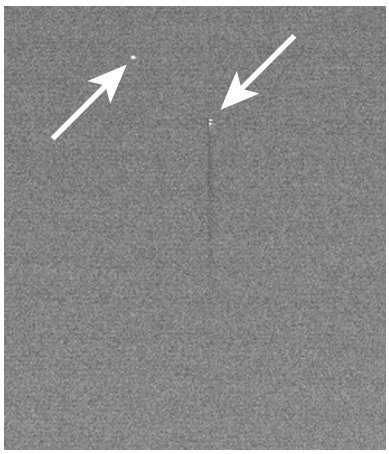

***Figure 1**. Image from a CCD sensor (1024 x 1024-pixel array, 19 x 19-μm pixels) showing defects. The left arrow points to a bright pixel. The right arrow points to a charge trap with smear.*

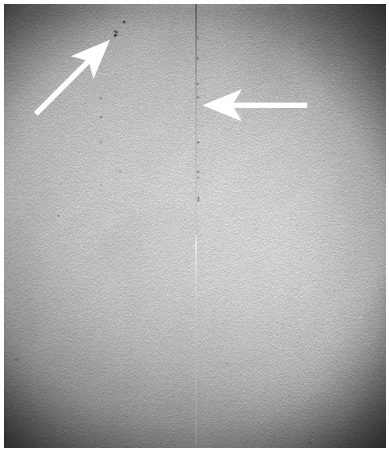

***Figure 2**. Image from a CCD sensor (530 x 526-pixel array, 13 x 13-μm pixels) showing defects. The left arrow points to several dark pixels. The right arrow points to a column defect.*

Grading Scientific CCD Sensors

Introduction

CCD-sensor cost is a primary determinant of the overall cost of a CCD camera system. The cost of sensors can be influenced by a number of factors, such as production volume, device configuration, pixel format, coatings, and grade. Realizing these potential buyer issues, camera-system manufacturers may offer systems that use lower-grade CCD sensors that can still meet customers' imaging requirements. Prospective buyers should get detailed sensor-grade, cost-issue information directly from the camera-system manufacturers.

Manufacturers of CCD sensors grade their devices according to the number and type of defects present. A grading scale is usually used where 0 is the highest grade (i.e., lowest number of defects), with 0 sometimes intended to mean zero defects according to the manufacturer's own specifications. A caveat is that the specifications may allow a sensor graded 0 to still contain some cosmetic defects.

Grades 1, 2, and 3 are progressively lower levels (i.e., more defects present with each increasing grade number). Occasionally, a manufacturer will also specify grades lower than 3, but these devices are seldom used for scientific-grade, high-performance CCD imaging systems.

One weakness of sensor grading is that manufacturers use different grading schemes and testing conditions for their devices. This makes it extremely important that a CCD buyer fully understand the sensor-grading characteristics of the cameras that are being considered. This technical note describes defects and compares grading for commonly used sensors from several leading manufacturers.

Some Relevant Definitions

Figure 1 and **Figure 2** are CCD images demonstrating several types of defects.

Central Zone: The central zone is an area in the center of the array, usually with an aspect ratio similar to that of the overall array. The exact definition is model specific. Defects in this critical zone are generally specified separately from those of the overall array.

Neighborhood (Neighboring): Neighborhood is the group of pixels surrounding the defect in question. It usually consists of approximately 10,000 pixels (100 x 100), depending on manufacturer and model. The definition can also refer to neighboring columns or rows, usually approximately ±50 columns or rows.

Point Defect: A point defect is a pixel for which the responsiveness differs by ±X% compared to the mean values for all pixels in the neighborhood. The value X generally ranges from 6-20%, depending on manufacturer.

Dark/Dead Pixel: A dark pixel is less responsive compared to other pixels in the neighborhood, resulting in darker spots in an image. A dead pixel is one that is nonresponsive (i.e., no response as light level changes).

Hot Defects: A hot defect is a pixel, cluster, column, or row that builds up charge faster than the average rate, resulting in bright spots (i.e., brighter [>+X%] than the neighborhood mean). Hot defects can disappear at lower operating temperatures.

Charge Trap: A charge trap is a pixel (or cluster of pixels) that traps charge during the charge-transfer process. Once a trap is filled, a steady state is reached where the trap no longer consumes signal electrons. Some manufacturers give specifications for both the number of low-level traps (e.g., filled with <2000 e-) and high-level traps (e.g., filled with <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 the signal of that column. Traps are often strongly dependent on the operating temperature of the CCD, exhibiting a temperature-dependent time constant for holding and releasing charge. They tend to be more obvious at lower temperatures due to the lower noise floor and increased time constant. In a highly varied image of light and dark pixels, a trap can cause light pixels to appear darker and can then slowly empty its contents into a row of passing dark pixels, producing a smear of abnormally brighter pixels. The effect of a trap cannot be completely removed, but clearing the CCD after each frame can at least ensure frame-to-frame consistency.

