

Contents

Notations	xix
1 Introduction to Optics and Elasticity	1
1.1 Optics and Telescopes – Historical Introduction	1
1.1.1 The Greek Mathematicians and Conics	1
1.1.2 The Persian Mathematicians and Mirrors	3
1.1.3 End of European Renaissance and Birth of Telescopes	5
1.1.4 Refractive Telescopes	6
1.1.5 Reflective Telescopes	13
1.2 Snell’s Law and Glass Dispersion	26
1.3 Fermat’s Principle	29
1.4 Gaussian Optics and Conjugate Distances	31
1.4.1 Diopter of Curvature $c = 1/R$	32
1.4.2 Mirror in Medium n	34
1.4.3 Power of Combined Systems	35
1.4.4 Lens in Air or in Vacuum	35
1.4.5 Afocal Systems	36
1.4.6 Pupils and Principal Rays	37
1.4.7 Aperture Ratio or Focal Ratio	37
1.5 Lagrange Invariant	38
1.6 Étendue Invariant and Lagrange Invariant	39
1.6.1 Lagrange Invariant	39
1.6.2 Étendue Invariant	39
1.6.3 Equivalence of the Étendue and Lagrange Invariants	40
1.7 Analytical Representation of Optical Surfaces	41
1.7.1 Conicoids	42
1.7.2 Spheroids	43
1.7.3 Non-Axisymmetric Surfaces and Zernike Polynomials	43
1.8 Seidel Representation of Third-Order Aberrations	45
1.8.1 The Seidel Theory	45
1.8.2 Seidel Aberration Modes – Elastic Deformation Modes ...	49
1.8.3 Zernike rms Polynomials	50
1.9 Stigmatism, Aplanatism, and Anastigmatism	52
1.9.1 Stigmatism	52

1.9.2	Aplanatism and Abbe's Sine Condition	55
1.9.3	Anastigmatism	59
1.10	Petzval Curvature and Distortion	62
1.10.1	Petzval Curvature	62
1.10.2	Distortion	64
1.11	Diffraction	65
1.11.1	The Diffraction Theory	66
1.11.2	Diffraction from a Circular Aperture	68
1.11.3	Diffraction from an Annular Aperture	71
1.11.4	Point Spread Function (PSF) and Diffracted Aberrations	71
1.11.5	Diffraction-Limited Criteria and Wavefront Tolerances	72
1.12	Some Image Processor Options	75
1.12.1	Human Eye	76
1.12.2	Eyepiece	77
1.12.3	Interferometer	77
1.12.4	Coronagraph	78
1.12.5	Polarimeter	78
1.12.6	Slit Spectrograph	78
1.12.7	Slitless Spectrograph	79
1.12.8	Multi-Object Spectroscopy with Slits or Fiber Optics	80
1.12.9	Integral Field Spectrographs	81
1.12.10	Back-Surface Mirrors	84
1.12.11	Field Derotator	85
1.12.12	Pupil Derotator	86
1.12.13	Telescope Field Corrector	86
1.12.14	Atmospheric Dispersion Compensator	87
1.12.15	Adaptive Optics	89
1.13	Elasticity Theory	91
1.13.1	Historical Introduction	91
1.13.2	Elasticity Constants of Isotropic Materials	101
1.13.3	Displacement Vector and Strain Tensor	104
1.13.4	The Stress-Strain Linear Relations and Strain Energy	105
1.13.5	Uniform Torsion of a Rod and Strain Components	107
1.13.6	Love-Kirchhoff Hypotheses and Thin Plate Theory	110
1.13.7	Bending of Thin Plates and Developable Surfaces	111
1.13.8	Bending of Thin Plates and Non-developable Surfaces	116
1.13.9	Bending of Rectangular Plates of Constant Thickness	121
1.13.10	Axisymmetric Bending of Circular Plates of Constant Thickness	123
1.13.11	Circular Plates and Axisymmetric Loading Manifolds	124
1.13.12	Deformation of a Plate in a Gravity Field	126
1.13.13	Saint-Venant's Principle	126
1.13.14	Computational Modeling and Finite Element Analysis	127
1.14	Active Optics	128
1.14.1	Spherical Polishing	128
1.14.2	Optical Surfaces Free from Ripple Errors	129

