Field Guide to

Lidar

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Introduction to the Series

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**.

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Field Guide to Lidar

This *Field Guide* covers active electro-optical sensing, in which a sensor sends out a laser pulse and then measures the parameters of the return signal. Various groups refer to this type of sensor as a ladar, lidar, LIDAR, LADAR, or laser radar. For simplicity, only the term lidar is used throughout this book.

The book is presented from the perspective of a lidar engineer. It covers a wide breadth, from simple 2D direct-detection lidars to multiple subaperture synthetic aperture lidars. It also covers a broad range of objects to be viewed, and distances from which to view the objects. Lasers and modulation are discussed in the context of their use in lidars. Other topics covered include receivers, apertures, and atmospheric effects in the context of lidar use and design.

All lidars will be limited by the media between the lidar and the target, but atmospheric compensation techniques can often mitigate this limitation. These limitations and compensation approaches are presented. Many types of lidars are included along with appropriate data processing techniques. The lidar range equation in its many variations is discussed along with receiver noise issues that determine how much signal must be received to detect an object.

This *Field Guide* is a handy reference to quickly access information on any aspect of lidars. It will be useful to students and lidar scientists or engineers who need an occasional reminder of the correct approaches or equations to use in certain applications. It will also be useful to systems engineers gaining a perspective on this rapidly growing technology.

Paul McManamon
March 2015

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Glossary of Symbols and Acronyms

a	amplitude of the (super) Gaussian
A	length of one side of a tetrahedral
A_{illum}	area illuminated by the transmitter
AO	acousto-optic
AOM	acousto-optic modulator
A_{p}	area of the pixel at the target location
APD	avalanche photodiode
APS	active-pixel sensor
A_{rec}	area of the receiver aperture
b	zero position, or offset, of the (super) Gaussian beam
B	bandwidth
c	Gaussian, or super-Gaussian, beam width
c	speed of light
cw	continuous wave
C_{l}	coherence length
CCD	charge-coupled device
CDMA	code-division multiple access
CMOS	complementary metal-oxide semiconductor
CNR	carrier-to-noise ratio
d	cross-range resolution
d	required lens thickness
d	width of the individual radiator or receiver
D	aperture diameter
D_{Airy}	diameter out to the zeros of the diffraction-limited spot at the focus for a circular aperture
DAS	detector angular subtense
DFLC	dual-frequency liquid crystal
DIAL	differential absorption lidar
DM	deformable mirror
DOP	degree of polarization
e	charge on an electron
E	energy at range
E_0	initial energy before traveling through the atmosphere
EBAPS®	electron-bombarded active-pixel sensor
EBS	electron-bombarded semiconductor
E_{in}	input electric field into a Jones matrix

Glossary of Symbols and Acronyms

E_{LO}	local oscillator field
EM	electromagnetic
EO	electro-optic
E_{out}	input electric field into a Jones matrix
E_p	energy in a photon
E_R	received energy per pulse
E_{sig}	returned signal field
E_T	transmitted energy per pulse
E_{th}	thermal energy
Ex_{in}	x portion of the input electric field
Ex_{out}	x portion of the output electric field
Ey_{in}	y portion of the input electric field
Ey_{out}	y portion of the output electric field
f	focal length of the lens
$f/\#$	F-number of an optical element
f_l	focal length of a lenslet
$f(x)$	Gaussian or super-Gaussian beam profile in one dimension
F	excess noise factor associated with the preamplifier gain
FDMA	frequency-division multiple access
FFT	fast Fourier transform
FLC	ferroelectric liquid crystal
FLIR	forward-looking infrared (camera)
FM	frequency modulated
FOV	field of view
FPA	focal plane array
FSM	fast-steering mirror
G	avalanche gain
GIQE	general image quality equation
GMAPD	Geiger-mode avalanche photodiode
GML	Geiger-mode lidar
h	Planck's constant
HWP	half-wave plate
i_{bk}	background current
i_{dk}	dark current
i_n	noise current in the detector
i_s	signal current in the detector
i_{shotLO}	shot noise from the local oscillator

