## **Bibliography**

- M. Born and E. Wolf, Principles of Optics, Pergamon, New York, 1985.
- A. E. Conrady, *Applied Optics and Optical Design*, Parts I and II, Oxford, London, 1929 (Reprinted by Dover, New York, 1957).
- H. H. Hopkins, Wave Theory of Aberrations, Oxford, London, 1950.
- F. A. Jenkins and H. E. White, Fundamentals of Optics, 4th ed., McGraw-Hill, New York, 1976.
- M. V. Klein and T. E. Furtak, Optics, 2nd ed., Wiley, New York, 1986.
- E. H. Linfoot, Recent Advances in Optics, Clarendon, Oxford, 1955.
- L. C. Martin and W. T. Welford, *Technical Optics*, Vol. I, 2nd ed., Pitman, London, 1966.
- E. L. O'Neill, *Introduction to Statistical Optics*, Addison-Wesley, Reading, Massachusetts, 1963.
- D. J. Schroeder, Astronomical Optics, Academic Press, New York, 1987.
- W. J. Smith, Modern Optical Engineering, McGraw-Hill, New York, 1966.
- W. T. Welford, Aberrations of the Symmetrical Optical System, Academic Press, New York, 1974.

## **Additional References**

- V. D. Andreeva, "Fundamental aberration coefficients of an optical system," Sov. J. Opt. Tech. 42, 321-323 (1975).
- 2. T. Asakura, "Axial intensity distribution for an annular aperture with primary spherical aberration," Oyo Buturi 31, 243–244 (1962).
- 3. T. Asakura and K. Fukui, "Study on the best focus with small amounts of primary spherical aberration," Oyo Buturi 31, 221–232 (1962).
- 4. T. Asakura and H. Mishina, "Irradiance distribution in the diffraction patterns of an annular aperture with spherical aberration and coma," Japan. J. Appl. Phys. 7, 751-758 (1968).
- 5. T. Asakura and H. Mishina, "Three dimensional distribution in the diffraction patterns of annular apertures with primary spherical aberration," Oyo Buturi 37, 805–809 (1968).
- 6. T. Asakura and R. Barakat, "Annular and annulus apertures with spherical aberration and defocusing," Oyo Buturi 30, 728–735 (1961).
- 7. R. Barakat, "Total illumination in a diffraction image containing spherical aberration," J. Opt. Soc. Am. 51, 152–157 (1961).
- 8. R. Barakat, "The intensity distribution and total illumination of aberration-free diffraction images," *Progress in Optics*, Vol. 1, ed. E. Wolf (North Holland, 1961) pp. 67–108.
- 9. R. Barakat, "Rayleigh wavefront criterion," J. Opt. Soc. Am. 55, 572-573 (1965).
- R. Barakat, "The calculation of integrals encountered in optical diffraction theory," in *The Computer in Optical Research*, ed. B. R. Frieden (Springer, 1980) pp. 35-80.
- R. Barakat and A. Houston, "Diffraction effects of coma," J. Opt. Soc. Am. 54, 1084–1088 (1964).
- 12. R. Barakat and A. Houston, "The aberration of non-rotationally symmetric systems and their diffraction effects," Optica Acta 13, 1-30 (1966).
- 13. R. Barakat and L. Riseberg, "Diffraction theory of the aberrations of a slit aperture," J. Opt. Soc. Am. 55, 878–881 (1965).
- 14. L. Beiser, "Perspective rendering of the field intensity diffracted at a circular aperture," Appl. Opt. 5, 869-870 (1966).

