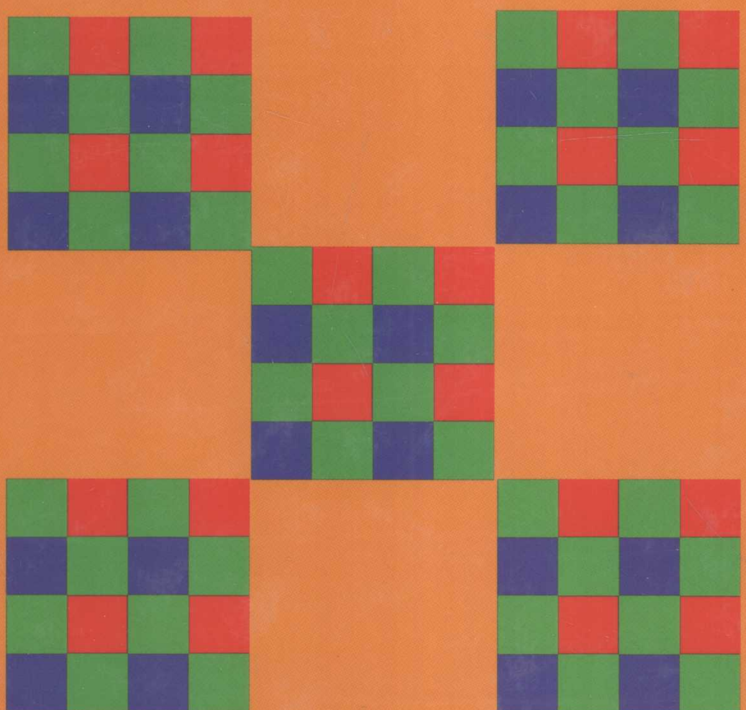
CMOS/CCD SENSORS and CAMERA SYSTEMS

second edition



Gerald C. Holst

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We are indebted to our colleagues in the EO sensor and CCD/CMOS industries for their innovative work. They provided guidance while we tried to capture the highlights of their work.

PREFACE

We appreciate the numerous compliments that we received on our first edition. We could have reprinted that edition, but much has happened since 2007 and we felt it was important to include this new material.

Separating arrays by application or functionality would make writing this book easier. In support of this separation is that each array or camera manufacturer focuses on a particular market segment. The market could be divided into consumer, industrial, scientific, and military areas. It could be divided into low and high performance. Unfortunately, all these overlap – making division difficult. As a result, some information is spread over several chapters.

The largest market today is the cell phone (mobile phone), with camcorders and digital cameras close behind. The goal is to make these cameras small, low-powered, and inexpensive. The high-volume manufacturers consider technological advances as company proprietary information. Hence, the published literature tends to cover only scientific array technology. Nevertheless, there is sufficient information in this book to make an intelligent choice when buying these products.

In the early 1990s, some thought that CMOS detectors would replace CCDs, This did not (nor will it) happen. Each has it advantages and disadvantages. CMOS manufacturing capability can produce smaller-sized detectors with 1 μm square detectors as a goal. These smaller detectors impact performance. The signal-to-noise ratio is relatively low and the dynamic range is small. While even smaller detectors may be possible, the optical blur diameter will ultimately limit spatial resolution.

Chapter 2 (Radiometry and photometry) has not changed. CCD fundamentals are presented in Chapter 3. The overflow drain functions are described in more detail. It can act as a variable shutter and extend dynamic range.

Chapter 4 is the CMOS equivalent of Chapter 3. It lists the differences and similarities between CCD and CMOS sensors. Emphasis is placed on the difficulty and limitations of the shrinking detector size. Pixel structures (3T, 4T, 5T, and 6T) and associated on-chip functionality are compared with a view towards manufacturability. The higher 'transistor' (4T, 5T, and 6T) designs are for scientific applications. High-volume manufacturers use the 3T design.

Array parameters (well capacity, dark pixels, microelenses, and color filter arrays) apply both to CCD and CMOS arrays (Chapter 5). Array sizes have grown over the years (e.g., HDTV and digital cameras). The optical format concept has been clarified. This chapter provides new color filter array (CFA) concepts and vertically stacked detectors. While Chapter 6 describes quantum efficiency, responsivity, and noise sources, the most important parameter is the signal-to-noise ratio. The section on dynamic range has been expanded.

Chapters 7 and 8 have not changed much. The order of Chapters 9 and 10 was reversed. Chapter 9 (Sampling) now includes the Nyquist frequency for CFAs. More pictures have been added to illustrate sampling artifacts. Sampling must be considered during the camera design phase. The mathematics associated with sampling theory are complex, but the human visual system is very tolerant. Aliasing, which is always present, is just ignored by many. As an example, we love our under-sampled TV.

