

CONTENTS

Preface	xi
1. Nonimaging Optical Systems and Their Uses	1
1.1 Nonimaging Collectors	1
1.2 Definition of the Concentration Ratio; The Theoretical Maximum	3
1.3 Uses of Concentrators	5
1.4 Uses of Illuminators	6
References	6
2. Some Basic Ideas in Geometrical Optics	7
2.1 The Concepts of Geometrical Optics	7
2.2 Formulation of the Ray-Tracing Procedure	8
2.3 Elementary Properties of Image-Forming Optical Systems	11
2.4 Aberrations in Image-Forming Optical Systems	13
2.5 The Effect of Aberrations in an Image-Forming System on the Concentration Ratio	14
2.6 The Optical Path Length and Fermat's Principle	16
2.7 The Generalized Étendue or Lagrange Invariant and the Phase Space Concept	18
2.8 The Skew Invariant	22
2.9 Different Versions of the Concentration Ratio	23
Reference	23
3. Some Designs of Image-Forming Concentrators	25
3.1 Introduction	25
3.2 Some General Properties of Ideal Image-Forming Concentrators	25
3.3 Can an Ideal Image-Forming Concentrator Be Designed?	31
3.4 Media with Continuously Varying Refractive Indices	34
3.5 Another System of Spherical Symmetry	37
3.6 Image-Forming Mirror Systems	38
3.7 Conclusions on Classical Image-Forming Concentrators	40
References	41

4. Nonimaging Optical Systems	43
4.1 Limits to Concentration	43
4.2 Imaging Devices and Their Limitations	44
4.3 Nonimaging Concentrators	45
4.4 The Edge-Ray Principle or "String" Method	47
4.5 Light Cones	49
4.6 The Compound Parabolic Concentrator	50
4.7 Properties of the Compound Parabolic Concentrator	56
4.8 Cones and Paraboloids As Concentrators	64
References	67
5. Developments and Modifications of the Compound Parabolic Concentrator	69
5.1 Introduction	69
5.2 The Dielectric-Filled CPC with Total Internal Reflection	69
5.3 The CPC with Exit Angle Less Than $\pi/2$	72
5.4 The Concentrator for A Source at A Finite Distance	74
5.5 The Two-Stage CPC	76
5.6 The CPC Designed for Skew Rays	78
5.7 The Truncated CPC	80
5.8 The Lens-Mirror CPC	84
5.9 2D Collection in General	85
5.10 Extension of the Edge-Ray Principle	85
5.11 Some Examples	87
5.12 The Differential Equation for the Concentrator Profile	89
5.13 Mechanical Construction for 2D Concentrator Profiles	89
5.14 A General Design Method for A 2D Concentrator with Lateral Reflectors	92
5.15 Application of the Method: Tailored Designs	95
5.16 A Constructive Design Principle for Optimal Concentrators	96
References	97
6. The Flow-line Method for Designing Nonimaging Optical Systems	99
6.1 The Concept of the Flow Line	99
6.2 Lines of Flow from Lambertian Radiators: 2D Examples	100
6.3 3D Example	102
6.4 A Simplified Method for Calculating Lines of Flow	103
6.5 Properties of the Lines of Flow	104
6.6 Application to Concentrator Design	105
6.7 The Hyperboloid of Revolution As A Concentrator	106
6.8 Elaborations of the Hyperboloid: the Truncated Hyperboloid	106
6.9 The Hyperboloid Combined with A Lens	107
6.10 The Hyperboloid Combined with Two Lenses	108
6.11 Generalized Flow Line Concentrators with Refractive Components	108
6.12 Hamiltonian Formulation	109
6.13 Poisson Bracket Design Method	115
6.14 Application of the Poisson Bracket Method	128
6.15 Multifoliate-Reflector-Based Concentrators	138

