

Contents

<i>Preface</i>	<i>xiii</i>
1 Introduction to LiDAR	1
1.1 Context of LiDAR	1
1.2 Conceptual Discussion of LiDAR	5
1.3 Terms for Active EO Sensing	6
1.4 Types of LiDARs	8
1.4.1 Some LiDARs for surface-scattering (hard) targets	10
1.4.2 Some LiDARs for volume-scattering (soft) targets	11
1.5 LiDAR Detection Modes	11
1.6 Flash LiDAR versus Scanning LiDAR	13
1.7 Eye Safety Considerations	14
1.8 Laser Safety Categories	16
1.9 Monostatic versus Bistatic LiDAR	17
1.10 Transmit/Receive Isolation	18
1.11 Major Devices in a LiDAR	18
1.11.1 Laser sources	18
1.11.2 Receivers	19
1.11.3 Apertures	19
1.12 Organization of the Book	20
Problems and Solutions	20
References	27
2 History of LiDAR	29
2.1 Rangefinders, Altimeters, and Designators	30
2.1.1 First steps of rangefinders	30
2.1.2 Long-distance rangefinders	32
2.1.3 Laser altimeters	34
2.1.4 Laser designators	35
2.1.5 Obstacle avoidance applications	36
2.2 Early Coherent LiDARs	38
2.2.1 Early work at MIT/Lincoln Lab	38
2.2.2 Early coherent LiDAR airborne applications	38
2.2.3 Autonomous navigation using coherent LiDAR	41

2.2.4	Atmospheric wind sensing	43
2.2.4.1	Early coherent LiDAR wind sensing	43
2.2.4.2	Early noncoherent wind measurement	46
2.2.5	Laser vibrometry	48
2.2.6	Synthetic-aperture LiDAR	50
2.3	Early Space-based LiDAR	51
2.4	Flight-based Laser Vibrometers	55
2.5	Environmental LiDARs	56
2.5.1	Early steps	56
2.5.2	Multiwavelength LiDARs	57
2.5.3	LiDAR sensing in China	57
2.5.4	LiDAR sensing in Japan	59
2.6	Imaging LiDARs	61
2.6.1	Early LiDAR imaging	61
2.6.2	Imaging LiDARs for manufacturing	63
2.6.3	Range-gated imaging programs	64
2.6.4	3D LiDARs	65
2.6.5	Imaging for weapon guidance	66
2.6.6	Flash-imaging LiDARs	67
2.6.7	Mapping LiDARs	68
2.6.7.1	Terrain mapping	68
2.6.8	LiDARs for underwater: Laser-based bathymetry	70
2.6.9	Laser micro-radar	71
2.6.9.1	Optical coherence tomography	71
2.6.9.2	Wavefront sensing	72
2.7	History Conclusion	74
	References	76
3	LiDAR Range Equation	89
3.1	Introduction to the LiDAR Range Equation	89
3.2	Illuminator Beam	89
3.3	LiDAR Cross-Section	92
3.3.1	Cross-section of a corner cube	95
3.4	Link Budget Range Equation	96
3.5	Atmospheric Effects	99
3.5.1	Atmospheric scattering	101
3.5.2	Atmospheric turbulence	102
3.5.3	Aero-optical effects on LiDAR	103
3.5.4	Extended (deep) turbulence	103
3.5.5	Speckle	104
	Problems and Solutions	105
	Notes and References	112

4	Types of LiDAR	113
4.1	Direct-Detection LiDAR	113
4.1.1	1D range-only LiDAR	113
4.1.2	Tomographic imaging LiDAR	114
4.1.3	Range-gated active imaging (2D LiDAR)	116
4.1.4	3D scanning LiDAR	117
4.1.5	3D flash imaging	119
4.1.6	3D mapping applications	120
4.1.6.1	GNSS position data collection	121
4.1.6.2	Ground surveys	121
4.1.6.3	Data acquisition conditions	122
4.1.6.4	Data processing and dissemination	123
4.1.7	Laser-induced breakdown spectroscopy	136
4.1.8	Laser-induced fluorescence	136
4.1.9	Active multispectral LiDAR	137
4.1.10	LiDARs using polarization as a discriminant	139
4.2	Coherent LiDAR	140
4.2.1	Laser vibration detection	140
4.2.2	Range-Doppler imaging LiDAR	142
4.2.3	Speckle imaging LiDAR	143
4.2.4	Aperture-synthesis-based LiDAR	144
4.2.4.1	Synthetic-aperture LiDAR (SAL)	146
4.2.4.2	Inverse SAL	149
4.3	Multiple-Input, Multiple-Output Active EO Sensing	150
	Appendix 4.1: MATLAB® program showing synthetic-aperture pupil planes and MTFs	160
	Problems and Solutions	172
	References	178
5	LiDAR Sources and Modulations	181
5.1	Laser Background Discussion	181
5.2	Laser Waveforms for LiDAR	184
5.2.1	Introduction	184
5.2.2	High time-bandwidth product waveforms	186
5.2.2.1	Polypulse waveforms	187
5.2.2.2	Linear frequency modulation	187
5.2.2.3	Pseudo-random-coded LiDAR	188
5.2.3	Radiofrequency modulation of a direct-detection LiDAR	189
5.2.4	Femtosecond-pulse modulation LiDAR	190
5.2.5	Laser resonators	191
5.2.6	Three-level and four-level lasers	192
5.2.7	Laser-pumping considerations	194
5.2.8	Q-switched lasers for LiDAR	194

