

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. Schaffer, 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).

Index

- aberrations, 2, 21, 33
- active actuators, 81, 83
- actuator, 47
- actuator locations, 79
- actuator observability, 77
- actuator slaving, 81, 82
- actuators, 57
- Airy disk, 39
- aliasing, 64
- amplitude fluctuation, 12
- artificial laser guide stars, 41
- astronomical brightness, 37
- astronomical seeing, 5
- atmospheric turbulence, 2, 12, 38
- atmospheric wind profile, 11
- azimuthal polynomials, 13

- back electromotive force, 53
- beam jitter, 34
- beam radius at the beam waist, 36
- Bessel function, 39
- bimorph mirrors, 25, 55
- blur, 25
- brightness, 37
- Buften wind model, 11

- Cassegrain, 14
- CCD camera, 23
- centroiding, 106
- closed-loop bandwidth, 19, 40
- closed-loop transfer function, 59
- coherence length, 8, 9
- complementary sensitivity function, 59
- cone effect, 41
- control computer, 1
- control system, 40, 47
- conventional (linear) adaptive optics system, 1
- correctability of the deformable mirror, 58
- Coulomb's law, 52
- coupling, 54
- crossover frequency, 10, 69
- curvature sensor, 25, 26

- deformable mirror, 1, 20, 48, 54
- deformable mirror actuators, 49
- deformable mirror dynamic model, 60
- delay, 63
- derivative, 22
- design trade-off, 70
- detected sodium-line photon flux, 43
- diffracted energy, 56
- diffraction, 4
- discrete-time model, 63
- discrete-time transfer function, 60
- disturbance injection, 104

Index

- duo-lateral
 - position-sensing detectors, 29
- dynamic range
 - requirement for the wavefront sensor, 44
- electrostatic actuators, 52
- electrostrictive actuators, 50
- electrostrictive effect, 50
- example system geometry, 74
- feedback control, 59
- ferroelectric actuators, 50
- fitting constant, 20
- fitting error, 19, 21
- flat-Earth assumption, 5
- flattening, 58
- focal anisoplanatism, 41, 43
- Fraunhofer diffraction pattern, 39
- Fried configuration, 74
- Fried's coherence length, 5
- Gaussian beam, 38
- Gaussian model, 11
- global average height, 85
- global tilt matrix, 84
- Gram–Schmidt
 - orthogonalization, 85
- Greenwood frequency, 10, 40
- guard bands, 108
- half-angle beam
 - divergence, 36
- halo, 4
- hexagonal array, 49
- high-frequency noise rejection, 70
- Hudgin geometry, 67
- Hufnagle–Valley (H-V), 8
- H-V 5/7 model, 8
- hysteresis, 51
- image degradation, 18
- influence function, 47, 54, 73
- intensity variations, 12
- interactuator shear suppression, 91
- inverse piezoelectric effect, 50
- inverse problems, 95
- isoplanatic angle, 6, 8, 41, 45
- isoplanatic error, 19
- jitter, 17
- jitter effects, 35
- Johnson noise, 28
- Kalman filter, 101
- Kolmogorov atmospheric turbulence, 10, 48
- Laplacian, 93
- laser beam quality, 36
- laser brightness, 35
- laser guide star, 43
- laser radar equation, 42
- latency, 63
- lateral-effect
 - position-sensing detectors, 29
- leak gains, 72
- leaky integrator, 61

Index

- least squares, 86
- Legendre polynomials, 15
- lenslet array, 22
- limiting velocity, 53
- local waffle, 93
- log-amplitude variance, 12
- loop gains, 72
- Lorentz force, 53
- low-frequency
 - disturbance rejection, 70

- magnetic flux density
 - magnitude, 53
- magnification, 17
- membrane mirror, 55
- micro-electro-mechanical
 - systems (MEMS), 52
- misregistration, 107
- modal feedback, 90, 94
- modal wavefront error, 20
- moderate turbulence, 12
- modulation transfer
 - function (MTF), 18
- Moore–Penrose
 - pseudo-inverse, 86
- multivariable systems, 102

- noise equivalent angle
 - (NEA), 32
- noise equivalent power
 - (NEP), 28
- non-common-path errors, 105
- nullspace projection
 - matrix, 92
- nullspace suppression, 92

- Nyquist frequency, 65
- Nyquist sampling
 - theorem, 57

- offload matrix, 99
- offloads, 99
- on-axis intensity, 33
- one-dimensional
 - sampling, 64
- open-loop
 - minimal-variance estimator, 100
- optical phase, 13
- optical power densities, 52
- overshoot, 69