Cluster Defect: A cluster defect is a group of dark or white adjacent point defects. The maximum allowable number of defective pixels in the cluster can vary between 5 and 9, depending on manufacturer. Some manufacturers use the term "spot" instead of "cluster defect", while some do not use either term.

Column (or Row) Defect: A column or row defect is a column or row, or partial column or row, where the responsiveness deviates by at least ±X% from the neighborhood mean. The value X is usually the same number as for point defects and generally ranges from 6-20%, depending on manufacturer.

Comparison of Sensor Grading

Table 1 compares grading of some common CCD sensors from six manufacturers. The specifications are for standard testing (room temperature) of front-illuminated, square-pixel devices; they can be different for the same sensor in back-illumination or specially coated configurations. As stated previously, sensor performance can also be different at lower temperatures, so buyers of high-performance CCD camera systems to be used in cooled conditions should consider the camera-system manufacturer's appropriate cold-testing specifications.

The information in these tables is intended to be general and broad. Individual specifications for a specific sensor in a series may be different or may change over time, so the current individual grading data should always be consulted.

The table shows clear differences among some manufacturers. For example, for sensors with a 1024 x 1024 or similar pixel array, grades 1 and 2 for the Kodak 1401E are moderately more stringent (based on the manufacturers' specifications) than grades 1 and 2 for the Marconi (formerly EEV) 47-10 and the Thomson-CSF 7896, as well as the imaging grade SITe 003. Grades 1 and 2 for the Marconi 47-10 and the Thomson-CSF 7896 are quite similar, with the imaging grade SITe 003 being close in specifications to grade 2 of the Marconi and Thomson-CSF sensors. In addition, the Kodak 1401E is the only one of these sensors for which a grade 3 is specified in the manufacturer's data sheets.

The information in **Table 1** also reflects an instance where grade 0 does not mean zero defects. For the SONY 205 chip, their grade 0 lists zero point, cluster, and column defects. In actuality, their specifications for the sensor reveal that there still can be black or white spots present (at high light) that differ by <20% from the neighborhood mean voltage at 30% of saturation.

Differences in Defect Specifications

Buyers of CCD sensors need to be aware that manufacturers' specifications of a defect or blemish can be quite different. **Table 2** shows standard defect specifications for the Kodak, Marconi, and Thomson-CSF sensors with 1024 x 1024 or similar pixel arrays. There are obvious differences among the three manufacturers for nearly all the specifications. Kodak is the only one of the three to provide clear descriptions for all of these commonly used grading terms, presumably because of this producer's experience of being a high-volume manufacturer.

Conclusions

Some sensor defects can be corrected with imaging software. For example, Roper Scientific™, the leading manufacturer of high-performance CCD camera systems, includes V++™/VPascal™, IPLab™, or Princeton Instruments WinView imaging software in its products to allow automated shading correction (flat fielding). Camera calibration by this method can correct for column/row, cluster/spot, and pixel/point dark and bright defects.

CCD purchasers are faced with a multitude of system and component choices when buying a high-performance imaging system. Important among these are type of CCD, chip size and array, digitizer speed, spectral sensitivity, well capacity, and CCD grade. This note should be considered as just the beginning – basic background knowledge and guidance – of consideration of scientific CCD grading aspects in a camera-system purchasing decision.

Manufac./ Sensor Series/#	Kodak 0401E	Kodak 1401E	Kodak 4202	Kodak 6303	Marconi 57-10	Marconi 42-10	Marconi 47-10	Marconi 05-30
Pixel Array (Pixel Size - μm)	512 x 768 (9 x 9)	1035 x 1320 (6.8 x 6.8)	2032 x 2044 (9 x 9)	2048 x 3072 (9 x 9)	512 x 512 (13 x 13)	521 x 2048 (13.5 x 13.5)	1024 x 1024 (13 x 13)	1152 x 1242 (22.5 x 22.5)
Maximum Defects Allowed								
Grade 0								
Total Point	0	0	0	0	5 b	20 b	15 b	20 b
Total Cluster	0	0	0	0	10 w	10 w	15 w	42 b
Total Column	0	0	0	0	0	0	0	0
Total Traps	NA	NA	NA	NA	1	1	1	2
Grade 1								
Total Point	5	5 [2]	15 [6]	22 [9]	10 b	40 b	25 b	40 b
Total Cluster	0	0	0	0	15 w	20 w	20 w	42 w
Total Column	0	0	0	0	1 b	1 b	1 b	2 b
					0 w	0 w	0 w	0 w
Total Traps	NA	NA	3 [0]	NA	2	2	2	5
Grade 2								
Total Point	10	10 [5]	30 [15]	45 [22]	30 b	100 b	100 b	213 b
Total Cluster	4	2 [0]	12 [6]	18 [9]	25 w	30 w	40 w	65 w
Total Column	0	0	6 [0]	9 [0]	3 b	6 b	4 b	6 b
					0 w	0 w	0 w	0 w
Total Traps	NA	NA	6 [3]	NA	3	5	5	12
Grade 3								
Total Point	NA	20 [10]	60 [30]	90 [45]	NA	NA	NA	NA
Total Cluster	NA	4 [4]	24 [12]	36 [18]	NA	NA	NA	NA
Total Column	NA	4 [2]	12 [6]	18 [9]	NA	NA	NA	NA
Total Traps	NA	NA	18 [9]	NA	NA	NA	NA	NA

[X] = in central region. b = black, w = white. NA = not applicable or not available.

