Field Guide to
Lidar

Paul McManamon

SPIE Field Guides
Volume FG36

John E. Greivenkamp, Series Editor

SPIE PRESS
Bellingham, Washington  USA
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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College of Optical Sciences
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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
## Table of Contents

**Glossary of Symbols and Acronyms**  x

**Introduction**  1
- Introduction  1
- Terms for Active Electro-optic Sensing  2
- Types of Lidars  3
- Lidars for Surface-Scattering (Hard) Targets  4
- Lidars for Volume-Scattering (Soft) Targets  5
- History of Lidar  6
- Lidar Detection Modes  7
- Spatial Coherence  8
- Temporal Coherence  9
- Eye Safety Considerations  10
- Laser Safety Categories  11
- Monostatic versus Bistatic Lidar  12
- Transmit/Receive Isolation  13

**Lidar Range Equation**  14
- Lidar Range Equation  14
- Lidar Cross Section  15
- Cross Section of a Corner Cube  16
- Speckle  17
- Atmospheric Absorption  18
- Atmospheric Scattering  19
- Atmospheric Turbulence  20
- Aero-optical Effects on Lidar  21
- Extended (Deep) Turbulence  22
- Laser Power for Lidar  23
- Lidar Signal-to-Noise Ratio  24
- Direct Detection Signal-to-Noise Ratio  25
- Noise Probability Density Functions  26
- Thermal Noise  27
- Shot Noise  28
- The Sun as Background Noise  29
- Dark Current, 1/f, and Excess Noise  30
- Avalanche Photodiodes and Direct Detection  31
- Number of Photons Required for a GMAPD Lidar Camera  32
- Heterodyne Detection  33
Temporal Heterodyne Detection 34
Heterodyne Mixing Efficiency 35
Quadrature Detection 36
Carrier-to-Noise Ratio for Temporal Heterodyne Detection 37
Spatial Heterodyne Detection/Digital Holography 38
SNR for Spatial Heterodyne Detection 39

Types of Lidars 40
1D Range-Only Lidar 40
Tomographic Imaging Lidar 41
Range-Gated Active Imaging (2D Lidar) 42
3D Scanning Lidar 43
3D Flash Imaging 44
Geiger-Mode APD Flash Lidar 45
Linear-Mode APD Flash Lidar 46
Polarization-based Flash Lidar using Framing Cameras 47
Laser Vibration Detection 48
Synthetic Aperture Lidar 49
Inverse Synthetic Aperture Lidar 50
Range Doppler Imaging Lidar 51
Laser-Induced Breakdown Spectroscopy 52
Laser-Induced Fluorescence Lidar 53
Active Multispectral Lidar 54
Lidars Using Polarization as a Discriminant 55
Speckle Imaging Lidar 56
Phased Array of Phased-Array Imaging Lidar 57
Multiple Subapertures on Receive for Lidar 58
Multiple-Input, Multiple-Output Lidar 59
Methods of Phasing MIMO Lidars 60

Lidar Sources and Modulations 61
Lidar Sources and Modulations 61
Laser Resonators 62
Three-Level and Four-Level Lasers 63
Bulk Solid State Lasers for Lidar 64
Fiber Lasers for Lidar 65
Higher-Peak-Power Waveguide Lasers for Lidar 66
Diode Lasers for Lidar 67
Quantum Cascade Lasers for Lidar 68
Laser Pumping Considerations 69
Nonlinear Devices to Change the Lidar Wavelength 70
Q-Switched Lasers for Lidar 71
Pockels Cells 72
Mode-Locked Lasers for Lidar 73
Laser Seeding for Lidar 74
Laser Amplifiers for Lidar 75
Multiple Coherent Laser Transmitters 76
Laser Waveforms for Lidar 77
Polypulse Laser Waveforms 78
Linear Frequency Modulation for Lidar 79
Pseudo-random-Coded Lidar 80
RF Modulation of a Direct Detection Lidar 81

