Contents

Preface – Second Edition *xiii*
Preface – First Edition *xv*

1 Origins and Manifestations of Speckle **1**
1.1 General Background 1
1.2 Intuitive Explanation of the Cause of Speckle 3
1.3 Some Mathematical Preliminaries 4

2 Random Phasor Sums **7**
2.1 First and Second Moments of the Real and Imaginary Parts of the Resultant Phasor 8
2.2 Random Walk with a Large Number of Independent Steps 10
2.3 Random Phasor Sum Plus a Known Phasor 13
2.4 Sums of Random Phasor Sums 16
2.5 Random Phasor Sums with a Finite Number of Equal-Length Components 18
2.6 Random Phasor Sums with a Nonuniform Distribution of Phases 20

3 First-Order Statistical Properties of Optical Speckle **25**
3.1 Definition of Intensity 25
3.2 First-Order Statistics of the Intensity and Phase 27
3.2.1 Large number of random phasors 28
3.2.2 Constant phasor plus a random phasor sum 30
3.2.3 Finite number of equal-length phasors 34
3.2.4 Finite number of random-length phasors 37
3.2.5 Random number of random-length phasors 42
3.3 Sums of Speckle Patterns 46
3.3.1 Sums on an amplitude basis 46
3.3.2 Sum of two independent speckle intensities 46
3.3.3 Sum of *N* independent speckle intensities 50
3.3.4 Sums of correlated speckle intensities 52
3.4 Partially Developed Speckle 55
3.5 Speckled Speckle, or Compound Speckle Statistics 59
3.5.1 Speckle driven by a negative-exponential intensity distribution 59
3.5.2 Speckle driven by a gamma intensity distribution 61

3.5.3 Sums of independent speckle patterns driven by a gamma intensity distribution 62

4 Higher-Order Statistical Properties of Speckle 65

4.1 Multivariate Gaussian Statistics 65
4.2 Application to Speckle Fields 66
4.3 Multidimensional Statistics of Speckle Amplitude, Phase, and Intensity 68
4.3.1 The bivariate density function 69
4.3.2 Joint density function of the amplitudes 71
4.3.3 Joint density function of the phases 73
4.3.4 Joint density function of the intensities 76
4.4 Bivariate Statistics of a Linearly Polarized Speckle Pattern 78
4.5 Speckle and Polarization 79
4.5.1 The polarization ellipse 79
4.5.2 The Stokes parameters and the Poincaré sphere 81
4.6 Statistics of the Stokes Parameters in a Fully Developed Speckle Pattern 83
4.6.1 Statistics of S_0 83
4.6.2 Statistics of S_1 87
4.6.3 Statistics of S_2 87
4.6.4 Statistics of S_3 91
4.6.5 Polarization speckle 93
4.7 Statistics of Integrated and Blurred Speckle 94
4.7.1 Mean and variance of integrated speckle 95
4.7.2 Approximate result for the probability density function of integrated intensity 100
4.7.3 "Exact" result for the probability density function of integrated intensity 102
4.7.4 Integration of partially polarized speckle patterns 108
4.8 Statistics of Derivatives of Speckle Intensity and Phase 110
4.8.1 Background 110
4.8.2 Derivatives of speckle phase: ray directions in a speckle pattern 113
4.8.3 Derivatives of speckle intensity 116
4.8.4 Level crossings of speckle patterns 119
4.9 Zeros of Speckle Patterns: Optical Vortices 122
4.9.1 Conditions required for a zero of intensity to occur 123
4.9.2 Properties of speckle phase in the vicinity of a zero of intensity 123
4.9.3 The density of vortices in fully developed speckle 125
4.9.4 The density of vortices for fully developed speckle plus a coherent background 127

5 Spatial Structure of Speckle **129**
5.1 Autocorrelation Function and Power Spectrum of Speckle 129
5.1.1 Free-space propagation geometry 129
5.1.2 Imaging geometry 137
5.2 Speckle Size in Depth 138
5.3 Dependence of Speckle on Scatterer Microstructure 141
5.3.1 Surface vs. volume scattering 141
5.3.2 Effect of a finite correlation area of the scattered wave 142
5.3.3 A regime where speckle size is independent of scattering spot size 147
5.4 Effects of Surface Microstructure on the Reflected Wave 149
5.4.1 Correlation function of the reflected wave 151
5.4.2 Illumination normal to the surface 153
5.5 Effects of a Change of Illumination Angle in Free-Space Propagation 156
5.6 Effect of a Change of Wavelength in Free-Space Propagation 158
5.7 Simultaneous Changes of Illumination Angle and Wavelength 161
5.8 Speckle in a Simple Imaging System: In-Focus Case 162
5.9 Speckle in a Simple Imaging System: Out-of-Focus Cases 166
5.10 Effects of Pupil Size and rms Roughness on Speckle Contrast 167
5.11 Properties of Speckle Resulting from Volume Scattering 170

6 Optical Methods for Suppressing Speckle **175**
6.1 Polarization Diversity 176
6.2 Temporal Averaging with a Moving Diffuser 177
6.2.1 Background 177
6.2.2 Smooth object 184
6.2.3 Rough object 186
6.3 Wavelength and Angle Diversity 188
6.3.1 Free-space propagation: reflection geometry 189
6.3.2 Free-space propagation: transmission geometry 199
6.3.3 Imaging geometry 203
6.4 Temporal and Spatial Coherence Reduction 205
6.4.1 Coherence concepts in optics 205
6.4.2 Moving diffusers and coherence reduction 208
6.4.3 Speckle suppression by reduction of temporal coherence 210
6.4.4 Speckle suppression by reduction of spatial coherence 215
6.5 Use of Temporal Coherence to Destroy Spatial Coherence 221
6.6 Compounding Speckle Suppression Techniques 222