1.14.3	Active Optics and Time-Dependence Control	129
1.14.4	Various Aspect of Active Optics	130
References		130
2	Dioptrics and Elasticity – Variable Curvature Mirrors (VCMs)	137
2.1	Thin Circular Plates and Small Deformation Theory	137
2.1.1	Plates of Constant Thickness Distribution – CTD	137
2.1.2	Plates of Variable Thickness Distribution – VTD – Cycloid-Like form – Tulip-Like Form	139
2.1.3	Optical Focal-Ratio Variation	144
2.1.4	Buckling Instability	144
2.2	Thin Plates and Large Deformation Theory – VTD	145
2.3	The Mersenne Afocal Two-Mirror Telescopes	150
2.4	Beam Compressors, Expanders and Cat’s Eyes – Active Optics Pupil Transfers	153
2.5	VCMs as Field Compensators of Interferometers	154
2.5.1	Fourier Transform Spectrometers	155
2.5.2	Stellar Interferometers and Telescope Arrays	156
2.6	Construction of VCMs with VTDs	158
2.6.1	Elastic Deformability and Choice of Material Substrate	158
2.6.2	Zoom Range and Choice of a Thickness Distribution	160
2.6.3	Achievement of Boundary Conditions	160
2.6.4	Design and Results with VTD Type 1 – Cycloid-Like Form	161
2.6.5	Design and Results with a VTD Type 2 – Tulip-Like Form	162
2.7	Plasticity and Hysteresis	163
2.7.1	Stress-Strain Linearization and Plasticity Compensation	163
2.7.2	Hysteresis Compensation and Curvature Control	166
References		168
3	Active Optics and Correction of Third-Order Aberrations	171
3.1	Elasticity Theory with Constant Thickness Distributions – CTD Class	171
3.2	Elasticity Theory with Variable Thickness Distributions – VTD Class	171
3.3	Active Optics and Third-Order Spherical Aberration	177
3.3.1	Configurations in the CTD Class ($A_1 = A_2 = 0$)	178
3.3.2	Configurations in the VTD Class	179
3.3.3	Hybrid Configurations	182
3.3.4	Balance with a Curvature Mode	184
3.3.5	Examples of Application	185
3.4	Active Optics and Third-Order Coma	188
3.4.1	Configuration in the CTD Class ($A_1 = 0$)	189
3.4.2	Configuration in the VTD Class	190
3.4.3	Hybrid Configurations	192
3.4.4	Balance with a Tilt Mode	192

- 3.4.5 Coma from a Pupil and Concave Mirror System 194
- 3.4.6 Examples of Active Optics Coma Correction 195
- 3.5 Active Optics and Third-Order Astigmatism 198
 - 3.5.1 Configuration in the CTD Class ($A_2 = 0$) 199
 - 3.5.2 Configuration in the VTD Class 200
 - 3.5.3 Hybrid Configurations 201
 - 3.5.4 Balance with a Curvature Mode and Cylindric Deformations 201
 - 3.5.5 Sagittal and Tangential Ray Fans in Mirror Imaging 202
 - 3.5.6 Aspherization of Concave Mirrors – Examples 206
 - 3.5.7 Concave Diffraction Gratings and Saddle Correction 209
 - 3.5.8 Aspherization of Single Surface Spectrographs – Example 212
 - 3.5.9 Higher-Order Aspherizations of Single Surface Spectrographs 213
- References 214

4 Optical Design with the Schmidt Concept – Telescopes and Spectrographs 217

- 4.1 The Schmidt Concept 217
 - 4.1.1 The Class of Two-Mirror Anastigmatic Telescopes 217
 - 4.1.2 Wavefront Analysis at the Center of Curvature of a Spherical Mirror 222
 - 4.1.3 Wavefront Equation Including the Magnification Ratio M 225
 - 4.1.4 Optical Design of Correctors – Preliminary Remarks 225
 - 4.1.5 Object at Infinity – Null Power Zone Positioning 226
 - 4.1.6 Optical Equation of Various Corrective Elements 227
 - 4.1.7 Under or Over Correction Factor s 228
- 4.2 Refractive Corrector Telescopes 229
 - 4.2.1 Off-axis Aberrations and Chromatism of a Singlet Corrector 229
 - 4.2.2 Achromatic Doublet-Plate Corrector 232
 - 4.2.3 Singlet Corrector in Blue and Additional Monocentric Filters in Red 233
- 4.3 All-Reflective Telescopes 234
 - 4.3.1 Centered Optical Systems used Off-axis 235
 - 4.3.2 Non-Centered Optical Systems 237
 - 4.3.3 Gain of Non-Centered Systems Over Centered Designs 239
 - 4.3.4 LAMOST: A Giant Non-Centered Schmidt with Active Optics 240
- 4.4 All-Reflective Spectrographs with Aspherical Gratings 242
 - 4.4.1 Comparison of Reflective Grating Spectrograph Designs 242
 - 4.4.2 Diffraction Grating Equation 243
 - 4.4.3 Axisymmetric Gratings ($\beta_0 = 0$) 244
 - 4.4.4 Bi-Axial Symmetric Gratings ($\beta_0 \neq 0$) 245
 - 4.4.5 Flat Fielding of All-Reflective Aspherized Grating Spectrographs 246