It might initially seem odd that so many pages are devoted to video standards, CRT and flat-panel displays, and printed images. The display type drives array size and camera design. Nearly every camera provides a digital output. Since digital data cannot be seen, imaging systems rely on the display medium and human visual system to produce a perceived continuous image. The display medium creates an image by painting a series of light spots onto a screen or ink spots onto paper. Since each display medium has a different spot size and shape, the perceived image will be different on each display type. Viewing distance (Chapter 11) significantly affects perceived image quality. Printers, monitors, and televisions are designed for an anticipated viewing distance. Chapter 12 has not changed.

For the mechanics, there 36 additional pages of text, 24 more figures, and 80 more references. We clarified numerous sections, deleted old material, and added the latest technological advances. We fixed the typos but probably introduced new ones.

Doug Marks, Pinnacle Communication Services, provided numerous updates to the artwork. We appreciated Doug's "instant" response to our requests for drawing modifications.

February 2011

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SYMBOL LIST

For symbol brevity parameters are not listed. For example spectral radiant sterance is listed as L_e not as $L_e(\lambda,T)$. Greek letters (lower case, upper case) are listed first followed by English letters (lower case, upper case) and then rms values denoted by brackets, [i.e., ⟨…⟩].

SYMBOL	DEFINITION	UNITS
α_{ABS}	spectral absorption coefficient	1/m
γ	gamma	numeric
ΔV	TDI velocity error	mm/s
$\Delta\lambda$	wavelength interval	µm
$\Delta\rho$	target-background reflectance difference	numeric
Δf_e	noise equivalent bandwidth	Hz
ε	charge transfer efficiency	numeric
η	quantum efficiency (also R_q)	numeric
$\eta_{CATHODE}$	photocathode quantum efficiency	numeric
η_{CCD}	CCD quantum efficiency	numeric
η_{SCREEN}	intensifier screen quantum efficiency	numeric
λ	wavelength	µm
λ_{AVE}	average wavelength	µm
λ_{MAX}	maximum wavelength	µm
λ_{MIN}	minimum wavelength	µm
λ_O	selected wavelength	µm
λ_P	wavelength of peak response	µm
ρ_{AVE}	spectrally averaged reflectance	numeric
ρ_B	spectral background reflectance	numeric
ρ_T	spectral target reflectance	numeric
σ_{ATM}	atmospheric spectral absorption	1/m
σ_{fo}	fiber optic spot size	mm
σ_{IIT}	image intensifier tube 1/e spot size	mm
σ_R	rms value of random motion	rms mm
σ_{SPOT}	display spot 1/e intensity size	mm
Φ	flux	W
$\Phi_{CATHODE}$	flux incident onto to intensifier photocathode	W
Φ_V	luminous flux	lumens
Ω	solid angle	steradians

A_D	detector photosensitive area	m^2
A_{DET}	projected CCD pixel on intensifier photocathode	m^2
A_I	area of source in image plane	m^2
A_O	lens area	m^2
A_{PIXEL}	pixel area (defined by detector pitch)	m^2
A_S	source area	m^2
c	speed of light, $c = 3 \times 10^8$	m/s
c_1	first radiation constant, $c_1 = 3.7418 \times 10^8$	W-μm^4/m^2
c_2	second radiation constant, $c_2 = 1.4388 \times 10^4$	μm-K
c_3	third radiation constant, $c_3 = 1.88365 \times 10^{27}$	photons-μm^3/s-m^2
C	sense node capacitance	farad
C_{NODE}	sense node integrated capacitance	farad
C_O	target's inherent contrast	numeric
C_{RO}	target's contrast at entrance aperture	numeric
d	detector width	mm
d_{CC}	detector pitch	mm
d_{CCH}	horizontal detector pitch	mm
d_{CCV}	vertical detector pitch	mm
d_{CIRCLE}	circular detector diameter	mm
d_{ERROR}	target displacement in TDI systems	mm
d_H	horizontal detector size	mm
d_O	selected target dimension	mm
d_{OLPF}	distance between spots created by birefringent crystal	mm
d_{FPW}	flat panel horizontal element size	mm
d_T	target detail	mm
d_V	vertical detector size	mm
D	observer to display distance	m
D_O	optical (aperture) diameter	mm
DAS_H	horizontal detector angular subtense	mrad
DAS_V	vertical detector angular subtense	mrad
E_e	spectral radiant incidance	W/(m^2-μm)
E_G	detector band gap	eV
E_T	impurity band gap	eV
E_v	luminous incidence	Candela (cd)
f_{CLOCK}	pixel clock rate	Hz
f_e	electrical frequency	Hz
f_{EYE}	spatial frequency at eye	cycles/deg
f_N	Nyquist frequency	cycles/mm
f_o	selected spatial frequency	cycles/mm
f_{PEAK}	peak frequency of eye MTF	cycles/deg
f_S	sampling frequency	cycles/mm
f_v	electrical frequency in the video domain	Hz
f_{v3dB}	one-half power frequency (video domain)	Hz
f_x	horizontal spatial frequency	cycles/mm
f_y	vertical spatial frequency	cycles/mm

