Field Guide to

Photographic Science

D. A. Rowlands

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J. Scott Tyo, Series Editor

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Introduction to the Series

In 2004, SPIE launched a new book series under the editorship of Prof. John Greivenkamp, the *SPIE Field Guides*, focused on SPIE's core areas of Optics and Photonics. The idea of these *Field Guides* is to give concise presentations of the key subtopics of a subject area or discipline, typically covering each subtopic on a single page, using the figures, equations, and brief explanations that summarize the key concepts. The aim is to give readers a handy desk or portable reference that provides basic, essential information about principles, techniques, or phenomena, including definitions and descriptions, key equations, illustrations, application examples, design considerations, and additional resources.

The series has grown to an extensive collection that covers a range of topics from broad fundamental ones to more specialized areas. Community response to the *SPIE Field Guides* has been exceptional. The concise and easy-to-use format has made these small-format, spiral-bound books essential references for students and researchers. Many readers tell us that they take their favorite one with them wherever they go. The popularity of the series led to its expansion into areas of general physics in 2019, with the launch of *Field Guides to General Physics*.

The core series continues as the *SPIE Field Guides to Optical Sciences and Technologies*. The concept of these books is a format-intensive presentation based on figures and equations supplemented by concise explanations. In most cases, this modular approach places a single topic on a page, and provides full coverage of that topic on that page. Highlights, insights, and rules of thumb are displayed in sidebars to the main text. The appendices at the end of each *Field Guide* provide additional information such as related material outside the main scope of the volume, key mathematical relationships, and alternative methods. While complete in their coverage, the concise presentation may be best as a supplement to traditional texts for those new to the field.

Introduction to the Series

The *SPIE Field Guides* are intended to be living documents. The modular page-based presentation format allows them to be updated and expanded. In the future, we will look to expand the use of interactive electronic resources to supplement the printed material. We are interested in your suggestions for new topics as well as what material should be added to an individual volume to make these books more useful to you. Please contact us at **fieldguides@SPIE.org**.

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Field Guide to Photographic Science

This *Field Guide* provides a concise summary of the photographic imaging chain and explains the connections between the science and photographic practice.

The book begins by summarizing the fundamental optics required for understanding photographic formulae. This is followed by optics-based sections (pp. 12–36) covering topics such as focusing, framing, depth of field, and photometric exposure.

The middle part of the book (pp. 37–73) describes the relationship between the photometric exposure distribution at the sensor plane and the resulting digital raw data produced by the camera, and the basics of the subsequent steps required to convert the raw data into an output color image designed for viewing on a display.

Later sections concentrate on photographic practice, covering topics such as lighting and strategies for obtaining a suitable exposure (pp. 74–107).

The final sections of the book cover the more technical topics relating to camera image quality.

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Glossary of Symbols and Notation

Image-space quantities are denoted using a prime symbol.

A_{det}	Flux detection area
A_{p}	Photosite area
ADC	Analog-to-digital converter
ADU	Analog-to-digital unit
AF	Autofocus
AFoV	Angular field of view
AS	Aperture stop
ATF	Aberration transfer function
AW	Adopted white
b	Bellows factor
$\mathcal{B}$	Camera raw space tristimulus value (blue channel)
$\bar{b}(\lambda)$	Color matching function for CIE RGB color space
B_{L}	Linear sRGB relative tristimulus value (blue)
$\mathcal{B}_{\text{WP}}$	Raw white balance multiplier (blue channel)
Bv	Brightness value
c	Speed of light; Circle of confusion diameter
C	Center of curvature; Sense node capacitance
$\underline{C}$	Color transformation matrix
CA	Chromatic adaptation
CAT	Chromatic adaptation transform
CCD	Charge-coupled device
CCT	Correlated color temperature
cd	Candela
CFA	Color filter array
CIPA	Camera and Imaging Products Association
CMF	Color matching function
CMOS	Complementary metal-oxide semiconductor
CoC	Circle of confusion
CSF	Contrast sensitivity function
d	Length of sensor diagonal
D	Diameter of entrance pupil
$\underline{D}_{\text{AW}}$	Diagonal white balance matrix for adopted white
$\underline{D}_{\text{D65}}$	Diagonal WB matrix for D65 illumination
D_{v}	Least distance of distinct vision