4.4.6	Examples of All-Reflective Aspherized Grating Spectrographs	247
4.4.7	All-Reflective Spectrographs Without Central Obstruction	252
4.4.8	Advantages of Quasi-all-Reflective Spectrographs	252
4.4.9	Diffraction Gratings and Electromagnetic Theoretical Models	252
4.4.10	Grating Manufacturing Methods	254
4.4.11	Towards Large Size Aspherized Reflective Gratings	255
4.4.12	Large All-Reflective Aspherized Grating Spectrographs	255
	References	258
5	Schmidt Correctors and Diffraction Gratings Aspherized by Active Optics	263
5.1	Various Types of Aspherical Schmidt Correctors	263
5.2	Refractive Correctors	263
5.2.1	Third-Order Optical Profile of Refractive Correctors	263
5.2.2	Elasticity and Circular Constant Thickness Plates	264
5.2.3	Refractive Correctors and the Spherical Figuring Method	265
5.2.4	Refractive Correctors and the Plane Figuring Method	268
5.2.5	Glass Rupture and Loading Time Dependence	273
5.3	Reflective Correctors	276
5.3.1	Optical Figure of the Primary Mirror	276
5.3.2	Axisymmetric Circular Primaries with $k = 3/2$ – Vase Form	277
5.3.3	Bisymmetric Circular Primaries with $k = 3/2$ – MDM	279
5.3.4	Bisymmetric Circular Primaries with $k = 0$ – Tulip Form	279
5.3.5	Bisymmetric Elliptical Primary Mirror with $k = 3/2$ – Vase Form – Biplate Form	282
5.3.6	LAMOST: A Segmented Bisymmetric Elliptical Primary	293
5.4	Aspherized Reflective Diffraction Gratings	293
5.4.1	Active Optics Replication for Grating Aspherization	293
5.4.2	Optical Profile of Aspherical Reflective Gratings	294
5.4.3	Axisymmetric Gratings with $k = 3/2$ and Circular Built-in Submasters	296
5.4.4	Axisymmetric Gratings with $k = 0$ and Circular Simply Supported Submasters	302
5.4.5	Bisymmetric Gratings with $k = 3/2$ and Elliptic Built-in Submasters	304
5.4.6	Constructional Replication Condition for Active Optics Process	309
	References	310
6	Theory of Shells and Aspherization of Axisymmetric Mirrors – Meniscus, Vase and Closed Forms	313
6.1	Active Optics Aspherization of Fast f-Ratio Mirrors	313
6.2	Theory of Shallow Spherical Shells	313

6.2.1	Equilibrium Equations for Axisymmetric Loadings	314
6.2.2	General Equation of Shallow Spherical Shells	315
6.2.3	Kelvin Functions	318
6.2.4	Flexure and Stress Function of Shallow Spherical Shells . .	320
6.3	Variable Thickness Shell and Continuity Conditions	322
6.3.1	Shell Relations for a Constant Thickness Ring Element . . .	323
6.3.2	Various Boundaries and Constant Thickness Plain Shells . .	323
6.3.3	Some Quantities Involved in a Variable Thickness Shell . . .	324
6.3.4	Continuity Conditions of a Shell Element Ring	325
6.4	Edge Cylinder Link and Boundary Conditions	327
6.4.1	Three Geometrical Configurations and Boundaries	327
6.4.2	Outer Cylinder Linked to a Meniscus Shell	328
6.5	Determination of a Variable Thickness Vase Shell	332
6.5.1	Flexure Representation in the Shell z, r Main Frame	332
6.5.2	Inverse Problem and Thickness Distribution	333
6.6	Active Optics Aspherization of Telescope Mirrors	333
6.6.1	Active Optics Co-addition Law	333
6.6.2	Parabolization of Concave Mirrors	334
6.6.3	Concave Paraboloid Mirrors with a Central Hole	339
6.6.4	Aspherization of Concave Spheroid Mirrors	342
6.6.5	Aspherization of Cassegrain Mirrors	345
6.6.6	Comparison of Various Wide-Field Telescope Designs	350
6.6.7	Modified-Rumsey Three-Reflection Telescope Mirrors	352
6.6.8	Mirror Aspherizations of a Large Modified-Rumsey Telescope	360
	References	363

