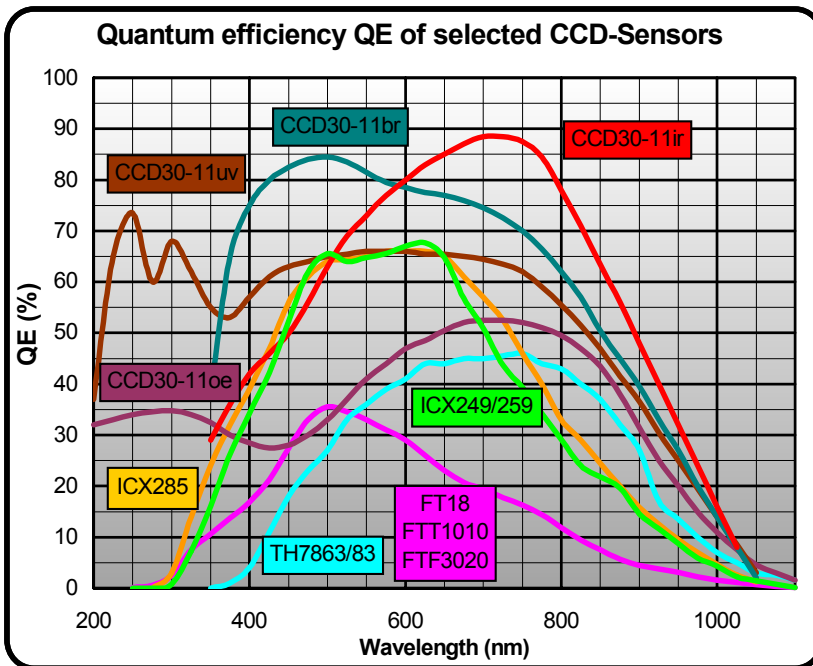


# Properties of CCD-Cameras

## Quantum Efficiency QE

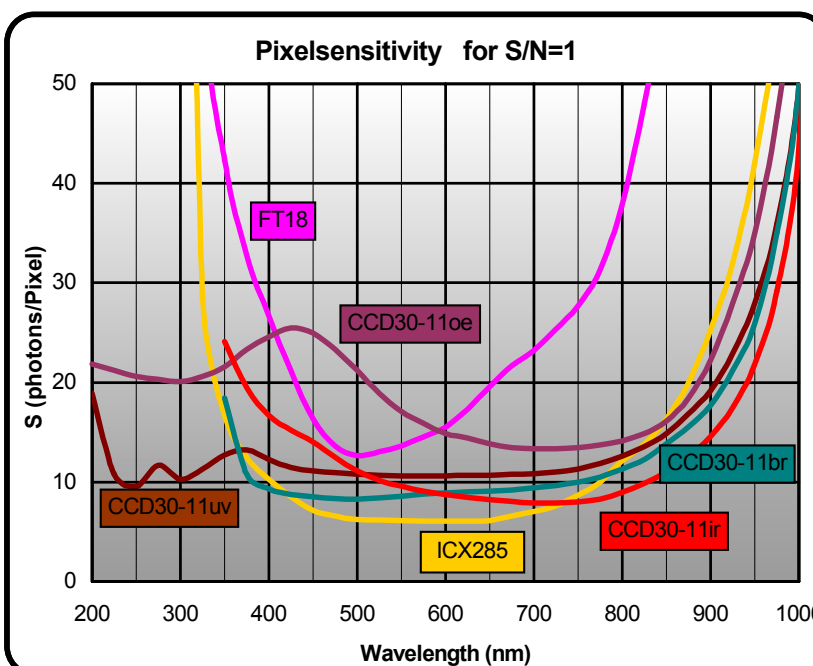


The quantum efficiency QE is defined as the percentage of the generated electronic charges by the incoming photons. This efficiency of the CCD-image sensor is determined by material properties, production and its design structure.

The diagram shows the wavelength dependence of the quantum efficiency of selected CCD image sensors, to give some help in the selection of different applications.