Lidar Receivers 82
Linear-Mode APD Arrays for Lidar 82
Geiger-Mode APD Arrays for Lidar 83
Receivers for Coherent Lidars 84
Acousto-optic Frequency Shifting 85
Long-Frame-Time Framing Detectors for Lidar 86
Gated Framing Cameras for 2D Lidar Imaging 87
Lidar Image Stabilization 88
Range Resolution of Lidar 89
Velocity Resolution of Lidar 90
Unambiguous Range 91
Point Spread Function 92

Beam Steering for Lidars 93
Gimbals for Use with Lidar 93
Fast-Steering Mirrors 94
Risley Prisms and Gratings 95
Rotating Polygonal Mirrors 96
Modulo 2\pi Beam Steering 97
Largest Steering Angle for an Optical Phased Array 98
Liquid Crystal Optical Phased Arrays 99
LC Fringing-Field Effect on Steering Efficiency 100
Reduction in Steering Efficiency Due to Quantization 101
Chip-Scale Optical Phased Arrays 102
MEMS Beam Steering for Lidar 103
Electrowetting Beam Steering for Lidar | 104
Steerable Electro-evanescent Optical Refractors | 105
Electro-optical Effects | 106
Polarization Birefringent Grating Beam Steering | 107
Step Angle Steering with LC Polarization Gratings | 108
Multiple-Stage LCPGs | 109
Lenslet-based Beam Steering | 110
Electronically Written Lenslets | 111
Mixed-Lenslet Arrays | 112
Holographic Gratings for Beam Steering | 113
Geometrical Optics | 114

**Lidar Processing** | 115
Inertial Measurement Units | 115
Microscanning of Lidar Images for Improved Sampling | 116
Range Measurement Processing | 117
Nyquist Sampling a Range Profile | 118
Threshold, Leading Edge, and Peak Detectors | 119
Range Resolution, Precision, and Accuracy | 120
Fourier Transforms | 121
Developing 3D Maps from Lidar | 122
3D Metrics for Lidar Images | 123
Multiple-Subaperture Spatial Heterodyne Processing | 124
Definitions of Lidar Data Processing Stages | 125
Processing Laser Vibrometry Data | 126
Target Classification Using Lidar | 127

**Equation Summary** | 128

**Figure Sources** | 138

**Bibliography** | 141

**Index** | 143
### 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
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{LO}$</td>
<td>local oscillator field</td>
</tr>
<tr>
<td>EM</td>
<td>electromagnetic</td>
</tr>
<tr>
<td>EO</td>
<td>electro-optic</td>
</tr>
<tr>
<td>$E_{out}$</td>
<td>input electric field into a Jones matrix</td>
</tr>
<tr>
<td>$E_p$</td>
<td>energy in a photon</td>
</tr>
<tr>
<td>$E_R$</td>
<td>received energy per pulse</td>
</tr>
<tr>
<td>$E_{sig}$</td>
<td>returned signal field</td>
</tr>
<tr>
<td>$E_T$</td>
<td>transmitted energy per pulse</td>
</tr>
<tr>
<td>$E_{th}$</td>
<td>thermal energy</td>
</tr>
<tr>
<td>$E_{x_{in}}$</td>
<td>$x$ portion of the input electric field</td>
</tr>
<tr>
<td>$E_{x_{out}}$</td>
<td>$x$ portion of the output electric field</td>
</tr>
<tr>
<td>$E_{y_{in}}$</td>
<td>$y$ portion of the input electric field</td>
</tr>
<tr>
<td>$E_{y_{out}}$</td>
<td>$y$ portion of the output electric field</td>
</tr>
<tr>
<td>$f$</td>
<td>focal length of the lens</td>
</tr>
<tr>
<td>$f/#$</td>
<td>F-number of an optical element</td>
</tr>
<tr>
<td>$f_l$</td>
<td>focal length of a lenslet</td>
</tr>
<tr>
<td>$f(x)$</td>
<td>Gaussian or super-Gaussian beam profile in one dimension</td>
</tr>
<tr>
<td>$F$</td>
<td>excess noise factor associated with the preamplifier gain</td>
</tr>
<tr>
<td>FDMA</td>
<td>frequency-division multiple access</td>
</tr>
<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
</tr>
<tr>
<td>FLC</td>
<td>ferroelectric liquid crystal</td>
</tr>
<tr>
<td>FLIR</td>
<td>forward-looking infrared (camera)</td>
</tr>
<tr>
<td>FM</td>
<td>frequency modulated</td>
</tr>
<tr>
<td>FOV</td>
<td>field of view</td>
</tr>
<tr>
<td>FPA</td>
<td>focal plane array</td>
</tr>
<tr>
<td>FSM</td>
<td>fast-steering mirror</td>
</tr>
<tr>
<td>$G$</td>
<td>avalanche gain</td>
</tr>
<tr>
<td>GIQE</td>
<td>general image quality equation</td>
</tr>
<tr>
<td>GMAPD</td>
<td>Geiger-mode avalanche photodiode</td>
</tr>
<tr>
<td>GML</td>
<td>Geiger-mode lidar</td>
</tr>
<tr>
<td>$h$</td>
<td>Planck’s constant</td>
</tr>
<tr>
<td>HWP</td>
<td>half-wave plate</td>
</tr>
<tr>
<td>$i_{bk}$</td>
<td>background current</td>
</tr>
<tr>
<td>$i_{dk}$</td>
<td>dark current</td>
</tr>
<tr>
<td>$i_n$</td>
<td>noise current in the detector</td>
</tr>
<tr>
<td>$i_s$</td>
<td>signal current in the detector</td>
</tr>
<tr>
<td>$i_{shotLO}$</td>
<td>shot noise from the local oscillator</td>
</tr>
</tbody>
</table>
Glossary of Symbols and Acronyms