7	Active Optics with Multimode Deformable Mirrors (MDM) Vase and Meniscus Forms	365
7.1	Introduction – Clebsch-Seidel Deformation Modes	365
7.2	Elasticity and Vase-Form MDMs	366
7.3	Elasticity and Meniscus-Form MDMs	374
7.4	Degenerated Configurations and Astigmatism Mode	376
7.4.1	Special Geometry for the Astigmatism Mode	376
7.4.2	Single Astm 3 Mode and Degenerated Meniscus Form	377
7.4.3	Single Astm 3 Mode and Degenerated Vase Form	378
7.5	Meniscus Form and Segments for Large Telescopes	378
7.5.1	Off-Axis Segments of a Paraboloid Mirror	379
7.5.2	Off-Axis Segments of a Conicoid Mirror	383
7.5.3	Segments of the Keck Telescope	384
7.6	Vase and Meniscus MDMs for Reflective Schmidts	385
7.6.1	Centered Systems with a Circular Vase-Form Primary	385
7.6.2	Non-Centered Systems and Circular Vase-Form Primary . .	386
7.6.3	Non-Centered Systems and Elliptical Vase-Form Primary .	388
7.6.4	In-situ Aspherized Meniscus Segments of LAMOST	388

- 7.7 Vase MDMs for Liquid Mirror Telescopes 390
 - 7.7.1 Zenithal Observations with LMTs 390
 - 7.7.2 Field Distortions and Four-Lens Correctors for LMTs 391
 - 7.7.3 LMT Concepts with MDMs for Off-Zenith Observations .. 392
- 7.8 MDMs as Recording Compensators for Holographic Gratings 395
 - 7.8.1 Holographic Gratings Correcting Aberrations 395
 - 7.8.2 Design Example for the COS Gratings of HST–Recording
Parameters 396
 - 7.8.3 Elasticity Design of a Six-Arm MDM as Recording
Compensator 398
- 7.9 Degenerated Configurations and Triangle Mode 402
 - 7.9.1 Special Geometry for the Triangle Mode 402
 - 7.9.2 Single Tri 3 Mode and Degenerated Meniscus Form 402
 - 7.9.3 Single Tri 3 Mode and Degenerated Vase Form 403
- 7.10 Single Mode and Deformable Outer Ring 404
 - 7.10.1 Outer Ring Designs for High Accuracy Correction 404
 - 7.10.2 Ring with Axial Thickness Variation 404
 - 7.10.3 Ring with Forces Acting on Angular Bridges 404
- 7.11 Future Giant Telescopes and Segment Aspherization 405
 - 7.11.1 Current Trends in Giant Telescope Concepts 405
 - 7.11.2 Active Optics Aspherization of Mirror Segments..... 406
- 7.12 Vase Form and Middle Surface 407
- 7.13 Vase Form and Saint-Venant’s Principle 408
- References 408
- 8 Own Weight Flexure and Figure Control of Telescope Mirrors 413**
 - 8.1 Primary Mirror Support Systems Against Gravity 413
 - 8.1.1 Introduction 413
 - 8.1.2 Axial and Lateral Support System Concepts..... 413
 - 8.1.3 Some Examples of Primary Mirror Geometries 415
 - 8.2 Density and Thermal Constants of Mirror Substrates 416
 - 8.3 Substrates for Large Mirrors 418
 - 8.4 Stiffness and Elastic Deformability Criteria 421
 - 8.4.1 Mirror Materials and Stiffness Criteria 421
 - 8.4.2 Mirror Materials and Elastic Deformability Criterion 422
 - 8.5 Axial Flexure of Large Mirrors Under Gravity 423
 - 8.5.1 Density Distribution of Mirror Support Pads 423
 - 8.5.2 Flexure of a Mirror Sub-Element Supported by a Ring Pad 424
 - 8.5.3 Density Criterion for Pad Distribution – Couder’s Law 428
 - 8.5.4 Other Axial Flexure Features 431
 - 8.5.5 Finite Element Analysis 437
 - 8.6 Lateral Flexure of Large Mirrors Under Gravity 437
 - 8.6.1 Various Supporting Force Distributions 437
 - 8.6.2 Flexure of a Mirror Supported at its Lateral Edge 439

