Lidar Engineering

Explore the spectrum of lidar engineering in this one-of-a-kind introduction. For the first time, this multidisciplinary resource covers all the scientific and engineering aspects of atmospheric lidar – including atmospheric science, spectroscopy, lasers and eye safety, classical optics and electro-optics, electrical and mechanical engineering, and software algorithms – in a single comprehensive and authoritative undergraduate textbook. Discover up-to-date material not included in any other book, including simple treatments of the lidar crossover range and depolarization in lidar signals, an improved explanation of lidar data inversion algorithms, digital signal processing applications in lidar, and statistical limitations of lidar signal-to-noise ratios. This is an ideal stand-alone text for students seeking a thorough grounding in lidar, whether through a taught course or self-study.

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Introduction to Basic Principles

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For Abbey, Allison, Lauren, Natasa, and Tiff

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Preface

The topic of this textbook is the engineering of lidars that are optical atmospheric remote sensing systems based on pulsed lasers. The technique was originally called laser radar, but as more applications of laser remote sensing arose, other names came into use. Broadly, the acronyms LIDAR and LADAR are now used for military surveillance and targeting and for automotive collision avoidance, and the term LiDAR has more recently been adopted by the airborne topographic and bathymetric mapping communities. Here we are concerned only with the atmosphere, and the name lidar is taken to be an acronym that has passed into the English language in the same way that RADAR became radar. This choice is a personal preference; there is unfortunately no standard naming convention. There is no standard notation for atmospheric lidar either, but the symbols used in this book are at least commonplace in the literature.

The book has its roots in a series of lectures that the authors developed for students at Agnes Scott College in Decatur, Georgia, in 2001–2003. Leanne West, John Stewart, and Jack Wood also contributed to developing and presenting the initial set of lectures. Our goal was to provide a comprehensive introduction to basic atmospheric lidar technology that was appropriate for advanced undergraduates, in preparation for building and operating their own lidar system. The lectures were later adapted into a three-and-a-half-day short course that is offered annually at Georgia Tech in Atlanta, Georgia. Technical material for this book also came from Lidar Tutorials that Dr. Gimmestad presented at each of the International Laser Radar Conferences starting in 2010 and from graduate-level courses on atmospheric lidar that he taught at Georgia Tech and at the National University of Ireland Galway. Developing a specialized set of lectures was necessary because the lidar technique is inherently multidisciplinary, requiring a basic understanding of laser technology, geometric optics, atmospheric optics, optomechanics, photodetectors, statistics, analog and digital electronics, and signal processing. The chapters in this book are expanded versions of the lectures, and because of the need to cover such a broad range of topics, the chapters are not definitive treatments; they are basic introductions to the topics at the advanced undergraduate level. References and suggestions for further reading are provided at the end of each chapter so that students can easily pursue a deeper and more detailed understanding of any of the topics.

Several other books on atmospheric lidar have been written since the first demonstration of the technique in 1963, but this is the only textbook on the topic. The chapters are written and arranged to be studied sequentially, and they include worked examples and homework problems. Working the problems is important – they include many key derivations. The chapters will serve as handy references on various lidar engineering topics for the student who has worked through them. When technical terms are first introduced, some are italicized to indicate that they deserve special attention, and a glossary of all symbols and a list of abbreviations are provided as well. This book is intended for all newcomers to lidar, including software engineers and atmospheric science researchers who use lidars. Thorough explanations of how lidar techniques are used to characterize different atmospheric parameters and why specific wavelengths must sometimes be used are included. Trade-offs among the engineering parameters of a lidar system are discussed, in terms of how they affect signal-to-noise ratios (SNRs). Guidance is also provided for identifying and understanding common problems in lidar systems and for evaluating their performance.

This book contains material not generally found in other lidar books, including a simple and thorough treatment of the geometrical (crossover) function, a treatment of depolarization in lidar that is consistent with scattering theory and optical physics, a detailed explanation of the signal inversion algorithm known as the Klett retrieval, information on digital signal processing applied to lidar signals, and several implications of Poisson statistics for noise levels in lidar signals. An elastic backscatter lidar, the most basic type, is emphasized because its engineering principles are common to all types of lidars. The basic principles of coherent detection are covered, but its implementation in lidar systems is outside the scope of this book. Software is a key element of any lidar system, so some general requirements for it are mentioned, but software engineering is also outside our scope.

