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 Petvzal 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 Coronograph 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 Dependance . . . 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 555

Subject Index 561

About the Author 575