5.2.8.1	Pockels cells	195
5.2.9	Mode-locked lasers for LiDAR	196
5.2.10	Laser seeding for LiDAR	199
5.2.11	Laser amplifiers for LiDAR	200
5.3	Lasers Used in LiDAR	202
5.3.1	Diode lasers for LiDAR	203
5.3.1.1	Interband, edge-emitting diode lasers	203
5.3.1.2	Interband, vertical-cavity diode lasers	207
5.3.1.3	Quantum cascade lasers	208
5.3.1.4	Interband cascade lasers	210
5.4	Bulk Solid State Lasers for LiDAR	210
5.4.1	Fiber lasers for LiDAR	211
5.4.1.1	Higher-peak-power waveguide lasers for LiDAR	212
5.4.2	Nonlinear devices to change the LiDAR wavelength	212
5.4.2.1	Harmonic generation and related processes	214
5.4.2.2	Optical parametric generation	218
5.5	Fiber Format	221
	Problems and Solutions	227
	References	232
6	LiDAR Receivers	235
6.1	Introduction to LiDAR Receivers	235
6.2	LiDAR Signal-to-Noise Ratio	237
6.2.1	Noise probability density functions	238
6.2.2	Thermal noise	240
6.2.3	Shot noise	241
6.2.4	Background noise	242
6.2.4.1	Spectral filter technology	243
6.2.4.2	Calculation of background from solar flux	244
6.2.5	Dark current, $1/f$ noise, and excess noise	248
6.3	Avalanche Photodiodes and Direct Detection	248
6.3.1	Linear-mode APD arrays for LiDAR	251
6.3.1.1	InGaAs LMAPD arrays	252
6.3.1.2	HgCdTe LMAPD cameras	265
6.3.1.3	Summary of the advantages and disadvantages of LMAPDs for direct detection	268
6.3.2	Direct-detection GMAPD LiDAR camera	268
6.3.2.1	The effect of a bright sun background on GMAPDs	273
6.3.2.2	Coincidence processing for detection	274
6.3.2.3	Summary of the advantages and disadvantages of GMAPDs for direct detection	278
6.4	Silicon Detectors	279
6.5	Heterodyne Detection	280
6.5.1	Temporal heterodyne detection	281

6.5.2	Heterodyne mixing efficiency	282
6.5.3	Quadrature detection	283
6.5.4	Carrier-to-noise ratio (CNR) for temporal heterodyne detection	285
6.5.5	Spatial heterodyne detection / digital holography	285
6.5.5.1	SNR for spatial heterodyne detection	286
6.5.6	Receivers for coherent LiDARs	287
6.5.6.1	Acousto-optic frequency shifting	287
6.5.7	Geiger-mode APDs for coherent imaging	289
6.5.8	A p-i-n diode or LMAPD for coherent imaging	291
6.5.9	Sampling associated with temporal heterodyne sensing	292
6.6	Long-Frame-Time Framing Detectors for LiDAR	292
6.7	Ghost LiDARs	293
6.8	LiDAR Image Stabilization	294
6.9	Optical-Time-of-Flight Flash LiDAR	295
6.9.1	Summary of the advantages and disadvantages of OTOF cameras	297
	Problems and Solutions	298
	Notes and References	307
7	LiDAR Beam Steering and Optics	311
7.1	Mechanical Beam-Steering Approaches for LiDAR	311
7.1.1	Gimbals	311
7.1.2	Fast-steering mirrors	313
7.1.3	Risley prisms and Risley gratings	315
7.1.4	Rotating polygonal mirrors	318
7.1.5	MEMS beam steering for LiDAR	320
7.1.6	Lenslet-based beam steering	324
7.1.6.1	All-convex-lens-based steering	324
7.1.6.2	Mixed-lenslet arrays	325
7.2	Nonmechanical Beam-Steering Approaches for Steering LiDAR	
	Optical Beams	326
7.2.1	OPD-based nonmechanical approaches	327
7.2.1.1	Modulo 2π beam steering	327
7.2.1.2	Finest pointing angle	330
7.2.1.3	Largest steering angle for an OPA	331
7.2.1.4	Liquid crystal OPAs	332
7.2.1.5	Liquid crystal fringing field effect on steering efficiency	334
7.2.1.6	Quantization-caused reduction in steering efficiency	335
7.2.1.7	Steerable electro-evanescent optical refraction	336
7.2.1.8	Ferroelectric-SmC*-based beam steering	337
7.2.2	Chip-scale optical phased arrays	338
7.2.3	Electrowetting beam steering for LiDAR	338