The SNR in lidar signals is used here as the measure of merit that addresses random errors that can be reduced by signal averaging. SNR is fundamental because, no matter what the application, some minimum SNRs must be achieved in the recorded lidar signal to enable the desired accuracy of a scientific measurement. Systematic errors are more problematic, as they cannot be reduced by averaging. They can arise from both optical and electronic distortions of the signal, so engineering “best practices” for avoiding signal distortions are emphasized throughout the book. The other main lidar challenges addressed here include accommodating the large dynamic range of lidar signals and the problem of having only one signal but several unknowns.

This book was written in the tradition of an older generation of researchers passing along technical expertise, gained through long experience, to younger generations. It is often said that we learn more from our mistakes than our successes, so in the hope that such knowledge is transferable, we have included examples of oversights, insufficient attention to detail, and outright blunders that we committed over a period of three decades. Most of the material is based on our direct experience, but for completeness, some sections had to be largely summarized from other books, which are cited. The chapters on atmospheric optics and on optical detection are examples of this practice. We apologize for any errors that we may have introduced in the summaries.

The lectures for the Agnes Scott College students were developed as part of their joint project with the GTRI to develop a lidar system for teaching and research in the undergraduate environment. The students chose the name EARL for Eye safe

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Atmospheric Research Lidar. EARL is used as an example system throughout the book. ALE (Astronomical Lidar for Extinction) is also used as an example; ALE resulted from a joint project between GTRI and the University of New Mexico.

Several other GTRI researchers contributed technical materials for the Georgia Tech short course over the years, especially Chris Valenta, Nathan Meraz, Ryan James, and Leda Sox. Kristin Youngquist drafted many of the illustrations for it. Their technical materials and illustrations also appear in this book. The chapter on optomechanics began with a guest lecture by David Smith. The projects with Agnes Scott College were funded by the National Science Foundation under the grant numbers 0116039 and DUE-0836997, and additional support was provided by Agnes Scott College and the College of Engineering at Georgia Tech. ALE was funded by the National Science Foundation grant number 0421087. Much of the work of developing this book would not have been possible without the resources of the Glen P. Robinson Chair in Electro-Optics in GTRI, which Dr. Gimmestad held from 2002 to 2015. The authors gratefully acknowledge all of these types of support.

Glossary

The symbols used in this book are listed below, with units where applicable. Because several technical disciplines are covered, many of the symbols have different meanings in different sections. For this reason, the section numbers are listed where the meanings are first used. Some symbols formed by adding subscripts, and others used only in one place, are not listed.

Symbol	First used in section	Units	Meaning
a	4.6.3		Angstrom parameter
a	8.7.1		parameter in model for PMT secondary emission ratio
A	2.2	m^2	receiver area
A	3.3.2	m	amplitude of oscillation
A	4.1.2	m^2	geometrical area of a particle
A	9.1	V	amplitude of electronic waveform
b	9.1		individual digital bit
B	8.1	Hz	electronic bandwidth
B_{opt}	2.3	µm	receiver optical bandpass
B_v	3.3.2	J, cm^{-1}	rotational energy scale
c	1.1	m/s	speed of light
c_n	10.1.1		filter function coefficient
C	2.2	(varies)	lidar calibration constant
C	4.1.2	m^2	Mie cross section of a particle
C	10.1.1		filter coefficient normalizing factor
d	3.3.2	m	distance or length
d	4.4		depolarized fraction of backscattered light
D	2.4	m	diameter
D_1, D_2	3.3.4		designations of sodium spectral lines
e^-	8.2		an electron
E	3.1.1	W/m^2	irradiance
E	5.2.8	V/m	electric field strength
E	8.7.1	V	voltage between dynodes
E_{phot}	2.2	J	energy of a photon