8.6.3	Other Force Distributions and Skew Surface of Forces	441
8.6.4	Finite Element Analysis	443
8.7	Active Optics and Active Alignment Controls	443
8.7.1	Introduction and Definitions	443
8.7.2	Monolithic Mirror Telescopes	445
8.7.3	Segmented Mirror Telescopes	448
8.7.4	Cophasing of Future Extremely Large Telescopes	452
8.8	Special Cases of Highly Variable Thickness Mirrors	452
8.8.1	Introduction – Mirror Flexure in Fast Tip-Tilt Mode	452
8.8.2	Minimum Flexure in Gravity of a Plate Supported at its Center	453
8.8.3	Field Stabilization Mirrors and Infrared Wobbling Mirrors	457
8.8.4	Design of Low Weight Wobbling Mirrors	459
	References	459
9	Singlet Lenses and Elasticity Theory of Thin Plates	465
9.1	Singlet Lenses	465
9.1.1	Aberrations of a Thin Lens with Spherical Surfaces	465
9.1.2	Stigmatic Lens with Descartes Ovoid and Spherical Surface	468
9.1.3	Aplanatic and Anastigmatic Singlet Lenses	469
9.1.4	Isoplanatic Singlet Lenses and Remote Pupil	471
9.1.5	Aspheric Lenses in the Third-Order Theory	473
9.1.6	Power of a Two-Lens System	474
9.2	Thin Lens Elastically Bent by Uniform Load	475
9.2.1	Equilibrium Equation of the Thin Plate Theory	475
9.2.2	Lens Deformation and Parabolic Thickness Distribution . .	476
9.2.3	Expansion Representation of the Flexure	479
9.2.4	Maximum Stresses at the Lens Surfaces	480
9.2.5	Lenses with Particular Thickness Distributions	487
9.2.6	Conclusions for Active Optics Aspherization	487
9.3	Spectrograph with Single Lens and Corrector Plate	488
	References	490
10	X-ray Telescopes and Elasticity Theory of Shells	491
10.1	X-ray Telescopes	491
10.1.1	Introduction – The Three Wolter Design Forms	491
10.1.2	Basic Stigmatic Paraboloid-Hyperboloid (PH) Telescopes .	491
10.1.3	Sine Condition and Wolter-Schwarzschild (WS) Telescopes	495
10.1.4	Aberration Balanced Hyperboloid-Hyperboloid (HH) Telescopes	497
10.1.5	Aberration Balanced Spheroid-Spheroid (SS) Telescopes . .	499
10.1.6	Existing and Future Grazing Incidence X-ray Telescopes . .	499
10.2	Elasticity Theory of Axisymmetric Cylindrical Shells	501

- 10.2.1 X-ray Mirrors and Super-Smoothness Criterion 501
- 10.2.2 Elasticity Theory of Thin Axisymmetric Cylinders 501
- 10.2.3 Radial Thickness Distributions and Parabolic Flexure 504
- 10.2.4 Radial Thickness Distributions and 4th-Degree Flexure 509
- 10.2.5 Thickness Distributions for Tubular Image Transports 510
- 10.3 Elasticity Theory of Weakly Conical Tubular Shells 514
 - 10.3.1 Flexure Condition for Pure Extension of Axisymmetric Shells 514
 - 10.3.2 Truncated Conical Shell Geometry and Cylindrical Flexure 515
 - 10.3.3 Linear Product Law – Flexure-Thickness Relation 516
- 10.4 Active Optics Aspherization of X-ray Telescope Mirrors 517
 - 10.4.1 Thickness Distributions for Monolithic Tubular Mirrors 517
 - 10.4.2 Boundaries for Segment Mirrors of Large Tubular Telescopes 519
 - 10.4.3 Concluding Remarks on the Aspherization Process 521
- References 522

- Portrait Gallery 525**

- Acronyms 537**

- Glossary 539**

- Author Index 553**

- Subject Index 559**

- About the Author 573**