$i_{\text{shot,sig}}$ shot noise from the signal

$i_{\text{th}}$ thermal noise current

$I$ intensity of the beat between the local oscillator and the return signal

$I_{\text{dbk}}$ bulk dark current

$I_{\text{dks}}$ 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

$L_\lambda$ 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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>numerical aperture</td>
</tr>
<tr>
<td>NEPh</td>
<td>noise-equivalent photons</td>
</tr>
<tr>
<td>NIIRS</td>
<td>National Imagery Interpretability Rating Scale</td>
</tr>
<tr>
<td>NIR</td>
<td>near infrared</td>
</tr>
<tr>
<td>OPA</td>
<td>optical parametric amplifier</td>
</tr>
<tr>
<td>OPA</td>
<td>optical phased array</td>
</tr>
<tr>
<td>OPD</td>
<td>optical path difference</td>
</tr>
<tr>
<td>OPO</td>
<td>optical parametric oscillator</td>
</tr>
<tr>
<td>( p(k) )</td>
<td>Gaussian probability distribution</td>
</tr>
<tr>
<td>( P )</td>
<td>number of modes</td>
</tr>
<tr>
<td>PAPA</td>
<td>phased array of phased arrays</td>
</tr>
<tr>
<td>( P_{\text{LO}} )</td>
<td>local oscillator power</td>
</tr>
<tr>
<td>PPLN</td>
<td>periodically poled lithium niobate</td>
</tr>
<tr>
<td>( P_S )</td>
<td>signal power received</td>
</tr>
<tr>
<td>PSD</td>
<td>power spectral density</td>
</tr>
<tr>
<td>PSF</td>
<td>point spread function</td>
</tr>
<tr>
<td>( P_T )</td>
<td>power transmitted</td>
</tr>
<tr>
<td>( P_{\text{thdbm}} )</td>
<td>thermal noise power</td>
</tr>
<tr>
<td>( q )</td>
<td>Poisson distribution probability</td>
</tr>
<tr>
<td>( q )</td>
<td>number of discrete steps</td>
</tr>
<tr>
<td>QCL</td>
<td>quantum cascade laser</td>
</tr>
<tr>
<td>QWP</td>
<td>quarter-wave plate</td>
</tr>
<tr>
<td>( r_0 )</td>
<td>Fried parameter</td>
</tr>
<tr>
<td>( R )</td>
<td>range to the target</td>
</tr>
<tr>
<td>( R )</td>
<td>detector responsivity</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>( R_L )</td>
<td>load resistance</td>
</tr>
<tr>
<td>ROIC</td>
<td>readout integrated circuit</td>
</tr>
<tr>
<td>( R_{\text{unambig}} )</td>
<td>unambiguous range</td>
</tr>
<tr>
<td>( S'_3 = S_3/S_0 )</td>
<td>normalized Stokes parameter corresponding to ellipticity of incident light</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>SPGD</td>
<td>stochastic parallel gradient descent</td>
</tr>
<tr>
<td>SS</td>
<td>solid state</td>
</tr>
<tr>
<td>SWIR</td>
<td>short-wave infrared</td>
</tr>
<tr>
<td>( t )</td>
<td>cell thickness</td>
</tr>
<tr>
<td>( t_{\text{lens}}(w_{az}, w_{el}) )</td>
<td>lens phase profile</td>
</tr>
<tr>
<td>( T )</td>
<td>temperature</td>
</tr>
</tbody>
</table>