Glossary of Symbols and Acronyms

$i_{\text{shot,sig}}$	shot noise from the signal
i_{th}	thermal noise current
I	intensity of the beat between the local oscillator and the return signal
I_{dkb}	bulk dark current
I_{dks}	surface dark current
IF	intermediate frequency
IMU	inertial measurement unit
IR	infrared
k	effective elastic constant
k	number of photons in M events
k	Boltzmann constant
L	distance flown
L	length of the laser cavity
LCPG	liquid crystal polarization grating
LFM	linear frequency modulation
LIBS	laser-induced breakdown spectroscopy
LIF	laser-induced fluorescence
LIMAR	laser imaging and ranging
LMAPD	linear-mode avalanche photodiode
LO	laser oscillator
LWIR	long-wave infrared
L_{λ}	radiance per wavelength
M	number of events
M^2	measure of the spatial coherence of a laser beam. An M^2 of 1 means it is diffraction limited.
MEMS	micro-electro-mechanical system
MIMO	multiple input, multiple output
MO	master oscillator
MPE	maximum permissible exposure
MWIR	midwave infrared
n	index of refraction
n	number of individual radiators or receivers
n_m	diffraction efficiency of the m^{th} order
N	number of photons per pixel received during a measurement time
N	super-Gaussian beam number. Higher numbers mean a more flat-topped beam shape.

Glossary of Symbols and Acronyms

NA	numerical aperture
NEPh	noise-equivalent photons
NIIRS	National Imagery Interpretability Rating Scale
NIR	near infrared
OPA	optical parametric amplifier
OPA	optical phased array
OPD	optical path difference
OPO	optical parametric oscillator
$p(k)$	Gaussian probability distribution
P	number of modes
PAPA	phased array of phased arrays
P_{LO}	local oscillator power
PPLN	periodically poled lithium niobate
P_{S}	signal power received
PSD	power spectral density
PSF	point spread function
P_{T}	power transmitted
P_{thdbm}	thermal noise power
q	Poisson distribution probability
q	number of discrete steps
QCL	quantum cascade laser
QWP	quarter-wave plate
r_0	Fried parameter
R	range to the target
$\Re$	detector responsivity
RF	radio frequency
R_{L}	load resistance
ROIC	readout integrated circuit
R_{unambig}	unambiguous range
$S'_3 = S_3/S_0$	normalized Stokes parameter corresponding to ellipticity of incident light
SNR	signal-to-noise ratio
SPGD	stochastic parallel gradient descent
SS	solid state
SWIR	short-wave infrared
t	cell thickness
$t_{\mathrm{lens}}(w_{\mathrm{az}}, w_{\mathrm{el}})$	lens phase profile
T	temperature

Glossary of Symbols and Acronyms

T	time separation between pulses
TDMA	time-division multiple access
T_{m}	time period over which a measurement is made
v	velocity of the lidar with respect to the surrounding air
V	platform velocity
V	relative velocity between the lidar and the target
V	voltage on an electrode
VCSEL	vertical-cavity surface-emitting laser
V_{t}	threshold voltage
$W_{az}^2 + W_{el}^2$	beam width in azimuth and elevation for a Gaussian profile
β	angle between the slow axis of the half-wave plate and the *x* axis in the Jones matrix
β	atmospheric decay constant
γ	viscosity
Δf	change in frequency due to the Doppler shift
Δn	change in index of refraction
Δz	surface roughness
ΔR	range resolution
Δt	mode-locked pulse width
ΔV	velocity resolution
Δx	lenslet motion
$\Delta\vartheta$	angular resolution for a synthetic aperture lidar
$\Delta\lambda$	linewidth of the laser in wavelength
$\Delta\phi$	angular motion used in an inverse synthetic aperture lidar image
η	steering efficiency due to quantization error
η_{atm}	transmission of the atmosphere in one direction
η_{h}	heterodyne mixing efficiency
η_{sys}	total transmission of the lidar system, both in and out
θ	angular motion created by the lenslet
θ_{max}	maximum steering angle

Glossary of Symbols and Acronyms

ϑ	angle of deflection for an AO modulator
ϑ	full beam width, half maximum diffraction limit
λ	wavelength
λ_i	wavelength of the idler laser
λ_p	wavelength of the pump laser
λ_s	wavelength of the signal laser
Λ	acousto-optical wavelength
Λ	width between resets
Λ_F	width of the flyback region
ν	carrier frequency of light ($\omega = 2\pi\nu$)
ρ	radius of the microlens
ρ_t	reflectance of the area
σ	cross section
τ_0	coherence time
τ_d	time required to return to no-voltage state
τ_m	mode-locked pulse separation
φ	phase retardation of the half-wave plate
ω_{sig}	frequency (in radians) of the return signal
ω_{LO}	frequency (in radians) of the local oscillator