E_{pulse}	2.2	J	energy in a pulse of laser light
E_{rot}	3.3.2	J, cm^{-1}	energy of rotation
E_{vib}	3.3.2	J, cm^{-1}	energy of vibration
E_0	4.6.1	W/m^2	exo-atmospheric solar irradiance
E	7.1	Pa	elastic modulus
E_c	8.7.2	eV	energy at bottom of conduction band
E_v	8.7.2	eV	energy at top of valence band
E_g	8.7.2	eV	band gap energy
E_F	8.7.2	eV	Fermi energy
E_{rms}	9.14	V	error in digital output for sine wave
f	5.1	m	focal length
f_c	8.1	Hz	critical frequency of an electronic filter
f_c	10.1.1	bin^{-1}	cutoff frequency of an FIR filter
f /	6.3.2		f-number (focal ratio)
F	7.1	N	force
F	8.7.2		APD noise factor
F	11.2		coefficient of finesse of an etalon
$F_v(J)$	3.3.2	J, cm^{-1}	term value for rotational energy
$F(E)$	8.7.2		occupancy of electronic states
Δf	8.6	Hz	width of electronic bandpass filter
g	11.3	m/s^2	acceleration due to gravity
$g(t)$	8.1		a function in the time domain
G	8.2		electronic gain
G	8.7.1		PMT current gain
G	10.1.1		gain of an FIR filter
G_v	3.3.2	J, cm^{-1}	term value for vibrational energy
$G(R)$	2.2		the geometrical function
$G(f)$	8.1		a function in the frequency domain
h	2.2	Js	Planck constant
h	3.2	m, km	altitude
h	6.3.2	m	image size
$h(n)$	9.14		measured probability of code n
$\hbar$	3.3.2	Js	Planck constant divided by 2π.
H	2.4	km	air density scale height
i	8.1	A	current
$\overline{i_N^2}$	8.3	A^2	mean-square noise current
I	3.1.1	(W/sr)	radiant intensity
I	3.3.2	(kg·m)	moment of inertia
I	4.4.1	W	power of backscattered light on receiver
J		3.3.2	rotational quantum number
J	8.7.1	e$^-$/cm^2·s	thermionic current density
k	3.3.1	J/K	Boltzmann constant
k	3.3.2	N/m	Hooke's law spring constant

k_T	2.2		optical efficiency of transmitter
k_R	2.2		optical efficiency of receiver
k_{ion}	8.7.2		hole-to-electron ionization coefficient ratio
$\vec{k}$	5.2.8	m^{-1}	wave vector
L	5.2.3	m	length
L_λ	2.3	$W/m^2{\cdot}\mu m{\cdot}sr$	spectral radiance
m	3.3.1	kg	mass
m	4.6.1		air mass
m	9.1.2		bin number in an FFT
m	11.5		mixing ratio
M	4.4		Mueller matrix
M	6.1.3		magnification
M	8.7.2		APD gain
M	9.1.2		number of points in an FFT
M	9.14		number of samples required
M^2	5.2.5		beam propagation ratio
n	3.2		refractive index
n	10.1.2		number of range bins
n_S	2.1		number of signal (laser) photons detected
n_B	2.1		number of background photons detected
n_D	2.1		number of dark counts
N_B	2.3		the number of background photons received per range bin (for each laser pulse)
N	3.2	m^{-3}	molecular number density
N	8.7.1		number of dynode stages
N	9.1		number of bits
N	10.1.1	range bins	filter width
N_0	2.2		number of photons in each laser pulse
$N_S(R)$	2.2		number of signal (laser) photons received in a bin at range R per laser pulse
$N(J)$	3.3.2		population of state with rotational quantum number J
$O(R)$	6.3.3		overlap function
$p(n)$	9.14		theoretical probability of code n
P	3.2	(kPa)	pressure
P	5.2.8	C/m^2	dielectric polarization
P	8.1	W	electrical power
P_0	2.2	W	power in the laser pulse
P_S	2.2	W	optical signal power
P_B	2.2	W	optical background power
$P(\theta)$	3.1.1		scattering phase function
q	5.2.6		laser cavity mode number
q	8.3	C	charge on the electron

Q	4.1.2		Mie scattering efficiency factor
Q	5.2.4		laser cavity quality factor
r_{avg}	8.3	s^{-1}	average rate
r_0	8.6	cm	Fried parameter
R	1.1	m	range
R	4.6.1	A.U.	Earth–Sun distance
R	6.2		reflectance
R	7.2.1	m	radius of mirror
R	8.1	Ω	resistance
R	9.2	1/s	count rate in photon counter
R	11.3	J/mol·K	gas constant
R_{sca}	4.5.1		scattering ratio
ΔR	2.2	m	range bin length
S	4.4.1		electronic signal from lidar receiver
S	8.3	A/W	detector responsivity
S_{m}	3.2	sr	molecular lidar ratio
S_{a}	4.2.4	sr	aerosol lidar ratio
S_k	10.1.1		the *k*th raw data point
S'_k	10.1.1		the *k*th filtered data point
$S(R)$	6.3.3	m	edge of cone of light or shadow
t	7.1	m	thickness of mirror
t_{a}	9.1.3	s	aperture error
t_{d}	9.2	s	dead time in photon counter
T	3.2	(°C, K)	temperature
$T^2(R)$	2.2		two-way transmittance
v	3.3.1	(m/s)	velocity
V	4.2.4	m	visibility
V	8.1	V	voltage
V_{out}	4.6.2	volts	photometer output signal
V_0	4.6.2	volts	photometer signal for zero air mass
V_{wind}	8.6	ms^{-1}	wind speed
V_Q	9.1	V	quantum voltage level
w_D	8.7.2	cm	width of depletion region
w_n	10.1.1		filter coefficient weight
W	5.2.5	m	laser beam radius
x_i	2.1		the *i*th outcome of a set of trials
$\overline{x}$	2.1		the mean of a set of trials
$X(R)$	2.2		range-corrected lidar signal
ΔY	7.1	m	mirror sag
z^*	2.1	std. dev.	confidence interval
z_R	5.2.5	m	Rayleigh range
δz	10.1.1	m	sampling interval
Δz	10.1.1	m	range resolution

