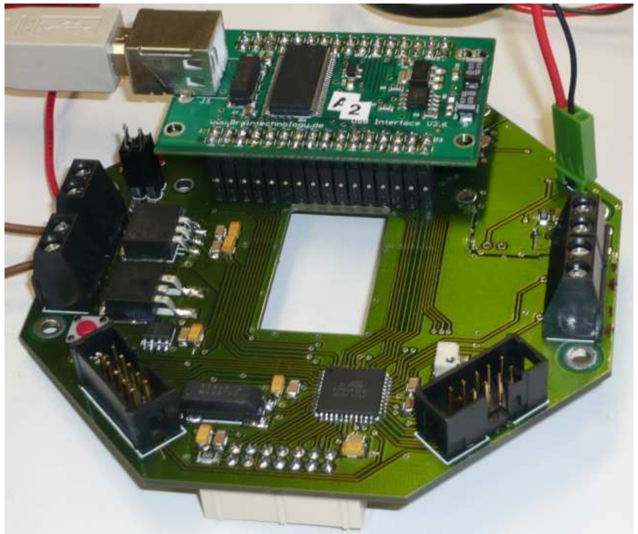
CCD 3041
Back-Illuminated 2K x 2K
Full Frame CCD Image Sensor

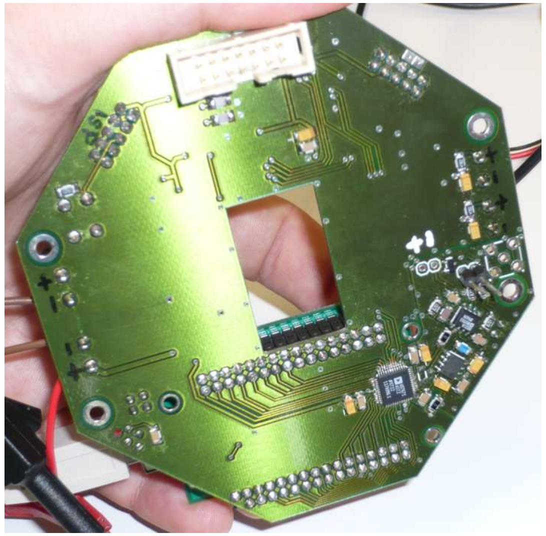
Prototyp mit TC237:



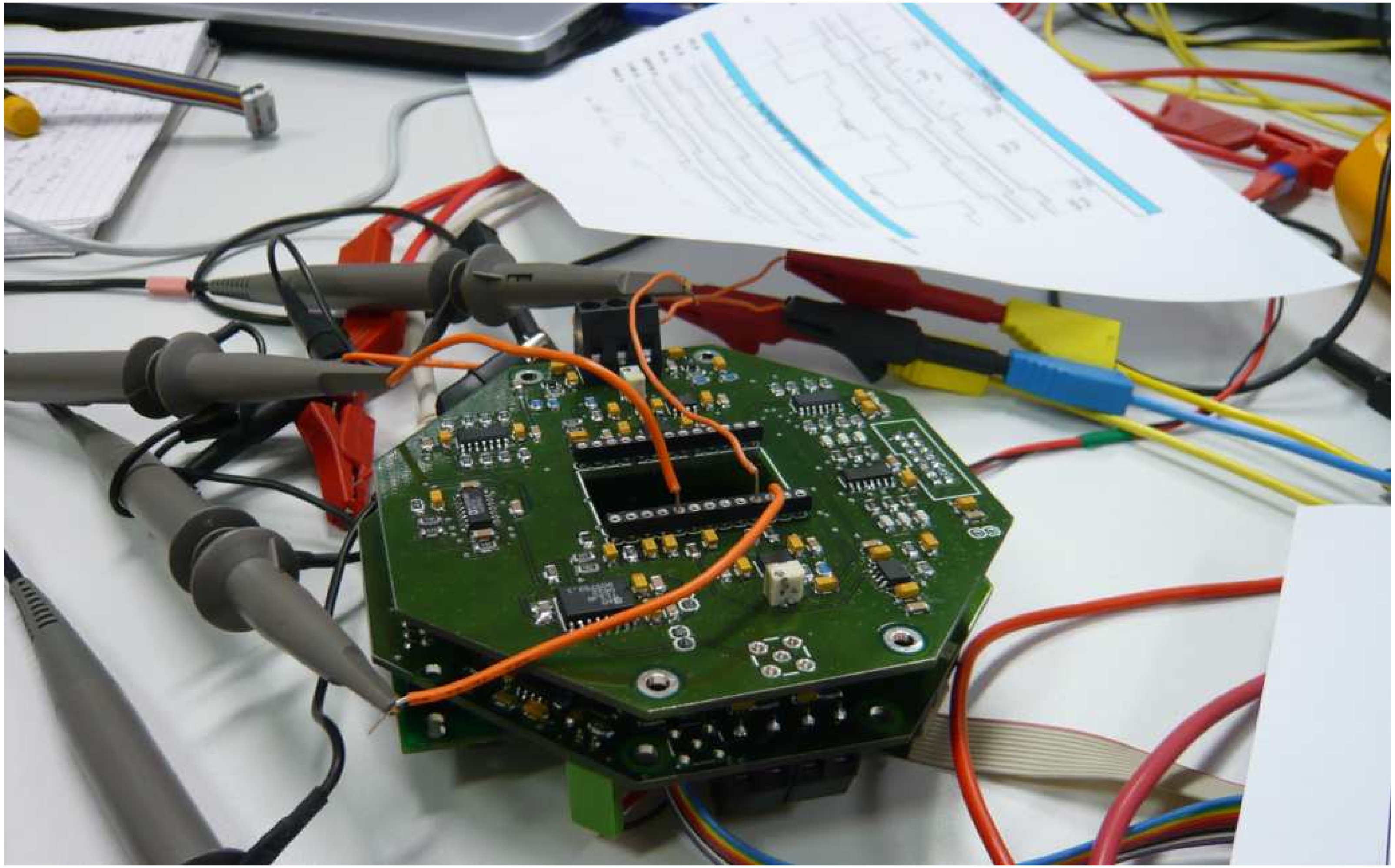
Prototyp mit KAF-6303E:







