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HANDBOOK OF OPTICS

CLASSICAL, VISION, & X-RAY OPTICS

• SECOND EDITION •

VOLUME

III

MICHAEL BASS, EDITOR IN CHIEF
RAY M. ENOCH • ERIC W. VAN STRYLAND • WILLIAM L. WOLFE, ASSOCIATE EDITORS

HANDBOOK OF OPTICS

Volume III
Classical Optics, Vision Optics, X-Ray Optics

Second Edition

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OPTICAL SOCIETY OF AMERICA

Michael Bass Editor in Chief

*School of Optics / The Center for Research and Education in Optics and Lasers (CREOL),
University of Central Florida
Orlando, Florida*

Jay M. Enoch Associate Editor

*School of Optometry, University of California at Berkeley
Berkeley, California
and
Department of Ophthalmology
University of California at San Francisco
San Francisco, California*

Eric W. Van Stryland Associate Editor

*School of Optics / The Center for Research and Education in Optics and Lasers (CREOL),
University of Central Florida
Orlando, Florida*

William L. Wolfe Associate Editor

*Optical Sciences Center, University of Arizona
Tucson, Arizona*

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CHAPTER 4

SOLID-STATE CAMERAS

Gerald C. Holst
JCD Publishing
Winter Park, Florida

4.1 GLOSSARY

Quantity	Definition	Unit
A_D	Photosensitive area of one detector	m^2
c	Speed of light	$3 \times 10^8 \text{ m/s}$
C	Sense node capacitance	F
$E_{e\text{-faceplate}}(\lambda)$	Spectral radiant incidence	$W \mu m^{-1} m^{-2}$
$E_{q\text{-faceplate}}(\lambda)$	Spectral photon incidence	$photons \text{ s}^{-1} \mu m^{-1} m^{-2}$
d	Detector size	mm
d_{CCH}	Detector pitch	mm
D	Optical diameter	m
DR_{array}	Array dynamic range	numeric
DR_{camera}	Camera dynamic range	numeric
fl	Optical focal length	m
F	f -number	numeric
G	Source follower gain	numeric
h	Planck's constant	$6.626 \times 10^{-34} \text{ J s}^{-1}$
M_e	Radiant exitance	W/m^2
$M_q(\lambda)$	Spectral photon exitance	$photons \text{ s}^{-1} \mu m^{-1} m^{-2}$
m_{optics}	Optical magnification	numeric
M_v	Photometric exitance	$lumen \text{ m}^2$
n_{dark}	Number of electrons created by dark current	numeric
n_{PE}	Number of photoelectrons	numeric
n_{well}	Charge well capacity	numeric
q	Electronic charge	$1.6 \times 10^{-19} \text{ C}$
R_{eq}	Equivalent resolution	mm

4.2 CLASSICAL OPTICS

$\mathfrak{R}_e(\lambda)$	Detector responsivity	A/W
$\mathfrak{R}_{ave}$	Average detector responsivity	V/(J cm ⁻²)
t_{int}	Integration time	s
U	Nonuniformity	numeric
V_{max}	Maximum output voltage	V
V_{signal}	Voltage created by photoelectrons	V
$\langle n_{floor} \rangle$	Noise created by on-chip amplifier	rms electrons
$\langle n_{pattern} \rangle$	Pattern noise	rms electrons
$\langle n_{PRNU} \rangle$	Photoresponse nonuniformity noise	rms electrons
$\langle n_{shot} \rangle$	Shot noise	rms electrons
$\langle n_{sys} \rangle$	Total array noise	rms electrons
η	Image space horizontal spatial frequency	cycles/mm
η_c	Optical cutoff in image space	cycles/mm
η_N	Nyquist frequency in image space	cycles/mm
η_s	Sampling frequency in image space	cycles/mm
$\eta_{(\lambda)}$	Spectral quantum efficiency	numeric
λ	Wavelength	μm

4.2 INTRODUCTION

The heart of the solid-state camera is the solid-state array. It provides the conversion of light intensity into measurable voltage signals. With appropriate timing signals, the temporal voltage signal represents spatial light intensities. When the array output is amplified and formatted into a standard video format, a solid-state camera is created. Because charge-coupled devices (CCDs) were the first solid-state detector arrays, cameras are popularly called CCD cameras even though they may contain charge injection devices (CIDs) or complementary metal-oxide semiconductors (CMOS) as detectors.

Boyle and Smith¹ and Amelis et al.² invented CCDs in 1970. Since then, considerable literature³⁻¹¹ has been written on CCD physics, fabrication, and operation. *Charge-coupled devices* refers to a semiconductor architecture in which charge is transferred through storage areas. The CCD architecture has three basic functions: (1) charge collection, (2) charge transfer, and (3) the conversion of charge into a measurable voltage. The basic building block of the CCD is the metal-insulator semiconductor (MIS) capacitor. The most important MIS is the metal-oxide semiconductor (MOS). Because the oxide of silicon is an insulator, it is a natural choice.

Charge generation is often considered as the initial function of the CCD. With silicon photodetectors, each absorbed photon creates an electron-hole pair. Either the electrons or holes can be stored and transferred. For frame transfer devices, charge generation occurs under an MOS capacitor (also called a photogate). For some devices (notably interline transfer devices), photodiodes create the charge.

The CID does not use a CCD for charge transfer. Rather, two overlapping silicon MOS capacitors share the same row and column electrode. Column capacitors are typically used to integrate charge while the row capacitors sense the charge after integration. With the CID architecture, each pixel is addressable (i.e., it is a matrix-addressable device).

Active pixel sensors (APSs) are fabricated with CMOS technology. The advantage is that one or more active transistors can be integrated into the pixel. As such, they become fully addressable (can read selected pixels) and can perform on-chip image processing.

Devices may be described functionally according to their architecture (frame transfer, interline transfer, etc.) or by application. To minimize cost, array complexity, and electronic processing, the architecture is typically designed for a specific application. For example, astronomical cameras typically use full-frame arrays, whereas video systems generally use interline transfer devices. The separation between general imagery, machine vision, scientific devices, and military devices becomes fuzzy as technology advances.

4.3 IMAGING SYSTEM APPLICATIONS

Cameras for the professional broadcast television and consumer camcorder markets are designed to operate in real time with an output that is consistent with a standard broadcast format. The resolution, in terms of array size, is matched to the bandwidth that is recommended by the standard. An array that provides an output of 768 horizontal by 484 vertical pixels creates a satisfactory image for conventional (U.S.) television. Eight bits (256 gray levels) provides an acceptable image in the broadcast and camcorder industry.

In its simplest version, a machine vision system consists of a light source, camera, and computer software that rapidly analyzes digitized images with respect to location, size, flaws, and other preprogrammed data. Unlike other types of image analysis, a machine vision system also includes a mechanism that immediately reacts to an image that does not conform to parameters stored in the computer. For example, defective parts are taken off a production line conveyor belt.

For scientific applications, low noise, high responsivity, large dynamic range, and high resolution are dominant considerations. To exploit a large dynamic range, scientific cameras may digitize the signal into 12, 14, or 16 bits. Scientific arrays may have 5000×5000 detector elements.¹² Theoretically, the array can be any size, but manufacturing considerations may ultimately limit the array size.

Although low-light-level cameras have many applications, they tend to be used for scientific applications. There is no industrywide definition of a low-light-level imaging system. To some, it is simply a solid-state camera that can provide a usable image when the lighting conditions are less than 1 lux (lx). To others, it refers to an intensified camera and is sometimes called a low-light-level television (LLLTV) system. An image intensifier amplifies a low-light-level image that can be sensed by a solid-state camera. The image intensifier/CCD camera combination is called an intensified CCD (ICCD). The image intensifier provides tremendous light amplification but also introduces additional noise. The spectral response of the ICCD is governed by the image intensifier.

