OPTICAL IMAGING
AND ABERRATIONS

PART III

WAVEFRONT ANALYSIS
OPTICAL IMAGING AND ABERRATIONS

PART III

WAVEFRONT ANALYSIS

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AND

COLLEGE OF OPTICAL SCIENCES - THE UNIVERSITY OF ARIZONA

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Bellingham, Washington USA
To my grandchildren

Maya, Leela, Rohan, and Krishan
For years Vini Mahajan has been publishing a book series on optical imaging and aberrations. Part I of the series on *Ray Geometrical Optics* was published in 1998, and Part II on *Wave Diffraction Optics* followed in 2001. A second edition of Part II appeared in 2011. Now Vini has written Part III on *Wavefront Analysis*, which should be of interest to anyone working in the fields of optical design, fabrication, or testing.

*Wavefront Analysis* is focused on the use of orthonormal polynomials for wavefront analysis of optical imaging systems with pupils of different shapes. The book starts with an excellent introduction to optical imaging and aberrations. These first two chapters should be of interest to anyone working in optics. Chapter 3 describes orthonormal polynomials and the Gram–Schmidt orthonormalization process for obtaining orthonormal polynomials over one domain from those that are orthonormal over another.

Chapter 4 is a long and complete chapter on imaging and aberrations for optical systems with circular pupils. The chapter covers the PSF and OTF for aberration-free imaging, Strehl ratio and aberration balancing and tolerancing, and a very complete description of Zernike circle polynomials. Isometric, interferometric, and imaging characteristics of the circle polynomial aberrations are very nicely explained and illustrated. The important relationship between the circle polynomials and the classical aberrations is discussed. Since optical systems generally have circular pupils, this chapter will be of use to almost anyone working in optics.

The next several chapters are intended for readers interested in optical systems with noncircular or apodized circular or annular pupils. Much of this material is difficult to find in such detail elsewhere. The chapters start with a brief discussion of aberration-free imaging that includes both the PSF and the OTF of the optical system, as this is potentially the ultimate goal of any optical design or test. Then the polynomials appropriate for systems with pupils of different shapes representing balanced classical aberrations are described in detail. As in the case of the circle polynomial aberrations, the isometric, interferometric, and PSF plots of the first forty-five polynomial aberrations for systems with hexagonal, elliptical, annular, rectangular, and square pupils facilitate understanding of their significance. Systems with circular and annular pupils with Gaussian illumination, anamorphic systems with square and circular pupils, and those with circular and annular sector pupils are also discussed thoroughly.

Anyone thinking of using the Zernike circle polynomials for wavefront analysis of systems with noncircular pupils should read Chapter 12, where their pitfalls are illustrated by applying them to systems with annular and hexagonal pupils. Numerical examples on the calculation of the orthonormal aberration coefficients from the wavefront or the wavefront slope data given in Chapter 14 add to the utility and
practicality of the book. A summary at the end of each chapter is quite useful, as it describes the essence of the content.

Vini is an excellent writer with the gift of writing complex topics in a simplified, yet rigorous, manner. As in the first two volumes of this book series, the material presented in Part III is thorough and detailed, and much of it is from his own publications. *Wavefront Analysis* is primarily analytical in nature, but it is generally easy to read with a lot of examples and numerical results. Both students and experienced optical engineers and scientists who have a need for wavefront analysis of optical systems will find it to be extremely useful.

Tucson, Arizona

June 2013

James C. Wyant
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PREFACE

This book is Part III of a series of books on Optical Imaging and Aberrations. Part I on *Ray Geometrical Optics* and Part II on *Wave Diffraction Optics* were published earlier. Part III is on *Wavefront Analysis*, which is an integral part of optical design, fabrication, and testing. In optical design, rays are traced to determine the wavefront and thereby the quality of a design. In optical testing, the fabrication errors and, therefore, the associated aberrations are measured by way of interferometry. In both cases, the quality of the wavefront is determined from the aberrations obtained at an array of points. The aberrations thus obtained are used to calculate the mean, the peak-to-valley, and the standard deviation values. While such statistical measures of the wavefront are part of wavefront analysis, the purpose of this book is to determine the content of the wavefront by decomposing the ray-traced or test-measured data in terms of polynomials that are orthogonal over the expected domain of the data. These polynomials must include the basic aberrations of wavefront defocus and tilt, and represent balanced classical aberrations.