Prototyp mit KAF-6303E:



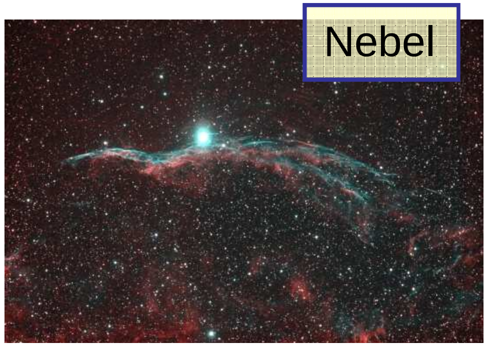
Prototyp mit KAF-6303E:

Zusammenfassung:

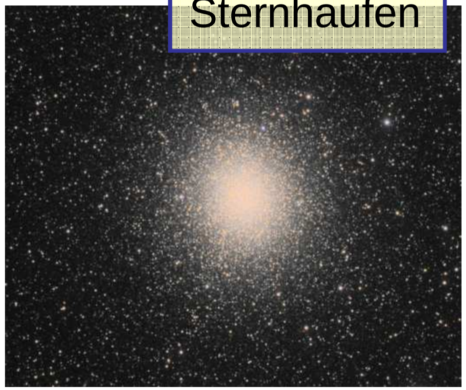
- Advantages:
  - Quantum efficiency (QE) ~ 80 % (400 nm - 1 μm)
  - Linearity to (better than) << 0.1 %
  - Dynamic range: Pixel well depth ~ 10^6 e^-, RMS readout noise ~ 4 to 10 e^-
  - Fixed format pixel grid
  - Can extend blue response (thinned back-illuminated chip or coronene coating)
- Disadvantages:
  - Readout noise 4 to 10 e^- RMS
  - Slow readout ≥ 10 to 100 s
  - Cosmic-ray hits limit exposure times
  - Saturation via wells filling up and limited ADC range
  - Charge “bleeding” down columns, then across rows
  - Blemishes (charge traps, hot pixels)
  - Gaps between pixels

Zusammenfassung:

