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OMT offers a broad line of Scientific grade cooled CCD cameras. They have numerous and significant advantages over video rate cameras. Particularly important are applications where there is a low light level or a need for precision measurement of light intensity as a function of position, high spatial resolution, or low contrast. Since scientific grade cooled CCD cameras are made in smaller volumes than video rate cameras and contain more costly components, such as high resolution A/Ds, low noise signal processors, and temperature regulating electronics, they are more expensive. In many scientific applications, however, the difference in performance can raise the signal level to the point where it can be quantitatively measured. For these cases, the scientific grade cooled CCD camera is well worth the additional cost. The most common Detectors for PSP measurements are offered in the following list. Please have also a look into the CCD fundamentals to get a better understanding why we are using Scientific grade cooled CCD cameras for PSP at OMT GmbH.

Selection Chart of CCD Detectors for PSP

Detector Type / Specifications	OMT-1024Y	OMT-1024EB	OMT-1024SB	OMT-1024EF	OMT-1300EB
CCD Architecture	Interline, Front-illuminated	Full Frame, Back-illuminated	Full Frame, Back-illuminated	Full Frame, Front-illuminated	Full Frame, Back-illuminated
CCD image sensor	Sony ICX xxxAK	EEV CCD47-10	SITe SI003AB	EEV CCD36-40	EEV CCD36-40
Number of Pixels	1280 x 1024	1024 x 1024	1024 x 1024	1340 x 1300	1340 x 1300
Pixel Size (µm)	6.7 x 6.7	13 x 13	24 x 24	20 x 20	20 x 20
Imaging Area (mm)	8.6 x 6.7	13.3 x 13.3	24.6 x 24.6	26.8 x 26.0	26.8 x 26.0
Full well per Pixel (e^-)	25.000	120.000	300.000	200.000	200.000
Readout Noise (e^- rms)	≤ 8 @ 12.5 MHz	≤ 9 @ 1 MHz	≤ 8 @ 100 kHz ≤ 16 @ 500 kHz	≤ 4 @ 100 kHz ≤ 8 @ 1 MHz	≤ 5 @ 100 kHz ≤ 10 @ 1 MHz
Dark Current (e^-/s/pixel)	< 0.1 @ -12 °C	< 0.5 @ -45 °C	< 2 @ -50 °C	< 0.5 @ -50 °C	< 0.5 @ -50 °C
Dynamic Range	< 12 bit	≤ 14 bit	16 bit	16 bit	16 bit
Peak QE	> 50 %	> 80 %	> 75 %	> 40 %	> 90 %
ADC converter	12.5 MHz, 12 bit	1 MHz, 16 bit & 100 kHz, 16 bit	500 kHz, 16 bit & 100 kHz, 16 bit	1 MHz, 16 bit & 100 kHz, 16 bit	1 MHz, 16 bit & 100 kHz, 16 bit
Readout time at maximum ADC rate	8 fps	1 fps	0.42 fps	0.55 fps	0.55 fps
Interface board	PCI	PCI	PCI	PCI	PCI
Coaxial cable link (m)	≤ 10	≤ 50	≤ 50	≤ 50	≤ 50
Optional Fiber optic link (m)	≤ 300	≤ 1000	≤ 1000	≤ 1000	≤ 1000
Detector head dimensions H x W x L (mm)	93 x 78 x 210	118 x 118 x 176	117 x 155 x 187	118 x 118 x 176	118 x 118 x 176
Detector head weight (kg)	1.6	3.2	3.5	3.2	3.2
Controller dimensions H x W x L (mm)	-	223 x 134 x 346	223 x 134 x 346	223 x 134 x 346	223 x 134 x 346
Controller weight (kg)	-	5.9	5.9	5.9	5.9

All detectors including Thermoelectric Cooling (forced air), C-Mount or Nikon-F-Mount

