

Overview of the basic parameters involved in determining the experimental detection limit of CCDs.

1.1 Detection Limit/Sensitivity of CCD

The detection limit of a CCD can be defined as the smallest signal that can be detected by the device. CCD manufacturers usually define this in terms of the noise specifications of the device (as in order to see a signal, it has to be greater than the noise floor of the system). On the other hand, the sensitivity of a CCD will be determined by the quantum efficiency (the ability to convert a photon of light to an electrical signal) as it is the QE which will ultimately determine what proportion of the signal is detected within the silicon.

In reality, to achieve the best detection limit the best noise performance is required. This unfortunately compromises the dynamic range, thus these devices are usually ~14-15 bit rather than true 16bit. However, in most cases, for applications that require the ultimate in detection, the slight reduction in dynamic range will not be a problem as they will usually not require the full dynamic range capabilities of the CCD. In practical experimental terms, the detection limit of a system is determined by a combination of the **Exposure time**, the **Total Noise** of the system and the **Quantum Efficiency** and will be measured experimentally by the signal to noise ratio of the sample of interest. These parameters are explained in the following paragraphs and their effect on the signal to noise ratio can be easily viewed using the online signal to noise calculator.

1.2 Exposure time

The exposure time will have to be as long as required to integrate the incident photons over the noise (readout noise or noise factor) of the system. It is related to the QE, as the higher the QE, the shorter the exposure time, for the same incident signal. In the majority of spectroscopy applications, the exposure times are typically seconds to minutes and for very low light level spectroscopy studies, sensitivity and quantitative measurements are the crucial issues. Even if a degradable sample is present which requires a short exposure time with high sensitivity, this can be achieved by a standard CCD with a slow readout—once the signal is captured, it is usually not a concern that it may take a few ms rather than microseconds to read out the spectrum. 100KHz to 2MHz readout rates are standard for spectroscopy CCDs. Current CCDs have excellent detection limits and can detect signals as low as 10s of photons—most standard spectroscopy applications will have light levels above this! If you consider, for example, that for CW Raman spectroscopy using excitation wavelengths of 532nm or 785nm, a good signal to noise ratio can easily be achieved using a standard front illuminated CCD, for a wide variety of Raman samples. For wider wavelength coverage, the

open electrode device offers relatively good QE over a wide wavelength range. However, for very weak Raman samples and more demanding spectroscopy applications, it may be necessary to have the added sensitivity, which results from the extra QE in a back-illuminated CCD. As back illuminated devices can also give wide wavelength coverage they offer the best of both worlds.

In particular, if the exposure times are so long that the noise from the dark current is affecting the detection limit, then moving to a back illuminated CCD will half the exposure time and the noise of the dark current will then be below the detection limit of the CCD.

1.3 Total System Noise

As mentioned previously, the detection limit of any CCD in spectroscopy is measured in practical terms by the signal to noise ratio. In order to do this properly, it is necessary to understand what the contributions are to the total noise of the system, in order to minimize it and optimize your signal to noise ratio.

$$\begin{aligned}
 N_{\text{total}} &= \sqrt{(N_{\text{Signal}}^2 + N_{\text{Darksignal}}^2 + N_{\text{readout}}^2)} \\
 &= \sqrt{(S + D + N_{\text{readout}}^2)}
 \end{aligned}
 \tag{Eqn.1}$$

The total noise of a standard CCD system is made up of three components as detailed in eqn. 1, i.e. the shot noise of the signal, the noise of the dark signal (or dark current) and the readout noise. The shot noise of the signal is usually overcome by accumulating a number of spectra so that the noise relative to the signal decreases, however in the following discussion, real time or single exposures are assumed.

The readout noise of the system is due to the readout electronics of the sensor and the analogue to digital converter. The system noise is always present and increases with increased readout speed. Standard CCDs can achieve 2-4 electrons readout noise at slow speeds and at speeds of 1MHz, readout noise of 10 electrons is typical. The noise of the dark current is usually minimized by cooling the detector. When back illuminated CCDs first appeared, they had much poorer dark current levels than their front illuminated counterparts, however they have evolved over the years and nowadays boast comparable dark current specifications. In practical situations, with the deep cooling of the commercially available CCDs, the noise of the dark current can be easily negated. If you consider a CCD with pixels of 20um at -80C, the dark current of such a standard back or front illuminated system is approximately 0.002e/p/s. Thus, for a slit height of 2mm, approx. 100pixels would be binned resulting in a dark current of 0.2e/s. If the readout noise of the system is 2e RMS, then an exposure time of 10secs

would be possible before the noise of the dark current will begin to affect the detection limit. Of course, for deep depletion systems, it is a different matter as the dark current levels are 50-60 times higher than standard BI CCDs, (0.1e/p/s at -80C) so that to achieve exposure times equivalent to those of standard back illuminated systems, it is really necessary to use LN cooled systems which, because of their excellent cooling capabilities to -120C reduce the dark current levels back to approx. 0.003e/p/s. In the majority of signal to noise calculations, it is assumed that the exposure times are short enough that the dark current levels are below the detection limit and in most practical situations this is also the case.

If you consider equation one, in terms of the contribution of each of the components and assume 2e readout noise, negligible dark current (e.g. 1 sec exp with 100 row binned = 0.2e), it is evident that even for light levels as low as 10 photons, the shot noise of the signal is the dominant noise source. Thus the detection limit here is due to the signal itself rather than the noise of the CCD or the noise of the dark current.

$$N_{\text{total}} = \sqrt{9.5 + 0.2 + 4} = 3.7e$$

Thus for a CCD the signal to noise ratio can be defined as follows, where the signal is the incident signal after QE conversion:

$$S/N_{\text{total}} = S/\sqrt{S + D + N_{\text{readout}}^2}$$

$$S/N = 9.5/3.7 = 2.6$$

Thus it can be seen that the conventional CCD has excellent sensitivity for low light level spectroscopy applications.

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