References

1. J. D. Jackson, *Classical Electrodynamics*, 3rd Ed., John Wiley & Sons, Inc., New York, NY (1998).

2. C. C. Davis, *Lasers and Electro-Optics: Fundamentals and Engineerng*, 3rd Ed., Cambridge University Press (1996).

3. J. Verdeyen, *Laser Engineering*, Prentice Hall (1994).

4. M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*, 7th Ed., Cambridge University Press (1999).

5. J. W. Goodman, *Introduction to Fourier Optics*, 3rd Ed., Roberts & Co., Greenwood Village, CO (2005).

6. J. W. Goodman, *Statistical Optics*, John Wiley & Sons, Inc., New York, NY (1985).

7. The Mathworks, "Matlab," 2007. Version 2007a.

8. E. O. Brigham, *Fast Fourier Transform and Its Applications*, Prentice Hall, Upper Saddle River, NJ (1998).

9. M. Frigo and S. G. Johnson, "The design and implementation of FFTW3," Proc. IEEE **93**(2), pp. 216–231 (2005). special issue on "Program Generation, Optimization, and Platform Adaptation".

10. W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes: The Art of Scientific Computing*, 3rd Ed., Cambridge University Press (2007).

11. Visual Numerics, Inc., "IMSL Numerical Libraries." computer software.

12. B. Sklar, *Digital Communications: Fundamentals and Applications*, 2nd Ed., Prentice Hall, Upper Saddle River, NJ (2001).

13. J. F. James, *A Student's Guide to Fourier Transforms: with Applications in Physics and Engineering*, 2nd Ed., Cambridge University Press, Cambridge, UK (2002).

14. F. G. Stremler, *Introduction to Communication Systems*, 3rd Ed., Prentice Hall (1990).

15. L. C. Andrews and R. L. Phillips, *Laser Beam Propagation Through Random Media*, 2nd Ed., SPIE Press, Bellingham, WA (2005).

16. Optical Research Associates, "CODE V." computer software.

17. Lambda Research Corporation, "OSLO." computer software.

18. ZEMAX Development Corporation, "ZEMAX." computer software.

19. V. N. Mahajan, *Optical Imaging and Aberrations Part II: Wave Diffraction Optics*, SPIE Press, Bellingham, WA (1998).

20. C. Zhao and J. H. Burge, "Orthonormal vector polynomials in a unit circle, Part I: basis set derived from gradients of Zernike polynomials," *Opt. Express* **15**(26), pp. 18014–18024 (2007).

21. C. Zhao and J. H. Burge, "Orthonormal vector polynomials in a unit circle, Part II : completing the basis set," *Opt. Express* **16**(9), pp. 6586–6591 (2008).

22. R. Noll, "Zernike polynomials and atmospheric turbulence," *J. Opt. Soc. Am.* **66**, pp. 207–211 (1976).

23. M. C. Roggemann and B. M. Welsh, *Imaging Through Turbulence*, CRC Press, Inc., New York, NY (1996).

24. R. Navarro, J. Arines, and R. Rivera, "Direct and inverse discrete Zernike transform," *Opt. Express* **17**(26), pp. 24269–24281 (2009).

25. E. Anderson, Z. Bai, C. Bischof, J. Demmel, J. Dongarra, J. D. Croz, A. Greenbaum, S. Hammarling, A. McKenney, and D. Sorenson, "LAPACK: A portable linear algebra library for high-performance computers," Tech. Rep. CS-90-105, University of Tennessee, Knoxville, TN (1990).

26. J. Dongarra, "Basic linear algebra subprograms technical forum standard," *International Journal of High Performance Applications and Supercomputing* **16**(1), pp. 1–111 (2002).

27. J. Dongarra, "Basic linear algebra subprograms technical forum standard," *International Journal of High Performance Applications and Supercomputing* **16**(2), pp. 115–199 (2002).