***Table 1**. Comparison of manufacturers' grading of CCD sensors.*

Manufac./ Sensor Series/#	SITe 502*	SITe 003*	SONY 205	Thomson-CSF 7895	Thomson-CSF 7896
Pixel Array (Pixel Size -μm)	512 x 512 (24 x 24)	1024 x 1024 (24 x 24)	1040 x 1392 (4.6 x 4.6)	512 x 512 (19 x 19)	1024 x 1024 (19 x 19)
Maximum Defects Allowed					
Grade 0					
Total Point	NA	NA	0	NA	NA
Total Cluster	NA	NA	0	NA	NA
Total Column	NA	NA	0	NA	NA
Total Traps	NA	NA	NA	NA	NA
Grade 1					
Total Point	20	NA	NA	20	25 [5]
Total Cluster	4	NA	NA	0	3 [1]
Total Column	0	NA	NA	0	0
Total Traps	NA	NA	NA	NA	NA
Grade 2					
Total Point	NA	80	NA	30	75 [25]
Total Cluster	NA	12 (6 adjacent)	NA	0	8 [2]
Total Column	NA	4 (0 adjacent)	NA	1	4 [1]
Total Traps	NA	NA	NA	NA	NA
Grade 3					
Total Point	NA	NA	NA	NA	NA
Total Cluster	NA	NA	NA	NA	NA
Total Column	NA	NA	NA	NA	NA
Total Traps	NA	NA	NA	NA	NA

[X] = in central region. b = black, w = white. NA = not applicable or not available.

*SITe defines only one grade as shown = imaging grade; for grading comparison purposes, the SITe sensors have therefore been arbitrarily assigned to the grade level that they most closely resemble.

***Table 1 (continuation)**. Comparison of manufacturers' grading of CCD sensors.*

Specification	Kodak 1401E (1035 x 1320 Pixels)	Marconi 47-10 (1024 x 1024 Pixels)	Thomson-CSF 7896 (1024 x 1024 Pixels)
Test Condition	25°C	20-25°C	25°C
Point Defect	Black: a pixel that deviates by more than 6% from neighboring pixels when illuminated to 70% of saturation. White: a pixel with dark current >5000 e-/pixel/sec.	Manufacturer uses "spot". Black spots: counted when they have a signal level of less than 90% of the local mean at a signal level of approximately half full-well. White spots: counted when they have a generation rate 125 times the specified maximum dark-signal generation rate.	Manufacturer uses "defect" and "blemish". Black defect: a defect not dependent on temperature, but the amplitude of which is proportional to the mean output voltage. White defect: a defect dependent on temperature, and the amplitude of which doubles for every 8-10°C rise. Both defects counted if they vary more than 20% from the mean. No blemish of more than 5 adjacent pixels allowed.
Cluster Defect	A grouping of ≤5 adjacent point defects.	NA, manufacturer does not use term.	NA, manufacturer does not use term.
Column Defect	A grouping of >5 contiguous point defects along a single column; OR a column containing a pixel with dark current >15,000 e-/pixel/sec; OR a column that does not meet the minimum vertical charge-capacity; OR a column that loses more than 250 e- under 2 ke- illumination (trap-like defect).	Black column: a column that contains ≥21 black defects. White column: a column that contains ≥21 white defects.	A one-pixel-wide defect, the height of which is constant with light level. The defect is counted if it varies by more than 10% from the mean.
Trap	NA, no specification for traps other than immediately above, under Column Defect.	Counted if they have a capacity greater than 200 e-.	Counted in two categories: those with capacity greater than 500 e- and those with capacity greater than 2000 e-.
Central Zone	Central 800H x 600V pixels.	NA, manufacturer does not use term.	Z1, central zone = 750 x 750 pixels.
Neighboring Pixels	The surrounding 128 x 128 pixels; OR ±64 columns/rows.	NA, manufacturer does not use term.	NA, manufacturer does not use term.
Defect Separation	Column/cluster defects are separated by ≥3 pixels in any direction (excluding single-pixel defects).	Used only for black columns; minimum separation between adjacent black columns = 50 pixels.	Used only for blemish specification above, under Point Defect.
Defect Region Exclusion	The outer two rows and columns at each side/end of the sensor.	NA, manufacturer does not use term.	NA, manufacturer does not use term.

NA = not applicable or not available.

***Table 2**. Comparison of manufacturers' grading specifications.*

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