7.2.4	Using electronically written lenslets for lenslet-based beam steering	339
7.2.5	Beam steering using EO effects	340
7.2.5.1	Prism-shaped-OPD-based beam steering	341
7.2.5.2	Space-charge-injection-mode KTN beam steering	353
7.2.5.3	Analysis of EO-crystal-film-based beam steering	363
7.2.6	Phased-based nonmechanical beam steering	364
7.2.6.1	Polarization birefringent grating beam steering	364
7.3	Some Optical Design Considerations for LiDAR	368
7.3.1	Geometrical optics	368
7.3.2	Adaptive optics systems	369
7.3.3	Adaptive optical elements	370
	Problems and Solutions	370
	Notes and References	378
8	LiDAR Processing	383
8.1	Introduction	383
8.2	Generating LiDAR Images/Information	383
8.2.1	Range measurement processing	383
8.2.2	Range resolution of LiDAR	384
8.2.2.1	Nyquist sampling a range profile	385
8.2.2.2	Unambiguous range	386
8.2.2.3	Threshold, leading edge, and peak detectors	387
8.2.2.4	Range accuracy, range precision, and range resolution	388
8.2.3	Angle LiDAR processing	389
8.2.3.1	Point spread function	389
8.2.3.2	Microscanning of LiDAR images for improved sampling	390
8.2.3.3	Multiple-subaperture spatial heterodyne processing	391
8.2.4	Gathering information from a temporally coherent LiDAR	392
8.2.4.1	Velocity resolution of LiDAR	393
8.2.4.2	Processing laser vibrometry data	394
8.2.5	General LiDAR Processing	396
8.2.5.1	Definitions of various LiDAR processing steps for geospatial images	396
8.2.5.2	Inertial measurement units	396
8.2.5.3	Data product types	397
8.2.5.4	Grayscale calculations	397
8.2.5.5	Fourier transforms	399
8.2.5.6	Developing 3D maps from LiDAR	400
8.2.6	Target classification using LiDAR	401
	Problems and Solutions	402
	References	408

9	Figures of Merit, Testing, and Calibration for LiDAR	409
9.1	Introduction	409
9.2	LiDAR Characterization and Figures of Merit	409
9.2.1	Ideal point response mainlobe width	410
9.2.2	Integrated sidelobe ratio	411
9.2.3	Peak sidelobe ratio	411
9.2.4	Spurious sidelobe ratio	411
9.2.5	Noise-equivalent vibration velocity	411
9.2.6	Abiguity velocity	412
9.2.7	Unambiguous range	412
9.3	LiDAR Testing	412
9.3.1	Angle/angle/range resolution testing	412
9.3.2	Velocity measurement	414
9.3.3	Measuring range walk	415
9.4	LiDAR Calibration	416
9.4.1	Dark nonuniformity correction	419
9.4.2	Results of correction	421
	Problems and Solutions	424
	References	425
10	LiDAR Performance Metrics	427
10.1	Image Quality Metrics	427
10.1.1	Object parameters	428
10.1.1.1	Additional object characteristics	432
10.2	LiDAR Parameters	433
10.3	Image Parameters: National Imagery Interpretability Rating Scale (NIIRS)	433
10.4	3D Metrics for LiDAR Images	437
10.5	General Image Quality Equations	437
10.6	Quality Metrics Associated with Automatic Target Detection, Recognition, or Identification	439
10.7	Information Theory Related to Image Quality Metrics	440
10.8	Image Quality Metrics Based on Alternative Basis Sets	441
10.9	Eigenmodes	441
10.10	Compressive Sensing	442
10.10.1	Knowledge-enhanced compressive sensing	442
10.10.2	Scale-invariant feature transforms	442
10.11	Machine Learning	443
10.12	Processing to Obtain Imagery	443
10.13	Range Resolution in EO/IR Imagers	444
10.14	Current LiDAR Metric Standards	445
10.15	Conclusion	445
	Appendix 10-1 MATLAB code to Fourier transform an image	445

Problems and Solutions	446
References	455
11 Significant Applications of LiDAR	459
11.1 Auto LiDAR	459
11.1.1 Introduction	459
11.1.2 Resolution	460
11.1.3 Frame rate	462
11.1.4 Laser options	464
11.1.5 Eye safety	464
11.1.6 Unambiguous range	465
11.1.7 Required laser energy per pulse and repetition rate	465
11.1.8 Obscurants considered for auto LiDAR	470
11.1.9 Keeping the auto LiDAR aperture clear	470
11.2 3D Mapping LiDAR	471
11.2.1 Introduction to 3D mapping LiDAR	471
11.2.2 3D Mapping LiDAR design	477
11.3 Laser Vibrometers	477
11.3.1 Designing a laser vibrometer	480
11.4 Wind Sensing	481
Problems and Solutions	483
References	496
<i>Index</i>	499