Full Frame CCDs

The Full Frame CCDs are devices in which the total area of the CCD is available for sensing incoming photons during the exposure charge is shifted sequentially across the array necessitating the use of a shutter to prevent smearing for almost all exposure lengths. (Technically, if the exposure time is much longer than the actual readout rate, then the level of smearing can be quite small.) This format has 100% fill factor, which means that 100% of each pixel area is being utilized to detect photons during the exposure. The pixels are typically square in format so there is no image distortion inherent to the detector. These devices are available with pixel sizes that range from 6.8 microns square (Kodak 1400 CCD) up to 24 microns square (SITe 512 or 1024 CCD) and with pixel formats of 512 × 512 up to 2k × 3k. The full frame CCDs can come designed for front side illumination or for back side illumination. With the front illuminated CCD, the light must traverse the SiO_2 gate structures overlying the photosensitive silicon called the depletion layer. These gate structures are essential for pixel formation in the CCD, but the differences in the indices of refraction between the gates and the silicon causes shorter wavelength light to reflect off the surface of the CCD, reducing the QE for those wavelengths.

Interline CCDs

The interline CCD is a hybrid sensor with photosensitive diodes on one part of the pixel which are electrically coupled to a CCD type storage region which resides under a mask structure. The masks are long structures running along the vertical axis of the CCD alternating with the open regions, hence the name interline CCD. The diode portion of the pixel has very good QE properties, but the diode only takes up approximately 25% of the pixel area (25 % fill factor), reducing the number of photons converted per unit area. As a way to drive up the fill factor, higher quality interline CCDs have small lenses annealed to the CCD that bring the light from a larger area down to the photodiode. This brings up the fill factor to around 70% and results in a better net QE across the visible spectrum than a CCD without the lenses. In this type of CCD, the signal accumulates on the photodiode and is then rapidly shifted to the adjacent CCD structure, taking approximately 1 microsecond to perform the transfer. This extremely fast transfer means that the smearing will be non-detectable for any exposure of a millisecond or longer. In addition, this type of rapid shifting allows for some interesting uses of the interline CCD such as very short exposures for fast moving objects, or for very bright objects (to reduce signal intensity). This is an ideal CCD to use with “slow gating” types of measurements such as the determination of the lifetimes.

One limitation of the interline CCD is the small well capacity available, which is typically reduced by the presence of an “overflow drain”. This type of CCD is called an anti-blooming chip since the drains keep saturating signals from overflowing into adjacent pixels and ruining the data. The net effect of this drain is to reduce the overall well size and to degrade the linearity of the CCD response for higher light signals.

The dynamic range of a CCD is usually calculated as the full well signal in electrons, that is the maximum possible signal, divided by the Root Mean Square (RMS) readout noise in electrons, which is the smallest step size on average which can be used by the digitizer. Getting the readout noise to the lowest level possible allows the maximum in dynamic range performance. In addition, the lower the noise level of the CCD, the higher the sensitivity to very low level signals.

Full Well Capacity

Full well capacity defines the amount an individual pixel can hold before saturating. Saturation must be avoided in high performance CCD imaging because it diminishes the quantitative nature of the CCD and produces image smearing due to a phenomenon known as blooming.

Full well is dependent upon the pixel size of the CCD, whether or not MPP mode is used, and the operating voltages used on the CCD. Larger full wells are found on large pixel devices such as the SI003AB from SITe. MPP mode reduces full well since a large gate potential is not applied to the CCD electrodes during integration. This has the intended effect of reducing dark current, but it can suffer the penalty of reduced full well. This trade-off should be considered when selecting a particular CCD for high performance imaging applications.

OMT provides a test report with every camera system listing the full well for that particular CCD. This value has been measured at the factory and the camera gain has been adjusted so that the full range of the ADC matches the single-pixel linear full well capacity of the CCD at 1x gain. Only the linear range of the full well capacity is used since this is where the CCD functions as a radiometric detector and produces quantitative results. For this reason, full well capacities reported for our cameras may be lower than those found in CCD manufacturers data sheets.

CCD	Pixel Size (μm)	Typical Full Well
SONY ICXxxxAK	6.7 x 6.7	25,000 e-
EEV CCD47-10	13 x 13	120,000 e-
SITe SI003AB	24 x 24	300,000 e-

Noise Sources

All electronic circuitry generates undesirable noise. The effect of this noise on performance is described by the signal-to-noise ratio (SNR). Photon noise, preamplifier noise and dark current noise are the three primary sources of noise in a CCD camera.

