

Field Guide to
Lidar

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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

| | |
|--------------------|---|
| α | 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_1 | 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

| | |
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| $i_{\text{shot,sig}}$ | 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

| | |
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| 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 |
| $t_{\text{lens}}(w_{\text{az}}, w_{\text{el}})$ | 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 |