Field Guide to

Astronomical Instrumentation

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Welcome to the *SPIE Field Guides*—a series of publications written directly for the practicing engineer or scientist. Many textbooks and professional reference books cover optical principles and techniques in depth. The aim of the *SPIE Field Guides* is to distill this information, providing readers with a handy desk or briefcase reference that provides basic, essential information about optical principles, techniques, or phenomena, including definitions and descriptions, key equations, illustrations, application examples, design considerations, and additional resources. A significant effort will be made to provide a consistent notation and style between volumes in the series.

Each *SPIE Field Guide* addresses a major field of optical science and technology. The concept of these *Field Guides* 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 not be appropriate for those new to the field.

The *SPIE Field Guides* are intended to be living documents. The modular page-based presentation format allows them to be updated and expanded. We are interested in your suggestions for new *Field Guide* topics as well as what material should be added to an individual volume to make these *Field Guides* more useful to you. Please contact us at **fieldguides@SPIE.org**.

John E. Greivenkamp, *Series Editor*
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Field Guide to Astronomical Instrumentation

This *Field Guide to Astronomical Instrumentation* is the one book that the three of us would want to carry with us if we had to single-handedly design an astronomical instrument on a remote mountain top. To keep it concise, it focuses on the ultraviolet to infrared wavelength range. The *Field Guide* is not intended to serve as a textbook, but as a handy desktop reference to be found in the labs and offices of instrument builders.

This book contains information on a wide range of topics, from fundamental physics to project management, and from technical concepts to material properties. Only the most important concepts and equations are presented here. In many areas, dedicated SPIE *Field Guides* discuss particular topics in much more detail. While we tried to maintain consistency with other volumes in this series, we wrote this *Field Guide* in the language that instrumental astronomers use, which might sometimes look strange to people working in other areas.

A *Field Guide* that strives to cover such a wide variety of topics will naturally overlook some potentially relevant topics. We look forward to suggestions from our readers on how to improve this *Field Guide* for its next edition.

Last but not least, we greatly appreciate the continuous support of our families in this endeavor.

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Glossary of Symbols and Acronyms

1D, 2D, 3D	One-, two-, or three-dimensional system
4QPM	Four-quadrant phase mask
A	Absorption
A	Surface area
A	Telescope aperture
$A(u, v)$	Amplitude of aperture function
AC	Alternating current
ADC	Analog-to-digital converter
ADC	Atmospheric dispersion corrector
AG	Aplanatic Gregorian
AIT	Assembly, integration, and testing
AIV	Assembly, integration, and verification
AO	Adaptive optics
APD	Apodizing phase plate
APP	Avalanche photodiode
AR	Anti-reflection
B	Baseline of an interferometer
B	Bias frame
BIB	Blocked-impurity-band (detectors)
BLIP	Background-limited performance
BS	Beamsplitter
CC	Closed cycle cooler
CCD	Charge-coupled device
CMOS	Complementary metal-oxide semiconductor
CNC	Computer numerical control
CP	Closure phase
CTE	Charge transfer efficiency
CTE	Coefficient of thermal expansion
CWL	Center wavelength
d	Actuator spacing
D	Dark frame
d	Diameter
D	Diameter
d	Distance
d	Grating groove spacing
d	Lens thickness
D	Telescope diameter
DC	Direct current

Glossary of Symbols and Acronyms

DHS	Data handling system
DQE	Detective quantum efficiency
DSN	Deep space network
E	Electrical field
E	Energy
e	Error signal
$\mathbf{e}$	Jones vector
ECSS	European Cooperation for Space Standardization
E_g	Bandgap energy
ELT	Extremely Large Telescope
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
ESA	European Space Agency
ESO	European Southern Observatory
ETC	Exposure time calculator
F	Finesse
F	Flat-field frame
F	Flux
f	Focal length
F	Focal ratio, f-number
f	Frequency
F	Fresnel number
$F_{1\to 2}$	View factor
FDR	Final design review
FEM	Finite element model
FFBD	Functional Flow Block Diagram
f_G	Greenwood frequency
FLC	Ferro-electric liquid crystals
FSR	Free spectral range
FTS	Fourier transform spectrometer
FWHM	Full width at half maximum
g	Gain
G	Strehl ratio gain
g_D	Derivative gain in a PID controller
g_I	Integral gain in a PID controller
g_P	Proportional gain in a PID controller
GLAO	Ground-layer adaptive optics
gP	Proportional gain in a PID controller

Glossary of Symbols and Acronyms

GR	Generation-recombination
h	Height of turbulence layer
H	Near-IR atmospheric band
HEB	Hot electron bolometer
HGA	High-gain antenna
I	Image
I	Intensity
IBF	Ion beam figuring
ICD	Interface control document
ICS	Instrument control system
I_D	Dirty image
IFS	Integral field spectrometer
IFU	Integral field unit
IR	Infrared
IRR	Integration readiness review
$\mathbf{J}$	Jones matrix
J	Near-IR atmospheric band
J_0	Zeroth-order Bessel function
J_1	First-order Bessel function
JWST	James Webb Space Telescope
k	Angular frequency
K	Conic constant
K	Near-IR atmospheric band
K	Temperature in Kelvin
k	Wave number
k_n	Normalized angular frequency
L	Grating width
L	Maximum path length difference
L2	Second Lagrangian point
LCVR	Liquid crystal variable retarders
LGS	Laser guide star
LHe	Liquid helium
LN_2	Liquid nitrogen
LO	Local oscillator
LSST	Large Synoptic Survey Telescope
LVDT	Linear variable differential transformer
m	Grating order, order of diffraction
$\mathbf{M}$	Mueller matrix
mbar	Millibar pressure

