

LST

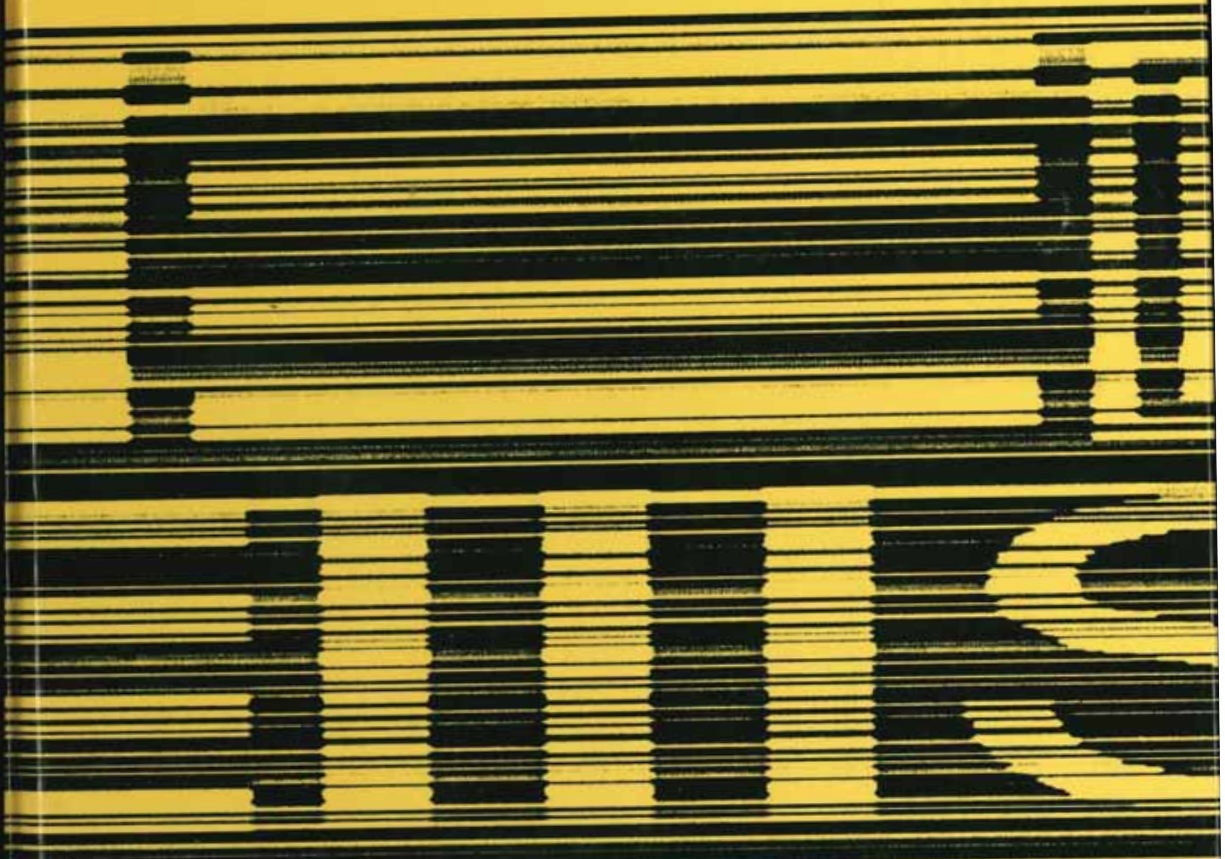
CCD Arrays, Cameras,

E
SS

CD
shing

CCD ARRAYS CAMERAS and DISPLAYS

second edition



Gerald C. Holst

CCD ARRAYS, CAMERAS, and DISPLAYS

Second edition

Gerald C. Holst

Copublished by

JCD Publishing
2932 Cove Trail
Winter Park, FL 32789

and



SPIE OPTICAL ENGINEERING PRESS

A Publication of SPIE—The International Society for Optical Engineering
Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Holst, Gerald C.