28. N. Delen and B. Hooker, "Free-space beam propagation between arbitrarily oriented planes based on full diffraction theory: a fast Fourier transform approach," *J. Opt. Soc. Am. A* **15**(4), pp. 857–867 (1998).

29. N. Delen and B. Hooker, "Verification and comparison of a fast Fourier transform-based full diffraction method for tilted and offset planes," *Appl. Opt.* **40**(21), pp. 3525–3531 (2001).

30. G. A. Tyler and D. L. Fried, "A wave optics propagation algorithm," Tech. Rep. TR-451, the Optical Sciences Company (1982).

31. P. H. Roberts, "A wave optics propagation code," Tech. Rep. TR-760, the Optical Sciences Company (1986).

32. W. A. Coles, J. P. Filice, R. G. Frehlich, and M. Yadlowsky, "Simulation of wave propagation in three-dimensional random media," *Appl. Opt.* **34**(12), pp. 2089–2101 (1995).

33. J. A. Rubio, A. Belmonte, and A. Comerón, "Numerical simulation of long-path spherical wave propagation in three-dimensional random media," *J. Opt. Soc. Am. A* **38**(9), pp. 1462–1469 (1999).

34. X. Deng, B. Bihari, J. Gan, F. Zhao, and R. T. Chen, "Fast algorithm for chirp transforms with zooming-in ability and its applications," *J. Opt. Soc. Am. A* **17**(4), pp. 762–771 (2000).

35. S. Coy, "Choosing mesh spacings and mesh dimensions for wave optics simulation," Proc. SPIE **5894**, (2005).

36. C. Rydberg and J. Bengtsson, "Efficient numerical representation of the optical field for the propagation of partially coherent radiation with a specified spatial and temporal coherence function," *J. Opt. Soc. Am. A* **23**(7), pp. 1616–1625 (2006).

37. D. G. Voelz and M. C. Roggemann, "Digital simulation of scalar optical diffraction: revisiting chirp function sampling criteria and consequences," *Appl. Opt.* **48**(32), pp. 6132–6142 (2009).

38. M. Nazarathy and J. Shamir, "Fourier optics described by operator algebra," *J. Opt. Soc. Am. A* **70**(2), pp. 150–159 (1980).

39. M. Nazarathy and J. Shamir, "First-order optics-a canonical operator representation: lossless systems," *J. Opt. Soc. Am. A* **72**(3), pp. 356–364 (1982).

40. J. M. Jarem and P. P. Banerjee, *Computational Methods for Electromagnetic and Optical Systems*, Marcel Dekker, Inc., New York, NY (2000).

41. R. A. Johnston and R. G. Lane, "Modeling scintillation from an aperiodic Kolmogorov phase screen," *Appl. Opt.* **39**(26), pp. 4761–4769 (2000).

42. J. D. Mansell, R. Praus, and S. Coy, "Determining wave-optics mesh parameters for complex optical systems," Proc. SPIE **6675** (2007).

43. J. M. Martin and S. M. Flatté, "Intensity images and statistics from numerical simulation of wave propagation in 3-D random media," *Appl. Opt.* **27**(11), pp. 2111–2126 (1988).

44. J. M. Martin and S. M. Flatté, "Simulation of point-source scintillation through three-dimensional random media," *J. Opt. Soc. Am. A* **7**(5), pp. 838–847 (1990).

45. F. L. Pedrotti, L. M. Pedrotti, and L. S. Pedrotti, *Introduction to Optics*, 3$^{\text{rd}}$ Ed., Benjamin Cummings (2006).

46. C. Palma and V. Bagini, "Extension of the Fresnel transform to ABCD systems," *J. Opt. Soc. Am. A* **14**(8), pp. 1774–1779 (1997).

47. A. J. Lambert and D. Fraser, "Linear systems approach to simulating optical diffraction," *Appl. Opt.* **37**(34), pp. 7933–7939 (1998).

48. J. D. Mansell, L. Xu, A. S. amd Robert Praus, and S. Coy, "Algorithm for implementing an ABCD ray matrix wave-optics propagator," Proc. SPIE **6675** (2007).

