dynamic – dynamic range

The dynamic or dynamic range of a CCD-camera system is a widely used term to characterize the ability of a camera system to measure or image light/dark differences. In the field of photography, the dynamic range is analogous to the contrast range. However, each manufacturer defines dynamic range differently. A distinction must be made, between the "dynamic range of a CCD image sensor", "dynamic range of an analog-to-digital-conversion" and "usable dynamic range".

dynamic range of a CCD image sensor

The dynamic range (DR) is defined as the ratio of the maximum possible signal (full well capacity), versus the total noise signal (in the dark). The data is expressed in decibels [dB] or is dimensionless:

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

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

common commercial CCD image sensor specifications

	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

Upon examination of these specifications, the ICX285 could be digitized using 4095 steps (corresponds to $\{2^{12}\}$ 12 bit resolution), while the KAI-11000 should be digitized using 8192 steps (corresponds to 13 bit resolution). This references to maximum values which are explained in detail in the usable dynamic range section.
Furthermore, additional gain makes sense only 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.

digitization or analog-to-digital conversion dynamic range

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

dynamic – dynamic range

CCD camera manufacturers usually optimize a combination of the dynamic range of the CCD image sensor, gain and conversion factor (defined as average conversion ratio that takes x electrons to generate one count in the image) to optimize the dynamic range of the CCD image sensor by the analog-to-digital converter.

The dynamic range of the digitization is not identical to the usable dynamic range.

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

The resolutions above directly correspond to the theoretical maximum limit of the converter devices. Analog-to-digital converters have an average conversion uncertainty of 0.4 - 0.7bit, which reduces the resolution for practical applications by 1bit. If the camera system is not limited in its dynamic range by A/D converter discrepancies, it is useful to inflate the A/D converter resolution by 1 or 2 bits. This is achieved by electronically adding a minute amount to the signal offset signal, so that the lower limit is solely provided via the image sensor and read out amplifier noise, with some resolution sacrifices from the converter.

usable dynamic range

The actual usable dynamic range of a camera system is determined by the general settings or adjustments of the system (e.g., the quality of the dynamic range of the CCD sensor, and the compatibility between the read out circuit's dynamic range or digitization). For example, if a full well capacity of 18 000 electrons with a CCD image sensor dynamic range ratio of 4500:1 is given, getting optimal range with a 12 bit A/D converter (4096 gray levels) is possible with a conversion factor of 4.4 electrons per step (count). For very low noise cameras, it is sometimes advantageous to shift the signal resolution towards the lower noise limit and ignore the total dynamic range of the CCD image sensor, particularly if it is of minor interest in the specific application.

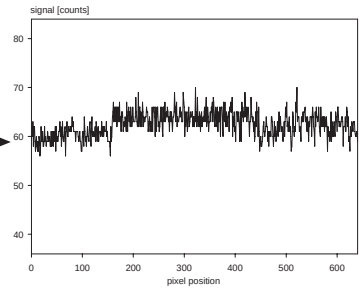
A particular application can also influence the usable dynamic range. Although some manufacturers attempt to define their dynamic ranges as being independent of application, these applications have a direct effect on the limits of the dynamic range. For example, in medium to high light level applications, which are photon noise limited, the intrascene dynamics may be smaller than the system's dynamic range.

dynamic – dynamic range

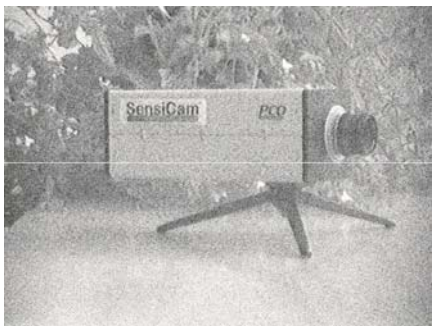
comparing 12 bit and 8 bit dynamic range

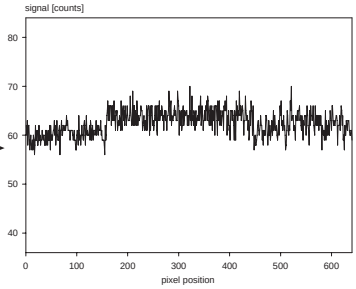
This low light application example was recorded using a 12 bit cooled CCD camera system. The full scale, 12 bit image is completely dark. However, when the image is scaled to the 54-76 counts range, the image becomes visible. Although noise can be seen due to a weak light signal, the image can be clearly seen. Under similar conditions, but recorded with an 8 bit system and scaling, the image can only be processed by the human eye, using the unique capabilities of the human brain, and could not be image processed in a computer.

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



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





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