Glossary of Symbols and Notation

d_x, d_y	Sides of rectangular photosite detection area
D_{XP}	Diameter of exit pupil
DCNU	Dark current non-uniformity
DN	Data number
DoF	Depth of field
DOL	Digital output level
DR	Dynamic range
DSLR	Digital single lens reflex
DSNU	Dark signal non-uniformity
e	Lens extension; Elementary charge
E	Illuminance
E_{e}	Irradiance
$E_{\mathrm{e},\lambda}$	Spectral irradiance
$\tilde{E}_{\mathrm{e},\lambda}$	Spectral irradiance averaged over detection area
E_{v}	Illuminance
EC	Exposure compensation
EP	Entrance pupil
ETTR	Expose to the right
Ev	Exposure value
f	Front effective focal length
F	Front focal point
f'	Rear effective focal length
F′	Rear focal point
f_{E}	Effective focal length
$f(x, y)$	Ideal spectral irradiance (real space)
$F(\mu_x, \mu_y)$	Ideal spectral irradiance (Fourier domain)
FEC	Flash exposure compensation
FF	Fill factor
FFP	Front focal plane
FP	Focal plane
FPN	Fixed pattern noise
FS	Field stop
FT	Fourier transform
FWC	Full-well capacity
g	Conversion factor between electrons and DN
G	Gain
$\mathcal{G}$	Camera raw space tristimulus value (green)
G_{base}	Base gain

Glossary of Symbols and Notation

G_{CG}	Conversion gain
G_{ISO}	Programmable ISO gain
$G_{\mathrm{ISO\text{-}less}}$	ISO-less gain setting
G_{L}	Linear sRGB relative tristimulus value (green)
G_{p}	Source follower amplifier gain
$\mathcal{G}_{\mathrm{WP}}$	Raw white balance multiplier (green channel)
$g(x, y)$	Real spectral irradiance (real space)
$\bar{g}(\lambda)$	Color matching function for CIE RGB color space
$G(\mu_x, \mu_y)$	Real spectral irradiance (Fourier domain)
GN	Guide number
h	Planck's constant; Hyperfocal distance approximation $h = f^2/(cN)$
$\mathcal{H}$	Hyperfocal distance
h, h'	Object and image heights
H, H′	First and second principal planes
$h(x, y)$	System point spread function
$H(\mu_x, \mu_y)$	System optical transfer function
h_{diff}	Diffraction point spread function
$\lvert H_{\mathrm{det}} \rvert$	Detector modulation transfer function
$\langle H \rangle$	Average photometric exposure
HDR	High dynamic range
HVS	Human visual system
i, i'	Paraxial angles of incidence and refraction
I, I'	Real angles of incidence and refraction
ICC	International Color Consortium
ih	Image height
IP	Image plane
IQ	Image quality
ISO	International Standards Organization
JPEG	Joint Photographic Experts Group
K	Reflected light meter calibration constant
K_{m}	Luminous efficacy constant for photopic vision
L	Viewing distance; Luminance; Tristimulus value in LMS color space
L_{e}	Radiance
$L_{\mathrm{e},\lambda}$	Spectral radiance
L_{max}	Maximum scene luminance
L_{v}	Luminance

Glossary of Symbols and Notation

L^*	Lightness
$\bar{l}(\lambda)$	Eye cone response function (long)
$\langle L \rangle$	Average scene luminance
LCD	Liquid crystal display
LENR	Long exposure noise reduction
lm	Lumen
lp	Line pair
LSI	Linear shift invariant
m	Magnification
M	Bit depth of ADC; Number of frames; Number of stops; Tristimulus value in LMS color space
m_{p}	Pupil magnification
$\underline{M}_{\mathrm{R}}$	Color rotation matrix
$\underline{M}_{\mathrm{sRGB}}$	sRGB to XYZ transformation matrix (D65 WP)
$\bar{m}(\lambda)$	Eye cone response function (medium)
MOS	Metal-oxide semiconductor
MTF	Modulation transfer function
N	f-number
n, n'	Object and image space refractive indices
n_{DN}	Raw level expressed using data numbers
n_e	Electron count per photosite
n_{lens}	Lens refractive index
N_{w}	Working f-number
ND	Neutral density
nm	Nanometer
OA	Optical axis
OLPF	Optical low-pass filter
OP	Object plane
OTF	Optical transfer function
p	Pixel pitch for square photosites
P	Photographic constant
p_x, p_y	Pixel pitch in x and y directions
P,P′	First and second principal points
$P(\lambda)$	Spectral power distribution function
PDAF	Phase-detect autofocus
PDR	Photographic dynamic range
PGA	Programmable gain amplifier