Open-electrode CCD can be selected for improving the QE in the UV region due to the absorption of the polysilicon gates, back illuminated CCD sensors with different wavelength optimised antireflection coatings or front illuminated

## Light sensitivity S



The light sensitivity S is the measure of the detectability of a CCD imaging system and is defined by the number of photons for the generation of as many electrons as are equivalent to the signal to noise ratio SNR=1.

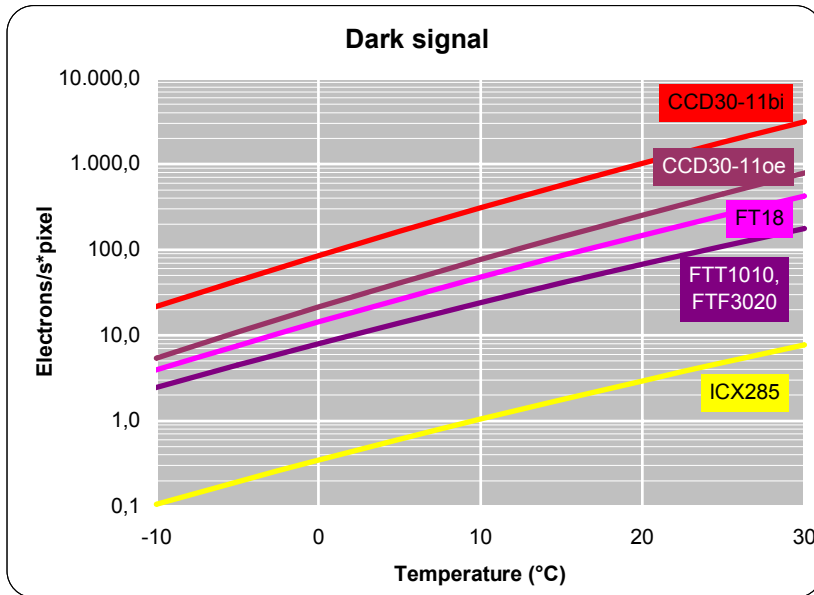
The light sensitivity is defined as the ratio of SNR and the quantum efficiency QE:

$$S = \text{SNR}/\text{QE}$$

The diagram shows the wavelength dependence of the sensitivity for the Scientific Imaging Systems SIS equipped with different CCD image sensors.

The light sensitivity is important for selecting a camera system for applications in the low light level region.

## Dark Current



The dark current of a CCD image sensor is an important factor for sensitivity.

It results from the temperature-dependent thermal generation of electrons. The nearly exponential behaviour of the dependence can be calculated roughly as a doubling of the dark current with every 6°C to 9°C rise in temperature, shown in the diagram for different CCD image sensors.

The dark electrons add to the electrons generated by photons and their statistical dark noise contributes to the total noise SNR.

The dark signals of the single pixels are not spread regularly over the CCD image sensor but vary due to inhomogeneities during the chip production process. The structure of the resulting dark image is called "fixed pattern noise". Sometimes single "hot pixels" have a greater dark

signal than the average CCD sensor. The fixed pattern and the hot pixels can be corrected by subtracting the dark image taken at the same integration time from the measuring image.

## Full Well Capacity, FWC

The full well capacity FWC is the maximum number of electrons which one pixel can contain before saturation. The FWC depends mainly on the size of the pixel, the kind of CCD image sensor and its operating characteristics. In conventional CCD devices, electrons over the saturation charge flow to the adjacent pixel with the resulting effect of blooming and influence the qualitative and quantitative image performance.

Antiblooming image sensors drain these overexposed electrons to special structures with an efficiency factor of 200 to 1000 above the full well capacity. This is very important for the measurement of very low intensities in the neighbourhood of high intensity regions. These structures take up space on the CCD-chip and thereby lower the quantum efficiency QE and/or the fill factor.

## Total Electron Capacity, TEC

The total electron capacity TEC of a CCD image sensor is the product of the full well capacity FWC and the total number of pixels. TEC is a good measure for the comparison of different CCD image sensors with respect to the total noise electrons TNE.