Photon Noise

Photon noise, also known as photonic or photon shot noise, is a fundamental property of the quantum nature of light. The total number of photons emitted by a steady source over any time interval varies according to a Poisson distribution. The charge collected by a CCD exhibits the same Poisson distribution, so that the noise is equal to the square root of the signal. Photon noise is unavoidable and is always present in imaging systems; it is simply the uncertainty in the data.

Preamplifier Noise

Preamplifier noise, also called read noise, is generated by the on-chip output amplifier. This noise can be reduced to a few electrons with the careful choice of operating conditions.

Dark Current

Dark current, or thermally generated charge, can be measured and subtracted from data, but its noise component cannot be isolated. Dark current noise is of particular concern in low light applications.
So the total Noise is calculated by:

$$\textbf{Total Noise} = (\text{read noise}^2 + \text{dark noise}^2 + \text{photon shot noise}^2)^{1/2}$$

Dynamic Range

Dynamic range refers to intrascene performance; that is, the ability to quantitatively detect very dim and very bright parts of a single image. Because the smallest measurable intensity varies between applications and experimental conditions, CCD manufacturers have adopted a definition for specifying dynamic range that is independent of how the camera is used. This definition is defined mathematically as:

$$\text{linear full well (electrons)} \;/\; \text{read noise (electrons)}$$

and is therefore a dimensionless number. The linear full well is a specific measure of pixel well capacity. With a high performance, cooled camera, the read noise (the noise associated with a single readout event) is therefore minimized to yield the largest dynamic range possible.
As a specific example, consider a Sony CCD, which has a full-well capacity of 25.000 electrons. At a typical readout rate of 12.5 MHz, the read noise is 8e- rms. The dynamic range of this chip is therefore 25.000 : 8, or 3.125 : 1. In order to take full advantage of this dynamic range, cameras incorporating Sony chips usually utilize a 12-bit A/D converter (4096 gray levels). It is important that the camera's readout and signal processing electronics be optimized so that low read noise is maintained, otherwise the dynamic range will be compromised.
To extend dynamic range beyond the 12 bits given in the previous example, a camera with a lower read noise, or a CCD with a larger full well capacity is required. Full well capacity is related to pixel size. For instance, the SITe SI003AB has a capacity of 300.,000e- and a read noise of 5e- rms at 100 kHz. The dynamic range is thus 60.000:1. In our cameras this is usually coupled to a 16-bit A/D converter (65,536 gray levels).
As a general rule, camera cost increases with increasing dynamic range, so dynamic range requirements should be considered very carefully when selecting a camera. Note that in an uncooled video camera the read noise is much higher, and the true dynamic range is usually 8 bits or lower.

Dark Current

Dark Current Noise

Dark current arises from thermal energy within the silicon lattice comprising the CCD. Electrons are created over time that are independent of the light falling on the detector. Said electrons are captured by the CCD's potential wells and counted as signal. Additionally, this increase in signal also carries a statistical fluctuation known as dark current noise. CCDs can be cooled either with thermoelectric coolers (TECs) or liquid nitrogen to reduce this effect. Practically, the dark current noise should be reduced to a point where its contribution is negligible over a typical exposure time.

MPP Operation

Some CCDs operate in Multi-Pinned-Phase (MPP) mode. MPP devices are fabricated and operated in such a way as to significantly reduce thermal charge generation (dark current). The largest contribution to dark current results from the interface between the silicon dioxide and epitaxial silicon layer within the CCD. Boron implantation into the epitaxial silicon layer and proper biasing of the various clock phases drive the dark current electrons away from the potential wells that comprise a pixel, thus reducing the number of electrons/pixel/sec collected due to dark current.

Dark Current vs Dark Current Noise

High-performance CCD (HCCD) cameras carry dark current specifications. This parameter carries units of electrons per pixel per second (e.g. 1.0 e/p/s). Dark current noise is the statistical variation of this charge generation. For instance, the OMT-1300EF carries a dark current specification of 0.5 e/p/s @ - 50°C. For a 8 second exposure, a total of 4 electrons/pixel are generated (0.5 e/p/s x 8 s). Since dark current noise follows Poisson statistics, the rms dark current noise is the square root of the dark current or, in this case, equal to 2 e/p.