fl	focal length	m
F	focal ratio (f-number)	numeric
F_{MAX}	maximum frame rate	Hz
F_R	frame rate	Hz
g	EMCCD unit cell gain	numeric
G	on-chip amplifier gain	numeric
G_1	off-chip amplifier gain	numeric
G_{MCP}	microchannel gain	numeric
h	Planck's constant, $h = 6.626 \times 10^{-34}$	J-s
H	target height	m
$H_{MONITOR}$	monitor height	m
$HFOV$	horizontal field of view	mrad
J_D	dark current density	A/cm^2
k	Boltzmann's constant, $k = 1.38 \times 10^{-23}$	J/K
k_{HIGH}	Super CCD gain multiplier	numeric
k_{LOW}	Super CCD gain multiplier	numeric
K_{EMCCD}	EMCCD excess noise factor	numeric
K_M	luminous efficacy, $K_M = 683$ (photopic)	lumens/W
k_{MCP}	microchannel excess noise factor	numeric
L_B	background luminance	lumen/m^2-sr
L_D	depletion length	µm
L_{DIFF}	diffusion length	µm
L	display brightness	lumen/m^2
L_e	spectral radiant sterance	W/(m^2-µm-sr)
L_q	spectral photon sterance	photons/(s-m^2-µm-sr)
L_T	target luminance	lumen/m^2-sr
Lv	luminance sterance	nit
M	EMCCD gain	numeric
M_e	spectral radiant exitance	W/(m^2-µm)
M_{OPTICS}	optical magnification	numeric
M_P	spectral power	W/µm
M_q	spectral photon exitance	photons/(s-m^2-µm)
M_v	luminous exitance	lumens/m^2
$n_{CATHODE}$	number of photoelectrons created by a photocathode	numeric
n_{DARK}	number of dark electrons	numeric
$n_{DETECTOR}$	number of photons incident onto detector	numeric
n_e	number of electrons	numeric
n_{IMAGE}	number of photons incident onto image plane	numeric
n_{LENS}	number of photons incident onto lens	numeric
n_{MCP}	number of photons incident on microchannel plate	numeric
n_{PE}	number of photoelectrons	numeric
n_{PE-B}	background photoelectrons	numeric

$n_{PE\text{-}T}$	target photoelectrons	numeric
$n_{PHOTON\text{-}CCD}$	number on photons incident onto CCD	numeric
$n_{R\text{-}PIXEL}$	number of photoelectrons created by a Super CCD	numeric
$n_{S\text{-}PIXEL}$	number of photoelectrons created by a Super CCD	numeric
n_{SCREEN}	photons incident onto intensifier screen	numeric
N_H	number of horizontal detectors	numeric
N_{TDI}	number of TDI elements	numeric
N_{TRANS}	number of charge transfers	numeric
N_{TV}	display resolution	TVL/PH
N_V	number of vertical detectors	numeric
N_{WELL}	charge well capacity	numeric
P	display line spacing or pixel spacing	mm/line
PAS_H	horizontal pixel angular subtense	mrad
PAS_V	vertical pixel angular subtense	mrad
q	electronic charge, $q = 1.6 \times 10^{-19}$	coul
r	radius	m
R	range to target	m
R_1	distance from lens to source	m
R_2	distance from lens to detector	m
R_{AVE}	spectral averaged responsivity	V/(μJ-cm^{-2}) or DN/(μJ-cm^{-2})
R_e	spectral responsivity	A/W
R_{EQ}	Schade's equivalent resolution	mm
$R_{PHOTOMETRIC}$	photometric responsivity	V/lux
R_q	spectral quantum efficiency (also η)	numeric
R_{SYS}	system angular resolution	mrad
R_{TVL}	horizontal display resolution	TVL/PH
R_V	photometric responsivity	A/lumen
S	display spot size (FWHM intensity)	mm
t_{ARRAY}	time to clock out the full array	s
t_{CLOCK}	time between pixels	s
$t_{H\text{-}LINE}$	time to read one pixel line	s
t_{INT}	integration time	s
t_{LINE}	video active line time	s
T	absolute temperature	Kelvin
$T/\#$	T-number	numeric
T_{ATM}	spectral atmospheric transmittance	numeric
T_{fo}	fiber optic bundle transmittance	numeric
T_{illum}	absolute temperature of illuminating source	Kelvin
$T_{IR\text{-}FILTER}$	spectrally transmittance of IR filter	numeric
$T_{OPTICS\text{-}AVE}$	spectrally averaged optical transmittance	numeric
T_{OPTICS}	spectral optical transmittance	numeric
$T_{RELAY\ LENS}$	relay lens transmittance	numeric
T_{WINDOW}	transmittance of intensifier window	numeric