The military is interested in detecting, recognizing, and identifying targets at long distances. This requires high-resolution, low-noise sensors. Target detection is a perceptible act. A human determines if the target is present. The military uses the minimum resolvable contrast (MRC) as a figure of merit.¹³

4.4 CHARGE-COUPLED DEVICE ARRAY ARCHITECTURE

Array architecture is driven by the application. Full-frame and frame transfer devices tend to be used for scientific applications. Interline transfer devices are used in consumer camcorders and professional television systems. Linear arrays, progressive scan, and time delay and integration (TDI) are used for industrial applications. Despite an ever-increasing demand for color cameras, black-and-white cameras are widely used for many scientific and industrial applications.

The basic operation of linear, full-frame, frame transfer, and interline transfer devices is described in Chap. 22, "Visible Array Detectors," *Handbook of Optics*, Vol. I. This section describes some additional features.

Full-Frame Arrays

In full-frame arrays, the number of pixels is often based upon powers of 2 (e.g., 512×512 , 1024×1024) to simplify memory mapping. Scientific arrays have square pixels and this simplifies image-processing algorithms.

Data rates are limited by the amplifier bandwidth and, if present, the conversion capability of the analog-to-digital converter. To increase the effective readout rate, the array can be divided into subarrays that are read out simultaneously. In Fig. 1, the array is divided into four subarrays. Because they are all read out simultaneously, the effective clock rate increases by a factor of 4. Software then reconstructs the original image. This is done in a video processor that is external to the CCD device where the serial data are decoded and reformatted.

Interline Transfer

The interline transfer array consists of photodiodes separated by vertical transfer registers that are covered by an opaque metal shield (Fig. 2). Although photogates could be used, photodiodes offer higher quantum efficiency. After integration, the charge that is generated by the photodiodes is transferred to the vertical CCD registers in about 1 microsecond (μs). The main advantage of interline transfer is that the transfer from the active sensors to the shielded storage is quick. There is no need to shutter the incoming light. The shields act like a venetian blind that obscures half the information that is available in the scene. The area fill factor may be as low as 20 percent. Because the detector area is only 20 percent of the pixel area, the output voltage is only 20 percent of a detector that would completely fill the pixel area. A microlens can optically increase the fill factor.

Because interline devices are most often found in general imagery products, most transfer register designs are based upon standard video timing. Figure 3 illustrates a four-phase transfer register that stores charge under two gates. With 2:1 interlace, both fields are collected

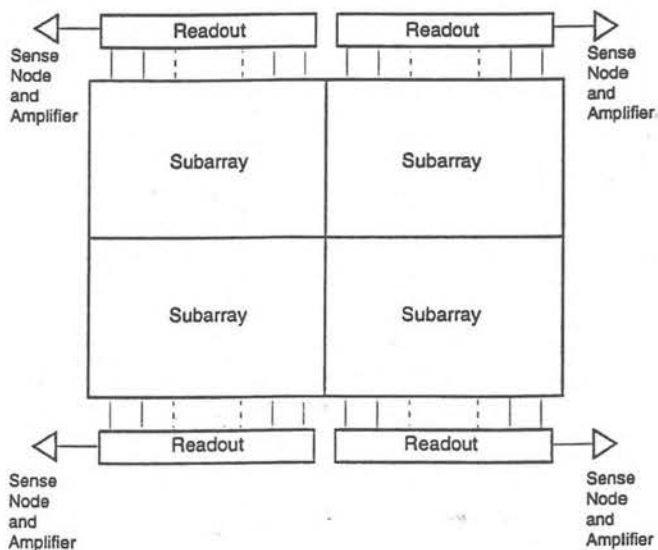


FIGURE 1 A large array divided into four subarrays. Each subarray is read out simultaneously to increase the effective data rate. Very large arrays may have up to 32 parallel outputs.

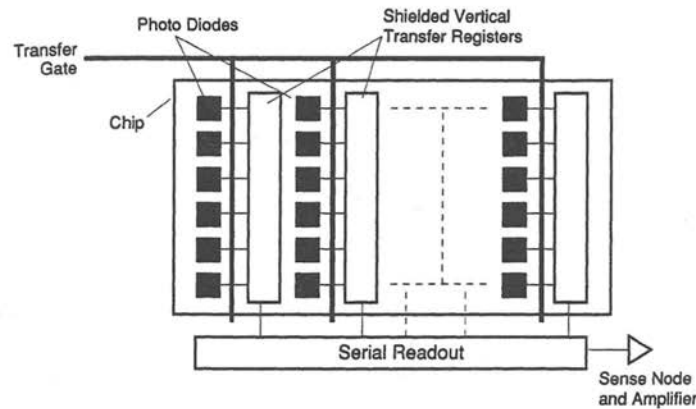


FIGURE 2 Interline transfer architecture. The charge is rapidly transferred to transfer registers via the transfer gate. Interline transfer devices can also have a split architecture similar to that shown in Fig. 1.

simultaneously but are read out alternately. This is called frame integration. With EIA 170 (formerly called RS 170), each field is read every $1/60$ s. Because the fields alternate, the maximum integration time is $1/30$ s for each field.

Pseudointerlacing (sometimes called field integration) is shown in Fig. 4. Changing the gate voltage shifts the image centroid by one-half pixel in the vertical direction. This creates 50 percent overlap between the two fields. The pixels have twice the vertical extent of standard interline transfer devices and therefore have twice the sensitivity. An array that appears to have 240 elements in the vertical direction is clocked so that it creates 480 lines. However,

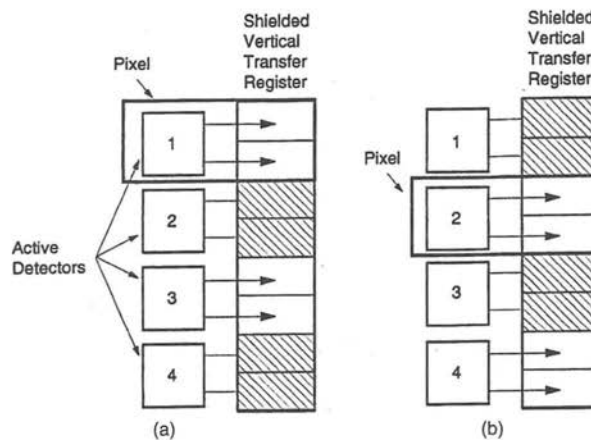


FIGURE 3 Detailed layout of the 2:1 interlaced array. (a) The odd field is clocked into the vertical transfer register, and (b) the even field is transferred. The vertical transfer register has four gates and charge is stored under two wells. The pixel is defined by the detector center-to-center spacing, and it includes the shielded vertical register area. The transfer gate is not shown.

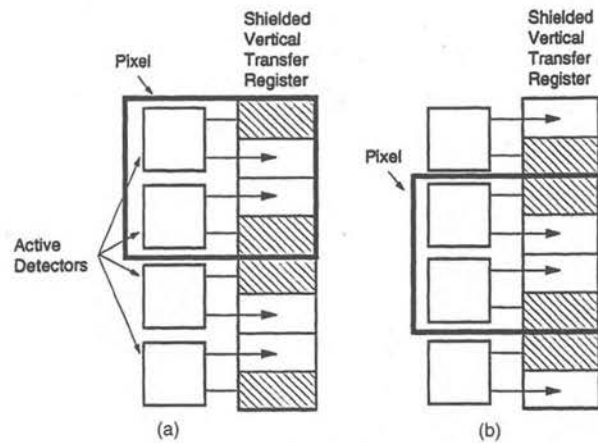


FIGURE 4 Pseudointerlace. By collecting charge from alternating active detector sites, the pixel centroid is shifted by one-half pixel. (a) Odd field and (b) even field.

this reduces the vertical modulation transfer function (MTF). With some devices, the pseudointerlace device can also operate in a standard interlace mode.