α	3.1.2		scattering parameter
α	7.1	1/°C	coefficient of thermal expansion (also CTE)
α	8.7.1		parameter in model for PMT secondary emission ratio
α	8.7.2	cm^{-1}	absorption coefficient
α	11.4	m^{-1}	lidar extinction coefficient
β	9.1.4		desired accuracy of measurement
β	3.1.1	m^{-1}	volume total scattering coefficient
$\beta(\theta)$	3.1.1	$\mathrm{m}^{-1}\mathrm{sr}^{-1}$	volume angular scattering coefficient
$\beta(R)$	2.2	$\mathrm{m}^{-1}\mathrm{sr}^{-1}$	volume backscatter coefficient
Γ	8.7.1		PMT excess noise factor
δ	4.4.3		lidar depolarization ratio
δ	6.3.3	radians	angle between transmitter and receiver OAs
δ	8.7.1		secondary emission ratio
ε	7.1		strain (normalized length change)
ε	9.1	V	quantization error
ε_0	5.2.8	F/m	dielectric constant
η	8.3		quantum efficiency
θ	2.3	rad	receiver FOV plane angle
θ	3.1.1	degrees, rad	scattering angle
θ	5.2.5	rad	laser beam divergence
λ	2.2	nm, µm, m	wavelength
μ	10.1.2	counts	background in lidar data
ν	2.2	Hz	frequency
ν	3.3.2		vibrational quantum number
ν	7.1		Poisson's ratio
$\bar{\nu}$	3.3.2	cm^{-1}	spatial frequency (wavenumbers)
$\Delta\nu$	8.6	Hz	range of signal frequencies
ρ	10.1.3		scale factor
σ	7.1	Pa	Stress
σ	2.1		standard deviation
σ^2	2.1		Variance
$\sigma(r)$	2.2	m^{-1}	extinction coefficient
$\sigma(\theta)$	4.1.1	m^2/sr	angular scattering cross section
σ_p	4.1.1	m^2/sr	scattering cross section of a particle
σ	11.4	m^2	absorption cross section of molecule
$(d\sigma / d\Omega)_\pi$	11.5.1	m^2/sr	Raman differential backscattering cross section
τ	1.1	s	time interval
τ	4.6.1		optical depth
τ_{pulse}	2.2	s	pulse width
τ_{int}	8.3	s	detector integration time
ϕ	3.2	rad	angle measured from y-axis

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ϕ	8.4	Wb	magnetic flux
ϕ	8.6	rad	phase angle
Φ	8.7.1	eV	work function
χ	5.2.8		susceptibility
χ_e	3.3.2		anharmonicity constant
ω	3.3.2	rad/s	angular velocity of rotation
ω	5.2.8	rad/s	angular frequency of light
ω_e	3.3.2	cm^{-1}	harmonic wavenumber
Ω	2.3	sr	receiver FOV solid angle

