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 Dioptr 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
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
Contents

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
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 ........3 14
6.2.2 General Equation of Shallow Spherical Shells ............3 15
6.2.3 Kelvin Functions ...........................................3 18
6.2.4 Flexure and Stress Function of Shallow Spherical Shells ...3 20
6.3 Variable Thickness Shell and Continuity Conditions ..........3 22
6.3.1 Shell Relations for a Constant Thickness Ring Element ....3 23
6.3.2 Various Boundaries and Constant Thickness Plain Shells . .3 23
6.3.3 Some Quantities Involved in a Variable Thickness Shell . .3 24
6.3.4 Continuity Conditions of a Shell Element Ring ............3 25
6.4 Edge Cylinder Link and Boundary Conditions .................3 27
6.4.1 Three Geometrical Configurations and Boundaries .........3 27
6.4.2 Outer Cylinder Linked to a Meniscus Shell .................3 28
6.5 Determination of a Variable Thickness Vase Shell ..........3 32
6.5.1 Flexure Representation in the Shell z, r Main Frame ......3 32
6.5.2 Inverse Problem and Thickness Distribution ...............3 33
6.6 Active Optics Aspherization of Telescope Mirrors ..........3 33
6.6.1 Active Optics Co-addition Law ................................3 33
6.6.2 Parabolization of Concave Mirrors .........................3 34
6.6.3 Concave Paraboloid Mirrors with a Central Hole ..........3 39
6.6.4 Aspherization of Concave Spheroid Mirrors .................3 42
6.6.5 Aspherization of Cassegrain Mirrors .......................3 45
6.6.6 Comparison of Various Wide-Field Telescope Designs ......3 50
6.6.7 Modified-Rumsey Three-Reflection Telescope Mirrors .....3 52
6.6.8 Mirror Aspherizations of a Large Modified-Rumsey Telescope ...........3 60

References .............................................................3 63

7 Active Optics with Multimode Deformable Mirrors (MDM) Vase
and Meniscus Forms ..............................................3 65
7.1 Introduction – Clebsch-Seidel Deformation Modes ..........3 65
7.2 Elasticity and Vase-Form MDMs ...............................3 66
7.3 Elasticity and Meniscus-Form MDMs ...........................3 74
7.4 Degenerated Configurations and Astigmatism Mode ..........3 76
  7.4.1 Special Geometry for the Astigmatism Mode ...............3 76
  7.4.2 Single Astm 3 Mode and Degenerated Meniscus Form ....3 77
  7.4.3 Single Astm 3 Mode and Degenerated Vase Form .........3 78
7.5 Meniscus Form and Segments for Large Telescopes ..........3 78
  7.5.1 Off-Axis Segments of a Paraboloid Mirror ...............3 79
  7.5.2 Off-Axis Segments of a Conicoid Mirror .................3 83
  7.5.3 Segments of the Keck Telescope .........................3 84
7.6 Vase and Meniscus MDMs for Reflective Schmids .........3 85
  7.6.1 Centered Systems with a Circular Vase-Form Primary .....3 85
  7.6.2 Non-Centered Systems and Circular Vase-Form Primary ..3 86
  7.6.3 Non-Centered Systems and Elliptical Vase-Form Primary .3 88
  7.6.4 In-situ Aspherized Meniscus Segments of LAMOST .......3 88
7.7 Vase MDMs for Liquid Mirror Telescopes
7.7.1 Zenithal Observations with LMTs
7.7.2 Field Distortions and Four-Lens Correctors for LMTs
7.7.3 LMT Concepts with MDMs for Off-Zenith Observations

7.8 MDMs as Recording Compensators for Holographic Gratings
7.8.1 Holographic Gratings Correcting Aberrations
7.8.2 Design Example for the COS Gratings of HST–Recording Parameters
7.8.3 Elasticity Design of a Six-Arm MDM as Recording Compensator

7.9 Degenerated Configurations and Triangle Mode
7.9.1 Special Geometry for the Triangle Mode
7.9.2 Single Tri 3 Mode and Degenerated Meniscus Form
7.9.3 Single Tri 3 Mode and Degenerated Vase Form

7.10 Single Mode and Deformable Outer Ring
7.10.1 Outer Ring Designs for High Accuracy Correction
7.10.2 Ring with Axial Thickness Variation
7.10.3 Ring with Forces Acting on Angular Bridges

7.11 Future Giant Telescopes and Segment Aspherization
7.11.1 Current Trends in Giant Telescope Concepts
7.11.2 Active Optics Aspherization of Mirror Segments