4.5 CHARGE INJECTION DEVICE

A CID consists of two overlapping MOS capacitors sharing the same row and column electrode. Figure 5 illustrates the pixel architecture. The nearly contiguous pixel layout provides a fill factor of 80 percent or greater. Charge injection device readout is accomplished by transferring the integrated charge from the column capacitors to the row capacitors. After this nondestructive signal readout, the charge moves back to the columns for more integration or is injected (discarded) back into the silicon substrate.

Although the capacitors are physically orthogonal, it is easier to understand their operation by placing them side by side. Figure 6 illustrates a functional diagram of an array, and Fig. 7 illustrates the pixel operation. In Fig. 7a, a large voltage is applied to the columns, and photogenerated carriers (usually holes) are stored under the column gate. If the column volt-

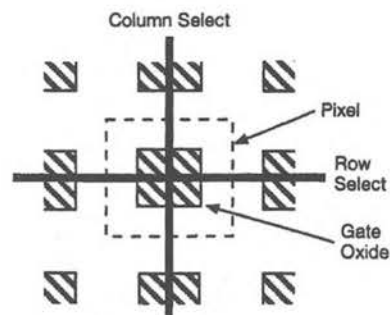


FIGURE 5 CID pixel architecture.

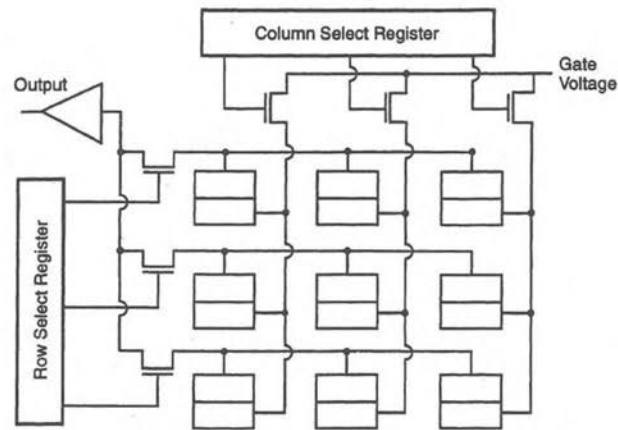


FIGURE 6 Functional layout of a 3×3 CID array. The row and column select registers are also called decoders. The select registers and readout electronics can be fabricated with CMOS technology.

age is brought to zero, the charge transfers to the row gate (Fig. 7b). The change in charge causes a change in the row gate potential that is then amplified and outputted. If V_1 is reapplied to the columns, the charge transfers back to the column gate. This is nondestructive readout and no charge is lost. By suspending charge injection, multiple-frame integration (time-lapse exposure) is created. In this mode, the observer can view the image on a display as the optimum exposure develops. Integration may proceed for up to several hours. Reset occurs by momentarily setting the row and column electrodes to ground. This *injects* the charge into the substrate (Fig. 7c).

The conversion of charge into voltage depends upon the pixel, readout line, and amplifier capacitance. The capacitance is high because all the pixels on a given row are tied in parallel. Therefore, when compared with a CCD, the charge conversion is small, yielding a small signal-to-noise ratio (SNR). Because the readout is nondestructive, it can be repeated numerous times. The multiple reads are averaged together to improve the SNR.

Because each pixel sees a different capacitance, CIDs tend to have higher pattern noise compared with CCDs. However, off-chip algorithms can reduce the amount of pattern noise. With no charge transfer, CIDs are not sensitive to charge transfer efficiency effects. Without

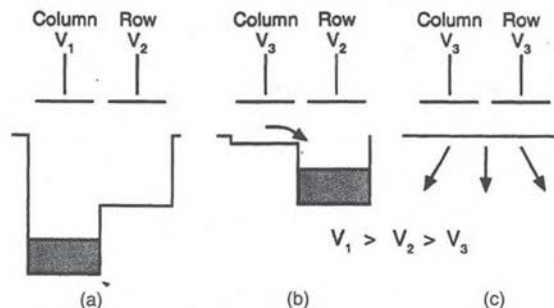


FIGURE 7 CID pixel operation. (a) Integration, (b) readout, and (c) injection.

multiple gates, CIDs have larger well capacities than comparably sized CCDs. Charge injection devices inherently have antibloom capability. Because charge is limited to a single pixel, it cannot overflow into neighboring pixels. Perhaps the greatest advantage of CIDs is random access to any pixel or pixel cluster. Subframes and binned pixels can be read out at high frame rates.

4.6 COMPLEMENTARY METAL-OXIDE SEMICONDUCTOR

With the APS approach, highly integrated image sensors are possible.¹⁴ By placing processing on the chip, a CMOS camera can be physically smaller than a CCD camera that requires clocks, image reformatting, and signal processing in separate hardware. A sophisticated APS array could create¹⁵ a "camera on a chip." It is possible to build a frame transfer device where pixels can be binned to enhance the SNR and provide variable resolution imaging.¹⁶

In 1993, Fossum¹⁷ described state-of-the-art active pixel concepts. At that time, they were the double-gate floating surface transistor, charge modulation device, bulk charge modulation device, based-stored image sensor, and the static induction transistor. That review continued¹⁴ in 1997.

The APS contains a photodiode, row select transistor, and a reset transistor. As shown in Fig. 8, by activating a row, the data from the pixels in that row are simultaneously copied into the columns. Each column will have a load transistor, a column select switch, and a sampling switch. The chip may also have an analog-to-digital converter and provide correlated double sampling. The pixels are then reset and a new integration is started. The APS does not rely upon charge transfer. Rather, the photodiode drives a capacitance line. The total capacitance limits the chip speed. Active pixel sensors can be fully addressable and subarrays can be read out at high frame rates just like CIDs.

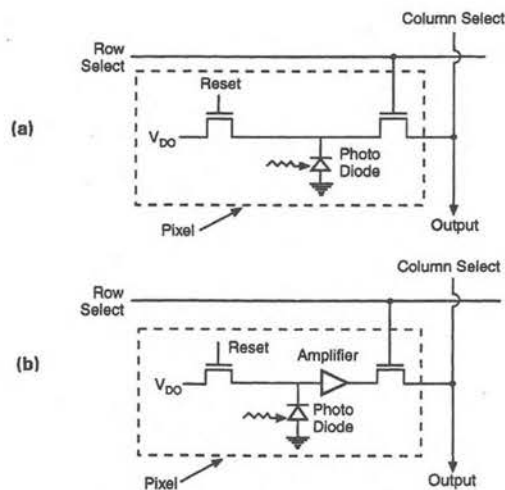


FIGURE 8 (a) Passive pixel device and (b) APS. Charge-coupled devices and CIDs are regarded as passive pixel sensors. Charge injection devices use photogates; CCDs use either photogates or photodiodes; CMOS devices typically use photodiodes.

Complementary metal-oxide semiconductor devices tend to have higher dark currents due to the highly doped silicon used. Therefore, it appears that CMOS sensors will not replace CCDs for low-noise scientific applications. Because the active devices often take up real estate, the area for the photosensor is reduced. This leads to reduced sensitivity that can be partially offset by a microlens. Because each pixel has its own amplifier, pattern noise is larger. However, more logic can be added to each pixel and it seems possible to use on-chip signal processing that suppresses pattern noise.¹⁸ With charge limited to a single pixel, it cannot overflow into neighboring pixels and create blooming as seen with CCDs.