The total dynamic TD of a camera system is the ratio  $TD = TEC/TNE$ .

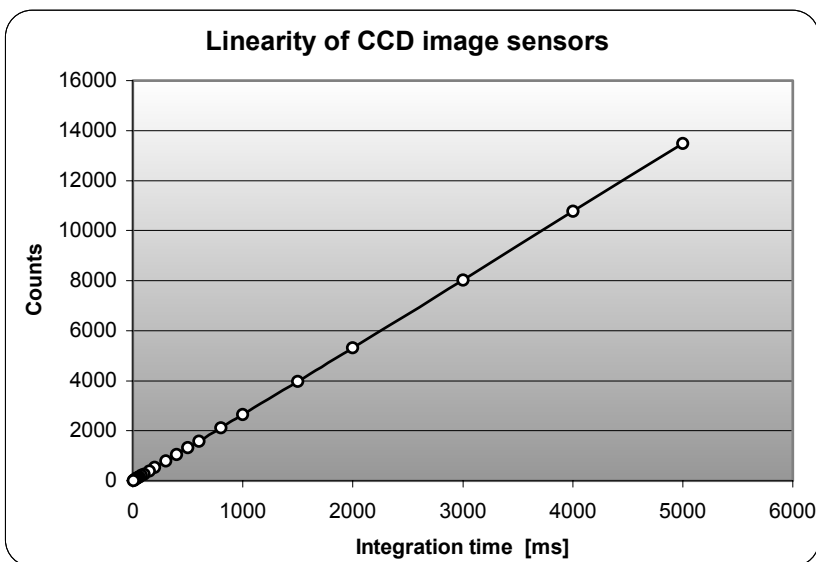
## Total Noise Electrons, TNE

The total noise electrons TNE of a CCD image sensor is the product of signal to noise ration SNR and the total number of pixels. The connection with the total electron capacity gives the total dynamic  $TD = TEC/TNE$  of the camera system.

## Fill factor

The fill factor is the active area of one pixel for the conversion of photons. CCD image sensors with a fill factor of less than 100% show moiré structures due to the spatial sampling characteristics. This behaviour influences the modulation transfer function and prevents the quantitative analysis of image intensities with small spatial structures. In addition, the quantum efficiency will be decreased. This effect can be reduced by the lens-on-chip technology, every pixel has its single lens, but with a result in a direction-dependent sensitivity. The quantum efficiency decreases with the increase of the angle of incoming photons, even for f numbers smaller than 2.8 or numerical apertures higher than of the optical systems. This is, especially in the low light level region, an important limiting factor for absolute sensitivity.

## Linearity, Lin



A very important characteristic of photometric applications of an imaging system is linearity. The digital signal should be proportional to the number of incoming photons. The linearity can be defined as the percentage of the deviation of a linear plot compared to the maximum intensity value.

$$\text{Lin}(\%) = (\text{deviation} \times 100) / \text{max. signal.}$$

The linearity depends on the CCD image sensor itself, the signal processing electronics and the A/D converter.

A typical linearity plot is shown normally in the diagram. Scientific imaging systems have nonlinearities in the range of a few tenths of a percent. Because the linearity