Dark Current Noise Contributions

Noise sources in HCCD cameras add in quadrature (the square root of the sum of the squares). In the low-light regime, the significant noise sources are read noise and dark current noise. Again, using the OMT-1300EF as an example, we can easily compare the relative sizes of these noise sources. Using 4 electrons/pixel @ 100 kHz as the read noise and the dark current noise calculated above (2 e/p) for a 8 second exposure the total camera noise is calculated as follows:

$$\begin{aligned}\textbf{Total Noise} &= (\text{read noise}^2 + \text{dark noise}^2)^{1/2} \\ &= (4^2 + 2^2)^{1/2} \\ &= \textbf{4. 5 electrons (for a 8 second exposure)}\end{aligned}$$

Thus, the dark current noise generated in a 8 second exposure has virtually no effect on total camera system noise! Similarly, for a 30 second exposure we find that the total system noise equals 4.5 electrons.

Hot Pixels

Occasionally an individual pixel may have a different dark current generation rate than the rest of the CCD array. The dark current specification is an ensemble average of the entire array. Those pixels that have a higher than average dark current are known as hot pixels. These pixels will repetitively have higher backgrounds than the vast majority of pixels. Since this is an effect that arises from the CCD manufacturing process each hot pixel location will remain fixed and can therefore be corrected.

Linearity

The fundamental process that occurs in CCD imaging is the conversion of photonic input to electronic output. Photons incident on the CCD will be converted to electron/hole pairs and the electrons will be captured under the gate electrodes of the CCD. These electrons are then transferred in a "bucket brigade" fashion to the output amplifier where the charge is converted to a voltage output signal. An analog processing chain further amplifies this signal and finally it is digitized before being transferred to a host computer for display, image processing and/or storage. The transfer function between the incident photonic signal and the final digitized output should vary linearly with the amount of light incident on the CCD. Hence, non-linearity is a measure of the deviation from the following relationship:

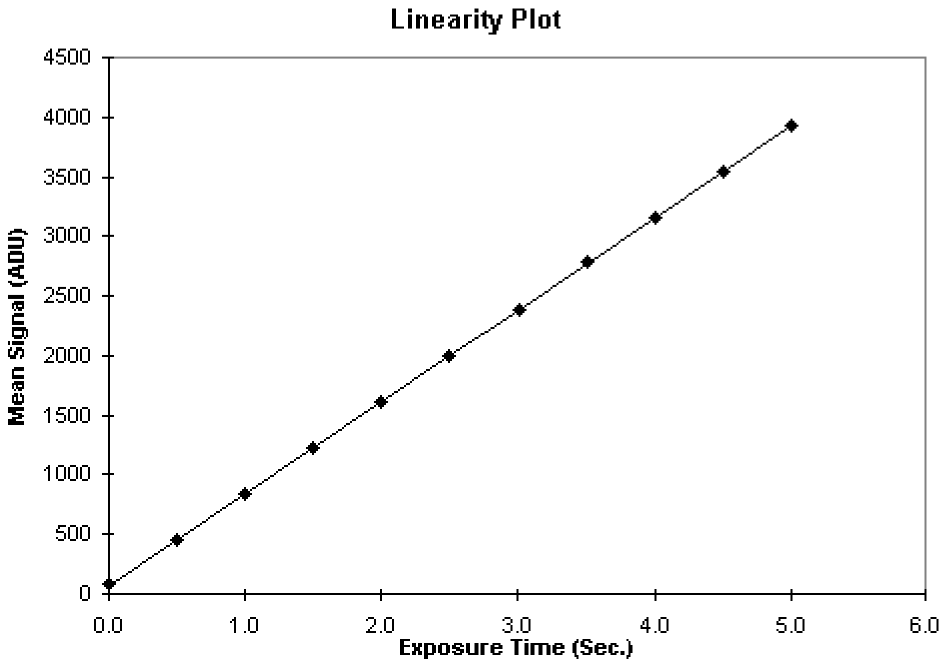
Digital Signal = Constant x Amount of Incident Light

High-performance CCD (HCCD) imagers have extremely good linearity. Deviations from linearity are often less than a few tenths of a percent for over five orders of magnitude. This is far superior to video CCDs and other solid-state imagers which can exhibit non-linearity of several percent or more. For quantitative imaging, linearity is a stringent requirement. CCDs must be linear in order to perform image analysis such as arithmetic ratios, shading correction, flat fielding, linear transforms, etc.