6.16	The Poisson Bracket Method in 2D Geometry	142
6.17	Elliptic Bundles in Homogeneous Media	144
6.18	Conclusion	155
	References	157
7.	Concentrators for Prescribed Irradiance	159
7.1	Introduction	159
7.2	Reflector Producing A Prescribed Functional Transformation	160
7.3	Some Point Source Examples with Cylindrical and Rotational Optics	161
7.4	The Finite Strip Source with Cylindrical Optics	162
7.5	The Finite Disk Source with Rotational Optics	166
7.6	The Finite Tubular Source with Cylindrical Optics	172
7.7	Freeform Optical Designs for Point Sources in 3D	173
	References	178
8.	Simultaneous Multiple Surface Design Method	181
8.1	Introduction	181
8.2	Definitions	182
8.3	Design of A Nonimaging Lens: the RR Concentrator	184
8.4	Three-Dimensional Ray Tracing of Rotational Symmetric RR Concentrators	189
8.5	The XR Concentrator	192
8.6	Three-Dimensional Ray Tracing of Some XR Concentrators	194
8.7	The RX Concentrator	195
8.8	Three-Dimensional Ray Tracing of Some RX Concentrators	198
8.9	The XX Concentrator	201
8.10	The RXI Concentrator	202
8.11	Three-Dimensional Ray Tracing of Some RXI Concentrators	207
8.12	Comparison of the SMS Concentrators with Other Nonimaging Concentrators and with Image Forming Systems	209
8.13	Combination of the SMS and the Flow-Line Method	211
8.14	An Example: the XRI_F Concentrator	212
	References	217
9.	Imaging Applications of Nonimaging Concentrators	219
9.1	Introduction	219
9.2	Imaging Properties of the Design Method	220
9.3	Results	225
9.4	Nonimaging Applications	231
9.5	SMS Method and Imaging Optics	233
	References	233
10.	Consequences of Symmetry (by Narkis Shatz and John C. Bortz)	235
10.1	Introduction	235
10.2	Rotational Symmetry	236
10.3	Translational Symmetry	247
	References	263

11. Global Optimization of High-Performance Concentrators	265
(by Narkis Shatz and John C. Bortz)	
11.1 Introduction	265
11.2 Mathematical Properties of Mappings in Nonimaging Optics	266
11.3 Factors Affecting Performance	267
11.4 The Effect of Source and Target Inhomogeneities on the Performance Limits of Nonsymmetric Nonimaging Optical Systems	268
11.5 The Inverse-Engineering Formalism	274
11.6 Examples of Globally Optimized Concentrator Designs	276
References	303
12. A Paradigm for a Wave Description of Optical Measurements	305
12.1 Introduction	305
12.2 The Van Cittert-Zernike Theorem	306
12.3 Measuring Radiance	306
12.4 Near-Field and Far-Field Limits	309
12.5 A Wave Description of Measurement	310
12.6 Focusing and the Instrument Operator	311
12.7 Measurement By Focusing the Camera on the Source	313
12.8 Experimental Test of Focusing	313
12.9 Conclusion	315
References	316
13. Applications to Solar Energy Concentration	317
13.1 Requirements for Solar Concentrators	317
13.2 Solar Thermal Versus Photovoltaic Concentrator Specifications	318
13.3 Nonimaging Concentrators for Solar Thermal Applications	327
13.4 SMS Concentrators for Photovoltaic Applications	350
13.5 Demonstration and Measurement of Ultra-High Solar Fluxes (C_g Up to 100,000)	366
13.6 Applications Using Highly Concentrated Sunlight	381
13.7 Solar Processing of Materials	385
13.8 Solar Thermal Applications of High-Index Secondaries	387
13.9 Solar Thermal Propulsion in Space	389
References	391
14. Manufacturing Tolerances	395
14.1 Introduction	395
14.2 Model of Real Concentrators	396
14.3 Contour Error Model	396
14.4 The Concentrator Error Multiplier	410
14.5 Sensitivity to Errors	411
14.6 Conclusions	412
References	413

