

## Bibliography

---

M. Bass, *Handbook of Optics, Vol. I*, McGraw-Hill, New York, 1995.

R. W. Boyd, *Radiometry and the Detection of Optical Radiation*, Wiley, New York, 1983.

Bureau of Naval Personnel, *Basic Optics and Optical Instruments*, Dover, New York, 1969.

R. Dittion, *Modern Geometrical Optics*, Wiley, New York, 1998.

R. E. Fischer and B. Tadic-Galeb, *Optical System Design*, McGraw-Hill, New York, 2000.

N. Goldberg, *Camera Technology: The Dark Side of the Lens*, Academic, San Diego, 1992.

D. S. Goodman, "Basic Optical Instruments," in *Geometrical and Instrumental Optics*, D. Malacara, Ed., Academic, San Diego, 1988.

J. W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, New York, 1968.

*Hoya Optical Glass Catalog*, Hoya Corporation, Tokyo, Japan.  
F. A. Jenkins and H. E. White, *Fundamentals of Optics*, McGraw-Hill, New York, 1976.

B. K. Johnson, *Optics and Optical Instruments*, Dover, New York, 1960.

M. J. Kidger, *Fundamental Optical Design*, SPIE Press, Bellingham, WA, 2002.

H. C. King, *The History of the Telescope*, Dover, New York, 1979.  
L. Levi, *Applied Optics – A Guide to Optical System Design, Volumes I and II*, Wiley, New York, 1968 and 1980.

---

## Bibliography

---

- R. Kingslake, *Lens Design Fundamentals*, Academic, San Diego, 1978.
- R. Kingslake, *Optical System Design*, Academic, Orlando, 1983.
- R. Kingslake, *History of the Photographic Lens*, Academic, San Diego, 1989.
- R. Kingslake, *Optics in Photography*, SPIE Press, Bellingham, WA, 1992.
- Y. Le Grand and S. G. El Hage, *Physiological Optics*, Springer Verlag, Berlin, 1980.
- V. N. Mahajan, *Optical Imaging and Aberrations: Ray Geometrical Optics*, SPIE Press, Bellingham, WA, 1998.
- V. N. Mahajan, *Optical Imaging and Aberrations: Wave Diffraction Optics*, SPIE Press, Bellingham, WA, 2001.
- Military Standardization Handbook: Optical Design*, MIL-HDBK-141, U. S. Department of Defense, 1962.
- P. Mouroulis and J Macdonald, *Geometrical Optics and Optical Design*, Oxford, New York, 1997.
- P. Mouroulis, *Visual Instrumentation*, McGraw-Hill, New York, 1999.
- Ohara Optical Glass Catalog*, Ohara Corporation, Kanagawa, Japan.
- D. C. O'Shea, *Elements of Modern Optical Design*, Wiley, New York, 1985.
- S. P. Parker, *Optics Source Book*, McGraw-Hill, New York, 1988.
- F. L. Pedrotti and L. S. Pedrotti, *Introduction to Optics*, Prentice Hall, Englewood Cliffs, NJ, 1993.
-

## Bibliography

---

L. S. Pedrotti and F. L. Pedrotti, *Optics and Vision*, Prentice Hall, Upper Saddle River, NJ, 1998.

S. F. Ray, *Scientific Photography and Applied Imaging*, Focal, Oxford, 1999.

S. F. Ray, *Applied Photographic Optics*, Focal, Oxford, 2002.

B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics*, Wiley, New York, 1991.

*Schott Optical Glass Catalog*, Schott Glass Technologies, Inc., Duryea, PA.