There is no standard method for measuring or reporting linearity values. Typically the numbers are reported as percent deviations from linearity (it may be specified as linearity or non-linearity, however).

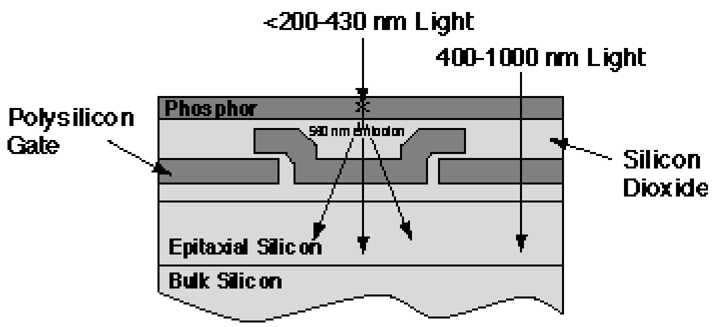
One method that can be used is to plot the mean signal value versus the exposure time over the full linear range (linear full-well) of the CCD. A linear least-squares regression can then be fit to the data. The deviation of each point from the calculated line gives a measure of the non-linearity of the system. The non-linearity can be reported as the sum of the maximum and minimum deviation divided by the maximum signal as a percentage:

Nonlinearity (%) = 100 x (MaxPositiveDeviation + MaxNegativeDeviation) / MaximumSignal



UV Coating

Metachrome II, Unichrome and Lumogen are composite phosphor coatings to improve sensitivity of CCDs in blue-visible and ultraviolet wavelengths. The application of a thin coating of Metachrome/Unichrome/Lumogen to the surface of a CCD effectively, reliably, and inexpensively achieves a dramatic increase in device sensitivity in the 120 to 430 nm range. Both front-illuminated and back-illuminated CCDs will achieve improved UV response using Metachrome/Unichrome/Lumogen.



Optical Properties

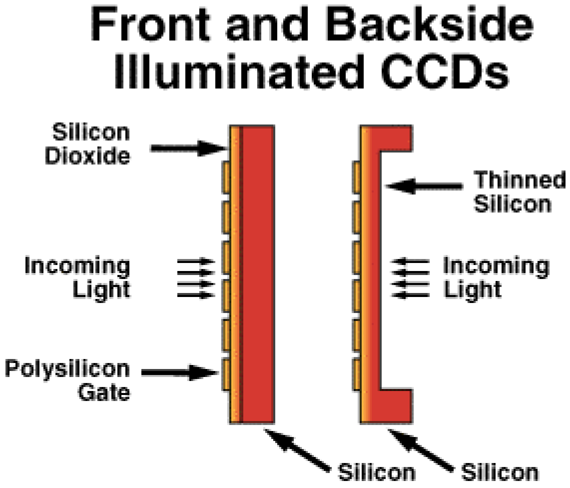
the UV coating emits light at approximately 540 to 580 nm when excited with light of wavelengths shorter than 450 nm. The high conversion efficiency of the coating combined with the high quantum efficiency of CCDs at the emission wavelength makes Metachrome/Unichrome/Lumogen an ideal ultraviolet downconverter for silicon detectors. At wavelengths longer than 460 nm, the thin layer of the UV coating becomes transparent and, thus, has no detrimental effect on the quantum efficiency of a CCD in the visible and near-infrared portions of the spectrum.

Quantum Efficiency of UV coated CCDs

The front-illuminated CCD has virtually no response below 350 nm and less than 5% quantum efficiency is typically observed at 400 nm (in the blue-visible range). The contrast-transfer functions for a coated and uncoated CCD with a 20 µm square pixel were compared and found to be identical. Smaller pixel CCD with 6.8 µm pixels, was tested. While a definite decrease in CTF was observed at mid- to high-spatial frequencies, contrast resolution remained high beyond the Nyquist frequency.

