# Tutorial Texts Series

- Optical Design: Applying the Fundamentals, Max J. Riedl, Vol. TT84
- Fundamentals of Polarimetric Remote Sensing, John Schott, Vol. TT81
- The Design of Plastic Optical Systems, Michael Schaub, Vol. TT80
- Matrix Methods for Optical Layout, Gerhard Kloos, Vol. TT77
- Fundamentals of Infrared Detector Materials, Michael A. Kinch, Vol. TT76
- Bioluminescence for Food and Environmental Microbiological Safety, Lubov Y. Brovko, Vol. TT74
- Introduction to Image Stabilization, Scott W. Teare, Sergio R. Restaino, Vol. TT73
- Introduction to Confocal Fluorescence Microscopy, Michiel Müller, Vol. TT69
- Artificial Neural Networks: An Introduction, Kevin L. Priddy and Paul E. Keller, Vol. TT68
- Basics of Code Division Multiple Access (CDMA), Raghuvineet Rao and Sohail Dianat, Vol. TT67
- Optical Imaging in Projection Microolithography, Alfred Kwok-Kit Wong, Vol. TT66
- Metrics for High-Quality Specular Surfaces, Lionel R. Baker, Vol. TT65
- Field Mathematics for Electromagnetics, Photonics, and Materials Science, Bernard Maxum, Vol. TT64
- High-Fidelity Medical Imaging Displays, Aldo Badano, Michael J. Flynn, and Jerzy Kanicki, Vol. TT63
- Thin-Film Design: Modulated Thickness and Other Stopband Design Methods, Bruce Perilloux, Vol. TT57
- Optische Grundlagen für Infrarotsysteme, Max J. Riedl, Vol. TT56
- An Engineering Introduction to Biotechnology, J. Patrick Fitch, Vol. TT55
- Image Performance in CRT Displays, Kenneth Compton, Vol. TT54
- Modulation Transfer Function in Optical and Electro-Optical Systems, Glenn D. Boreman, Vol. TT52
- Fundamentals of Antennas, Christos G. Christodoulou and Parveen Wahid, Vol. TT50
- Basics of Spectroscopy, David W. Ball, Vol. TT49
- Resolution Enhancement Techniques in Optical Lithography, Alfred Kwok-Kit Wong, Vol. TT47
- Copper Interconnect Technology, Christoph Steinbrückel and Barry L. Chin, Vol. TT46

For a complete listing of Tutorial Texts, visit [http://spie.org/tutorialtexts.xml](http://spie.org/tutorialtexts.xml)
Optical Design
Applying the Fundamentals

Max J. Riedl

Tutorial Texts in Optical Engineering
Volume TT84

SPIE PRESS
Bellingham, Washington USA
I dedicate this book to **Warren J. Smith**, my friend and colleague for more than 50 years. He has influenced my life more than anyone else.
Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to more than 80 titles covering many diverse fields of science and engineering. The initial idea for the series was to make material presented in SPIE short courses available to those who could not attend and to provide a reference text for those who could. Thus, many of the texts in this series are generated by augmenting course notes with descriptive text that further illuminates the subject. In this way, the TT becomes an excellent stand-alone reference that finds a much wider audience than only short course attendees.

Tutorial Texts have grown in popularity and in the scope of material covered since 1989. They no longer necessarily stem from short courses; rather, they are often generated by experts in the field. They are popular because they provide a ready reference to those wishing to learn about emerging technologies or the latest information within their field. The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, fiber optics, and laser technologies. Authors contributing to the TT series are instructed to provide introductory material so that those new to the field may use the book as a starting point to get a basic grasp of the material. It is hoped that some readers may develop sufficient interest to take a short course by the author or pursue further research in more advanced books to delve deeper into the subject.