F. W. Sears, *Optics*, Addison-Wesley, Reading, MA, 1958.

R. R. Shannon, *The Art and Science of Optical Design*, Cambridge, New York, 1997.

G. Smith and D. A. Atchison, *The Eye and Visual Optical Instruments*, Cambridge, Cambridge, 1997.

W. J. Smith, *Modern Lens Design*, McGraw-Hill, New York, 1992.

W. J. Smith, *Practical Optical System Layout*, McGraw-Hill, New York, 1997.

W. J. Smith, *Modern Optical Engineering*, McGraw-Hill, New York, 2000.

W. T. Welford, *Aberrations of Optical Systems*, Adam Hilger, Bristol, 1986.

W. T. Welford, *Optics*, Oxford, Oxford, 1988.

W. T. Welford, *Useful Optics*, Chicago, Chicago, 1991.

---

## Index

---

- 1:1 imaging, 16  
 180° deviation prisms, 40  
 45° deviation prisms, 40  
 45° prism, 40  
 90° deviation prisms, 39
- AΩ product, 28, 85  
 Abbe number, 62–64, 67–69  
 aberration theory, 81  
 accommodation, 90, 92  
 achromatic doublet, 69  
 achromatic thin prism, 67  
 achromatic wedge, 67  
 achromatization, 67  
 acid resistance, 64  
 active triangulation, 54  
 aerial image, 48  
 afocal system, 6, 18, 34, 44, 46, 47, 52, 99, 102  
 Airy disk, 88, 89, 93  
 Amici prism, 39  
 angle of minimum deviation, 76  
 angular resolution, 88  
 aperture stop, 24, 26, 31, 32  
 area scanner, 96  
 artificially flattened field, 79  
 aspherics, 82  
 astigmatism, 73, 78, 79, 81, 92  
 astronomical telescope, 46–48, 50, 83  
 axial chromatic aberration, 68  
 axial color, 68
- back focal distance (BFD), 15, 20, 22, 43, 44, 99, 101  
 barrel distortion, 80  
 basic radiance, 85
- bending a lens, 76  
 binoculars, 18, 41, 47  
 biological objectives, 52  
 BK7, 64, 65  
 blackbody sources, 87  
 brilliant reflex viewfinder, 53
- camera equation, 85  
 cardinal points and planes, 6, 8, 11, 12, 15, 18, 20, 22, 99  
 Cassegrain objective, 22, 23  
 Cassegrain telescope, 83  
 chief ray, 25–30, 32–34, 58, 68, 69, 98  
 ciliary muscle, 90  
 circle (geometric), 82  
 climatic resistance, 64  
 coefficients of thermal expansion, 64  
 cold mirror, 60  
 collinear transformation 6  
 collimator, 43  
 coma, 73, 77, 81, 83  
 complimentary colors, 95  
 compound eyepiece, 49  
 concave mirror, 53, 59, 60  
 condenser, 55, 58–60  
 cones (of the eye), 91, 92  
 conics, 82, 83  
 conjugates, 6, 8–10, 17, 18, 27, 29, 33, 52, 54, 76, 99  
 conjugate matrix 99  
 contact lens 92  
 cornea, 90, 92, 93  
 corner cube, 40  
 cosine fourth law, 32, 85  
 critical angle, 4, 57  
 critical illumination, 55  
 crystalline lens, 90–93  
 cubic coma, 73
-

## Index

---

- dark adaptation, 91
  - dark field illumination, 61
  - dark field system, 61
  - defocus 33, 48, 51, 73, 74, 76, 81, 89
  - depth of field, 32, 35, 36, 95
  - depth of focus (DOF), 32, 35, 102
  - determinant of the ray matrix, 98
  - diffraction, 2, 35, 88, 89, 93, 95
  - diffraction limited system 89, 104
  - diffuse illumination, 55–57
  - diffuser, 56, 57
  - dihedral angle, 38
  - dihedral line, 38
  - diode lasers, 87
  - diopters, 14, 66
  - direct vision prism, 67
  - directed distances, 1, 6
  - dispersing prism, 65
  - dispersion, 62, 63, 65, 67, 68, 97, 103
  - dispersion of a thin prism, 67
  - distortion, 36, 73, 80, 81
  - double telecentricity, 34, 52
  - dove prism, 41
  
  - effective (or equivalent) focal length (EFL) 7–9, 15, 17, 28, 43, 44, 46, 48, 68, 69, 75, 90, 94, 101
  - ellipse, 82, 83
  - elliptical coma, 73
  - emittance, 87
  - emmotropia, 92
  - empty magnification, 93
  - energy, 84, 88
  
  - entrance pupil (EP) 24–27, 29, 33, 34, 46, 55, 72, 90
  - erector lens, 50
  - etendue, 28
  - excess power, 69
  - exit pupil (XP), 24–26, 33–35, 46–49, 70, 74, 89
  - exitance, 84, 86, 87
  - exposure, 85, 86, 95
  - eye, 45–49, 53, 54, 66, 90–93, 95, 96
  - eye circle, 46
  - eye relief (ER), 46, 48, 49
  - eyepiece, 49
  
  - F2, 64, 65
  - faceted parabolic reflector, 59
  - far point, 92
  - farsighted, 92
  - Fermat's principle, 3
  - field curvature, 73, 79, 81
  - field diaphragm, 58
  - field lens, 48–50, 53, 54, 58
  - field of view (FOV), 27, 31, 32, 39, 41, 43, 47, 48, 49, 53, 55, 61, 72, 91, 94, 102
  - field stop, 49
  - field-dependent phase, 73
  - fifth-order astigmatism, 73
  - fifth-order distortion, 73
  - fifth-order field curvature, 73
  - fifth-order linear coma, 73
  - fifth-order spherical aberration, 73
  - film and detector formats 94
  - first-order optics, 2
  - flux, 84, 85
  - flying spot scanner, 96
  - F-number ( $f/\#$ ), 29, 102
-