CCD arrays, cameras, and displays/ Gerald C. Holst. -- 2nd ed.
p. cm.

Includes bibliographical references (p.) and index.

ISBN 0-9640000-4-0 (hardcover)

1. Charge coupled devices. 2. Information display systems.

I. Title

TK7871.99.C45H65 1998

621.36'7--dc21

98-10770

CIP

Copublished by

JCD Publishing

2932 Cove Trail

Winter Park, FL 32789

Phone: 407/629-5370

Fax: 407/629-5370

ISBN: 0-9640000-4-0

SPIE - The International Society for Optical Engineering

P.O. Box 10

Bellingham, WA 98227-0010

Phone: 360/676-3290

Fax: 360/647-1445

WWW: <http://www.spie.org>

ISBN: 0-8194-2853-1

Notice:

Reasonable efforts have been made to publish reliable data and information, but the Author and Publishers cannot assume responsibility for the validity of all materials or the consequences of their use.

Copyright © 1998 Gerald C. Holst

All rights reserved. No part of this book may be reproduced in any form by any means without written permission from the copyright owner.

The second edition is dedicated to

Emily, Irma, and Deanne

CCD ARRAYS, CAMERAS, and DISPLAYS

Second edition

TABLE of CONTENTS

1. INTRODUCTION	1
1.1. Solid State Detectors	2
1.2. Imaging System Applications	3
1.2.1. General Imagery	6
1.2.2. Machine Vision	7
1.2.3. Scientific Applications	8
1.2.4. Military Applications	8
1.3. Configurations	9
1.4. Image Quality	12
1.5. Pixels, Datels, Disels, and Resels	14
1.6. References	17
2. RADIOMETRY and PHOTOMETRY	18
2.1. Radiative Transfer	19
2.2. Planck's Blackbody Law	21
2.3. Photometry	23
2.3.1. Units	25
2.3.2. Typical Illumination Levels	27
2.4. Sources	29
2.4.1. Calibration Sources	29
2.4.2. Real Sources	30
2.5. Camera Formula	33
2.6. Normalization	37
2.7. Normalization Issues	39
2.8. References	44
3. SOLID STATE ARRAYS	45
3.1. Photodetection	46
3.1.1. Photogate	47
3.1.2. Photodiode	47
3.2. CCD Array Operation	47
3.3. CCD Array Architecture	58
3.3.1. Linear Arrays	58
3.3.2. Full Frame Arrays	59
3.3.3. Frame Transfer	61
3.3.4. Interline Transfer	63
3.3.5. Progressive Scan	68
3.3.6. Time Delay and Integration	70
3.4. Charge Transfer Efficiency	74

3.5. Charge Conversion (Output Structure)	78
3.6. Dark Current	79
3.7. Dark Pixels	83
3.8. Antibloom Drain	85
3.9. CID	89
3.10. CMOS	91
3.11. Physical Parameters	93
3.11.1. Microlenses	93
3.11.2. Color Filter Arrays	94
3.11.3. Number of Detectors	97
3.11.4. Video Chip Size	98
3.12. References	100
4. ARRAY PERFORMANCE	102
4.1. Signal	103
4.1.1. Spectral Response	104
4.1.2. Responsivity	111
4.1.3. Minimum Signal	119
4.1.4. Maximum Signal	120
4.1.5. Dynamic Range	121
4.2. Noise	123
4.2.1. Shot Noise	127
4.2.2. Reset Noise	127
4.2.3. On-chip Amplifier Noise	128
4.2.4. Off-chip amplifier Noise	130
4.2.5. Quantization Noise	130
4.2.6. Pattern Noise	131
4.2.7. Photon Transfer	133
4.3. Array Signal-to-Noise Ratio	139
4.4. Correlated Double Sampling	141
4.5. Frame Rates	142
4.6. Defects	143
4.7. References	144
5. CAMERAS	146
5.1. Camera Operation	147
5.2. Video Formats	149
5.2.1. Video Timing	151
5.2.2. Broadcast/Non-broadcast Design	155
5.2.3. Component/Composite Signals	156
5.2.4. IRE Units	157
5.2.5. Digital Television	159