APPENDICES	
APPENDIX A Derivation and Explanation of the Étendue Invariant, Including the Dynamical Analogy; Derivation of the Skew Invariant	415
A.1 The generalized étendue	415
A.2 Proof of the generalized étendue theorem	416
A.3 The mechanical analogies and liouville's theorem	418
A.4 Conventional photometry and the étendue	419
References	419
APPENDIX B The Edge-Ray Theorem	421
B.1 Introduction	421
B.2 The Continuous Case	421
B.3 The Sequential Surface Case	426
B.4 The Flow-Line Mirror Case	427
B.5 Generation of Edge Rays at Slope Discontinuities	429
B.6 Offence Against the Edge-Ray Theorem	430
References	432
APPENDIX C Conservation of Skew and Linear Momentum	433
C.1 Skew Invariant	433
C.2 Luneburg Treatment for Skew Rays	434
C.3 Linear Momentum Conservation	435
C.4 Design of Concentrators for Nonmeridian Rays	435
References	437
APPENDIX D Conservation of Etendue for Two-Parameter Bundles of Rays	439
D.1 Conditions for Achromatic Designs	441
D.2 Conditions for Constant Focal Length in Linear Systems	446
References	447
APPENDIX E Perfect Off-Axis Imaging	449
E.1 Introduction	449
E.2 The 2D Case	450
E.3 The 3D Case	452
References	459
APPENDIX F The Luneberg Lens	461
APPENDIX G The Geometry of the Basic Compound Parabolic Concentrator	467
APPENDIX H The θ_i/θ_o Concentrator	471
APPENDIX I The Truncated Compound Parabolic Concentrator	473
APPENDIX J The Differential Equation for the 2D Concentrator Profile with Nonplane Absorber	477
Reference	479
APPENDIX K Skew Rays in Hyperboloidal Concentrator	481
APPENDIX L Sine Relation for Hyperboloid/Lens Concentrator	483

APPENDIX M	The Concentrator Design for Skew Rays	485
M.1	The Differential Equation	485
M.2	The Ratio of Input to Output Areas for the Concentrator	486
M.3	Proof That Extreme Rays Intersect at the Exit Aperture Rim	488
M.4	Another Proof of the Sine Relation for Skew Rays	489
M.5	The Frequency Distribution of h	490
Index		493
APPENDIX A		
A.1	The generalized sine relation	505
A.2	Proof of the generalized sine relation	506
A.3	The mechanical analogues and Liouville's theorem	507
A.4	Conventional photometry and the étendue	508
APPENDIX B		
B.1	Introduction	508
B.2	The Continuous Case	509
B.3	The Sequential Surface Case	510
B.4	The Row-Line Mirror Case	511
B.5	Generation of Edge Rays at Slope Discontinuities	512
B.6	Offset Against the Edge-Ray Theorem	513
APPENDIX C		
C.1	Skew Invariant	514
C.2	Linear Treatment for Skew Rays	515
C.3	Linear Momentum Conservation	516
C.4	Design of Concentrators for Nonmeridian Rays	517
APPENDIX D		
Conservation of Étendue for Two-Parameter Bundles of Rays		
D.1	Conditions for Achromatic Designs	518
D.2	Conditions for Constant Focal Length in Linear Systems	519
APPENDIX E		
Bundling of Rays		
E.1	Introduction	520
E.2	The 2D Case	521
E.3	The 3D Case	522
APPENDIX F		
The Lambert Law		
F.1	Introduction	523
F.2	Derivation of the Lambert Law	524
F.3	Applications Using Highly Concentrated Radiation	525
F.4	Solar Processing of Materials	526
F.5	Solar Thermal Applications	527
APPENDIX G		
The Geometry of the Basic Compound Parabolic Concentrator		
G.1	Introduction	528
G.2	Derivation of the Basic Compound Parabolic Concentrator	529
G.3	Properties of the Basic Compound Parabolic Concentrator	530
G.4	References	531
APPENDIX H		
The 60° Concentrator		
H.1	Introduction	532
H.2	Derivation of the 60° Concentrator	533
H.3	Properties of the 60° Concentrator	534
H.4	References	535
APPENDIX I		
The Truncated Compound Parabolic Concentrator		
I.1	Introduction	536
I.2	Derivation of the Truncated Compound Parabolic Concentrator	537
I.3	Properties of the Truncated Compound Parabolic Concentrator	538
I.4	References	539
APPENDIX J		
The Differential Equation for the Profile with Nonplane Absorber		
J.1	Introduction	540
J.2	Derivation of the Differential Equation	541
J.3	Properties of the Profile with Nonplane Absorber	542
J.4	References	543
APPENDIX K		
Skew Rays in Hyperbolic Concentrators		
K.1	Introduction	544
K.2	Derivation of the Sine Relation for Hyperbolic Concentrators	545
K.3	Properties of Hyperbolic Concentrators	546
K.4	References	547
APPENDIX L		
Sine Relation for Hyperbolic Concentrators		
L.1	Introduction	548
L.2	Derivation of the Sine Relation	549
L.3	Properties of Hyperbolic Concentrators	550
L.4	References	551