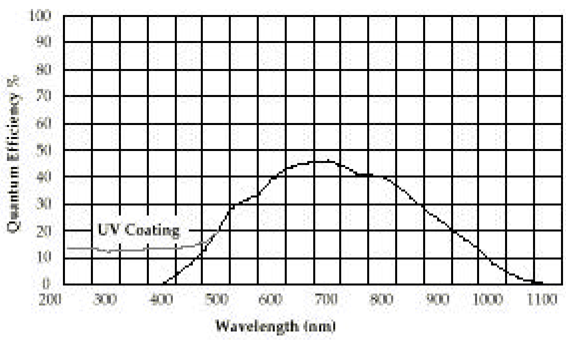
Quantum Efficiency

Quantum efficiency is the measure of the effectiveness of an imager to produce electronic charge from incident photons. This is an especially important property when doing low-light-level imaging. Because most CCD imagers are made from silicon, it is useful to examine the properties of this element and the way in which it interacts with light.



In the high purity crystalline form, each atom of silicon is covalently bonded to its neighbor. Energy greater than the band gap energy, about 1.1 eV, is required to break a bond and create an electron hole pair. The wavelength of incoming light and photon absorption depth are directly related; the shorter the wavelength, the shorter the penetration depth into the silicon.
Light normally enters the CCD through gates of the parallel register (front-illuminated CCD). These gates are made of very thin polysilicon, which is reasonably transparent at long wavelengths, but becomes opaque at wavelengths shorter than 400 nm. Thus, at short wavelengths, gate structure attenuates incoming light.

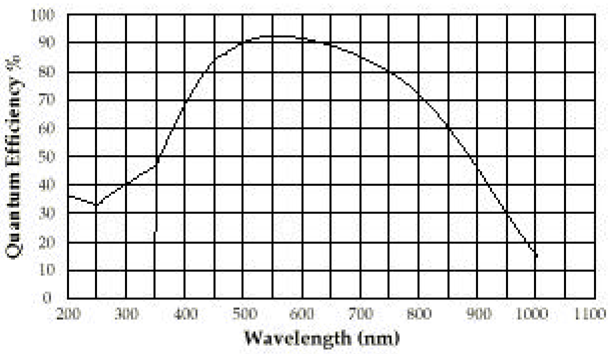
QE-Curve of OMT-1300EF with UV-Coating



Back-illuminated CCDs

It is possible, using acid-etching techniques, to uniformly thin a CCD to a thickness of approximately 10 µm and focus an image on the backside of the CCD register where there is no gate structure (back-illuminated CCD). Thinned CCDs exhibit high sensitivity to light from the soft x-ray to the near-infrared regions of the spectrum. To improve sensitivity of CCDs in the blue visible and ultraviolet wavelengths (200 nm - 400 nm), it is also possible to coat a CCD with a UV converter.

QE-Curve of OMT-1300EB with UV-Coating



Flat Field Correction

A CCD imager is composed of a two dimensional array of light sensitive detectors or pixels. The CCD array is mechanically quite stable with the pixels retaining a rigidly fixed geometric relationship. Each pixel within the array, however, has its own unique light sensitivity characteristics. As these characteristics affect camera performance, they must be removed through calibration. The process by which a CCD camera is calibrated is known as "Flat Fielding" or "Shading Correction".
Flat fielding can be illustrated in the following equation:

$$IC = [(IR - IB) * M] / (IF - IB)$$

Where IC is the calibrated image; IR is the non-calibrated object exposure; IB is the bias or dark frame; M is the average pixel value of the corrected flat field frame; and IF is the flat field frame.
IB Flat fielding requires the acquisition of two calibration frames. First, a bias frame or a dark frame should be taken. Bias clears the camera of any accumulated charge and reads out the cleared CCD. The resulting image is a low signal value image. In this image, all of the pixels have approximately the same value, which consists of the electronic offset of the system of the inherent structure of the CCD. Dark clears the CCD of charge, allows charge to accumulate for a specified amount of time with the shutter closed and then reads out that charge (dark current). A dark frame contains the standard bias component as well as the dark signal. The dark command is most useful when taking long exposures with low light levels.
IF The second calibration image, the flat field frame, measures the response of each pixel in the CCD array to illumination and is used to correct for any variation in illumination over the field of the array. The optical system most likely introduces some variation in the illumination pattern over the field of the array. The flat fielding process corrects for uneven illumination, if that illumination is a stable characteristic of each object exposure. Thus, it is necessary to illuminate the CCD with a light pattern that is as representative of the background illumination as possible. This illumination should be bright enough, or the exposure made long enough, so that the CCD pixels signals are at least 25 percent full scale or preferably higher. For a camera equipped with a 12 bit analog processing card, the level should be at least 1000 ADUs.
IR : An exposure of the object of interest is acquired.
(IR - IB) : The object frame must be corrected for electronic offset by subtraction of the bias/dark frame from it.
(IF - IB) : The flat field frame must also be corrected for electronic offset by subtraction of the bias/dark frame from it.
The average pixel value of the bias/dark corrected flat field frame must then be ascertained (M).