A further advantage is their low power consumption. Active pixel sensors can operate from a 5-volt (V) battery or less (compared with 10 to 15 V for a CCD). It appears at this time that CMOS will compete with CCDs in the general video marketplace where weight, size, and power consumption are factors.

4.7 ARRAY PERFORMANCE

The most common array performance measures are responsivity, read noise, and charge well capacity. From these the minimum signal, maximum signal, SNR, and dynamic range can be calculated. Full characterization includes quantifying the various noise sources, charge transfer efficiency, spectral quantum efficiency, linearity, and pixel nonuniformity.¹⁹ These additional metrics are necessary for the most critical scientific applications.

Signal

Device specifications depend, in part, upon the application. Arrays for general video applications may have responsivity expressed in units of volts per lux. For scientific applications, the units may be in $V/(J\text{ cm}^{-2})$ or, if a digital output is available, $DN/(J\text{ cm}^{-2})$ where DN refers to a digital number. For example, in an 8-bit system, the digital numbers range from 0 to 255. These units are incomplete descriptors unless the device spectral response and source spectral characteristics are furnished.

The number of photoelectrons created by a detector is

$$n_{PE} = A_D \int_{\lambda_1}^{\lambda_2} E_{q\text{-faceplate}}(\lambda) \eta(\lambda) t_{INT} d\lambda \quad (1)$$

where A_D is the effective photosensitive area, t_{INT} is the integration time, $\eta(\lambda)$ is the spectral quantum efficiency, and $E_{q\text{-faceplate}}(\lambda)$ is the spectral photon incidence with unit of photons $s^{-1} \mu m^{-1} m^{-2}$ (further discussed in Sec. 4.8). Some arrays have a transparent window protecting the array. The faceplate is the front surface of that window. With this approach, the array quantum efficiency includes the transmittance of the window.

For CCDs, charge is converted to a voltage by a floating diode or floating diffusion. The diode, acting as a capacitor, is precharged at a reference level. The capacitance, or sense node, is partially discharged by the amount of negative charge transferred. The difference in voltage between the final status of the diode and its precharged value (reset level) is linearly proportional to the number of photoelectrons. The signal voltage after the source follower is

$$V_{\text{signal}} = V_{\text{reset}} - V_{\text{out}} = n_{PE} \frac{qG}{C} \quad (2)$$

The gain, G , of a source follower amplifier is approximately unity, and q is the electronic charge (1.6×10^{-19} C). The charge conversion is q/C . The output gain conversion is qG/C . It typically ranges from $0.1 \mu V/e^-$ to $10 \mu V/e^-$. The signal is then amplified and processed by electronics external to the CCD sensor.

Responsivity. The spectral quantum efficiency is important to the scientific and military communities. When the array is placed into a general video or industrial camera, it is convenient to specify the output as a function of incident flux density or energy density averaged over the spectral response of the array.

The faceplate spectral photon incidence can be converted into the spectral radiant incidence by

$$E_{e\text{-faceplate}}(\lambda) = \frac{hc}{\lambda} E_{q\text{-faceplate}}(\lambda) \frac{w}{\mu\text{m} - \text{m}^2} \quad (3)$$

where h is Planck's constant ($6.626 \times 10^{-34} \text{ J s}^{-1}$) and c is the speed of light ($3 \times 10^8 \text{ m s}^{-1}$). Quantities associated with power (watts) have the subscript e , and those associated with photons have the subscript q . The quantum efficiency can be converted to amps per watt by

$$\mathfrak{R}_e(\lambda) = \frac{q\lambda}{hc} \eta(\lambda). \quad (4)$$

Then, the array output voltage (after the source follow amplifier) is

$$V_{\text{signal}} = \frac{G}{C} A_D \int_{\lambda_1}^{\lambda_2} E_{e\text{-faceplate}}(\lambda) \mathfrak{R}_e(\lambda) t_{\text{int}} d\lambda \quad (5)$$

It is desirable to express the responsivity in the form

$$V_{\text{signal}} = \mathfrak{R}_{\text{ave}} \left[\int_{\lambda_1}^{\lambda_2} E_{e\text{-faceplate}}(\lambda) t_{\text{INT}} d\lambda \right] \quad (6)$$

The value $\mathfrak{R}_{\text{ave}}$ is an average responsivity that has units of volts per joule per square centimeter and the quantity in the brackets has units of joules per square centimeter. Combining the two equations provides

$$\mathfrak{R}_{\text{ave}} = \frac{G}{C} A_D \frac{\int_{\lambda_1}^{\lambda_2} E_{e\text{-faceplate}}(\lambda) \mathfrak{R}_e(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{e\text{-faceplate}}(\lambda) d\lambda} \text{ V/(J cm}^{-2}\text{)} \quad (7)$$

The value $\mathfrak{R}_{\text{ave}}$ is an average responsivity that depends upon the source characteristics and the spectral quantum efficiency. While the source can be standardized (e.g., CIE illuminant A or illuminant D₆₅₀₀), the spectral quantum efficiency varies by device. Therefore, extreme care must be exercised when comparing devices solely by the average responsivity.

If a very small wavelength increment is selected, $E_{e\text{-faceplate}}(\lambda)$ and $\mathfrak{R}_e(\lambda)$ may be considered as constants and Eq. 7 can be approximated as

$$\mathfrak{R}_{\text{ave}} \approx \frac{G}{C} A_D \mathfrak{R}_e(\lambda_0) \quad (8)$$

Minimum Signal. The noise equivalent exposure (NEE) is an excellent diagnostic tool for production testing to verify noise performance. NEE is a poor array-to-array comparison parameter and should be used cautiously when comparing arrays with different architectures. This is so because it depends on array spectral responsivity and noise. The NEE is the exposure that produces an SNR of one. If the measured root-mean-square (rms) noise on the analog output is V_{noise} , then the NEE is calculated from the radiometric calibration:

$$NEE = \frac{V_{\text{noise}}}{\mathfrak{R}_{\text{ave}}} \text{ J/cm}^2 \text{ rms} \quad (9)$$

When expressed in electrons, NEE is simply the noise value in rms electrons. The absolute minimum noise level is the noise floor, and this value is used most often to calculate the NEE. Although noise is an rms value, the notation "rms" is often omitted.

Maximum Signal. The maximum signal is that input signal that saturates the charge well and is called the saturation equivalent exposure (SEE). It is

$$SEE = \frac{V_{\text{max}}}{\mathfrak{R}_{\text{ave}}} \text{ J/cm}^2 \quad (10)$$

The total number of electrons that can be stored is the well capacity, n_{well} . The well size varies with architecture, number of phases, and pixel size. It is approximately proportional to pixel area. Small pixels have small wells. If an antibloom drain is present, the maximum level is taken as the white clip level. The maximum signal is

$$V_{\text{max}} = \frac{qG}{C} (n_{\text{well}} - n_{\text{dark}}) \quad (11)$$

For back-of-the-envelope calculations, the dark current is often considered negligible ($n_{\text{dark}} \approx 0$).