5.2.6. HDTV/ATS	160
5.3. Consumer/Broadcast Cameras	163
5.3.1. The Knee	164
5.3.2. Color Correction	165
5.3.3. Gamma Compensation	169
5.3.4. Aperture Correction	172
5.4. Industrial/Scientific Cameras	172
5.4.1. Analog-to-Digital Converters	174
5.4.2. Intensified Solid State Cameras	176
5.5. References	179
6. CAMERA PERFORMANCE	182
6.1. Nomenclature	183
6.2. Camera Metrics	185
6.2.1. Camera SNR	186
6.2.2. Camera Dynamic Range	187
6.2.3. Maximum Signal	189
6.2.4. Minimum Signal	189
6.3. Intensified CCD Camera	195
6.3.1. ICCD Signal	196
6.3.2. ICCD Noise	197
6.3.3. ICCD SNR	198
6.4. References	200
7. CRT-BASED DISPLAYS	201
7.1. The Observer	203
7.2. CRT Overview	205
7.2.1. Monochrome Displays	207
7.2.2. Color Displays	207
7.2.3. HDTV	210
7.3. Spot Size	210
7.4. Disels	213
7.5. Resolution	218
7.5.1. Vertical Resolution	219
7.5.2. Theoretical Horizontal Resolution	219
7.5.3. TV Limiting Resolution	220
7.5.4. MTF	221
7.6. Addressability	222
7.7. Shades of Gray	227
7.8. Character Recognition	227
7.9. Contrast	228
7.10. References	230

attractive feature for man-portable, battery-operated devices. It appears at this time, CMOS will compete with CCDs in the general video marketplace where weight, size, and power consumption are factors.

3.11. PHYSICAL PARAMETERS

All detector arrays are fabricated for specific applications. Microlenses are used to increase the optical fill factor. Color filter arrays employ filters that are placed over the detectors to create specific spectral responses that lend themselves to color imagery. For general video applications, the number of detectors is matched to the video standard to maximize bandwidth and image sharpness. The overall array size follows the convention used with vidicons.

3.11.1. MICROLENSES

Optical fill factor may be less than 100% due to manufacturing constraints in full transfer devices. In interline devices, the shielded vertical transfer register can reduce the fill factor to less than 20%. Microlens assemblies (also called microlenticular arrays or lenslet arrays) increase the effective optical fill-factor (Figure 3-42). But it may not reach 100% due to slight misalignment of the microlens assembly, imperfections in the microlens itself, nonsymmetric shielded areas, and transmission losses. As shown by the camera formula (Equation 2-16, page 35), the output is directly proportional to the detector area. Increasing the optical fill factor with a microlens assembly increases the effective detector size and, therefore, the output voltage.

The photosensitive area is below the gate structure and the ability to collect the light depends upon gate thickness. The cone of light reaching the microlens depends upon the f-number of the primary camera lens. Figure 3-42 illustrates nearly parallel rays falling on the microlens. This case is encountered with high f-number lens systems. Low f-number primary camera lenses increase the cone angle and the effective fill-factor decreases with decreasing f-number.²⁷ Microlenses are optimized for most practical f-numbers. As the array size grows, off-axis detectors do not obtain the same benefit as on-axis detectors.²⁸

Hyper-HAD is a Sony trademark which indicates the presence of a microlens assembly over a hole accumulation diode. While many camera manufacturers use the Hyper-HAD detectors, they do not identify the detector by Sony's trademark. This leads the user to believe that there are many different detectors and hence many different cameras on the market.