CCD Grading and Defect Specifications

Manufacturers of CCD sensors grade devices according to the number and type of defective pixels. The manufacturing yield of each sensor grade strongly affects the CCD cost, the more perfect the sensor, the higher its cost. Because the CCD sensor is a large cost component in the overall HCCD camera system, the choice of sensor grade is an important consideration when purchasing a camera. Unfortunately, each CCD manufacturer uses a different scheme to grade devices. Grading schemes typically run from a grade 0 device, designating the highest quality available (nominally defect-free), to grade 1, 2, or 3, with the number of defects increasing with the grade number. To assist customers in choosing the proper grade, we've provided the definitions below, as well as a few examples to compare grading between manufacturers.

Central Zone:
The central zone is an area in the middle of the CCD array. The exact location and size varies with the manufacturer. Defects in this region are usually specified separately from the overall number of defects.

Neighborhood:
This is the group of pixels surrounding the defect in question, usually 10,000 pixels or less. Again, the exact specification is manufacturer-specific.

Point Defect:
A point defect is a pixel whose response differs by ±N% compared to the mean values of all pixels in the neighborhood. "N" can be as low as 6% or as high as 20% depending on the manufacturer.

Cluster Defect:
This is a group of adjacent point defects. The maximum allowable number of defective pixels in a cluster varies between 3 and 9, depending on the manufacturer.

Column or Row Defect:
A column or row defect refers to a column or row, or partial column or row, whose response varies by at least ±N% from the neighborhood mean value. "N" is usually the same number as for point defects.

Charge Trap:
A trap is a pixel that traps charge during the charge-transfer process. Charge transfers out of the trap at a lower rate, leading to charge being "left behind." Once a trap is filled, a steady state is reached where it no longer consumes

signal electrons. Some manufacturers give specifications for both the number of low-level traps (filled with typically <2000 e-) and high-level traps (filled with typically <10,000 e-). The physical location of the trap is also important, particularly for low-light applications. Traps in the serial register of the CCD can affect signal from nearly the entire sensor. Traps in a column only affect that column's signal. Traps are often quite dependent on the CCDs operating temperature.

Hot Defects:

Some defects (pixel, cluster, or column) are substantially brighter than adjacent regions. Often, this is due to higher-than-average dark current. These defects tend to disappear as the device is cooled. Because their location and dark current rate are constant, they can often be compensated for by dark current subtraction.

CCD Defect Specifications for Several Selected CCDs and Manufacturers

CCD Manufacturer	EEV Inc.	Kodak	SITe	Thomson
CCD	CCD30-11	KAF1400	SI003AB	TH7896M
Grade 1 Specifications (maximum number in total)				
Point Defects	10 hot pixels 3<3 dark pixel cluster 2<5 dark pixel cluster	5	40	25
Cluster Defects		0	6	3
Column Defects	1 dark, 0 white	0	0	0
Trap Defects	2	1	3	0
Grade 2 Specifications (maximum number in total)				
Total Defects	15 hot pixels 15<3 dark pixel cluster 8<5 dark pixel cluster 1<10 dark pixel cluster	10	80	75
Cluster Defects		4	12	8
Column Defects	6 black, 0 white	2	4	4
Trap Defects	5	2	6	4

This table compares some of the defect specifications for a few popular CCD arrays. The defect amounts are defined by the manufacturer in terms of number of pixels, columns, or clusters whose response differs by ±N%. The deviation, N, is defined independently by each CCD manufacturer and definitions vary widely. Contact us for the exact definitions of the device you are considering.