Dynamic Range. The array dynamic range is

$$DR_{\text{array}} = \frac{n_{\text{well}} - n_{\text{dark}}}{\langle n_{\text{sys}} \rangle} \quad (12)$$

where $\langle n_{\text{sys}} \rangle$ is the overall rms noise. The array noise consists of dark current, shot, pattern, and readout noise (noise floor). In the absence of light and negligible dark current, the dynamic range is most often quoted as

$$DR_{\text{array}} = \frac{n_{\text{well}}}{\langle n_{\text{floor}} \rangle} \quad (13)$$

Noise

Many books⁴⁻⁸ and articles²⁰⁻²³ have been written on noise sources. The level of detail used in noise modeling depends on the application. The noise sources include shot noise, reset noise, pattern noise, on-chip amplifier noise, and quantization noise. It is customary to specify all noise sources in units of equivalent rms electrons at the detector output.

Reset noise can be reduced to a negligible level with correlated double sampling (CDS). Correlated double sampling also reduces the source follower 1/f noise. The off-chip amplifier is usually a low-noise amplifier such that its noise is small compared with the on-chip amplifier noise. The use of an analog-to-digital converter that has more bits reduces quantization noise.

On-chip amplifier noise may be called readout noise, mux noise, noise-equivalent electrons, or the noise floor. The value varies by device and manufacturer. For most system analyses, it is sufficient to consider

$$\langle n_{\text{sys}} \rangle = \sqrt{\langle n_{\text{shot}}^2 \rangle + \langle n_{\text{floor}}^2 \rangle + \langle n_{\text{pattern}}^2 \rangle} \quad (14)$$

where $\langle n^2 \rangle$ is the noise variance and $\langle n \rangle$ is the standard deviation measured in rms electrons.

Shot Noise. Both photoelectrons and dark current contribute to shot noise. These follow Poisson statistics so that the variance is equal to the mean:

$$\langle n_{\text{shot}}^2 \rangle = n_{\text{PE}} + n_{\text{dark}} \quad (15)$$

While the dark current average value can be subtracted from the output to provide only the signal due to photoelectrons, the dark current noise cannot. Cooling the array can reduce the dark current to a negligible value and thereby reduce dark current noise to a negligible level.

Pattern Noise. Pattern noise refers to any spatial pattern that does not change significantly from frame to frame. Pattern noise is not noise in the usual sense. This variation appears as spatial noise to the observer. Fixed-pattern noise (FPN) is caused by pixel-to-pixel variations in dark current.^{24, 25} As a signal-independent noise, it is additive to the other noise powers. Fixed-pattern noise is due to differences in detector size, doping density, and foreign matter getting trapped during fabrication.

Photoresponse nonuniformity (PRNU) is the variation in pixel-to-pixel responsivities and, as such, is a signal-dependent noise. This noise is due to differences in detector size, spectral response, and thickness in coatings. Photoresponse nonuniformity can be specified as a peak-to-peak value or an rms value referenced to an average value. This average value may either be full well or one-half full well value. That is, the array is uniformly illuminated and a histogram of responses is created. The PRNU can be the rms of the histogram divided by the average value or the peak-to-peak value divided by the average value. The definition varies by manufacturer so that the test conditions must be understood when comparing arrays. For this text, the rms value is used.

Because dark current becomes negligible when the array is sufficiently cooled, PRNU is the dominant pattern component for most arrays. As a multiplicative noise, PRNU is traditionally expressed as a fraction of the total number of charge carriers. If U is the fixed pattern ratio or nonuniformity, then

$$\langle n_{\text{pattern}} \rangle \approx \langle n_{\text{PRNU}} \rangle = Un_{\text{PE}} \quad (16)$$

Frame averaging will reduce all the noise sources except FPN and PRNU. Although FPN and PRNU are different, they are sometimes collectively called scene noise, pixel noise, pixel nonuniformity, or simply pattern noise.

Photon Transfer. For many applications it is sufficient to consider photon shot noise, noise floor, and PRNU. The simplified noise model provides

$$\langle n_{\text{sys}} \rangle = \sqrt{n_{\text{PE}} + \langle n_{\text{floor}}^2 \rangle + (Un_{\text{PE}})^2} \quad (17)$$

Recall that the mean square photon fluctuation is equal to the mean photon rate. Either the rms noise or noise variance can be plotted as a function of signal level. The graphs are called the photon transfer curve and the mean-variance curve, respectively. Both graphs convey the same information.

For very low photon fluxes, the noise floor dominates. As the incident flux increases, the photon shot noise dominates. For very high flux levels, the noise may be dominated by PRNU. Figure 9 illustrates the rms noise as a function of photoelectrons when the dynamic range ($n_{\text{well}}/\langle n_{\text{floor}} \rangle$) is 60 dB. With large signals and small PRNU, the total noise is dominated by photon shot noise. When PRNU is large, U dominates the array noise at high signal levels. General video and industrial cameras tend to operate in high-signal environments, and cooling will have little effect on performance. A full SNR analysis is required before selecting a cooled camera.

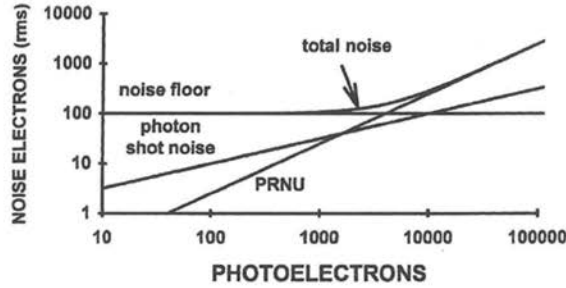


FIGURE 9 Photon transfer curve when $U = 2.5$ percent. The charge well capacity is 100,000 electrons and the noise floor is $100 \text{ e}^- \text{ rms}$ to produce a dynamic range of 60 dB. The noise floor, photon shot noise, and PRNU have slopes of 0, 0.5, and 1, respectively. Dark noise is considered negligible.

4.8 CAMERA PERFORMANCE

Camera performance metrics are conceptually the same as array metrics. The camera is limited by the array noise and charge well capacity. The camera's FPN and PRNU may be better than the array pattern noise when correction algorithms are present. Frame averaging and binning can reduce the random noise floor and thereby appear to increase the camera's dynamic range. If the camera does not introduce any additional noise, modify the noise bandwidth, or minimize the maximum output, the camera SNR and DR_{camera} will be identical to the array values.

Camera Formula

The number of photoelectrons created by an object is

$$n_{\text{PE}} = \int_{\lambda_1}^{\lambda_2} \eta(\lambda) \frac{M_q(\lambda)}{4F^2(1 + m_{\text{optics}})^2} A_D t_{\text{int}} \tau_{\text{optics}}(\lambda) d\lambda \quad (18)$$

where $M_q(\lambda)$ is the object's spectral photon exitance in photons per second per micrometer per square meter and $\tau_{\text{optics}}(\lambda)$ is the lens system transmittance. The f -number has the usual definition ($F = fl/D$), and the optical magnification is $m_{\text{optics}} = R_2/R_1$. Here, R_1 and R_2 are related to the system's effective focal length, fl , by

$$\frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{fl} \quad (19)$$

As the target moves to infinity ($R_1 \rightarrow \infty$), m_{optics} approaches zero.

Electronic still cameras are matched to conventional photographic cameras. In photography, shutter speeds (exposure times) vary approximately by a factor of two (e.g., 1/30, 1/60, 1/125, 1/250, etc.). Thus, changing the shutter speed by one setting changes n_{PE} approximately by a factor of 2. F -stops have been standardized to 1, 1.4, 2, 2.8, 4, 5.6, 8, ... The ratio of adjacent f -stops is $\sqrt{2}$. Changing the lens speed by one f -stop changes the f -number by a factor of $\sqrt{2}$. Here, also, the n_{PE} changes by a factor of 2.