- photodiode noise, 28
- photodiodes, 27
- piezoelectric actuators, 50
- piston, 85
- piston basis vector, 85
- PMN actuators, 50
- point spread function, 2
- poke matrix, 60, 73, 84
- poke matrix smoothing, 80
- principle of phase
 - conjugation, 3
- projection matrix, 85
- PZT actuators, 50

- quad cells, 30

- reconstructor, 83
- reconstructor generation, 86
- reflecting telescopes, 14
- regularizing filter, 87
- residual errors, 19

Index

- residual wavefront error, 20
- response time, 27
- responsivity, 27
- rise time, 69
- robustness requirement, 71

- sampling frequency, 64
- sampling rate, 67
- sampling time, 60
- scintillation, 12
- second difference, 91
- segmented deformable mirrors, 56
- sensitivity and complementary sensitivity functions, 70
- sensitivity function, 59
- sensor error, 22
- sensor noise error, 19
- settling time, 69
- Shack–Hartmann lenslet array, 24
- Shack–Hartmann wavefront sensor, 22
- shot noise, 28
- single curvature measurement variance, 25
- singular values, 87
- singular-value decomposition, 76, 86
- slave actuators, 81, 83
- slave logic, 82
- slope discrepancy, 98
- slopes, 75
- SNR, 23

- Southwell geometry, 57
- spatial filtering properties, 93
- spatial frequency response, 18
- spatial mode, 47
- spatial-fitting error, 47
- spot size, 30, 38, 39
- square array, 49
- stability, 68
- Strehl ratio, 33, 34, 47
- stroke, 48
- strong turbulence, 12
- subaperture, 22–24, 26, 74, 78, 80, 105, 106, 108
- subaperture grid, 79
- subaperture observability, 77
- subaperture spillover, 108
- subapertures, 57
- suppression operations, 90
- system crossover frequency, 72

- temporal error, 19
- temporal power spectrum, 10
- T-filter, 89, 93
- third-order optical aberrations, 14
- thresholding, 106
- Tikhonov regularization, 88
- tilt, 48
- tilt correction, 84
- tilt projection matrix, 84
- tilt-corrector mirror, 46

Index

- tropopause, 11
- two-dimensional
 - sampling, 66
- visual magnitude, 37
- voice coil actuators, 53
- voltage–strain curves, 51
- waffle, 85
- waffle basis vector, 85
- wavefront beacon, 6, 19
- wavefront control
 - experiment, 57
- wavefront error, 13, 45
- wavefront error variance, 34, 44
- wavefront measurement
 - errors, 41
 - wavefront sensor, 1, 13, 41, 44
 - wavefront sensor calibration, 105
 - wavefront sensor dynamic model, 62
 - wavefront sensor output, 62
 - wavefront tilt, 22
 - wavefront variance, 21, 34
- weak turbulence, 12, 33
- weighting matrices, 93
- woofer-tweeter systems, 99
- zenith angle, 5
- Zernike modes, 20, 21, 47
- Zernike series, 13



Robert K. Tyson is an Associate Professor of Physics and Optical Science at The University of North Carolina at Charlotte. He has a B.S. in physics from Penn State University and M.S. and Ph.D. degrees in physics from West Virginia University. He was a senior systems engineer with United Technologies Optical Systems from 1978 to 1987 and a senior scientist with Schafer Corporation until 1999. He is the author of *Principles of Adaptive Optics* [Academic Press (1991), Second Edition (1998), Third Edition, CRC Press (2011)], *Lighter Side of Adaptive Optics*, SPIE Press (2009), and *Introduction to Adaptive Optics*, SPIE Press (2000) and the editor of ten volumes on adaptive optics. He is also a Fellow of SPIE. Professor Tyson's current research interests include atmospheric turbulence studies, classical diffraction, novel wavefront sensing, and amplitude and phase manipulation techniques to enhance propagation, laser communications, and imaging.



Benjamin W. Frazier is a Principal Electro-Optical Engineer with AOA Xinetics, a small business unit of Northrop Grumman Aerospace Systems. He has B.S.E.E. and M.S.E.E. degrees from the University of North Carolina at Charlotte, where he focused on control theory for adaptive optics systems. Frazier has extensive experience with systems integration and testing of beam control systems and components, particularly deformable mirrors and wavefront control systems for high-power and solid state lasers. He currently supports multiple programs in systems engineering, integration and test, data analysis, and performance assessment.