The books in this series are distinguished from other technical monographs and textbooks in the way in which the material is presented. In keeping with the tutorial nature of the series, there is an emphasis on the use of graphical and illustrative material to better elucidate basic and advanced concepts. There is also heavy use of tabular reference data and numerous examples to further explain the concepts presented. The publishing time for the books is kept to a minimum so that the books will be as timely and up-to-date as possible. Furthermore, these introductory books are competitively priced compared to more traditional books on the same subject.

When a proposal for a text is received, each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that would serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the science and technologies under discussion.

It is my goal to maintain the style and quality of books in the series and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

James A. Harrington
Rutgers University
# Contents

Preface............................................................................................................................ xv

Chapter 1 Law of Refraction:
The Foundation of Geometrical Optics ............... 1

1.1 Introduction................................................................................................. 1
1.2 Fermat’s Principle.................................................................................... 1
1.2.1 Historic remarks ............................................................................ 1
1.2.2 Derivation....................................................................................... 1
1.3 Snell and the Lens.................................................................................... 3
1.4 Graphical Ray Tracing............................................................................. 4
1.5 Paraxial Ray Tracing................................................................................ 5
1.5.1 Equations, symbols, and sign conventions...................................... 6

Chapter 2 Best Shape for a Thin Lens ............................ 11

2.1 Concept of Thin Lens............................................................................... 11
2.2 Object at Any Position............................................................................ 12
2.3 Object at Infinity with Added Field of View....................................... 16
2.3.1 Spherical aberration........................................................................ 16
2.3.2 Chromatic aberration....................................................................... 18
2.3.3 Coma............................................................................................... 19
2.3.4 Astigmatism.................................................................................... 19
2.3.5 Total blur-spot size.......................................................................... 21
2.4 Special Case................................................................................................ 21

Chapter 3 Best Shapes for Multiple Thin Lenses,
Aspherizing, and the Natural Stop Position......... 23

3.1 Introduction.................................................................................................. 23
3.2 Best Shapes for Minimum Spherical Aberration............................... 23
3.3 Aspherizing a Singlet to Eliminate Spherical Aberration................ 26
3.4 Correcting Coma and Spherical Aberration........................................ 28
3.4.1 Eliminating coma............................................................................ 28
3.4.2 Eliminating spherical aberration.................................................... 29
3.5 Natural Stop Position............................................................................... 31
Chapter 4  Transition from a Thin Lens to a Thick Lens ........... 33
  4.1 Introduction ............................................................................ 33
  4.2 Adding a Thickness and Changing
      the Second Surface Radius ..................................................... 33
      4.2.1 VIS singlet with $n = 1.5$ .............................................. 34
      4.2.2 MWIR singlet with $n = 3.4$ ......................................... 35
      4.2.3 LWIR singlet with $n = 4$ ............................................. 35
  4.3 Change of Spherical Aberration with Added Thickness ...... 35

Chapter 5  Achromats .................................................................. 39
  5.1 Introduction ............................................................................ 39
  5.2 Thin Achromat for the VIS Spectrum,
      On-Axis Performance ............................................................ 39
      5.2.1 Adding a field to the on-axis corrected achromat ....... 43
      5.2.2 Optimizing .................................................................. 45
  5.3 Smith’s Method of Determining the Surface Shapes ...... 45
      5.3.1 Curvatures and inverse object distances ..................... 45
      5.3.2 The K-functions .......................................................... 46
      5.3.3 The calculations .......................................................... 47
  5.4 Achromat for the MWIR Region ........................................... 48
  5.5 Achromat for the LWIR Region ............................................ 50
  5.6 Diamond-Turned Hybrid ....................................................... 50
      5.6.1 Hybrid for the MWIR region ...................................... 51
      5.6.1.1 Basic lens shape ..................................................... 51
      5.6.1.2 Aspherizing ............................................................ 52
      5.6.1.3 The diffractive phase profile .................................. 52
      5.6.1.4 Comments .............................................................. 53
      5.6.2 Useful nomograms ...................................................... 55