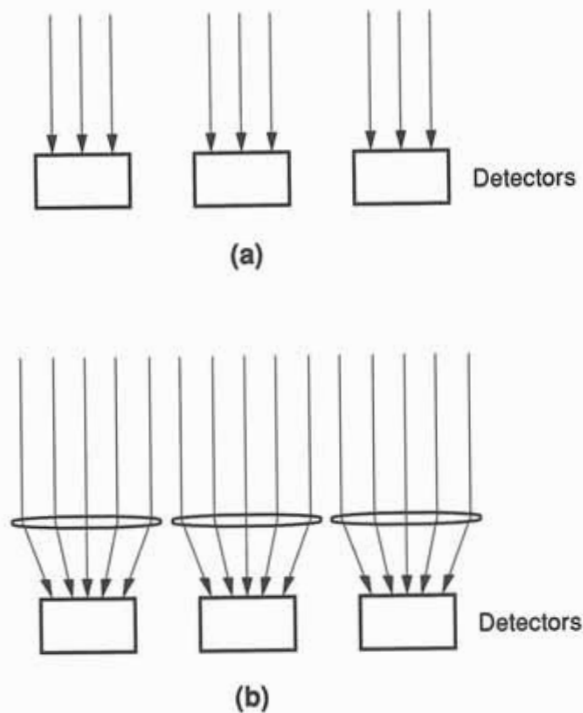


Figure 3-42. Optical effect of a microlens assembly. (a) With no microlens, a significant amount of photon flux is not detected. (b) The microlens assembly can image nearly all the flux onto the detector when a high f-number lens is used. These lenslets can either be grown on the array during the fabrication process or manufactured out of a material such as quartz and placed on the array surface during packaging.

3.11.2. COLOR FILTER ARRAYS

The subjective sensation of color can be created from three primary colors. By adjusting the intensity of each primary (additive mixing), a full gamut (rainbow) of colors is experienced. This approach is used on all color displays. They have red, green, and blue phosphors that, when appropriately excited, produce a wide spectrum of perceived colors. The CIE committee standardized a color perception model for the human observer in 1931. The literature²⁹ is rich with visual data that form the basis for color camera design.

The "color" signals sent to the display must be generated by three detectors, each sensitive to a primary or its complement. The primary additive colors are red, green, and blue (R, G, B) and their complementary colors are yellow, cyan and magenta (Ye, Cy, Mg). For high quality color imagery, three separate detectors (discussed in Section 5.3.3., *Color Correction*) are used whereas for consumer applications, a single array is used. The detectors are covered with different filters that, with the detector response, can approximate the primaries or their complements (Figure 3-43). A single array with filters is called a color filter array (CFA).