The measurement of faceplate illumination (see Eq. 1) is usually performed with a calibrated lens. The value M_q is measured with a calibrated radiometer or photometer, and then $E_{q\text{-faceplate}}$ is calculated:

$$E_{q\text{-faceplate}} = \frac{M_q}{4F^2(1 + m_{\text{optics}})^2} \tau_{\text{optics}} \quad (20)$$

Minimum Signal

The maximum and minimum signals depend on the spectral output of the source and the spectral response of the detector. The source color temperature is not always listed but is a critical parameter for comparing systems. Although the CIE illuminant A is used most often, the user should not assume that this was the source used by the camera manufacturer.

Based on signal detection theory, the minimum illumination would imply that the SNR is one. However, the definition of minimum illumination is manufacturer dependent. Its value may be (a) when the video signal is, for example, 30 IRE units, (b) when the SNR is one, or (c) when an observer just perceives a test pattern. Because of its incredible temporal and spatial integration capability, the human visual system can perceive SNRs as low as 0.05. Therefore, comparing cameras based on "minimum" illumination should be approached with care.

The voltage signal (Eq. 5) exists at the output of the array. This voltage must be amplified by the camera electronics (gain = G_{camera}) to a value that is consistent with video standards. The minimum signal provided with gain "on" (G_{camera} greater than one) is usually calculated due to the difficulty of performing accurate, low-level radiometric and photometric measurements. These values may be provided at 30, 50, or 80 percent video levels. That is, the illumination that is given produces an output video that gives 30, 50, or 80 IRE units, respectively. Although a higher-gain amplifier could provide 100 percent video, the user can optimize the image by adjusting the gain and level of the display. That is, the display's internal amplifiers can be used for additional gain. In this context, the camera system consists of the camera and display.

If G_{camera} is expressed in decibels, it must be converted to a ratio. The scene illumination that creates a 30 percent video signal is

$$M_v (30\% \text{ video}) = \frac{0.3M_v (\text{max video})}{G_{\text{camera}}} \quad (21)$$

where $M_v (\text{max video})$ is the scene illumination that produces the maximum output. The subscript v indicates photometric units, which are usually lux. For 50 and 80 percent video, the factor becomes 0.5 and 0.8, respectively. The input signal that produces an SNR of one is

$$M_v (\text{SNR} = 1) = M_v (\text{max video}) 10^{-\frac{DR_{\text{camera-dB}}}{20}} \quad (22)$$

where the camera's dynamic range is expressed in decibels (dB). Although photometric units are used most often, radiometric quantities can be used in Eqs. 21 and 22.

Camera Dynamic Range

Dynamic range depends on integration time, binning, and frame integration. In addition, the spectral content of the source and the array spectral responsivity affect the camera output voltage. Thus, the camera dynamic range can be quite variable depending on test conditions.

Although the theoretical maximum signal just fills the charge wells, the manufacturer may limit the maximum output voltage to a lower stored-charge value. Because the dynamic range is often expressed in decibels,

$$DR_{\text{camera-dB}} = 20 \log \left(\frac{V_{\text{max}}}{V_{\text{noise}}} \right) \quad (23)$$

Many camera manufacturers list the dynamic range as the signal-to-noise ratio. This value should not be confused with the actual SNR. With most cameras, the noise level is approxi-

mately equivalent to the array read noise. The electronics may increase the camera noise and image processing techniques may reduce it somewhat. Usually the dynamic range is calculated from the measured signal and noise. Because the read noise is amplifier white noise, it is appropriate to include the bandwidth as part of the measurements. For standard video-compatible cameras, the bandwidth is equal to the video format bandwidth.

4.9 MODULATION TRANSFER FUNCTION

The MTF of the camera is the product of all the subsystem MTFs. Usually, the electronics MTF does not significantly affect the overall MTF. Therefore, it is often adequate to consider only the optics and detector MTFs.

The MTF of a single rectangular detector in image space is

$$\text{MTF}_{\text{detector}}(u) = \left| \frac{\sin(\pi d \eta)}{(\pi d \eta)} \right| \quad (24)$$

where d is the horizontal extent of the photosensitive surface and η is the image-space horizontal spatial frequency variable (in cycles/mm). The detector size may be different in the horizontal and vertical directions, resulting in different MTFs in the two directions.

The MTF for a circular, clear-aperture, diffraction-limited lens is

$$\text{MTF}_{\text{optics}}(\eta) = \frac{2}{\pi} \left[\cos^{-1} \left(\frac{\eta}{\eta_c} \right) - \frac{\eta}{\eta_c} \sqrt{1 - \left(\frac{\eta}{\eta_c} \right)^2} \right] \quad (25)$$

The optical cutoff is $\eta_c = D/(\lambda_{\text{ave}} f l)$, where D is the aperture diameter and λ_{ave} is the average wavelength.

4.10 RESOLUTION

Detector arrays are specified by the number of pixels, detector size, and detector pitch. These are not meaningful until an optical system is placed in front of the array. The most popular detector resolution measure is the detector angular subtense. In object space, it is

$$\text{DAS} = \frac{d}{f l} \text{ mrad} \quad (26)$$

and in image space, the detector size, d , becomes the measure of resolution.

Perhaps the most popular measure of optical resolution is Airy disk size. It is the bright center of the diffraction pattern produced by an ideal optical system. In the focal plane of the lens, the Airy disk diameter is

$$d_{\text{airy}} = 2.44 \frac{\lambda}{D} f l = 2.44 \lambda F \quad (27)$$

While often treated independently, the camera resolution depends upon both the optical and detector resolutions.

Shade created a metric for system performance. As reported by Lloyd,²⁶ Sendall modified Shade's equivalent resolution such that

$$R_{\text{eq}} = \frac{1}{2 \int_0^\infty |\text{MTF}_{\text{sys}}(\eta)|^2 d\eta} \quad (28)$$

As a summary metric, R_{eq} provides a better indication of system performance than a single metric, such as the detector size or blur diameter. R_{eq} cannot be directly measured. It is a mathematical construct simply used to express overall performance. As the MTF increases, R_{eq} decreases and the resolution "improves" (smaller is better). As an approximation, the system resolution may be estimated from the subsystem equivalent resolutions by

$$R_{eq} \approx \sqrt{R_{optics}^2 + R_{detector}^2} \quad (29)$$

Placing the diffraction-limited MTF into Eq. 28 provides

$$R_{optics} = 1.845\lambda F \quad (30)$$

Note that Shade's approach provides a value that is smaller than the Airy disk diameter. Recall that R_{eq} is only a mathematical construct used to analyze system performance. When R_{optics} dominates R_{eq} , we say the system is optics-limited.

Placing the detector MTF into Eq. 28 provides

$$R_{detector} = d \quad (31)$$

Here, Shade's resolution matches the common method of describing detector performance: The smallest target that can be discerned is limited by the detector size. When $R_{detector}$ dominates R_{eq} , we say the system is detector-limited.

Using Eq. 29 to estimate the composite resolution in image space,

$$R_{eq} \approx d \sqrt{\left(\frac{1.845\lambda F}{d}\right)^2 + 1} \quad (32)$$

As $\lambda F/d$ decreases, R_{eq} approaches d . For large values of $\lambda F/d$, the system becomes optics-limited and the equivalent resolution increases.

The more common 1/2-inch-format CCD arrays have detectors that are about 10 μm in size. Figure 10 illustrates R_{eq} as a function of f -number. Reducing the f -number below 5 does not improve resolution because the system is in the detector-limited region.

