

OPTICAL IMAGING AND ABERRATIONS

PART I

RAY GEOMETRICAL OPTICS



VIRENDRA N. MAHAJAN

TABLE OF CONTENTS

PART 1. RAY GEOMETRICAL OPTICS

Preface	xvii
Acknowledgments	xi
Symbols and notation	xxiii

CHAPTER 1: GAUSSIAN OPTICS	1
1.1 Introduction	3
1.2 Foundations of Geometrical Optics	5
1.2.1 Fermat's Principle	5
1.2.2 Laws of Geometrical Optics	8
1.2.3 Optical Path Lengths of Neighboring Rays	10
1.2.4 Malus-Dupin Theorem	11
1.2.5 Hamilton's Point Characteristic Function and Direction of a Ray.....	13
1.3 Gaussian Imaging	14
1.3.1 Introduction	14
1.3.2 Sign Convention	14
1.3.3 Spherical Refracting Surface	15
1.3.3.1 Gaussian Imaging Equation	15
1.3.3.2 Focal Lengths and Refracting Power	18
1.3.3.3 Magnifications and Lagrange Invariant	19
1.3.3.4 Graphical Imaging	22
1.3.3.5 Newtonian Imaging Equation.....	24
1.3.4 Thin Lens	24
1.3.4.1 Gaussian Imaging Equation	24
1.3.4.2 Focal Lengths and Refracting Power	25
1.3.4.3 Undeviated Ray	26
1.3.4.4 Magnifications and Lagrange Invariant	28
1.3.4.5 Newtonian Imaging Equation.....	30
1.3.5 Refracting Systems	31
1.3.5.1 Cardinal Points and Planes	31
1.3.5.2 Gaussian Imaging, Focal Lengths, and Magnifications	33
1.3.5.3 Nodal Points	36
1.3.5.4 Newtonian Imaging Equation.....	38
1.3.6 Afocal Systems	38
1.3.7 Spherical Reflecting Surface (Spherical Mirror)	42
1.3.7.1 Gaussian Imaging Equation	42
1.3.7.2 Focal Length and Reflecting Power	44
1.3.7.3 Magnifications and Lagrange Invariant	46
1.3.7.4 Graphical Imaging	49
1.3.7.5 Newtonian Imaging Equation.....	52

1.4	Paraxial Ray Tracing	52
1.4.1	Refracting Surface	52
1.4.2	Thin Lens	54
1.4.3	Two Thin Lenses	57
1.4.4	Thick Lens	59
1.4.5	Reflecting Surface (Mirror).....	62
1.4.6	Two-Mirror System.....	65
1.4.7	Catadioptric System: Thin Lens-Mirror Combination	67
1.5	Two-Ray Lagrange Invariant.....	69
1.6	Matrix Approach to Paraxial Ray Tracing and Gaussian Optics	73
1.6.1	Introduction	73
1.6.2	System Matrix	73
1.6.3	Conjugate Matrix	77
1.6.4	System Matrix in Terms of Gaussian Parameters	81
1.6.5	Gaussian Imaging Equations	81
References		84
Problems.....		85

CHAPTER 2: RADIOMETRY OF IMAGING	89	
2.1	Introduction	91
2.2	Stops, Pupils, and Vignetting.....	92
2.2.1	Introduction	92
2.2.2	Aperture Stop, and Entrance and Exit Pupils	92
2.2.3	Chief and Marginal Rays	94
2.2.4	Vignetting	95
2.2.5	Size of an Imaging Element	98
2.2.6	Telecentric Aperture Stop.....	98
2.2.7	Field Stop, and Entrance and Exit Windows.....	98
2.3	Radiometry of Point Sources	100
2.3.1	Irradiance of a Surface	100
2.3.2	Flux Incident on a Circular Aperture	103
2.4	Radiometry of Extended Sources	104
2.4.1	Lambertian Surface	104
2.4.2	Exitance of a Lambertian Surface	105
2.4.3	Radiance of a Tube of Rays	106
2.4.4	Irradiance by a Lambertian Surface Element	107
2.4.5	Irradiance by a Lambertian Disc	108
2.5	Radiometry of Point Object Imaging	112
2.6	Radiometry of Extended Object Imaging	114
2.6.1	Image Radiance	114
2.6.2	Pupil Distortion	117
2.6.3	Image Irradiance: Aperture Stop in Front of the System	118
2.6.4	Image Irradiance: Aperture Stop in Back of the System.....	121