7.12 Vase Form and Middle Surface
7.13 Vase Form and Saint-Venant’s Principle

References

8 Own Weight Flexure and Figure Control of Telescope Mirrors
8.1 Primary Mirror Support Systems Against Gravity
8.1.1 Introduction
8.1.2 Axial and Lateral Support System Concepts
8.1.3 Some Examples of Primary Mirror Geometries
8.2 Density and Thermal Constants of Mirror Substrates
8.3 Substrates for Large Mirrors
8.4 Stiffness and Elastic Deformability Criteria
8.4.1 Mirror Materials and Stiffness Criteria
8.4.2 Mirror Materials and Elastic Deformability Criterion
8.5 Axial Flexure of Large Mirrors Under Gravity
8.5.1 Density Distribution of Mirror Support Pads
8.5.2 Flexure of a Mirror Sub-Element Supported by a Ring Pad
8.5.3 Density Criterion for Pad Distribution – Couder’s Law
8.5.4 Other Axial Flexure Features
8.5.5 Finite Element Analysis
8.6 Lateral Flexure of Large Mirrors Under Gravity
8.6.1 Various Supporting Force Distributions
8.6.2 Flexure of a Mirror Supported at its Lateral Edge
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.6.3 Other Force Distributions and Skew Surface of Forces</td>
<td>441</td>
</tr>
<tr>
<td>8.6.4 Finite Element Analysis</td>
<td>443</td>
</tr>
<tr>
<td>8.7 Active Optics and Active Alignment Controls</td>
<td>443</td>
</tr>
<tr>
<td>8.7.1 Introduction and Definitions</td>
<td>443</td>
</tr>
<tr>
<td>8.7.2 Monolithic Mirror Telescopes</td>
<td>445</td>
</tr>
<tr>
<td>8.7.3 Segmented Mirror Telescopes</td>
<td>448</td>
</tr>
<tr>
<td>8.7.4 Cophasing of Future Extremely Large Telescopes</td>
<td>452</td>
</tr>
<tr>
<td>8.8 Special Cases of Highly Variable Thickness Mirrors</td>
<td>452</td>
</tr>
<tr>
<td>8.8.1 Introduction – Mirror Flexure in Fast Tip-Tilt Mode</td>
<td>452</td>
</tr>
<tr>
<td>8.8.2 Minimum Flexure in Gravity of a Plate Supported at its Center</td>
<td>453</td>
</tr>
<tr>
<td>8.8.3 Field Stabilization Mirrors and Infrared Wobbling Mirrors</td>
<td>457</td>
</tr>
<tr>
<td>8.8.4 Design of Low Weight Wobbling Mirrors</td>
<td>459</td>
</tr>
<tr>
<td>References</td>
<td>459</td>
</tr>
<tr>
<td>9 Singlet Lenses and Elasticity Theory of Thin Plates</td>
<td>465</td>
</tr>
<tr>
<td>9.1 Singlet Lenses</td>
<td>465</td>
</tr>
<tr>
<td>9.1.1 Aberrations of a Thin Lens with Spherical Surfaces</td>
<td>465</td>
</tr>
<tr>
<td>9.1.2 Stigmatic Lens with Descartes Ovoid and Spherical Surface</td>
<td>468</td>
</tr>
<tr>
<td>9.1.3 Aplanatic and Anastigmatic Singlet Lenses</td>
<td>469</td>
</tr>
<tr>
<td>9.1.4 Isoplanatic Singlet Lenses and Remote Pupil</td>
<td>471</td>
</tr>
<tr>
<td>9.1.5 Aspheric Lenses in the Third-Order Theory</td>
<td>473</td>
</tr>
<tr>
<td>9.1.6 Power of a Two-Lens System</td>
<td>474</td>
</tr>
<tr>
<td>9.2 Thin Lens Elastically Bent by Uniform Load</td>
<td>475</td>
</tr>
<tr>
<td>9.2.1 Equilibrium Equation of the Thin Plate Theory</td>
<td>475</td>
</tr>
<tr>
<td>9.2.2 Lens Deformation and Parabolic Thickness Distribution</td>
<td>476</td>
</tr>
<tr>
<td>9.2.3 Expansion Representation of the Flexure</td>
<td>479</td>
</tr>
<tr>
<td>9.2.4 Maximum Stresses at the Lens Surfaces</td>
<td>480</td>
</tr>
<tr>
<td>9.2.5 Lenses with Particular Thickness Distributions</td>
<td>487</td>
</tr>
<tr>
<td>9.2.6 Conclusions for Active Optics Aspheration</td>
<td>487</td>
</tr>
<tr>
<td>9.3 Spectrograph with Single Lens and Corrector Plate</td>
<td>488</td>
</tr>
<tr>
<td>References</td>
<td>490</td>
</tr>
<tr>
<td>10 X-ray Telescopes and Elasticity Theory of Shells</td>
<td>491</td>
</tr>
<tr>
<td>10.1 X-ray Telescopes</td>
<td>491</td>
</tr>
<tr>
<td>10.1.1 Introduction – The Three Wolter Design Forms</td>
<td>491</td>
</tr>
<tr>
<td>10.1.2 Basic Stigmatic Paraboloid-Hyperboloid (PH) Telescopes</td>
<td>491</td>
</tr>
<tr>
<td>10.1.3 Sine Condition and Wolter-Schwarzschild (WS) Telescopes</td>
<td>495</td>
</tr>
<tr>
<td>10.1.4 Aberration Balanced Hyperboloid-Hyperboloid (HH) Telescopes</td>
<td>497</td>
</tr>
<tr>
<td>10.1.5 Aberration Balanced Spheroid-Spheroid (SS) Telescopes</td>
<td>499</td>
</tr>
<tr>
<td>10.1.6 Existing and Future Grazing Incidence X-ray Telescopes</td>
<td>499</td>
</tr>
<tr>
<td>10.2 Elasticity Theory of Axisymmetric Cylindrical Shells</td>
<td>501</td>
</tr>
</tbody>
</table>
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
Astronomical Optics and Elasticity Theory
Active Optics Methods
Lemaitre, G.R.
2009, XXI, 575 p., Hardcover
ISBN: 978-3-540-68904-1