49. H. M. Ozaktas and D. Mendlovic, "Fractional Fourier optics," *J. Opt. Soc. Am. A* **12**(4), pp. 743–750 (1995).

50. J. García, D. Mas, and R. G. Dorsch, "Fractional Fourier transform calculation through the fast-Fourier-transform algorithm," *Appl. Opt.* **35**(35), pp. 7013–7018 (1996).

51. F. J. Marinho and L. M. Bernardo, "Numerical calculation of fractional Fourier transforms with a single fast-Fourier-transform algorithm," *J. Opt. Soc. Am. A* **15**(8), pp. 2111–2116 (1998).

52. D. Mas, J. García, C. Ferreira, L. M. Bernardo, and F. J. Marinho, "Fast algorithms for free-space diffraction patterns calculation," *Opt. Commun.* **164**(4), pp. 233–245 (1999).

53. S. M. Flatté, G.-Y. Wang, and J. Martin, "Irradiance variance of optical waves through atmospheric turbulence by numerical simulation and comparison with experiment," *J. Opt. Soc. Am. A* **10**(11), pp. 2363–2370 (1993).

54. S. Coy, "How to choose mesh spacings for wave-optics simulations," tech. rep., MZA Associates (2003).

55. L. Onural, "Some mathematical properties of the uniformly sampled quadratic phase function and associated issues in digital Fresnel diffraction simulations," *Opt. Eng.* **43**(11), pp. 2557–2563 (2004).

56. R. Frehlich, "Simulation of laser propagation in a turbulent atmosphere," *Appl. Opt.* **39**(3), pp. 393–397 (2000).

57. T.-C. Poon and P. P. Banerjee, *Contemporary Optical Image Processing With Matlab*, Elsevier Science, Ltd., Oxford, UK (2001).

58. T.-C. Poon and T. Kim, *Engineering Optics with* MATLAB, World Scientific Publishing Co. (2006).

59. V. P. Lukin and B. V. Fortes, *Adaptive Beaming and Imaging in the Turbulent Atmosphere*, SPIE Press, Bellingham, WA (2002).

60. S. V. Mantravadi, T. A. Rhoadarmer, and R. S. Glas, "Simple laboratory system for generating well-controlled atmospheric-like turbulence," Proc. SPIE **5553** (2004).

61. T. A. Rhoadarmer and R. P. Angel, "Low-cost, broadband static phase plate for generating atmosphericlike turbulence," *Appl. Opt.* **40**, pp. 2946–2955 (2001).

62. A. N. Kolmogorov, "The local structure of turbulence in an incompressible viscous fluid for very large Reynolds numbers," *C. R. (Doki) Acad. Sci. U.S.S.R.* **30**, pp. 301–305 (1941).

63. A. M. Obukhov, "Structure of the temperature field in turbulent flow," *Izv. Acad. Nauk. SSSR, Ser. Georgr. I Geofiz.* **13**, pp. 58–69 (1949).

64. S. Corrsin, "On the spectrum of isotropic temperature fluctuations in isotropic turbulence," *J. Appl. Phys.* **22**, pp. 469–473 (1951).

65. A. Ishimaru, *Wave Propagation and Scattering in Random Media*, Wiley-IEEE Press, New York, NY (1999).

66. A. D. Wheelon, *Electromagnetic Scintillation: Volume 2, Weak Scattering*, Cambridge University Press (2003).

67. S. F. Clifford, *Laser Beam Propagation in the Atmosphere*, ch. The Classical Theory of Wave Propagation in the Atmosphere. Springer-Verlag (1978).

68. R. J. Sasiela, *Electromagnetic Wave Propagation in Turbulence: Evaluation and Application of Mellin Transforms*, 2nd Ed., SPIE Press, Bellingham, WA (2007).

69. D. L. Fried, "Statistics of a geometric representation of wavefront distortion," *J. Opt. Soc. Am.* **55**(11), pp. 1427–1431 (1965).