Planetarische Nebel



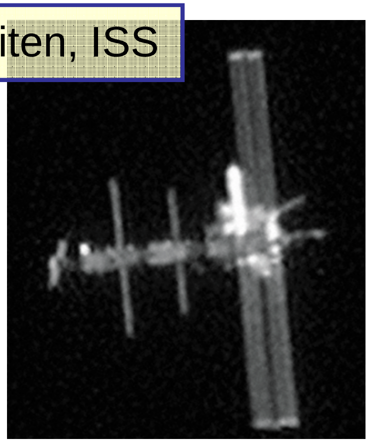
Nebel



Sternhaufen

Mond

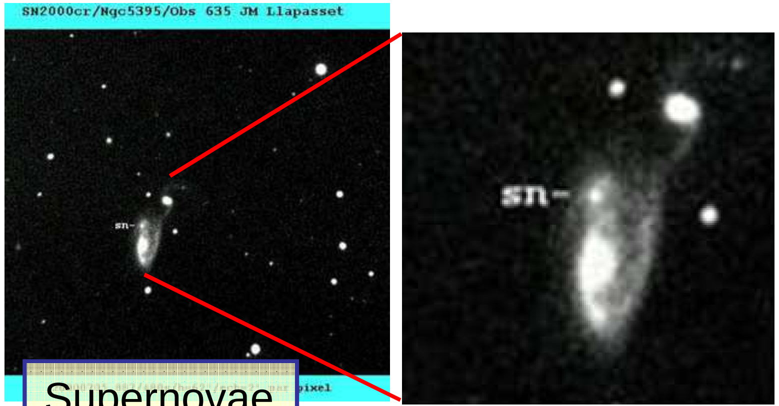
Planeten



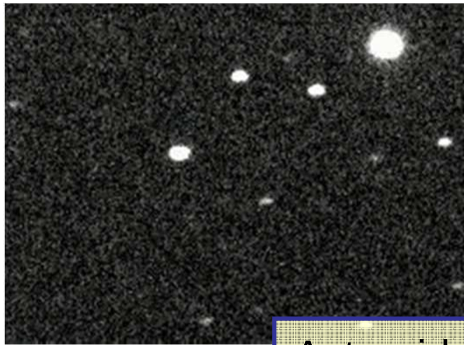
Satelliten, ISS

Galaxien

Zusammenfassung:

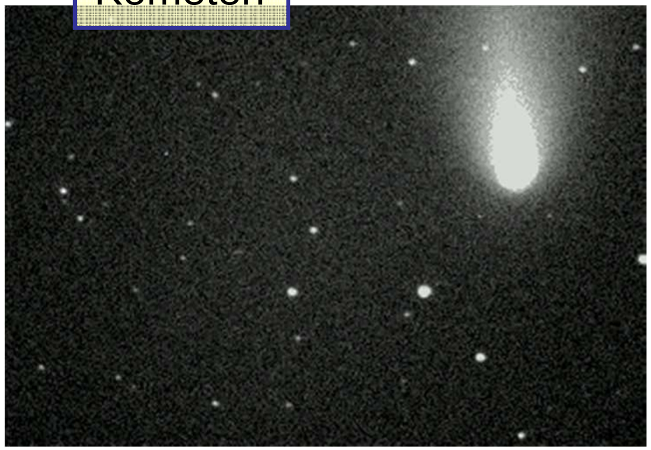


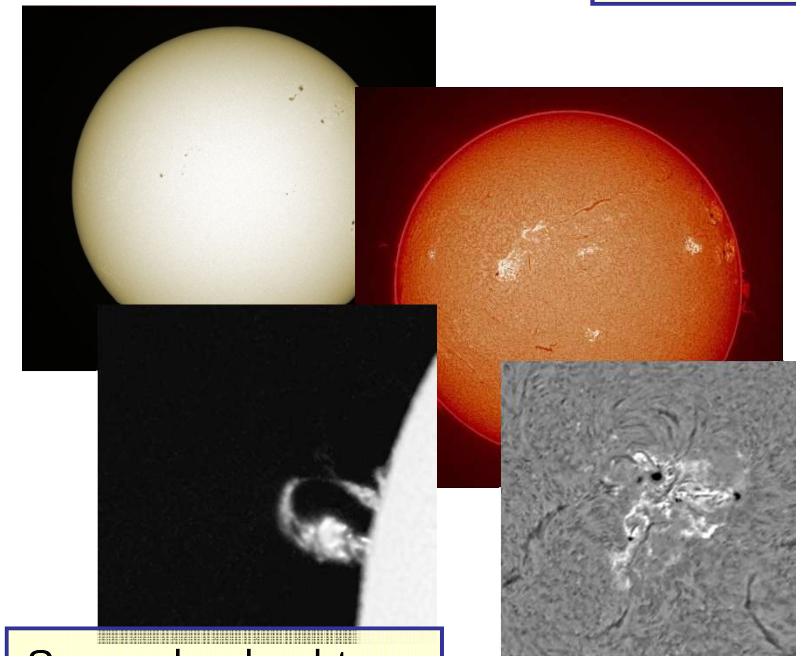
Supernovae



Asteroiden

Kometen





Sonnenbeobachtung