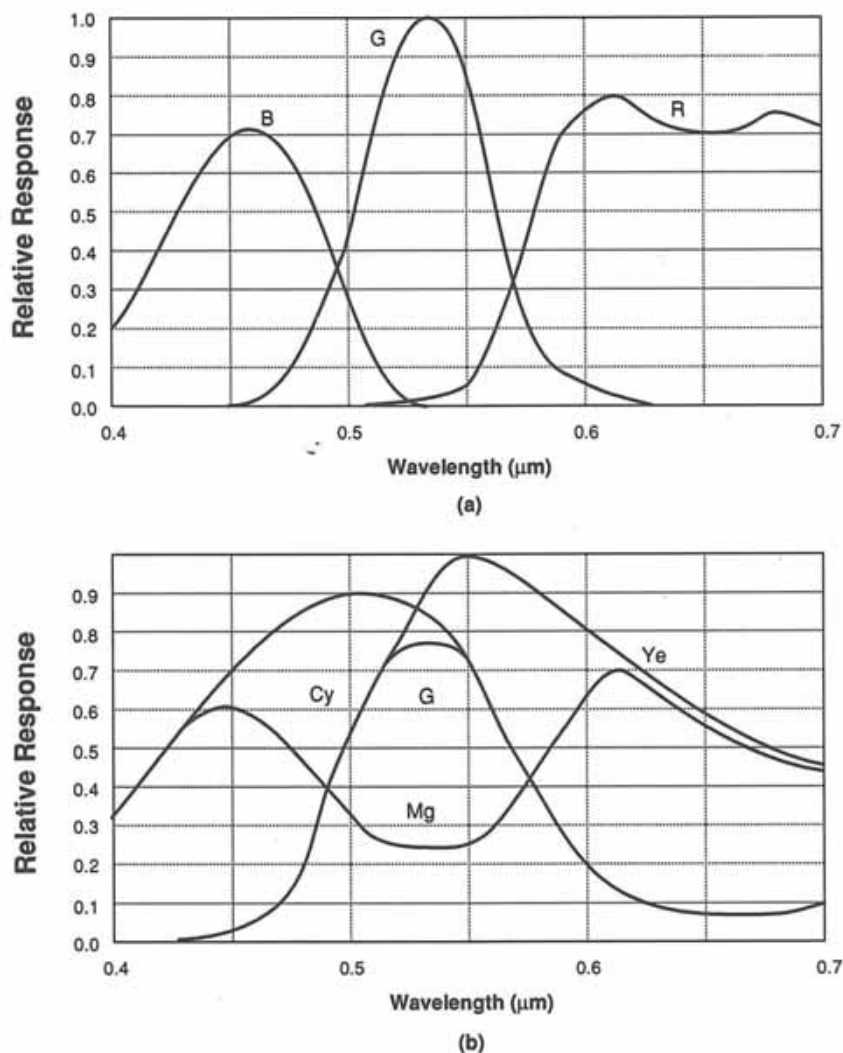


Figure 3-43. Desired spectral response for the three primaries and their complements. (a) The primaries and (b) their complements.

While CFAs can have filters with the appropriate spectral transmittance to create the primaries, it is more efficient to create the complementary colors. Complementary filters have higher transmittances than the primary filters. The luminance channel is identical to the green channel and is often labeled Y. "White" (no color filter) is represented by $W = R + G + B$.

A linear set of equations relates the primaries to their complements. These equations are employed (called matrixing) in cameras to provide either or both output formats. Matrixing can convert RGB into other color coordinates:

$$\begin{aligned} Y_e &= R + G + B \\ M_g &= R + B - W - G \\ C_y &= G + B - W - R \end{aligned} \quad (3-12)$$

The arrangement of the color filters for a single array system is either a stripe or a mosaic pattern (Figure 3-44). The precise layout of the mosaic varies by manufacturer. One basic CFA patent³⁰ was granted to Bryce E. Bayer at Eastman Kodak in 1976.