---

**Index**

---

- focal length, 7–9, 15, 17, 28, 43, 44, 46, 48, 68, 69, 75, 90, 94, 101
- focal plane arrays, 94
- focal plane to focal plane matrix, 99
- focal system, 6, 8, 11–13
- fractional object (FOB), 27
- frequency, 2
- Fresnel lens, 54, 60
- Fresnel reflection
- coefficients, 4
- front focal length, 6–9
- front cardinal points, 20
- front focal distance (FFD), 15, 20, 99, 101
- front focal plane, 6, 33, 52, 53
- front focal point, 6, 17, 18, 20, 43, 51, 92
- front principal plane, 6, 13, 48
- full field of view (FFOV), 27
- fused silica, 64
- Galilean telescope, 47
- Gaussian equations, 9, 101
- Gaussian optics, 2, 6, 15
- Gaussian reduction, 13, 15, 22, 23, 101
- generalized asphere, 82
- glass code, 64
- glass map, 63
- graticles, 49
- Gregorian telescope, 83
- half field of view (HFOV), 27
- heat absorbing glass, 60
- heat management, 60
- hot mirror, 60
- human eye, 45–49, 53, 54, 66, 90–93, 95, 96
- Huygens eyepiece, 49
- hyperbola, 82
- hyperfocal distance, 36, 102
- hyperopia, 92
- illuminance, 86
- illumination systems, 55
- image blur, 35, 68, 72, 77, 79, 80, 95
- image erection prisms, 41
- image rotation, 37, 41, 54
- image rotation prisms, 41
- image space 5, 6, 8, 12, 13, 18–20, 24, 26, 29, 33, 34, 71, 88, 98
- image-space telecentric, 33
- index of refraction, 1, 2, 5, 9, 62, 63
- infinity corrected objectives, 52
- integrating bar, 57
- integrating sphere, 57
- intensity, 84
- interlace scan, 96
- internal transmission, 64
- intra-ocular lens, 93
- invert, 37
- iris, 24, 90
- irradiance, 32, 84, 85
- K prism, 41
- kaleidoscope, 57
- Kellner eyepiece, 49
- Keplerian telescope, 46–48, 50, 83
- keystone distortion, 36
- Koehler illumination, 58
-

## Index

---

- Lagrange invariant, 28, 29, 85, 98, 102  
 Lambertian source, 84  
 laser in situ keratomileusis, 93  
 laser wavelengths, 87  
 LASIK, 93  
 lateral chromatic aberration, 68  
 lateral color, 68  
 lateral magnification, 6, 36, 68  
 law of reflection, 4, 37  
 light pipe, 57  
 line coma, 73  
 linear array scanner, 96  
 long focus lenses, 94  
 longitudinal aberration, 75  
 longitudinal magnification, 10, 18  
 longitudinal ray errors, 70, 75  
 lumens, 86  
 luminance, 86  
 luminous exitance, 86  
 luminous intensity, 86  
 luminous photopic efficacy, 86  
 luminous power, 86  
  
 macula, 90, 91  
 magnifier, 45, 48, 51, 54, 103  
 magnifying power (MP), 45-48, 50, 51, 53, 93, 103  
 marginal focus, 75, 76  
 marginal ray, 25, 26, 29, 30, 31, 58, 71, 75, 76  
 matrices, 98, 99  
 matrix methods, 98  
 mean solar constant, 85  
  
 mechanical tube length, 52  
 mechanically compensated zoom, 44  
 medial focus, 78, 79  
 medial surface, 79  
 meridional rays, 25, 71, 78  
 metallurgical objective 52  
 metrology, 34, 39  
 microscope, 34, 49, 51, 52, 58, 93, 103  
 minimum circle, 76  
 minimum deviation, 65, 76  
 minimum wavefront variance, 76  
 mirror-based telescopes, 83  
 modulation transfer function (MTF), 89  
 myopia, 92  
  
 natural stop position, 77  
 near point, 45, 92, 95  
 nearsighted, 92  
 Newtonian equations, 8, 18, 101  
 Newtonian telescope, 83  
 nodal plane to nodal plane matrix, 99  
 nodal points, 11, 14, 16, 34, 90  
 normalized image height, 70  
 normalized pupil coordinates, 70  
 numerical aperture (NA), 29, 51, 93, 102  
  
 object space, 5, 6, 8, 13, 18-20, 24, 33, 34, 51, 52, 98  
 object-image conjugates, 17  
 object-image zones, 12
-