Glossary of Symbols and Acronyms

MCAO	Multi-conjugate adaptive optics
MEMS	Micro-electro-mechanical system
MKID	Microwave kinetic inductance detector
MLI	Multi-layer isolation
MOAO	Multi-object adaptive optics
MOS	Multi-object spectrometer
MTF	Modulation transfer function
n	Index of refraction
n	Noise
N	Number of actuators
N	Number of illuminated grooves
n	Number of photons
N	Number of telescopes
NA	Numerical aperture
NASA	National Aeronautics and Space Administration
n_{eff}	Effective index of refraction
NGS	Natural guide star
n_m	Index of refraction of medium
n_p	number of photons per m^2
n_s	Index of refraction of substrate
o	Object
OCS	Observatory control system
OPD	Optical path difference
OTCCD	Orthogonal-transfer CCD
OTF	Optical transfer function
P	Degree of polarization
p	Point spread function
$\mathbf{P}$	Poke matrix
P	Pressure
$P(v)$	Instrumental profile
$P(x, \mu)$	Probability for value x around a mean μ
PDR	Preliminary design review
PEM	Piezo-elastic modulator
PIAA	Phase-induced amplitude apodization
PID	Proportional-integral-derivative
P_L	Degree of linear polarization
PS	Point source (diffraction limited)
PSF	Point spread function

Glossary of Symbols and Acronyms

Pt100, Pt1000	Platinum temperature sensor
PTF	Phase transfer function
PVA	Polyvinyl alcohol
Q	Heat transfer
Q	Stokes Q
QA	Quality assurance
QC	Quality control
QMS	Quality management system
r	Radial distance
R	Radius of curvature
$\mathbf{R}$	Reconstructor
R	Reflectivity
R	Spectral resolution
R&D	Research and development
r_0	Fried's parameter
RAM	Risk assessment matrix
RAMS	Risk assessment and method statement
RC	Ritchey–Chrétien (telescope)
RFI	Radio frequency interference
RMS	Root mean square
ROI	Region of interest
r_p	Reflection amplitude for p-polarization
r_s	Reflection amplitude for s-polarization
RVDT	Rotary variable differential transformer
R_X, R_Y, R_Z	Rotation around X, Y, Z coordinates
S	Science frame
s	Sensor data
S	Signal
$\mathbf{s}$	Stokes vector
SH	Shack–Hartmann wavefront sensor
Si	Silicon
SIS	Superconductor–insulator–superconductor
SL	Seeing limited
SNR	Signal-to-noise ratio
STEP	Standard for exchange of product data
STF	Spectral transfer function
SUR	Sample-up-the-ramp
T	Temperature
t	Thickness

Glossary of Symbols and Acronyms

t	Time
T	Transmission
T1, T2	Telescopes
TCS	Telescope control system
t_D	Dark frame exposure time
TDRSS	Tracking and data relay satellite system
TES	Transition edge sensor
t_F	Flat-field frame exposure time
TIR	Total internal reflection
TIS	Total integrated scatter
TLR	Top-level requirements
TMA	Three-mirror anastigmat
t_p	Transmission amplitude for p-polarization
TRL	Technology readiness level
t_S	Science frame exposure time
t_s	Transmission amplitude for s-polarization
T_X, T_Y, T_Z	Translation in X, Y, Z coordinates
u	Control signal
(u, v)	Coordinates in Fourier space
U	Stokes U
UV	Ultraviolet
V	Fringe visibility
V	Stokes V
v	Wind speed
VPH	Volume phase hologram
W	Watt
WBS	Work breakdown structure
WFS	Wavefront sensor
W_i	Weighting coefficient
x	Path-length difference
X, Y, Z	X, Y, Z coordinates
y	Actuator position
y	Distance from field center
Y	Yield strength
z	Surface zag
z	Zenith angle
α	Linear polarization orientation
α	Absorption coefficient
α	Prism apex angle

Glossary of Symbols and Acronyms

α	Incident angle on grating
β	Reflected angle on grating
γ	Groove center to edge phase difference
δ	Phase change on total internal reflection
δ	Retardation in birefringent material
δ	Dispersion angle
δ	Angle of linear polarization
Δ	OPD in an interferometer
$\Delta\lambda_{FWHM}$	Filter transmission profile FWHM
$\Delta\lambda$	Spectral resolution element
ϵ	Emissivity
η	Relative grating efficiency
η	Throughput
θ	Half-angle
θ	Position or rotation angle
θ	Angular resolution in radians
θ_B	Brewster angle
θ_B	Blaze angle
θ_i	Angle of incidence
θ_i'	Refracted angle of incidence
$\theta_{isoplanatic}$	Isoplanatic angle
θ_o	Angle of dispersed beam
θ_r	Angle of reflected beam
θ_t	Angle of transmitted beam
λ	Wavelength
λ_B	Blaze wavelength
λ_c	Center wavelength
λ_c	Cutoff wavelength
λ_{fsr}	Free spectral range
μm	micrometer
ν	Frequency
σ	Stefan Boltzmann constant
σ	Standard deviation
$\sigma^2_{control}$	Control system lag induced variance
σ^2_{DM}	Fitting error induced variance
$\sigma^2_{offaxis}$	Anisoplanatism wavefront variance
σ^2_{total}	Total wavefront variance
σ^2_{WFS}	Wavefront sensor induced variance
τ	Internal transmission

Glossary of Symbols and Acronyms

τ	Frequency in Nyquist sampling
τ_i	Internal transmission
τ_s	Servo lag time
τ_0	Atmospheric coherence time
ϕ_0	Intrinsic phase
ϕ_{obs}	Observed phase
ϕ_{atmos}	Phase shifted by atmospheric effects
ϕ_s	Angular slit width
$\varphi(u, v)$	Phase of aperture function
φ	Wedge angle
ω	Angular frequency