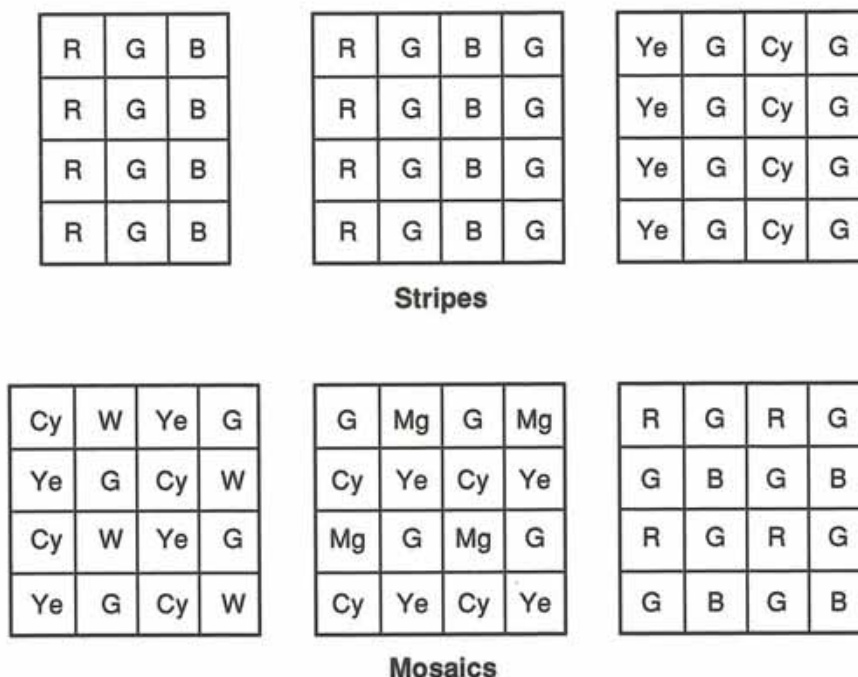


Figure 3-44. Representative stripe and mosaic arrays. Although shown as a full frame device for clarity, they typically are interline transfer devices. The layout depends upon the manufacturer's philosophy and cleverness in reducing color aliasing.

In many sensors, the number of detectors 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 associated 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. A birefringent crystal (discussed in Section 10.3.4., *Optical Anti-alias Filter*), inserted between the lens and the array, accommodates the different sampling rates (discussed in Section 8.3.2., *Detector Array Nyquist Frequency*). The video signal from the CFA is embedded in the architecture of the CFA. The color video from a single chip CFA must be decoded (unscrambled) to produce usable R, G, and B signals.

3.11.3. NUMBER OF DETECTORS

Each detector array is designed for a specific application (discussed in Section 5.2.2., *Broadcast/Non-Broadcast Design*) The EIA 170 video standard supports 485 lines (discussed in Section 5.2.1., *Video Timing*). However, one line is split between the even and odd fields so that there are only 484 continuous lines. Thus detector arrays designed for EIA 170 compatibility tend to have 484 detectors in the vertical direction. For convenience, this has been reduced to 480 detectors. Image processing algorithms are more efficient with square pixels. With a 4:3 aspect ratio, the desired number of detectors is 640×480 . Less expensive arrays will have a submultiple (for easy interpolation) such as 320×240 .

For video applications, several rows or columns are devoted to dark current and for light leakage. Therefore an array may be 650×492 but the light sensitive part may be 640×480 . It is manufacturer dependent whether to specify the array size by the number of active pixels or the total number of pixels (which includes the dark pixels).

Beat frequencies are very obvious in color images. To avoid beat frequencies, the color pixel rate should be a multiple of the chrominance subcarrier frequency (3.579545 MHz). This results in arrays that contain 384, 576, or 768 horizontal detectors. While CFAs are designed for NTSC operation, the same chip can be used for monochrome video without the CFA. Therefore, many monochrome arrays also contain 384, 576, or 768 horizontal detectors. These arrays do not have square pixels. But, from a manufacturing point-of-view, this reduces the inventory of arrays offered.

Scientific array size tends to a power of 2 (e.g., 512×512 , 1024×1024) for easy image processing. There is a perception that "bigger is better" both in terms of array size and dynamic range. Arrays may reach 8192×8192 with a dynamic range of 16 bits. This array requires $(8192)(8192)(16)$ or 1.07 Gbits of storage for each image. Image compression schemes may be required if storage space is limited. The user of these arrays must decide which images are significant and through data reduction algorithms, store only those that have value. Otherwise, he will be overwhelmed with mountains of data.

While large format arrays offer the highest resolution, their use is hampered by readout rate limitations. For example, consumer camcorder systems operating at 30 frames/s have a data rate of about 10 Mpixels/s. An array with 5120×5120 elements operating at 30 frames/s has a data rate of about 768 Mpixels/s. Large arrays can reduce readout rates by having multiple parallel ports servicing subarrays. Each subarray requires separate vertical and horizontal clock signals. The tradeoff is frame rate (speed) versus number of parallel ports (complexity of CCD design) and interfacing with downstream electronics. Because each subarray is serviced by different on-chip and off-chip amplifiers, the displayed image of the subarrays may vary in contrast and level. This is due to differences in amplifier gains and level adjustments.