## Index

---

- objectives, 22, 23, 33, 34, 43, 44, 46–48, 50–54, 61, 93, 95
  - object-space telecentric, 33, 34, 52
  - object-to-image distance, 16
  - ocular, 49
  - optical angle, 9, 10
  - optical axis, 11, 19, 36, 40, 41, 66, 77, 80, 82, 84, 85, 90
  - optical density, 95
  - optical invariant, 28, 98
  - optical order, 23, 98
  - optical path length (OPL), 3
  - optical spaces, 5, 9, 12, 13, 19, 23–30, 34, 37, 98
  - optical tube length (OTL), 51, 52
  - overhead projector, 60
  
  - parabola, 59, 82, 83
  - parallax, 53, 54
  - parallel plane mirrors, 38
  - paraxial optics, 2, 19, 28
  - paraxial raytrace, 19, 20, 22, 23, 81, 98, 102
  - parfocal objectives, 52
  - parity, 37–39, 54, 60
  - partial dispersion, 62, 67
  - passive triangulation system, 54
  - Pechan prism, 41
  - Pechan-roof prism, 41, 50
  - Pentaprism, 39, 40
  - periscope, 38, 50
  - Petzval objective, 43
  - Petzval surface, 79
  - phakic IOL, 93
  - photometric units, 86
  - photometry, 86
  - photopic response, 86
  - photorefractive keratectomy (PRK), 93
  - pincushion distortion, 80
  - piston, 73
  - Planck's equation, 87
  - plane mirror, 37–39
  - plane parallel plate, 42
  - point spread function (PSF), 89
  - polycarbonate, 64
  - polystyrene, 64
  - Porro prism, 40, 41, 50
  - Porro system, 41
  - Porro-Abbe system, 41
  - power of an optical surface, 7
  - presbyopia, 92
  - primary colors, 95
  - primary rainbow, 97
  - principal dispersion, 62
  - principal section, 38, 66
  - prism diopters, 66
  - prism dispersion, 65, 67
  - prism systems, 39–41
  - progressive scan, 96
  - projected area, (Lambert's law) 84
  - projection condenser system, 58
  - projection lens, 58, 59
  - projection screen, 60
  - projector, 55, 60
  - pupil (of the eye), 90–92
  - pupil locations, 25, 26
  - push broom scanner, 96
  
  - radial keratotomy (RK), 93
  - radiance, 84, 85, 87
  - radiative transfer, 28, 32, 85, 86, 104
-



## Index

---

- radiometry, 84–86, 104
  - radius of curvature, 1, 7, 90, 92
  - rainbow, 97
  - Ramsden circle, 46
  - Ramsden eyepiece, 49
  - rare earth glasses 63
  - ray bundle, 30–32
  - ray fans, 71, 72, 75, 77, 80, 81
  - ray intercept curves, 71, 72, 75, 77, 80, 81
  - Rayleigh criterion, 88, 89
  - Rayleigh scattering, 97
  - real image, 5
  - real object, 5
  - rear cardinal points, 20, 22
  - rear focal length, 6–9, 17, 90, 92
  - rear focal point/plane, 6, 8, 17, 18, 20, 33, 51, 92
  - rear principal plane, 6, 36, 43, 48, 90
  - reciprocal magnifications, 16
  - reduced diagram, 42
  - reduced distance, 9, 10
  - reduced schematic eye, 91
  - reduced thickness, 42, 99
  - reduced tunnel diagram, 42
  - reference image point, 70–72, 74
  - reference sphere, 70, 74
  - reference wavefront 70, 71
  - reflectance, 4, 84
  - reflex prism, 39, 54
  - reflex viewfinder, 53
  - refraction matrix, 98
  - refractive surgery
    - techniques, 93
  - refractivity, 62
  - relative partial dispersion ratio, 62
  - relay lens, 50
  - relayed Keplerian telescope, 50, 83
  - resolution of the eye, 91, 93, 95
  - reticle, 49, 52, 53
  - retina, 91–93
  - retrofocus objective, 43
  - reverse Galilean viewfinder, 53
  - reverse raytrace, 19, 20
  - reverse telephoto objective, 43
  - reverse telephoto zoom, 44
  - reversed Galilean telescope, 47
  - reversion prism, 41
  - revert, 37
  - right angle prism, 39, 40
  - right circular cone, 30, 84
  - Risley prism, 66
  - Ritchey-Chretien telescope, 83
  - RMS spot size 72, 76
  - rods, 91
  - roof mirror, 38, 39
  - roof prism, 39
  - root-mean-squared spot size, 72, 76
  - sag of a spherical surface, 83, 104
  - sagittal coma, 77
  - sagittal focus, 78
  - sagittal oblique spherical aberration, 73
  - sagittal ray fan, 71, 72
-