u	horizontal spatial frequency object space)	cycles/mrad
u_d	horizontal spatial frequency (display space)	cycles/mm
u_i	horizontal spatial frequency (image space)	cycles/mm
u_{iC}	horizontal optical cutoff (image space)	cycles/mm
u_{iD}	horizontal detector cutoff (image space)	cycles/mm
u_{iN}	horizontal Nyquist frequency (image space)	cycles/mm
u_P	spatial frequency (printer space)	cycles/mm
u_r	radial spatial frequency (image space)	cycles/mm
u_{RES}	system resolution (image space)	cycles/mm
U_{FPN}	fixed pattern noise	numeric
U_{PRNU}	photoresponse nonuniformity	numeric
v	vertical spatial frequency	cycles/mrad
v_d	vertical spatial frequency (display space)	cycles/mm
v_i	vertical spatial frequency (image space)	cycles/mm
v_{iD}	vertical detector cutoff (image space)	cycles/mm
v_{iN}	vertical Nyquist frequency (image space)	cycles/mm
V and V'	photopic, scotopic eye response	numeric
V_{CAMERA}	camera output voltage	V
V_{GRID}	voltage on CRT grid	V
V_{LSB}	voltage of the least significant bit	V
V_{MAX}	maximum signal	numeric
V_{MIN}	minimum signal	numeric
V_{NOISE}	noise voltage after on-chip amplifier	V rms
V_{OUT}	voltage after on-chip amplifier	V
V_{RESET}	reset voltage after on-chip amplifier	V
V_{SCENE}	video voltage before gamma correction	V
V_{SIGNAL}	signal voltage after on-chip amplifier	V
V_{VIDEO}	video voltage after gamma correction	V
$VFOV$	vertical field of view	mrad
W	target width	m
$W_{MONITOR}$	monitor width	m
x	horizontal distance	m
y	vertical distance	m
$\langle n_{ADC} \rangle$	quantization noise	rms electrons
$\langle n_{CCD\text{-}DARK} \rangle$	dark current CCD noise in an ICCD	rms electrons
$\langle n_{CCD\text{-}PHOTON} \rangle$	noise before CCD in an ICCD	rms electrons
$\langle n_{CCD} \rangle$	CCD noise in an ICCD	rms electrons
$\langle n_{DARK} \rangle$	dark current shot noise	rms electrons
$\langle n_{FLOOR} \rangle$	noise floor	rms electrons
$\langle n_{FPN} \rangle$	fixed pattern noise	rms electrons
$\langle n_{MCP} \rangle$	microchannel noise	rms electrons
$\langle n_{OFF\text{-}CHIP} \rangle$	off-chip amplifier noise	rms electrons
$\langle n_{ON\text{-}CHIP} \rangle$	on-chip amplifier noise	rms electrons
$\langle n_{PATTERN} \rangle$	pattern noise	rms electrons
$\langle n_{PC\text{-}DARK} \rangle$	intensifier dark current shot noise	rms electrons

$\langle n_{PC\text{-}SHOT}\rangle$	intensifier photon shot noise	rms electrons
$\langle n_{PE}\rangle$	photon shot noise	rms electrons
$\langle n_{PRNU}\rangle$	photoresponse nonuniformity noise	rms electrons
$\langle n_{RESET}\rangle$	reset noise	rms electrons
$\langle n_{SCREEN}\rangle$	intensifier screen noise	rms electrons
$\langle n_{SHOT}\rangle$	shot noise	rms electrons
$\langle n_{SYS}\rangle$	system noise	rms electrons
$\langle V_{NOISE}\rangle$	noise voltage	rms V

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