3.11.4. VIDEO CHIP SIZE

Vidicon vacuum tubes were originally used for professional television applications. These were specified by the tube diameter. To minimize distortion and nonuniformities within the tube, the recommended³¹ image size was considerably less than the overall tube diameter. When CCDs replaced the tubes, the CCD industry maintained the image sizes but continued to use the tube format nomenclature (Table 3-2).

Table 3-2
ARRAY SIZE for STANDARD FORMATS

CAMERA FORMAT	STANDARDIZED ARRAY SIZE (H $\times$ V)	ARRAY DIAGONAL
1 inch	12.8 mm $\times$ 9.6 mm	16 mm
2/3 inch	8.8 mm $\times$ 6.6 mm	11 mm
1/2 inch	6.4 mm $\times$ 4.8 mm	8 mm
1/3 inch	4.8 mm $\times$ 3.6 mm	6 mm
1/4 inch	3.2 mm $\times$ 2.4 mm	4 mm

Although each manufacturer supplies a slightly different array size and pixel size, nominal sizes for a 768×480 array are given in Table 3-3. With interline transfer devices, approximately one-half of the pixel width is devoted to the shielded vertical transfer register. That is, the detector active width is one-half of the pixel width. Thus the active area of the pixel is rectangular in interline transfer devices. This asymmetry does not appear to affect image quality in consumer video products significantly.

Table 3-3
NOMINAL PIXEL SIZE for a 768×480 ARRAY
Sizes vary by manufacturer. Detector sizes are smaller.

CAMERA FORMAT	NOMINAL PIXEL SIZE (H $\times$ V)
1 inch	$16.7 \mu\text{m} \times 20 \mu\text{m}$
2/3 inch	$11.4 \mu\text{m} \times 13.8 \mu\text{m}$
1/2 inch	$8.33 \mu\text{m} \times 10 \mu\text{m}$
1/3 inch	$6.25 \mu\text{m} \times 7.5 \mu\text{m}$
1/4 inch	$4.17 \mu\text{m} \times 5 \mu\text{m}$

The decrease in optical format is related to cost. The price of CCD arrays is mainly determined by the cost of processing semiconductor wafers. As the chip size decreases, more devices can be put on a single wafer and this lowers the price of each individual device. The trend of going to smaller devices will probably continue as long as the optical and electrical performance of the imagers does not change. However, smaller pixels reduce the charge well size. For a fixed flux level and lens f-number, the smaller arrays have reduced sensitivity.

Smaller chips make for smaller cameras. However, to maintain resolution, pixels can only be made so small. Here, the tradeoff is among pixel size, optical focal length, and overall chip size. Further unless the lens f-number is reduced as the chip size is reduced, the system will move from being detector-limited to optically-limited (discussed in Section 10.4., *Optical-Detector Subsystem*). As this happens, the system MTF will change and smaller detectors will provide a less sharp image.

This completely revised book includes

- ▶ CCD and intensified CCD systems
- ▶ CID and CMOS technology
- ▶ Signal-to-noise ratio
- ▶ Minimum illumination definitions

CCD ARRAYS, CAMERAS, and DISPLAYS *second edition*

Topics include

Full-frame
Frame transfer
Progressive scan
Interline transfer
MTF
Radiometry
Photometry

Sampling and aliasing
Dark current
Antibloom drain
Electronic shutter
Noise analysis
Time-delay and integration
Minimum resolvable contrast

Also by Gerald C. Holst

Sampling, Aliasing, and Data Fidelity
Electro-Optical Imaging System Performance
Testing and Evaluation of Infrared Imaging Systems

CCD Arrays, Cameras, and Displays *second edition*

JCD Publishing
2932 Cove Trail
Winter Park, FL 32789
ISBN: 0-9640000-4-0

SPIE PRESS
PO Box 10
Bellingham, WA 98227
ISBN: 0-81294-2853-1

HO
and Displays *second edition*


S P I
P R E

JC
Publi