

Bibliography

- Born, M. and E. Wolf, *Principles of Optics*, Fifth Edition, Oxford, UK, Pergamon Press (1975).
- Buften, J. L., "Comparison of vertical profile turbulence structure with stellar observations," *Appl. Opt.* **12**, 1785 (1973).
- Churnside, J. H., "Aperture averaging of optical scintillations in the turbulent atmosphere," *Appl. Opt.* **30**, 1982 (1991).
- Ellerbroek, B. L., "Efficient computation of minimum-variance wave-front reconstructors with sparse matrix techniques," *J. Opt. Soc. Am. A* **19**, 1803–1816 (2002).
- Ellerbroek, B. L., L. Gilles, and C. R. Vogel, "Computationally efficient wavefront reconstructor for simulation of multiconjugate adaptive optics on giant telescopes," *Proc. SPIE* **4839**, 989–1000 (2003) [doi:10.1117/12.459673].
- Forbes, F. F., "Bimorph PZT active mirror," *Proc. SPIE* **1114**, 146–151 (1989).
- Franklin, G. F., J. D. Powell, and M. L. Workman, *Digital Control of Dynamic Systems*, Second Edition, Addison-Wesley, Reading, MA (1990).
- Fried, D. L., "Focus anisoplanatism in the limit of infinitely many artificial-guide-star reference spots," *J. Opt. Soc. Am. A* **12**, 939 (1995).
- Fried, D. L., "Anisoplanatism in adaptive optics," *J. Opt. Soc. Am.* **72**, 52 (1982).
- Gardner, C. S., B. M. Welsh, and L. A. Thompson, "Design and performance analysis of adaptive optical telescopes using laser guide stars," *Proc. IEEE* **78**, 1721–1743 (1990).
- Gonzalez, R. C. and R. E. Woods, *Digital Image Processing*, Second Edition, Prentice Hall, Upper Saddle River, NJ (2002).
- Goodman, J. W., *Introduction to Fourier Optics*, Second Edition, McGraw-Hill, New York (1996).

Bibliography

Goodman, J. W., *Statistical Optics*, John Wiley and Sons, New York (1985).

Greenwood, D. P., "Bandwidth specification for adaptive optics systems," *J. Opt. Soc. Am.* **67**, 390 (1977).

Grosso, R. P. and M. Yellin, "The membrane mirror as an adaptive optical element," *J. Opt. Soc. Am.* **67**, 399 (1977).

Hardy, J. W., *Adaptive Optics for Astronomical Telescopes*, Oxford Univ. Press, Oxford, UK (1998).

Hayes, M. H., *Statistical Digital Signal Processing and Modeling*, John Wiley and Sons, New York (1996).

Hudgin, R. H., "Wave-front compensation error due to finite corrector-element size," *J. Opt. Soc. Am.* **67**, 393 (1977).

Hyver, G. A. and R. M. Blankinship, "ALI high-power beam control," *Advances in the Astronautical Sciences* **88**, 445–469 (1995).

ISO Standard 11146, "Lasers and laser related equipment – Test methods for laser beam widths, divergence angles and beam propagation ratios," International Organization for Standardization, Geneva, Switzerland (2005).

Johnson, B. and D. V. Murphy, *Thermal Blooming Laboratory Experiment*, Part I, Lincoln Laboratory MIT Project Report BCP-2 (November 1988).

Kalman, R. E., "A new approach to linear filtering and prediction problems," *Transaction of the ASME—Journal of Basic Engineering* **82**(D), 35–45 (1960).

Lee, L. H., "Loopshaped wavefront control using open-loop reconstructors," *Optics Express* **14**(17), 7477–7486 (2006).

Miller, M. G. and P. L. Zieske, "Turbulence environment characterization," RADC-79-131, ADA072379, Rome Air Development Center, U.S. Air Force, Rome, NY (1979).

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

Bibliography

Oppenheim, A. V., R. W. Schafer, and J. R. Buck, *Discrete-Time Signal Processing*, Second Edition, Prentice Hall, Upper Saddle River, NJ (1999).

O'Neil, P. V., *Advanced Engineering Mathematics*, Sixth Edition, Nelson, Toronto, Canada (2007).

OSI Optoelectronics, "Application Note No. 2, Silicon Photodiode Physics and Technology," OSI Optoelectronics (1982).

OSI Optoelectronics, "Application Note No. 8, Lateral Effect Photodiodes," OSI Optoelectronics (1982).

Perram, G. P., S. J. Cusumano, R. L. Hengehold, and S. T. Fiorino, *An Introduction to Laser Weapon Systems*, Directed Energy Professional Society, Albuquerque, NM (2010).

Poyneer, L. A, D. T. Gavel, and J. M. Brase, "Fast wavefront reconstruction in large adaptive optics system with use of the Fourier transform," *J. Opt. Soc. Am. A* **19**(10), 2100–2111 (2002).

Poyneer, L. A. and B. Macintosh, "Spatially filtered wavefront sensor for high order adaptive optics," *J. Opt. Soc. Am. A* **21**(5), 810–819 (2004).

Roddier, F., "Curvature sensing and compensation: a new concept in adaptive optics," *Appl. Opt.* **27**, 1223 (1988).

Simon, D, *Optimal State Estimation, Kalman, H - ∞ , and Nonlinear Approaches*, John Wiley and Sons, Hoboken, NJ (2006).

Sinha, N. K. and B. Kuszta, *Modeling and Identification of Dynamic Systems*, Van Nostrand Reinhold, New York (1983).

Skogestad, S. and I. Postlethwaite, *Multivariable Feedback Control, Analysis and Design*, John Wiley and Sons, Hoboken, NJ (2009).

Bibliography

Taranenko, V. G., G. P. Koshelev, and N. S. Romanyuk, "Local deformations of solid mirrors and their frequency dependence," *Sov. J. Opt. Technol.* **48**, 650 (1981).

Trefethen L. N. and D. Bau III, *Numerical Linear Algebra*, Society for Industrial and Applied Mathematics, Philadelphia (1997).

Tyler, G., "Reconstruction and assessment of the least-squares and slope discrepancy components of the phase," *J. Opt. Soc. Am. A* **17**, 1828–1839 (2000).

Tyson, R. K., *Introduction to Adaptive Optics*, SPIE Press, Bellingham, WA (2000) [doi:10.1117/3.358220].

Tyson, R. K., *Principles of Adaptive Optics*, Third Edition, CRC Press, Boca Raton, FL (2011).

Tyson, R. K., "Adaptive optics and ground-to-space laser communications," *Appl. Opt.* **35**, 3640–3646 (1996).

Uchino, K., *Ferroelectric Devices*, CRC Press, Boca Raton, FL (2000).

Ulrich, P. B., "Hufnagel-Valley profiles for specified values of the coherence length and isoplanatic patch angle," W. J. Schafer Associates, WJSA/MA/TN-88-013, Arlington, VA (1988).

Vogel, C. R., *Computational Methods for Inverse Problems*, Society for Industrial and Applied Mathematics, Philadelphia (2002).

Vogel, C. R. and Q. Yang, "Fast optimal wavefront reconstruction for multi-conjugate adaptive optics using the Fourier domain preconditioned conjugate gradient algorithm," *Optics Express* **14**(17), 7487–7498 (2006).

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