dynamic – dynamic range

The **dynamic or dynamic range** of a CCD-camera system is a widely applied term, which in principle should characterize the ability of a camera system to measure or image light-dark-differences. In the field of photography it corresponds to the range of contrast. However, looking at advertisements a couple of different dynamic ranges are described by the manufacturers. A distinction has to be made between the **dynamic range of a CCD-image sensor**, the **dynamic range of the analog-to-digital-conversion** and the **utilizable dynamic range**.

dynamic range of a CCD-image sensor:
This range DR is defined by the CCD-image sensor manufacturers as the ratio between the maximum possible signal (full well capacity) vs. total noise signal (in the dark), and is mainly given either as dezibel [dB] or dimensionless:

$$DR_{CCD} = \frac{\text{full well capacity}}{\text{rms noise}_{dark}}$$

$$DR_{CCD} = 20 \cdot \log\left(\frac{\text{full well capacity}}{\text{rms noise}_{dark}}\right) [\text{dB}]$$

data of some popular commercial CCD-image sensors

	Sony ICX 285	Kodak KAI-1020	Kodak KAI-11000
full well cap. [e^-]	18.000	40.000	60.000
noise rms [e^-]	6	10-15	12-14
dynamic range [x/1]	3000:1	3200:1	5000:1
dynamic range [dB]	73.1	70.1	74.0

Therefore the ICX285 could be reasonably digitized with 4095 steps (corresponds to $\{2^{12}\}$ 12 Bit resolution) or in case of the KAI-11000, it should be digitized with 8192 steps (corresponding to 13 Bit resolution). All these considerations refer to maximum values, as can be seen below about the utilizable dynamic range.
Furthermore, additional gain only makes sense if the dynamic range of the A/D-converter is smaller than the dynamic range of the CCD-image sensor, for example if the dynamic range of the CCD is 70 dB and the dynamic range of the A/D-converter is 48 dB a useful gain or amplification would be 22 dB. Alternatively a programmable gain would increase the performance of such a system.

dynamic range of the digitization or analog-to-digital conversion:
The generated charge carriers are usually converted by an optimized read out circuit into voltage signals, which are amplified and finally digitized by an analog-to-digital converter. Therefore the light signal, the photons, are converted into digital values - counts. Here the analog-to-digital converters have a given resolution or dynamic range, that in most cases is given as a power of the base 2, (2^x). Therefore an 8 Bit resolution corresponds to 256 steps, which can be used to subdivide or convert the full scale voltage signal.

dynamic – dynamic range

Manufacturers of CCD-cameras usually optimize a combination of the dynamic range of the CCD-image sensor, gain and conversion factor (average conversion ratio, it takes x electrons to generate 1 count in the image) to achieve an optimum utilization of the dynamic range of the CCD-image sensor by the analog-to-digital converter.

However, just the dynamic range of the digitization is not identical to the utilizable dynamic range, as it is evoked by some advertisements, which just praise “14bit conversion”:

resolution [bit] x => 2^x	dynamic range of analog-to-digital conversion [digitizing steps]	dynamic range of analog-to-digital conversion [dB]
8	256	48.2
10	1024	60.2
12	4096	72.3
14	16384	84.3
16	65536	96.3

It should be noted, that these resolutions always correspond to the theoretical maximum limit of the converter devices. Every real analog-to-digital converter has an average conversion uncertainty of 0.4 - 0.7bit, reducing thereby the real useful resolution for practical applications by 1bit. If a camera system should not be limited in dynamic range by the A/D converter inaccuracy, it can be useful to oversize the A/D converter resolution by 1 or 2 bits and add electronically a defined small offset to the signal, so the lower limit is just given by image sensor and readout amplifier noise, on the expense of some resolution of the converter.

utilizable dynamic range

The utilizable dynamic range of a camera system is first of all dependent of the general settings or adjustments of the system, e.g. it is dependent on how good the dynamic range of the CCD image sensor and the dynamic range of the readout circuits or the digitization are attuned to each other. A common approach is for example, if a full well capacity of 18 000 electrons and a dynamic range of a CCD image sensor of 4500:1 is given, to utilize this range optimally with a 12bit A/D-converter (4096 gray levels), which is possible with a conversion factor of 4.4 electrons per step (count). For very low noise cameras it might make sense to shift the signal resolution range towards the lower noise limit and not use the total dynamic range of the CCD image sensor, if it is anyway only of minor interest for the application.
This gives the second important dependency, which influences the utilizable dynamic range - the application. While the system manufacturer definition of dynamic range tries to be independent of the application, the application itself limits the available dynamic range. For example it is often neglected, that in medium and high light applications which are photon noise limited, the intrascene dynamics might be smaller than the dynamic range of the system.

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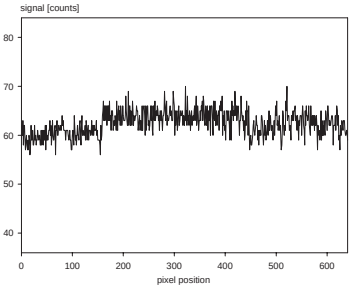
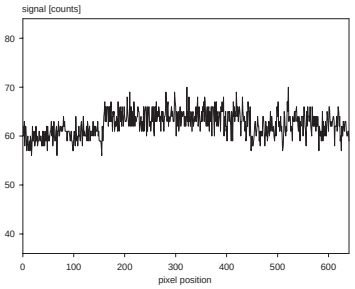
dynamic – dynamic range

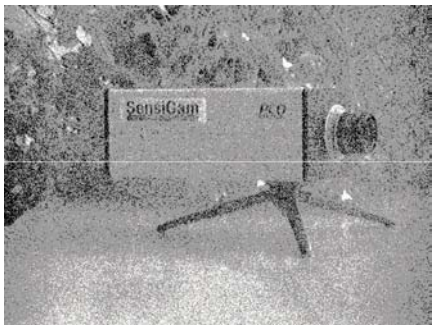
example of 12bit dynamic versus 8bit dynamic:
The following low light scene was recorded with a 12bit cooled CCD camera system. In a full scale 12bit image nothing is visible. If the image is scaled to the range of 54-76 counts, the scene becomes visible, although noisy because of the weak light signal, but present structures could be analyzed, since the camera, which is imaged can be clearly detected. If under similar conditions the image would have been recorded with a 8bit system, even after scaling the image information can only be processed because of the excellent capabilities of our brains, for image processing in computers it can not be used at all.

Weakly illuminated image with 12bit total dynamic displayed with 255 gray levels.
scaled: 0-4095 -> 0-255
graph below shows readout line

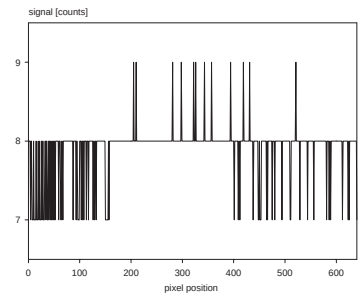


Same image like above with 12bit total dynamic displayed with 255 gray levels.
scaled: 53-70 -> 0-255
graph below shows readout line





Same image like above but with 8bit total dynamic displayed with 255 gray levels.
scaled: 7-9 -> 0-255
graph below shows readout line



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