2.6.5	Telecentric Systems	123
2.6.6	Throughput	123
2.6.7	Condition for Uniform Image Irradiance	123
2.6.8	Concentric Systems	125
2.7	Photometry.....	126
2.7.1	Photometric Quantities and Spectral Response of the Human Eye	126
2.7.2	Imaging by a Human Eye	127
2.7.3	Brightness of a Lambertian Surface	129
2.7.4	Observing Stars in the Daytime.....	130
Appendix: Radiance Theorem		134
References.....		136
Problems.....		137
CHAPTER 3: OPTICAL ABERRATIONS		139
3.1	Introduction	141
3.2	Wave and Ray Aberrations	142
3.2.1	Definitions	142
3.2.2	Relationship Between Wave and Ray Aberrations	145
3.3	Defocus Aberration	148
3.4	Wavefront Tilt	150
3.5	Aberration Function of a Rotationally Symmetric System	152
3.5.1	Rotational Invariants	152
3.5.2	Power-Series Expansion	155
3.5.2.1	Explicit Dependence on Object Coordinates.....	156
3.5.2.2	No Explicit Dependence on Object Coordinates	159
3.5.3	Zernike Circle-Polynomial Expansion	163
3.5.4	Relationships Between Coefficients of Power-Series and Zernike-Polynomial Expansions	168
3.6	Observation of Aberrations	169
3.6.1	Primary Aberrations	172
3.6.2	Interferograms	173
3.7	Conditions for Perfect Imaging.....	178
3.7.1	Imaging of a 3-D Object.....	178
3.7.2	Imaging of a 2-D Transverse Object	181
3.7.3	Imaging of a 1-D Axial Object	183
3.7.4	Linear Coma and the Sine Condition	184
3.7.5	Optical Sine Theorem.....	186
3.7.6	Linear Coma and Offense Against the Sine Condition	188
Appendix A: Degree of Approximation in Eq. (3-11)		192
Appendix B: Wave and Ray Aberrations: Alternative Definition and Derivation.....		194
References.....		200
Problems.....		201

CHAPTER 4: GEOMETRICAL POINT-SPREAD FUNCTION..... 203

4.1	Introduction	205
4.2	Theory	205
4.3	Application to Primary Aberrations.....	209
4.3.1	Spherical Aberration	210
4.3.2	Coma.....	217
4.3.3	Astigmatism and Field Curvature.....	224
4.3.4	Distortion.....	233
4.4	Balanced Aberrations for Minimum RMS Spot Radius.....	235
4.5	Spot Diagrams.....	236
4.6	Aberration Tolerance and Golden Rule of Optical Design	240
References.....		243
Problems.....		244

CHAPTER 5: CALCULATION OF PRIMARY ABERRATIONS: REFRACTING SYSTEMS 245

5.1	Introduction	247
5.2	Spherical Refracting Surface with Aperture Stop at the Surface	249
5.2.1	On-Axis Point Object	249
5.2.2	Off-Axis Point Object	252
5.2.2.1	Aberrations with Respect to Petzval Image Point	253
5.2.2.2	Aberrations with Respect to Gaussian Image Point	259
5.3	Spherical Refracting Surface with Aperture Stop Not at the Surface	261
5.3.1	On-Axis Point Object	262
5.3.2	Off-Axis Point Object	264
5.4	Aplanatic Points of a Spherical Refracting Surface	266
5.5	Conic Refracting Surface.....	271
5.5.1	Sag of a Conic Surface	271
5.5.2	On-Axis Point Object	275
5.5.3	Off-Axis Point Object	278
5.6	General Aspherical Refracting Surface	281
5.7	Series of Coaxial Refracting (and Reflecting) Surfaces.....	281
5.7.1	General Imaging System	282
5.7.2	Petzval Curvature and Corresponding Field Curvature Wave Aberration.....	282
5.7.3	Relationship among Petzval Curvature, Field Curvature, and Astigmatism Wave Aberration Coefficients.....	287