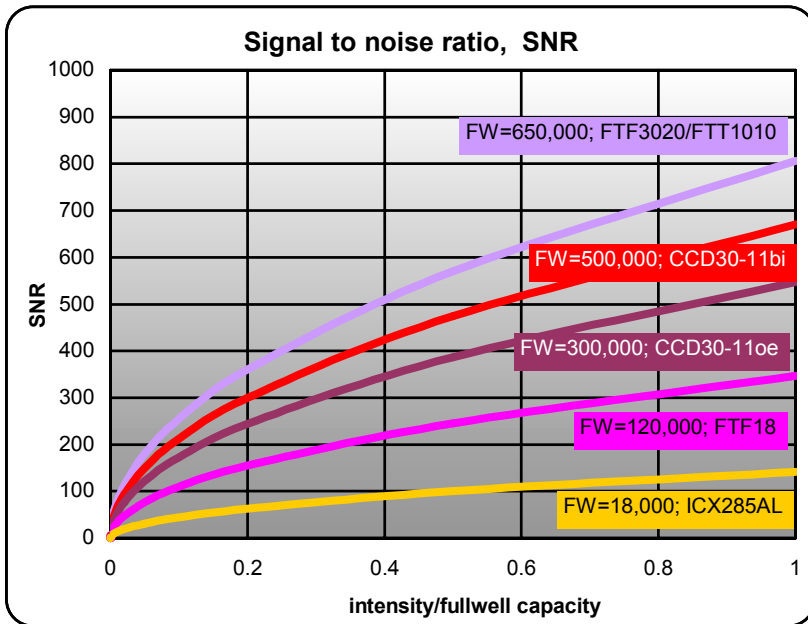
becomes nearly constant for an imaging system, one can correct the nonlinearity to values down less than one-tenth of a percent with lookup correction tables.

## Dynamic Range

The dynamic range of a camera system is the relation of the full well capacity FWC to the signal to noise ratio SNR. This important characteristic specifies the ability to measure very dim and very bright parts and therefore the intensity range of a single image. THETA SYSTEM uses 14bit A/D converters with 3MHz and 10MHz conversion speeds and 18bit (16bit used) A/D converters with 1MHz conversion speed. This high digitalization dynamic avoids the need to implement different detection modes for high, medium and low light levels to optimise the system to the application.

Especially in the case of signal averaging over many images, the high digitalisation dynamic extends the total dynamic range up to 19 bit with the 18 bit system and 15 bit with the 14 bit system, compared to a maximum of 13 bit with a 12 bit system.

## Signal to Noise Ratio, SNR



The signal to noise ratio SNR depends on:

- ▶ the natural photon statistics  $\sqrt{I_s}$  of the incoming photons  $I_s$
- ▶ the dark noise  $\sqrt{I_D}$
- ▶ the read-out noise  $A$ , resulting from the CCD and the processing electronics.

$$SNR = I_s / \text{SQR}(I_s + I_D + A^2).$$

The diagram shows the typical SNR of camera system with the noted CCD image sensors and full well capacity.

In the region of higher intensities, e.g. in the case of photometric studies, absorption and beamprofile measurements and microscopic applications, one should select a sensor with high full well capacity, because the SNR depends on intensities higher than a few percent mainly on the photon statistics

The dark noise and the read-out noise dominate in applications with low intensities, e.g. fluorescence, and the light sensitivity  $S$  is the selection of choice.

## Binning

Binning is the combination of intensities of adjacent pixels into an image with a resulting lower spatial resolution. Hardware binning is the addition of electronic charges of several pixels generated directly on the CCD chip during the read-out. These combined charges will be read only one time from the sensor output stage with the resulting lower read-out noise corresponding to the binned pixel number. Hardware binning is therefore convenient for low intensities when the reduced spatial resolution can be accepted. Care must be taken with the maximum electron capacity of the read-out register and the output stage due to blooming effects.

Software binning is the addition of adjacent pixel intensities in the image memory after the image acquisition. The summarization increases the number of electrons of one image element and therefore the signal to noise ratio SNR corresponding to the square root of the number of binned pixels.

Hardware binning of sensor lines lowers the read-out time and therefore speeds up the frame rate.

Intelligent choice of the combination of the hard- and software binning factors results in a good compromise between spatial and time resolution for acquisition of time-dependent image sequences.

Schematic cycle of a 2x2 hardware binning of a 4x4 CCD-Matrix:

After illumination of the single pixel with the relative intensity of 1, the charges of all lines will be transferred with the line shift 1 one step toward the output register. The charges of the lowest line are now in the output register and the uppermost line contains no charges. In a similar way the line shift 2 happens, and the charges of the lowest line will be added to the charges of the output register. Analogously the transfer processes occur with the column shift 1 and column shift 2 into the output stage. The resulting intensity of 4 will be read out of the output stage by the camera electronics and with the following reset the system is ready for the next cycle.