7 Speckle in Certain Imaging Applications **223**
7.1 Speckle in the Eye 223
7.2 Speckle in Holography 226
7.2.1 Principles of holography 226
7.2.2 Speckle suppression in holographic images 228

7.3 Speckle in Optical Coherence Tomography 231
7.3.1 Overview of the OCT imaging technique 231
7.3.2 Analysis of OCT 232
7.3.3 Speckle and speckle suppression in OCT 236
7.4 Speckle in Optical Projection Displays 240
7.4.1 Anatomies of projection displays 241
7.4.2 Speckle suppression in projection displays 244
7.4.3 Polarization diversity 245
7.4.4 A moving screen 246
7.4.5 Wavelength diversity 248
7.4.6 Angle diversity 249
7.4.7 Overdesign of the projection optics 250
7.4.8 Changing the diffuser projected onto the screen 252
7.4.9 Specially designed screens 264
7.5 Speckle in Projection Microlithography 266
7.5.1 Coherence properties of excimer lasers 267
7.5.2 Temporal speckle 268
7.5.3 From exposure fluctuations to line position fluctuations 270
7.6 Speckle in the Image of a "Smooth" Surface 272
7.6.1 Symmetry of the spectral intensity in the focal plane 274
7.6.2 Bright-field imaging 275
7.6.3 Dark-field imaging 277

8 Speckle in Certain Nonimaging Applications 279

8.1 Speckle in Multimode Fibers 279
8.1.1 Modal noise in fibers 281
8.1.2 Statistics of constrained speckle 283
8.1.3 Frequency dependence of modal noise 287
8.2 Effects of Speckle on Optical Radar Performance 293
8.2.1 Spatial correlation of the speckle returned from distant targets 294
8.2.2 Speckle at low light levels 297
8.2.3 Detection statistics: direct detection 300
8.2.4 Detection statistics: heterodyne detection 305
8.2.5 Comparison of direct detection and heterodyne detection 315
8.2.6 Reduction of the effects of speckle in optical radar detection 318
8.3 A Spectrometer Based on Speckle 318

9 Speckle and Metrology 321

9.1 Speckle Photography 321
9.1.1 In-plane displacement 323
9.1.2 Simulation 325
9.1.3 Properties of the spectra $I_k(\nu_X, \nu_Y)$ 327
9.1.4 Limitations on the amount of the motion (x_0, y_0) 330
9.1.5 Analysis with multiple specklegram windows 331

9.1.6 Object rotation 332
9.2 Speckle Interferometry 333
9.2.1 Systems that use photographic detection 333
9.2.2 Electronic speckle pattern interferometry (ESPI) 337
9.2.3 Speckle shearing interferometry 340
9.3 From Fringe Patterns to Phase Maps 343
9.3.1 The Fourier transform method 344
9.3.2 Phase-shifting speckle interferometry 345
9.3.3 Phase unwrapping 347
9.4 Vibration Measurement Using Speckle 349
9.5 Speckle and Surface Roughness Measurements 352
9.5.1 RMS surface height and surface covariance area from speckle contrast 353
9.5.2 RMS surface height from two-wavelength decorrelation 354
9.5.3 RMS surface height from two-angle decorrelation 355
9.5.4 Surface-height standard deviation and covariance function from measurement of the angular power spectrum 356

10 Speckle in Imaging Through the Atmosphere 359
10.1 Background 359
10.2 Short- and Long-Exposure Point-Spread Functions 361
10.3 Long- and Short-Exposure Average Optical Transfer Functions 362
10.4 Statistical Properties of the Short-Exposure OTF and MTF 364
10.5 Astronomical Speckle Interferometry 370
10.5.1 Object information that is retrievable 370
10.5.2 Results of a more complete analysis of the form of the speckle transfer function 373
10.6 The Cross-Spectrum or Knox–Thompson Technique 374
10.6.1 The cross-spectrum transfer function 375
10.6.2 Recovering full object information from the cross-spectrum 377
10.7 The Bispectrum Technique 379
10.7.1 The bispectrum transfer function 380
10.7.2 Recovering full object information from the bispectrum 381
10.8 Speckle Correlography 382

Appendix A Linear Transformations of Speckle Fields 385

Appendix B Contrast of Partially Developed Speckle Intensity and Phase 389

Appendix C Calculations Leading to the Statistics of the Derivatives of Intensity and Phase 395
C.1 The Correlation Matrix 395
C.2 Joint Density Function of the Derivatives of Phase 398
C.3 Joint Density Function of the Derivatives of Intensity 399
C.4 Parameters for Various Scattering Spot Shapes 400

Appendix D Analysis of Wavelength and Angle Dependence of Speckle **403**
D.1 Free-Space Geometry 403
D.2 Imaging Geometry 407

Appendix E Speckle Contrast When a Dynamic Diffuser is Projected onto a Random Screen **411**
E.1 Random Phase Diffusers 411
E.2 Diffuser that Just Fills the Projection Optics 414
E.3 Diffuser that Overfills the Projection Optics 415

Appendix F Statistics of Constrained Speckle **417**

Appendix G Sample *Mathematica* Programs for Simulating Speckle **421**
G.1 Speckle Simulation With Free-Space Propagation 421
G.2 Speckle Simulation With an Imaging Geometry 421

References *425*

Index *439*