Abbreviations

AC	alternating current
ACCD	accumulation CCD
ADC	analog-to-digital converter (also A to D, A–D, A/D)
AERONET	aerosol robotic network
ALADIN	atmospheric laser Doppler instrument
ALE	Astronomical Lidar for Extinction
ALOMAR	Arctic Lidar Observatory for Middle Atmosphere Research
AMU	atomic mass unit
AMV	atmospheric motion vector
ANSI	American National Standards Institute
AOD	aerosol optical depth
APD	avalanche photodiode
AR	anti-reflection
AU	arbitrary units (on plot axes)
BBO	β-barium borate
BPP	beam parameter product
CAD	cloud-aerosol discriminator
CALIOP	cloud-aerosol lidar with orthogonal polarization
CALIPSO	cloud-aerosol lidar and infrared pathfinder satellite
CB	citizen’s band (radio)
CCFU	cloud climatology field unit
CDRH	Center for Devices and Radiological Health
CH	Chanin–Hauchecorne (algorithm)
CR	color ratio
CTE	coefficient of thermal expansion
CW	continuous wave
DAOD	differential atmospheric optical depth
DC	direct current
DFG	difference frequency generation
DIAL	differential absorption lidar
DNL	differential nonlinearity
EARL	Eye safe Atmospheric Research Lidar
EMI	electromagnetic interference
ENOB	effective number of bits

ERBW	effective resolution bandwidth
FAA	Federal Aviation Administration
FADOF	Faraday anomalous dispersion optical filter
FDA	Food and Drug Administration
FFT	fast Fourier transform
FHWM	full width at half maximum
FIR	far infrared, also finite impulse response
FOV	field of view
FPA	focal plane array
FSR	full-scale range
GHG	greenhouse gas
GLOW	Goddard Lidar Observatory for Winds
GMAO	Global Modeling and Assimilation Office
GTRI	Georgia Tech Research Institute
HERA	hybrid extinction retrieval algorithm
HF	high frequency
HHG	high harmonic generation
HITRAN	high-resolution transmission molecular absorption database
HLOS	horizontally projected line of sight
HSRL	high spectral resolution lidar
IABS	integrated aerosol backscatter
IMD	intermodulation distortion
INL	integral nonlinearity
IPDA	integrated path differential absorption
ISO	International Organization for Standardization
KDP	potassium dihydrogen phosphate
KTP	potassium titanyl phosphate
LBLRTM	line-by-line radiative transfer model
LCVR	liquid crystal variable phase retarder
LHC	left-hand circular polarization
LO	local oscillator
LR	long range (receiver)
LSB	least significant bit
LWIR	long-wave infrared
MERLIN	methane remote sensing lidar mission
MOPA	master oscillator – power amplifier
MPE	maximum permissible exposure
MWIR	mid-wave infrared
NAT	nitric acid trihydrate
NCAR	National Center for Atmospheric Research
ND	neutral density
NDACC	Network for the Detection of Atmospheric Composition Change
NEP	noise equivalent power

NIR	near infrared
NLC	noctilucent cloud (also called polar mesospheric cloud)
NOHD	nominal ocular hazard distance
NWP	numerical weather prediction
OA	optical axis
OD	optical depth
OPA	optical parametric amplification
OPO	optical parametric oscillator
PBL	planetary boundary layer
PDF	probability density function
PDR	particle depolarization ratio
PER	polarization extinction ratio
PHD	pulse height distribution
PIN	P-type, intrinsic, N-type photodiode
PIV	particle imaging velocimetry
PM	10 particulate matter with aerodynamic diameter less than 10 µm
PM	2.5 particulate matter with aerodynamic diameter less than 2.5 µm
PMT	photomultiplier tube
PRF	pulse repetition frequency
PSC	polar stratospheric cloud
QE	quantum efficiency (also called η)
REAL	Raman-shifted Eye safe Aerosol Lidar
RF	radio frequency
RHC	right-hand circular polarization
RISTRA	rotated image singly resonant twisted rectangle
RTV	room temperature vulcanizing
SAE	Society of Automotive Engineers
SFDR	spurious-free dynamic range
SFG	sum frequency generation
SHG	second harmonic generation
SIBYL	selective iterated boundary locator
SNDR	signal-to-noise-and-distortion ratio (also S/N+D, SINAD)
SNR	signal-to-noise ratio
SOP	standard operating procedure
SPAD	single-photon avalanche diode
SR	short range (receiver)
SRS	stimulated Raman scattering
SSW	sudden stratospheric warming
STP	standard temperature and pressure
SWIR	short-wave infrared
TEM	transverse electromagnetic mode
THD	total harmonic distortion
THG	third harmonic generation
TIA	transimpedance amplifier

TIR	Total internal reflection
TROPOS	Leibniz Institute for Tropospheric Research
ULE	ultra-low expansion
UTS	unified thread standard
UV	ultraviolet
VHF	very high frequency
VIL	volume imaging lidar
VIS	visible