- 15. U. Bose, "Optical tolerances I. Rayleigh λ/4 criterion," Bull. Opt. Soc. India 2, 47-51 (1968).
- 16. A. D. Budgor, "Exact solutions in the scalar diffraction theory of aberrations," Appl. Opt. 19, 1597-1600 (1980).
- 17. S. N. Bezdidko, "The use of Zernike polynomials in optics," Sov. J. Opt. Tech. 41, 425-429 (1974).
- S. N. Bezdidko, "Calculation of the Strehl coefficient and determination of best focus plane in polychromatic light," Opt. Tech. 42, 514-516 (1975).
- S. N. Bezdidko, "Determination of the Zernike polynomial expansion coeffi-19. cients of the wave aberration," Sov. J. Opt. Tech. 42, 426-427 (1975).
- S. N. Bezdidko, "Numerical method of calculating the Strehl coefficients using 20. Zernike polynomials," Sov. J. Opt. Tech. 43, 222-225 (1976).
- S. N. Bezdidko, "Use of orthogonal polynomials in the case of optical systems with annular pupils," Opt. Spectrosc. 43, 200-203 (1977).
- J. Campos and M. J. Yzuel, "Axial and extra-axial responses in aberrated optical systems with apodizers, maximization of the Strehl ratio," J. Mod. Opt. 36, 733-749 (1989).
- 23. H. S. Coleman and S. W. Harding, "The loss of resolving power caused by primary astigmatism, coma and spherical aberration," J. Opt. Soc. Am. 38, 217-221 (1948).
- 24. G. Conforti, "Zernike aberration coefficients from Seidel and higher-order power-series coefficients," Opt. Lett. 8, 407-408 (1983).
- 25. J. C. Dainty, "The image of a point for an aberration-free lens with a circular pupil," Opt. Commun. 1, 176-178 (1968).
- H. S. Dhadwal and J. Hantgan, "Generalized point spread function for a diffraction-limited aberration-free imaging system under polychromatic illumination," Opt. Eng. 28, 1237-1240 (1989).
- 27. J. B. DeVelis, "Comparison of methods for image evaluation," J. Opt. Soc. Am. 55, 165-174 (1965).
- 28. F. A. Dixon, "The influence of aberration and detector response on optical images," Proc. Phys. Soc. 75, 713-728 (1960).
- D. B. Fenneman and D. R. Cruise, "Far-field illumination of targets by annular 29. apertures," J. Opt. Soc. Am. 65, 1300-1305 (1975).

- 30. I. L. Goldberg and A. W. McCulloch, "Annular aperture diffracted energy distribution for an extended source," Appl. Opt. 8, 1451–1458 (1969).
- 31. A. Greeve and G. C. Hunt, "The Strehl number of degraded diffraction patterns," Optik 40, 18-23 (1974).
- 32. D. S. Grey, "Computed aberrations of spherical Schwarzchild reflecting microscore objectives," J. Opt. Soc. Am. 41, 183-192 (1951).
- 33. A. K. Gupta, R. N. Singh and K. Singh, "Diffraction images of extended circular targets in presence of coma," Can. J. Phys. 55, 1025–1032 (1977).
- 34. H. H. Hopkins and M. J. Yzuel, "The computation of diffraction patterns in the presence of aberrations," Optica Acta 17, 157–182 (1970).
- 35. C. B. Hogge, R. R. Butts, and M. Burlakoff, "Characteristics of phase aberrated nondiffraction-limited laser beams," Appl. Opt. 13, 1065–1070 (1974).
- R. Herloski, "Strehl ratio for untruncated aberrated Gaussian beams," J. Opt. Soc. Am. A2, 1027-1030 (1985).
- 37. R. B. Johnson, "Polynomial ray aberrations computed in various lens designs programs," Appl. Opt. 12, 2079–2082 (1973).
- C. J. Kim and R. R. Shannon, "Catalog of Zernike polynomials," *Applied Opitcs and Optical Engineering*, eds., R. R. Shannon and J. C. Wyant, Vol. 10 pp. 193–221 (Academic Press, 1987)
- 39. W. B. King, "A direct approach to the evaluation of the variance of the wave aberration," Appl. Opt. 7, 489-494 (1968).
- 40. W. B. King, "Dependence of the Strehl ratio on the magnitude of the variance of the wave aberration," J. Opt. Soc. Am. 58, 655–661 (1968).
- 41. W. B. King and J. Kitchen, "The evaluation of the variance of the wave-aberration difference function," Appl. Opt 7, 1193-1197 (1968).
- 42. W. S. Kovach, "Energy distribution in the PSF for an arbitrary pass band," Appl. Opt. 13, 1769–1771 (1974).
- 43. Y. Li, "Dependence of the focal shift on Fresnel number and f number," J. Opt. Soc. Am. 72, 770-774 (1982).
- 44. E. H. Linfoot, "Focal tolerances and best focal setting for model photographic images with primary spherical aberration," Optica Acta 8, 233-253 (1961).
- 45. E. H. Linfoot and E. Wolf, "Diffraction images in systems with an annular aperture," Proc. Phys. Soc. (London) **B66**, 145-149 (1953).