5.8	Aberration Function in Terms of Seidel Sums or Seidel Coefficients	287
5.9	Effect of Change in Aperture Stop Position on the Aberration Function	290
5.9.1	Change of Peak Aberration Coefficients.....	291
5.9.2	Illustration of the Effect of Aperture-Stop Shift on Coma and Distortion.....	295
5.9.3	Aberrations of a Spherical Refracting Surface with Aperture Stop Not at the Surface Obtained from Those with Stop at the Surface	298
5.10	Thin Lens.....	299
5.10.1	Imaging Relations.....	300
5.10.2	Thin Lens with Spherical Surfaces and Aperture Stop at the Lens.....	301
5.10.3	Petzval Surface	306
5.10.4	Spherical Aberration and Coma	307
5.10.5	Aplanatic Lens	310
5.10.6	Thin Lens with Conic Surfaces	313
5.10.7	Thin Lens with Aperture Stop Not at the Lens.....	313
5.11	Field Flattener.....	314
5.11.1	Imaging Relations.....	315
5.11.2	Aberration Function	316
5.12	Plane-Parallel Plate	318
5.12.1	Introduction	318
5.12.2	Imaging Relations.....	318
5.12.3	Aberration Function	321
5.13	Chromatic Aberrations.....	323
5.13.1	Introduction	323
5.13.2	Single Refracting Surface	324
5.13.3	Thin Lens	327
5.13.4	General System: Surface-by-Surface Approach	331
5.13.5	General System: Use of Principal and Focal Points	335
5.13.6	Chromatic Aberrations as Wave Aberrations.....	347
5.14	Symmetrical Principle	348
5.15	Pupil Aberrations and Conjugate-Shift Equations	349
5.15.1	Introduction	349
5.15.2	Pupil Aberrations	350
5.15.3	Conjugate-Shift Equations	355
5.15.4	Invariance of Image Aberrations	357
5.15.5	Simultaneous Correction of Aberrations for Two or More Object Positions	358
References.....	360	
Problems.....	361	

CHAPTER 6: CALCULATION OF PRIMARY ABERRATIONS: REFLECTING AND CATADIORTRIC SYSTEMS	365
6.1 Introduction	367
6.2 Conic Reflecting Surface.....	367
6.2.1 Conic Surface	367
6.2.2 Imaging Relations.....	370
6.2.3 Aberration Function	370
6.3 Petzval Surface	375
6.4 Spherical Mirror	377
6.4.1 Aberration Function and Aplanatic Points for Arbitrary Location of Aperture Stop	377
6.4.2 Aperture Stop at the Mirror Surface	379
6.4.3 Aperture Stop at the Center of Curvature of Mirror	381
6.5 Paraboloidal Mirror.....	384
6.6 Catadioptric Systems	385
6.6.1 Introduction	385
6.6.2 Schmidt Camera	385
6.6.3 Bouwers-Maksutov Camera	394
6.7 Beam Expander	398
6.7.1 Introduction	398
6.7.2 Gaussian Parameters.....	398
6.7.3 Aberration Contributed by Primary Mirror.....	400
6.7.4 Aberration Contributed by Secondary Mirror.....	401
6.7.5 System Aberration	402
6.8 Two-Mirror Astronomical Telescopes	402
6.8.1 Introduction	402
6.8.2 Gaussian Parameters.....	403
6.8.3 Petzval Surface	408
6.8.4 Aberration Contributed by Primary Mirror.....	408
6.8.5 Aberration Contributed by Secondary Mirror.....	410
6.8.6 System Aberration	412
6.8.7 Classical Cassegrain and Gregorian Telescopes	413
6.8.8 Aplanatic Cassegrain and Gregorian Telescopes	416
6.8.9 Afocal Telescope	416
6.8.10 Couder Anastigmatic Telescopes	417
6.8.11 Schwarzschild Telescope	418
6.8.12 Dall-Kirkham Telescope	421
6.9 Astronomical Telescopes Using Aspheric Plates	422
6.9.1 Introduction	422
6.9.2 Aspheric Plate in a Diverging Object Beam.....	422
6.9.3 Aspheric Plate in a Converging Image Beam	425
6.9.4 Aspheric Plate and a Conic Mirror.....	426
6.9.5 Aspheric Plate and a Two-Mirror Telescope	428

References	431
Problems	432
CHAPTER 7: CALCULATION OF PRIMARY ABERRATIONS: PERTURBED OPTICAL SYSTEMS	435
7.1 Introduction	437
7.2 Aberrations of a Misaligned Surface	438
7.2.1 Decentered Surface	438
7.2.2 Tilted Surface	442
7.2.3 Despaced Surface	444
7.3 Aberrations of Perturbed Two-Mirror Telescopes	445
7.3.1 Decentered Secondary Mirror	445
7.3.2 Tilted Secondary Mirror	447
7.3.3 Decentered and Tilted Secondary Mirror	448
7.3.4 Despaced Secondary Mirror	451
7.4 Fabrication Errors	454
7.4.1 Refracting Surface	454
7.4.2 Reflecting Surface	456
References	458
Problems	459
Bibliography	461
Index	463