Glossary of Symbols and Notation

ph	Picture height
PSF	Point spread function
q	Exposure equation constant (value = 0.65)
Q	Charge signal
Q_{FWC}	Charge signal at full well capacity
QE	Quantum efficiency
$\mathrm{QE}(\lambda)$	External quantum efficiency
R	Radius of curvature; Tristimulus value in CIE RGB color space; Focal length multiplier or equivalence ratio
$\mathcal{R}$	Camera raw space tristimulus value (red channel)
$\bar{r}(\lambda)$	Color matching function for CIE RGB color space
$R_i(\lambda)$	Camera response functions
R_{L}	Linear sRGB relative tristimulus value (red)
$\mathcal{R}_{\mathrm{WP}}$	Raw white balance multiplier (red channel)
RA	Relative aperture
REI	Recommended exposure index
RFP	Rear focal plane
RP	Resolving power
S	ISO setting; Tristimulus value in LMS color space
s, s'	OP and IP distances measured from H and H′
S_{base}	Base ISO setting
s_{EP}	Distance from H to entrance pupil
s_{f}	Distance from H to far DoF boundary
s'_{f}	H′ to far DoF boundary distance in image space
s_{n}	Distance from H to near DoF boundary
s'_{n}	H′ to near DoF boundary distance in image space
s'_{XP}	Distance from H′ to exit pupil
$\bar{s}(\lambda)$	Eye cone response function (short)
SA	Spherical aberration
SLR	Single lens reflex
SNR	Signal-to-noise ratio
SOS	Standard output sensitivity
SP	Sensor plane
SPD	Spectral power distribution
t	Exposure duration or shutter speed; Integration time

Glossary of Symbols and Notation

T	Lens transmittance factor; Color temperature
$T_{\mathrm{CFA},i}$	CFA transmission function
TIFF	Tagged image file format
TTL	Through the lens
U	Unity gain
u, u'	Ray tangent slopes
U, U'	Real ray angles
V_{p}	Photosite voltage
$V_{\mathrm{p,FWC}}$	Photosite voltage at full well capacity
WB	White balance
WP	White point
x	Real space positional coordinate; Chromaticity coordinate
X	Enlargement factor; Tristimulus value in XYZ color space
$\bar{x}(\lambda)$	Color matching function for XYZ color space
XP	Exit pupil
y	Paraxial ray height in extended paraxial region; Real space positional coordinate; Chromaticity coordinate for XYZ color space
Y	Tristimulus value in XYZ color space; Relative luminance Absolute luminance L_{v}
$\bar{y}(\lambda)$	Color matching function for XYZ color space (same as standard luminosity function)
Z	Tristimulus value in XYZ color space
$\bar{z}(\lambda)$	Color matching function for XYZ color space
α, α'	Angles defining the AFoV
$\eta(\lambda)$	Charge collection efficiency or internal QE
γ_{D}	Decoding gamma
γ_{E}	Encoding gamma
λ	Wavelength
μ_{c}	System cutoff frequency
$\mu_{\mathrm{c,det}}$	Detector cutoff frequency
$\mu_{\mathrm{c,diff}}$	Diffraction cutoff frequency
μ_{Nyq}	Sensor Nyquist frequency for square photosites
μ_r	Radial spatial frequency on SP
μ_x, μ_y	Spatial frequencies on SP

Glossary of Symbols and Notation

μm	Micrometer
Φ	Total refractive power
Φ_e	Radiant flux
$\Phi_{e,\lambda}$	Spectral flux
Φ_s	Surface power
Φ_v	Luminous flux
$\sigma_{DN,read}$	Read noise measured in data numbers
$\sigma_{e,DN}$	Photon shot noise measured in data numbers
$\sigma_{e,psn}$	Photon shot noise measured in electrons
$\sigma_{e,read}$	Read noise measured in electrons