- 46. D. D. Lowenthal, "Maréchal intensity criteria modified for Gaussian beams," Appl. Opt. 2126–2133 (1974). Errata, Appl. Opt. 13, 2774 (1974)
- 47. D. D. Lowenthal, "Far-field diffraction patterns for Gaussian beams in the presence of small spherical aberrations," J. Opt. Soc. Am. 65, 853-855 (1975).
- 48. A. Magiera and K. Pietraszkiewicz, "Position of the optimal reference sphere for apodized optical systems," Optik 58, 85-91 (1981).
- 49. M. N. Malakhow, "Effect of optical system aberrations on the location of the energy center of gravity of the image of a point source," Sov. J. Opt. Tech. 45, 131-132 (1978).
- J. T. McCrickerd, "Coherent processing and depth of focus of annular aperture 50. imagery," Appl. Opt. 10, 2226-2230 (1971).
- 51. T. S. McKechnie, "The effect of defocus on the resolution of two points," Optica Acta 20, 253-262 (1973).
- 52. J. Meiron, "The use of merit functions based on wavefront aberrations in automatic lens design," Appl. Opt. 7, 667-672 (1968).
- 53. J. P. Mills and B. J. Thompson, "Effect of aberrations and apodization on the performance of coherent optical systems. I. The amplitude impulse response," J. Opt. Soc. Am. A3, 694-703 (1986).
- J. P. Mills and B. J. Thompson, "Effect of aberrations and apodization on the performance of coherent optical systems. II. Imaging," J. Opt. Soc. Am. A3, 704-716 (1986).
- K. Miyamoto, "Wave optics and geometrical optics in optical design," Progress in Optics Vol. 1, ed. E. Wolf (North Holland, 1960) pp. 31-66.
- 56. B. R. A. Nijboer, "The diffraction theory of optical aberrations. Part I: General discussion of the geometrical aberrations," Physica 10, 679-692 (1943).
- B. R. A. Nijboer, "The diffraction theory of optical aberrations. Part II: Diffrac-57. tion pattern in the presence of small aberrations," Physica 13, 605-620 (1947).
- K. Nienhuis and B. R. A. Nijboer, "The diffraction theory of aberrations. Part 58. III: General formulae for small aberrations: experimental verification of the theoretical results," Physica 14, 590-603 (1949).
- 59. H. Osterberg and L. W. Smith, "Defocusing images to increase resolution," Science 134, 1193-1196 (1961).
- 60. K. Pietraszkiewicz, "Determination of the optimal reference sphere," J. Opt. Soc. Am 69, 1045-1046 (1979).