70. L. C. Andrews, S. Vester, and C. E. Richardson, "Analytic expressions for the wave structure function based on a bump spectral model for refractive index fluctuations," *J. Mod. Opt.* **40**, pp. 931–938 (1993).

71. M. C. Roggemann, B. M. Welsh, D. Montera, and T. A. Rhoadarmer, "Method for simulating atmospheric turbulence phase effects for multiple time slices and anisoplanatic conditions," *Appl. Opt.* **34**(20), pp. 4037–4051 (1995).

72. C. M. Harding, R. A. Johnston, and R. G. Lane, "Fast simulation of a Kolmogorov phase screen," *Appl. Opt.* **38**(11), pp. 2161–2170 (1999).

73. F. Assémat, R. W. Wilson, and E. Gendron, "Method for simulating infinitely long and non stationary phase screens with optimized memory storage," *Opt. Express* **14**(3), pp. 988–999 (2006).

74. A. Beghi, A. Cenedese, and A. Masiero, "Stochastic realization approach to the efficient simulation of phase screens," *J. Opt. Soc. Am. A* **25**(2), pp. 515–525 (2008).

75. V. Sriram and D. Kearney, "An ultra fast Kolmogorov phase screen generator suitable for parallel implementation," *Opt. Express* **15**(21), pp. 13709–13714 (2007).

76. G. Cochran, "Phase screen generation," Tech. Rep. TR-663, the Optical Sciences Company (1982).

77. B. J. Herman and L. A. Strugala, "Method for inclusion of low-frequency contributions in numerical representation of atmospheric turbulence," Proc. SPIE **1221**, pp. 183–192 (1990).

78. R. G. Lane, A. Glindemann, , and J. C. Dainty, "Simulation of a Kolmogorov phase screen," *Waves in Random Media* **2**, pp. 209–224 (1992).

79. H. Jakobssen, "Simulations of time series of atmospherically distorted wave fronts," *Appl. Opt.* **35**, pp. 1561–1565 (1996).

80. B. M. Welsh, "A Fourier series based atmospheric phase screen generator for simulating anisoplanatic geometries and temporal evolution," Proc. SPIE **3125**, pp. 327–338 (1997).

81. G. Sedmak, "Performance analysis of and compensation for aspect-ratio effects of fast-Fourier-transform-based simulations of large atmospheric wave fronts," *Appl. Opt.* **37**, pp. 4605–4613 (1998).

82. R. J. Eckert and M. E. Goda, "Polar phase screens: a comparative analysis with other methods of random phase screen generation," Proc. SPIE **6303** (2006).

83. D. Kouznetsov, V. V. Voitsekhovich, and R. Ortega-Martinez, "Simulations of turbulence-induced phase and log-amplitude distortions," *Appl. Opt.* **36**, pp. 464–469 (1997).

84. F. Dios, J. Recolons, A. Rodríguez, and O. Batet, "Temporal analysis of laser beam propagation in the atmosphere using computer-generated long phase screens," *Opt. Express* **16**(3), pp. 2206–2220 (2008).

85. D. L. Fried and T. Clark, "Extruding Kolmogorov-type phase screen ribbons," *J. Opt. Soc. Am. A* **25**(2), pp. 463–468 (2008).

86. B. L. McGlamery, "Restoration of turbulence-degraded images," *J. Opt. Soc. Am.* **57**(3), pp. 293–297 (1967).

87. N. A. Roddier, "Atmospheric wavefront simulation using Zernike polynomials," *Opt. Eng.* **29**, pp. 1174–1180 (1990).

88. E. M. Johansson and D. T. Gavel, "Simulation of stellar speckle imaging,"Proc. SPIE **2200**, pp. 372–383 (1994).

89. G. J. Gbur, "Simulating fields of arbitrary spatial and temporal coherence," *Opt. Express* **14**(17), pp. 7567–7578 (2006).

90. H. J. Weber and G. B. Arfken, *Mathematical Methods for Physicists*, 6th Ed., Academic Press (2005).

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