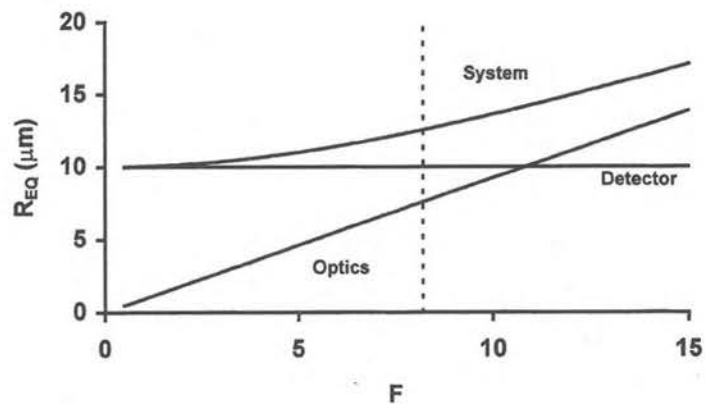


FIGURE 10 Resolution of a typical 1/2-inch-format CCD camera as a function of f -number. $\lambda = 0.5 \mu\text{m}$. The vertical line at $F = 8.20$ separates optics-limited from detector-limited operation. It occurs when the Airy disk size is equal to the detector size.

For most CCD camera applications, it is assumed that the camera is operating in the detector-limited region. This is only valid if $\lambda F/d$ is small. If $\lambda F/d$ is large, then the minimum discernable target size is definitely affected by the optics resolution.

We live in a world where "smaller is better." Detector sizes are shrinking. This allows the system designer to create physically smaller cameras. Replacing a $\frac{1}{2}$ -inch-format array with a $\frac{1}{4}$ -inch-format array (typical detector size is $5\ \mu\text{m}$) implies a $2\times$ improvement in resolution. However, this is only true if the system is operating in the detector-limited region. As d decreases, the f -number must also decrease to stay within the detector-limited region. Further, the f -number must also decrease to maintain the same signal intensity (Eq. 18). Reducing the f -number can place a burden on the optical designer.

4.11 SAMPLING

Sampling is an inherent feature of all electronic imaging systems. The scene is spatially sampled in both directions due to the discrete locations of the detector elements. The horizontal sample rate is

$$\eta_s = \frac{1}{d_{\text{CCH}}} \text{ cycles/mm} \quad (33)$$

Staring arrays can faithfully reproduce signals up to the Nyquist frequency:

$$\eta_N = \frac{\eta_s}{2} = \frac{1}{2d_{\text{CCH}}} \text{ cycles/mm} \quad (34)$$

The pitch in the horizontal and vertical directions, d_{CCH} and d_{CCV} , respectively, may be different and, therefore, the sampling rates will be different. Any input frequency above the Nyquist frequency will be aliased to a lower frequency (Fig. 11). After aliasing, the original signal can never be recovered. Diagonal lines appear to have jagged edges, or "jaggies," and periodic patterns create moiré patterns. Periodic structures are rare in nature and aliasing is seldom reported when viewing natural scenery, although aliasing is always present. Aliasing may become apparent when viewing periodic targets such as test patterns, picket fences, plowed fields, railroad tracks, and venetian blinds. It becomes bothersome when the scene

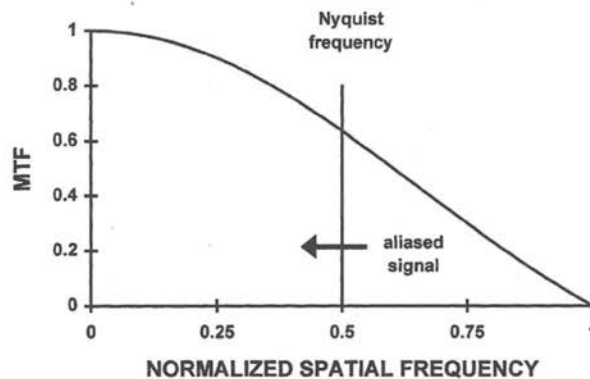


FIGURE 11 Signals above Nyquist frequency are aliased down to the base band. $\eta_s = 1$ and $\eta_N = 0.5$. The area bounded by the MTF above η_N may be considered as an "aliasing" metric.²⁷

geometric properties must be maintained as with mapping. It affects the performance of most image-processing algorithms. While this is a concern to scientific and military applications, it typically is of little consequence to the average professional television broadcast and consumer markets.

We have become accustomed to the aliasing in commercial televisions. Periodic horizontal lines are distorted due to the raster. Cloth patterns, such as herringbones and stripes, produce moiré patterns. Cross-color effects occur in color imagery (red stripes may appear green or blue). Many videotape recordings are undersampled to keep the price modest, and yet the imagery is considered acceptable when observed at normal viewing distances.

Because the aliasing occurs at the detector, the signal must be band limited by the optical system to prevent it. Optical band limiting can be achieved by using small-diameter optics, blurring the image, or by inserting a birefringent crystal between the lens and array. The birefringent crystal changes the effective detector size and is found in almost all single-chip color cameras. Unfortunately, these approaches also degrade the MTF (reduce image sharpness) and are considered unacceptable for scientific applications.

If a system is Nyquist frequency-limited, then the Nyquist frequency is used as a measure of resolution. Because no frequency can exist above the Nyquist frequency, many researchers represent the MTF as zero above the Nyquist frequency (Fig. 12). This representation may be too restrictive for modeling purposes.

The fill factor can vary from 20 percent for interline transfer devices to nearly 100 percent for frame transfer devices. In the detector-limited region, the detector MTF determines the potential spatial frequencies that can be reproduced. The center-to-center spacing uniquely determines the Nyquist frequency (Fig. 13). A microlens will increase the effective detector size, but it does not affect the center-to-center spacing. The absolute value of the Nyquist frequency ($1/2d_{\text{CCH}}$) does not change. By increasing the detector size, the detector cutoff decreases. The *relative* locations of the sampling and Nyquist frequencies change. The figures in this text use relative (normalized) frequency scales.

Less-expensive color cameras contain only a single CCD chip. A color filter array (CFA) is placed over the chip to create red, green, and blue pixels. Figure 20 in Chap. 22 of *Handbook of Optics*, Vol. 1, provides a variety of CFA patterns. In many sensors, the number of detectors that are devoted to each color is different. The basic reason is that the human visual system (HVS) derives its detail information primarily from the green portion of the spectrum. That is, luminance differences are associated with green, whereas color perception is associ-

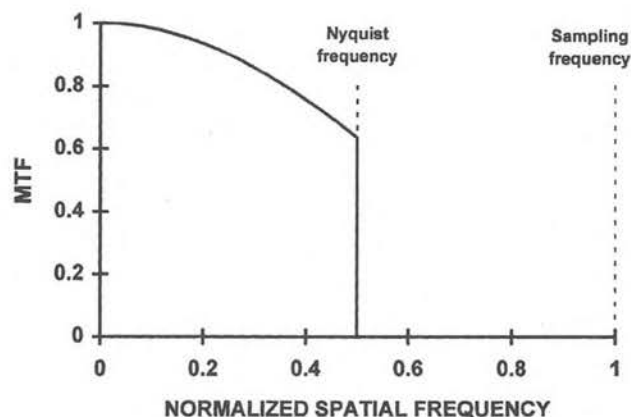


FIGURE 12 MTF representation of an undersampled system. $\eta_s = 1$ and $\eta_N = 0.5$. This restrictive representation erroneously suggests that there is no response above η_N .