## Index

---

- sagittal rays or transverse rays, 71, 78  
 sagittal surface, 79  
 scanners, 96  
 Scheimpflug condition, 36  
 schematic eyes, 91  
 schlieren system, 61  
 Schmidt prism, 40  
 scotopic response, 86  
 scratch suppression, 56  
 secondary chromatic aberration, 69  
 secondary color, 69  
 secondary dispersion, 67  
 secondary rainbow, 97  
 Seidel aberration coefficients, 81  
 sensitivity of the eye, 91  
 shoulder height, 52  
 sign conventions, 1  
 simple eyepiece, 49  
 simple objective, 43  
 single lens reflex system, 39, 54  
 skew ray, 71  
 SLR system, 39, 54  
 Snell's law of refraction, 4  
 Snellen visual acuity, 93  
 source mirror, 59  
 spectacle lens, 92  
 specular illumination, 55, 58  
 spherical aberration (SA), 73, 75, 76, 83  
 spherochromatism, 76  
 spot diagram, 72  
 stain resistance, 64  
 standard lens, 94  
 Stefan-Boltzmann law, 87  
 Stiles-Crawford effect, 92  
 Strehl ratio, 89  
 substage diaphragm, 58  
 subtractive colors, 95  
 sunsets, 97  
 surface vertices, 7, 14, 15  
 system matrix, 98, 99  
 system of plane mirrors, 38  
  
 tangential coma, 77  
 tangential focus, 78  
 tangential oblique spherical aberration, 73  
 tangential rays or meridional rays, 25, 71, 78  
 tangential surface, 79  
 tapered integrating bar, 57  
 telecentricity, 33, 34  
 telephoto objective, 43, 83  
 telephoto zoom, 44  
 telescopes, 46–50, 83  
 temperature coefficients of refractive index, 64  
 thermal sources, 87  
 thick lens, 14, 36, 60  
 thick lens matrix, 99  
 thin lens, 10, 14–17, 27, 29, 35, 36, 43, 68, 69, 76, 77, 102  
 thin lens matrix, 99  
 thin prisms, 66, 103  
 third-order optics, 2  
 throughput, 28, 85  
 total internal reflection (TIR), 4  
 transfer matrix, 98  
 transmission, 56, 61, 63, 64, 84, 95  
 transverse aberration, 75  
 transverse axial chromatic aberration, 68, 103
-

## Index

---

- transverse magnification, 6, 8
  - transverse ray errors, 70–72
  - trigonometric identities, 100
  - tunnel diagram, 39, 42, 57
  - two separated thin lenses, 14
  - two-component system, 13
  
  - undercorrected (SA), 76
  
  - Van Albada viewfinder, 53
  - vernier acuity, 91
  - vertex distances, 15
  - vertex matrix, 99
  - video sensors, 94
  - viewfinders, 39, 47, 53
  - vignetting, 31–33, 39, 48, 49, 54, 102
  - virtual image, 5
  - virtual object, 5
  - visual astigmatism, 92
  - visual magnification 51, 93
  - vitreous, 90
  
  - wave fans, 71, 72, 81
  - wavefront errors, 70
  - wavefront expansion, 73
  - wavefront tilt, 73, 74, 80, 81
  - wavefronts, 3, 71
  - wavelength, 2
  - wavenumber, 2
  - Wein's displacement law, 87
  - wide angle lenses, 94
  - working distance (WD), 22, 23, 52
  - working  $f$ -number, 29
  
  - YNU raytrace, 19, 21
  - YNU raytrace worksheet, 21
-



John E. Greivenkamp is a Professor at the Optical Sciences Center of the University of Arizona where he has taught courses in optical engineering since 1991. After receiving a Ph.D. from the Optical Sciences Center in 1980, he was employed by Eastman Kodak. He is a fellow of SPIE–The International Society for Optical Engineering, of the Optical Society of America, and he has served a member of the National Research Council Committee on Optical Science and Engineering (COSE).

Professor Greivenkamp's research interests include interferometry and optical testing, optical fabrication, ophthalmic optics, optical measurement systems, optical systems design, and the optics of electronic imaging systems.