- 61. J. L. Rayces, "Exact relation between wave aberration and ray aberration," Optica Acta 11, 85–88 (1964).
- 62. M. Rimmer, "Analysis of perturbed lens systems," Appl. Opt. 9, 533-537 (1970).
- 63. C. J. R. Sheppard and T. Wilson, "Imaging properties of annular lenses," Appl. Opt. 18, 3764–3768 (1979).
- R. M. Sillito, "Diffraction of uniform and Gaussian Beams: an application of Zernike polynomials," Optik 48, 271–277 (1977).
- 65. J. J. Stamnes, H. Heier, and S. Ljunggren, "Encircled energy for systems with centrally obscured circular pupils," Appl. Opt. 21, 1628–1633 (1982).
- 66. W. H. Steel, "Etude des effets de aberrations et d'une obturation centrale de la pupille sur le contraste des images optiques," Rev. d' Opt. 32, 4-26, 143-178, 269-304 (1953).
- 67. W. H. Steel, "The defocused image of sinusoidal gratings," Opt. Acta 3, 65–74 (1956).
- 68. R. E. Stephens and L. E. Sutton, "Diffraction image of a point in the focal plane and several out-of-focus planes," J. Opt. Soc. Am. 58, 1001-1002 (1968).
- 69. G. C. Steward, The Symmetrical Optical System (Cambridge, U. P. 1928).
- P. A. Stokseth, "Properties of a defocused optical system," J. Opt. Soc. Am. 59, 1314–1321 (1969).
- S. Szapiel, "Maréchal intensity criteria modified for circular apertures with nonuniform intensity transmission: Dini series approach," Opt. Lett. 2, 124–126 (1978).
- S. Szapiel, "Aberration balancing techniques for radially symmetric amplitude distributions: a generalization of the Maréchal approach," J. Opt. Soc. Am. 72, 947-957 (1982).
- 73. S. Szapiel, "Aberration-variance-based formula for calculating point-spread functions: rotationally symmetric aberrations," Appl. Opt. 25, 244–251 (1986).
- B. Tatian, "Aberration balancing in rotationally symmetric lenses," J. Opt. Soc. Am. 64, 1083-1091 (1974).
- 75. C. A. Tayler and B. J. Thompson, "Attempt to investigate experimentally the intensity distribution near the focus in the error-free diffraction patterns of circular and annular apertures," J. Opt. Soc. Am. 48, 844–850 (1958).

- 76. R. Tyson, "Conversion of Zernike aberration coefficients to Seidel and higherorder power-series aberration coefficients," Opt. Lett. 7, 262-264 (1982).
- 77. J. J. H. Wang, "Tolerance condition for aberrations," J. Opt. Soc. Am. 62, 598-599 (1972).
- 78. J. Y. Wang and D. E. Silva, "Wavefront interpretation with Zernike polynomials," Appl. Opt. 19, 1510-1518 (1980).
- W. T. Welford, "On the limiting sensitivity of the star test for optical instru-79. ments," J. Opt. Soc. Am. 50, 21-23 (1959).
- 80. W. T. Welford, "Use of annular apertures to increase focal depth," J. Opt. Soc. Am. 50, 749-753 (1960).
- W. T. Welford, "Aberration tolerances for spectrum line images," Optica Acta 10, 81. 121-127 (1963).
- W. B. Wetherell, "The calculation of image quality," in Applied Optics and Optical Engineering, eds. R. R. Shannon and J. C. Wyant (Academic Press, 1980), pp. 171-315.
- 83. E. Wolf, "The diffraction theory of aberrations," Rep. Prog. Phys. 14, 95-120 (1951).
- 84. E. Wolf, "Light distribution near focus in an error-free diffraction image," Proc. Roy. Soc. A204, 533-548 (1951).
- A. T. Young, "Photometric error analysis X. Encircled energy (total illuminance) calculations for annular apertures," Appl. Opt. 9, 1874-1878 (1970).
- M. J. Yzuel and F. J. Arlegui, "A study on the computation accuracy in the aberrational diffraction images," Optica Acta 27, 549-562 (1980).
- 87. M. J. Yzuel and F. Calvo, "Point-spread function calculation for optical systems with residual aberrations and a non-uniform transmission pupil," Optica Acta 30, 233-242 (1983).

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