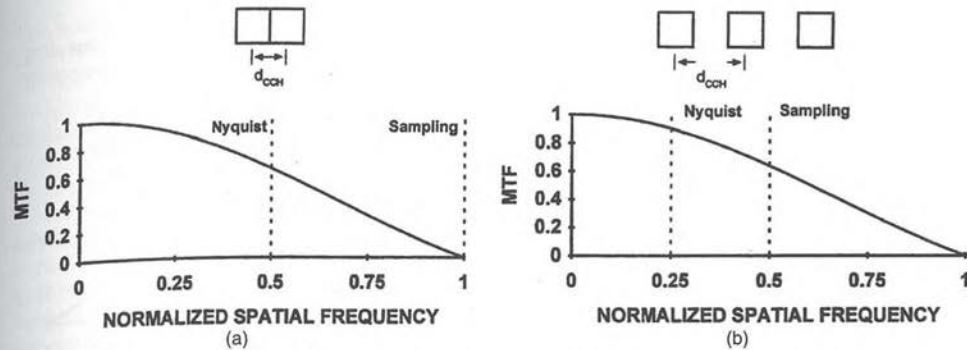


FIGURE 13 Two arrays with different horizontal center-to-center spacings. The detector size, d , is the same for both. (a) $d/d_{CCH} = 1$. This typifies frame transfer devices. (b) $d/d_{CCH} = 0.5$. This is representative of an ideal interline transfer CCD array. The detector MTF is plotted as a function of ηd .

ated with red and blue. The HVS requires only moderate amounts of red and blue to perceive color. Thus, many sensors have twice as many green as either red or blue detector elements. An array that has 768 horizontal elements may devote 384 to green, 192 to red, and 192 to blue. This results in an unequal sampling of the colors (Fig. 14). The output R, G, and B signals are created by interpolation of the sparse data (sparse pixels). The output signals *appear* as if there are 768 red, green, and blue pixels. This interpolation does not change the Nyquist frequency of each color. A birefringent crystal²⁸ inserted between the lens and the array effectively increases the detector sizes. A larger detector will have reduced MTF and this reduces aliasing. It also reduces edge sharpness.

Pseudointerlacing (Fig. 4) doubles the size of the detector. This reduces the detector cut-off and makes it equal to the Nyquist frequency (Fig. 15). From an aliasing point of view, aliasing has been significantly reduced. However, the MTF has also been reduced, and this results in reduced-edge sharpness.

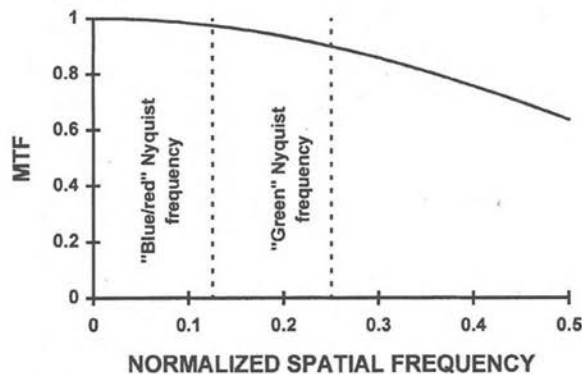


FIGURE 14 Horizontal detector MTF normalized to ηd . Unequally spaced red-, green-, and blue-sensitive detectors create different array Nyquist frequencies. This creates different amounts of aliasing and black-and-white scenes may break into color. The spacing between the red and blue detectors is twice the green detector spacing.

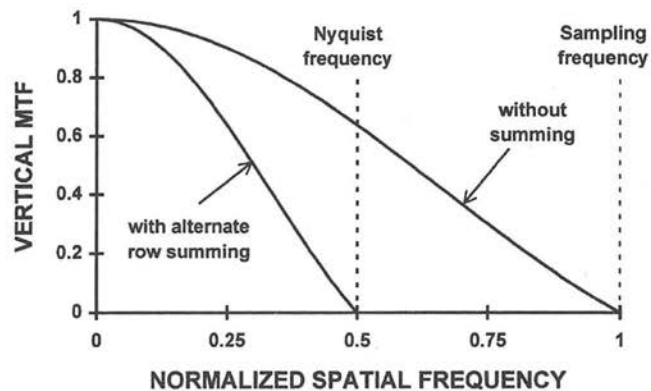


FIGURE 15 Alternate detector summing (pseudointerlacing) can reduce aliasing in the vertical direction. Vertical MTF with and without summing normalized to ηd .

4.12 STORAGE, ANALYSIS, AND DISPLAY

Chapter 22, "Visible Array Detectors," *Handbook of Optics*, Vol. I, describes the physics of CCD detectors. This chapter described some additional features of CCDs and introduced CID and CMOS detectors. These solid-state devices are the basic building blocks of the solid-state array. Certain array architectures lend themselves to specific applications. Once the camera is fabricated, the user selects an optical system. The minimum signal, maximum signal, and resolution discussed in this chapter included the lens f -number. It would appear that with all this knowledge, it would be easy to select a camera. A camera only becomes operational when its output is analyzed. Analysis is performed by an observer (general video) or a computer (machine vision).

For general video, the camera output must be formatted into a data stream consistent with the display device. The monochrome standard is often called EIA 170 (originally called RS 170) and the color format is simply known as NTSC (originally called EIA 170A or RS 170A). Worldwide, three color broadcast standards exist: NTSC, PAL, and SECAM. For higher vertical resolution, more lines are required. EIA 343A (originally RS 343A) is a high-resolution monochrome standard used for closed-circuit television cameras (CCTV). Although the standard encompasses equipment that operates from 675 to 1023 lines, the recommended values are 675, 729, 875, 945, and 1023 lines per frame.

These standards are commonplace. Monitors that display these formats are readily available. For computer analysis of this imagery, frame grabbers that accept multiple standards are easily obtained. The output of most general video cameras is an analog signal, and the frame grabber digitizes this signal for computer processing.

In principle, the clock rate of an analog-to-digital converter within the frame grabber can be set at any rate. However, to conserve on memory requirements and minimize clock rates, some frame grabbers tend to just satisfy the Nyquist frequency of a standard video signal. That is, if the highest frequency of the video bandwidth is f_{BW} , then the frame grabber sampling clock operates at $2f_{BW}$.

Some frame grabbers have an internal antialias filter. This filter ensures that the frame grabber does not produce any additional aliasing. The filter cutoff is linked to the frame grabber clock and is not related to the camera output. Once aliasing has occurred in the camera, the frame grabber antialias filter cannot remove it. If the filter does not exist, the frame grabber may create additional aliasing.²⁹ On the other hand, some frame grabbers have antialiasing filters that significantly limit the analog signal bandwidth and thereby reduce resolution.

The number of digital samples is simply related to the frame grabber clock rate and is not necessarily equal to the number of detector elements. Even if the number of digital samples matches the number of detector elements, phasing effects will corrupt the resolution. Imaging-processing algorithms operate on the digitized signal and the image-processing specialist must be aware of the overall resolution of the system. The frame grabber is an integral part of that system. These issues are mitigated when the camera output is in digital form and the frame grabber can accept digital signals.

As society moves toward digital television [high-definition television (HDTV) or advanced television system (ATS)], new demands are placed upon displays and frame grabbers. New standards also require new video-recording devices. This creates storage, frame grabber, and display problems. New standards do not impose any difficulties on camera design. The solid-state array can be made any size and appropriately designed electronics can support any video format.

Industrial and scientific applications require some forethought. The camera output is no longer a conventional format. Web inspection cameras may contain a linear array with as many as 4096 elements. Split architecture (Fig. 1) may have as many as 32 parallel outputs. Charge injection devices and CMOS cameras may offer variable-sized subframes at variable frame rates. Finding suitable frame grabbers is a challenge for these applications. Nonstandard formats (even after digitization) are not easy to display.

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