Chapter 6  Systems with Two Separated Components ............. 57
  6.1 Introduction ............................................................................ 57
  6.2 Dialyte—An Air-Spaced Achromat ....................................... 57
      6.2.1 Example for the MWIR region .................................. 59
      6.2.1.1 Aspheric deformation
              coefficients of surface 3 ............................................. 61
      6.2.1.2 Phase coefficients ............................................... 61
      6.2.1.3 Step height at the zone transition ......................... 62
  6.3 Telephoto and Reversed Telephoto ..................................... 62
      6.3.1 Examples for the MWIR and LWIR regions .......... 63
11.3  Cassegrain Version with a Maksutov-Mangin Mirror
Combination for the LWIR Region ............................................. 98
11.3.1  Pegel diagram ........................................................... 98

Chapter 12 The Single-Imaging Mirror ......................................... 101

12.1  Introduction ............................................................................ 101
12.2  Spherical Mirror ..................................................................... 101
12.3  Toroidal Mirrors .................................................................... 104
12.4  Examples ................................................................................ 104
12.4.1  Spherical mirror ........................................................ 106
12.4.1.1  Additional comments ............................................. 106
12.4.2  Toroidal mirror ......................................................... 107
12.5  Parabolic Mirror ..................................................................... 107
12.6  Manufacturing Remarks ......................................................... 109
12.7  Mangin Mirror ....................................................................... 109

Chapter 13 Eight Single Optical Elements
as Imaging Objectives ................................................................. 113

13.1  Introduction ............................................................................ 113
13.2  Diffraction Limit .................................................................... 113
13.3  Eight Chosen Configurations ................................................. 113
13.4  Shapes of the Elements .......................................................... 115
13.5  Aberrations ............................................................................. 116
13.6  Examples ................................................................................ 117

Chapter 14 A Progression of Performance with
an Increase in Lens Complexity ................................................. 119

14.1  Objectives .............................................................................. 119

Chapter 15 Two-Mirror Systems as Telescope
and Microscope Objectives .......................................................... 121

15.1  Introduction ............................................................................ 121
15.2  Basic Cassegrain Telescope Layout........................................ 122
15.2.1  Equations ......................................................................... 123
15.3  Cassegrain with Two Spherical Mirrors ............................... 123
15.4  Classic Cassegrain System..................................................... 124
15.5  Dall-Kirkham Arrangement ................................................... 124
15.6  Ritchey–Chretien Configuration ............................................ 125
15.7  Examples ................................................................................ 125
15.8  Cassegrain with Mangin as a Secondary Reflector .......... 126
15.9  Gregorian Telescope .............................................................. 127
Preface

This book is written for engineers and scientists who have some experience in the field of optics and want to know more about the details and derivations of equations used in optical design. Such knowledge is especially valuable in the layout stages of an optical system, when the question is “Where shall I begin?” The other question may be “How come?” instead of just using a given equation.

The book begins with the derivation of the fundamental law of geometrical optics, Snell’s law of refraction, and states the paraxial ray trace equations. The following discussions are organized by subjects, starting with a thin lens and progressing to increasingly more sophisticated components and multi-element systems. Each subject is covered in depth to provide a good understanding for performance and limitations. The often ignored effects of plane-parallel plates are included as a separate subject.

While the text is based on general optical laws, special emphasis has been placed on the two major infrared regions, the mid-wave (MWIR) and the long-wave (LWIR). This is particularly apparent in the discussion about diffractive hybrids, which have found their place in these long wavelengths areas for the correction of chromatic aberrations and athermalization. Comments relating to single-point diamond turning have been included because this process is predominantly used to produce optical elements for the infrared regions.

The final subject gradually leads the reader from a single element as an imaging objective for the visible spectrum, the historic Höegh, to a four-element anastigmat. This is done by successively adding and shaping elements and selecting suitable glasses for aberration reduction.

Finally, I thank Tim Lamkins, Scott Schrum, and Gwen Weerts of SPIE for their special support and editorial assistance.

Max J. Riedl
July 2009