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
- $\beta$: angle between the slow axis of the half-wave plate and the $x$ axis in the Jones matrix
- $\beta$: atmospheric decay constant
- $\gamma$: viscosity
- $\Delta f$: change in frequency due to the Doppler shift
- $\Delta n$: change in index of refraction
- $\Delta z$: surface roughness
- $\Delta R$: range resolution
- $\Delta t$: mode-locked pulse width
- $\Delta V$: velocity resolution
- $\Delta x$: lenslet motion
- $\Delta \theta$: 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
- $\eta$: steering efficiency due to quantization error
- $\eta_{atm}$: transmission of the atmosphere in one direction
- $\eta_h$: heterodyne mixing efficiency
- $\eta_{sys}$: total transmission of the lidar system, both in and out
- $\theta$: angular motion created by the lenslet
- $\theta_{max}$: maximum steering angle
### Glossary of Symbols and Acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ</td>
<td>angle of deflection for an AO modulator</td>
</tr>
<tr>
<td>δ</td>
<td>full beam width, half maximum diffraction limit</td>
</tr>
<tr>
<td>λ</td>
<td>wavelength</td>
</tr>
<tr>
<td>λ&lt;sub&gt;i&lt;/sub&gt;</td>
<td>wavelength of the idler laser</td>
</tr>
<tr>
<td>λ&lt;sub&gt;p&lt;/sub&gt;</td>
<td>wavelength of the pump laser</td>
</tr>
<tr>
<td>λ&lt;sub&gt;s&lt;/sub&gt;</td>
<td>wavelength of the signal laser</td>
</tr>
<tr>
<td>Λ</td>
<td>acousto-optical wavelength</td>
</tr>
<tr>
<td>Λ&lt;sub&gt;F&lt;/sub&gt;</td>
<td>width between resets</td>
</tr>
<tr>
<td>ν</td>
<td>width of the flyback region</td>
</tr>
<tr>
<td>υ&lt;sub&gt;LO&lt;/sub&gt;</td>
<td>frequency (in radians) of the local oscillator</td>
</tr>
<tr>
<td>v&lt;sub&gt;sig&lt;/sub&gt;</td>
<td>frequency (in radians) of the return signal</td>
</tr>
<tr>
<td>ρ</td>
<td>carrier frequency of light (ω = 2πν)</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;t&lt;/sub&gt;</td>
<td>radius of the microlens</td>
</tr>
<tr>
<td>σ</td>
<td>reflectance of the area</td>
</tr>
<tr>
<td>σ</td>
<td>cross section</td>
</tr>
<tr>
<td>τ&lt;sub&gt;0&lt;/sub&gt;</td>
<td>coherence time</td>
</tr>
<tr>
<td>τ&lt;sub&gt;d&lt;/sub&gt;</td>
<td>time required to return to no-voltage state</td>
</tr>
<tr>
<td>τ&lt;sub&gt;m&lt;/sub&gt;</td>
<td>mode-locked pulse separation</td>
</tr>
<tr>
<td>φ</td>
<td>phase retardation of the half-wave plate</td>
</tr>
<tr>
<td>ω&lt;sub&gt;s&lt;/sub&gt;</td>
<td>frequency (in radians) of the return signal</td>
</tr>
<tr>
<td>ω&lt;sub&gt;LO&lt;/sub&gt;</td>
<td>frequency (in radians) of the local oscillator</td>
</tr>
</tbody>
</table>