We start Part III with an outline of optical imaging in the presence of aberrations in Chapter 1, i.e., on how to obtain the point-spread and optical transfer functions of an imaging system with an arbitrary shaped pupil. The Strehl ratio of a system as a measure of image quality is introduced in this chapter, and shown to be dependent only on the aberration variance when the aberration is small. It is followed in Chapter 2 with a brief discussion of the wavefronts and aberrations. This chapter introduces the nomenclature of aberrations. How to obtain the orthogonal polynomials over a certain domain from those over another is discussed in Chapter 3. For systems with a circular pupil, the Zernike circle polynomials are well known for wavefront analysis. They are discussed at length in Chapter 4. These polynomials are orthogonalized over an annular pupil in Chapter 5, and over a Gaussian pupil in Chapter 6. They are obtained similarly for systems with hexagonal, elliptical, rectangular, square, and slit pupils in the succeeding chapters. For each pupil, the polynomials are given in their orthonormal form so that an expansion coefficient (with the exception of piston) represents the standard deviation of the corresponding polynomial aberration term. The standard deviation of a Seidel aberration with and without aberration balancing is also discussed in these chapters.

Since the Zernike circle polynomials form a complete set, a wavefront over any domain can be expanded in terms of them. However, the pitfalls of their use over a domain other than circular and resulting from the lack of their orthogonality over the chosen domain are discussed in Chapter 12. Finally, the aberrations of anamorphic systems are discussed, and polynomials suitable for their aberration analysis are given in Chapter 13 for both rectangular and circular pupils. The use of the orthonormal polynomials for determining the content of a wavefront is demonstrated in Chapter 14 by computer simulations of circular wavefronts. The determination of the aberrations coefficients from the wavefront slope data, as in a Shack–Hartmann sensor, is also discussed in this chapter.

El Segundo, California

Virendra N. Mahajan

June 2013
ACKNOWLEDGMENTS

Once again, it is a great pleasure to acknowledge the generous support I have received over the years from my employer, The Aerospace Corporation, in preparing Part III on Wavefront Analysis in a series of books on Optical Imaging and Aberrations. My special thanks go to my former classmate, Dr. Bill Swantner, for his constant advice on and constructive critique of my work. I have benefitted greatly from his practical expertise in both optical design and testing. The Sanskrit verse on p. xxiii was provided by Professor Sally Sutherland of the University of California at Berkeley. Many thanks to Professor James W. Wyant for writing the Foreword for this book.

I am grateful to Professor José Antonio Díaz Navas for carrying out many computer calculations and preparing many of the figures. My thanks to Drs. Barry Johnson, James Harvey, and Daniel Topa for reading an early version of the manuscript and suggesting to include examples of wavefront analysis. I am grateful to Professor Eva Acosta for her help with writing Chapter 14 on Numerical Wavefront Analysis, as my response to their suggestion. Of course, any shortcomings or errors anywhere in the book are totally my responsibility.

As in the past, I cannot say enough about the constant support I have received from my wife Shashi over the many years it has taken me to complete this three-part series. I dedicate Part III to my grandchildren.

Finally, I would like to thank SPIE Press Editors Dara Burrows and Scott McNeill, and Manager Tim Lamkins for their quality support in bringing this book to publication. It has always been a pleasure to work with the SPIE staff, starting with the Publications Director, Eric Pepper.
### SYMBOLS AND NOTATION

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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$a_i$</td>
<td>aberration coefficient</td>
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<tr>
<td>$A$</td>
<td>amplitude</td>
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<tr>
<td>$A_i$</td>
<td>peak aberration coefficient</td>
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<td>$B_d$</td>
<td>defocus coefficient</td>
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<td>$B_j$</td>
<td>wave aberration polynomial</td>
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<td>$B_t$</td>
<td>tilt coefficient</td>
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<td>$c$</td>
<td>aspect ratio</td>
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<td>$E_j$</td>
<td>elliptical polynomial</td>
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<td>$F$</td>
<td>focal ratio</td>
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<td>$G_j$</td>
<td>Gaussian or vector polynomial</td>
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<td>$j$</td>
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<td>$P'$</td>
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<td>$P_{ex}$</td>
<td>power in the exit pupil</td>
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<td>$R_{nm}(\rho)$</td>
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<td>$S$</td>
<td>Strehl ratio</td>
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<td>$S_{ex}$</td>
<td>area of exit pupil</td>
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<tr>
<td>$x, y$</td>
<td>Cartesian coordinates of a point</td>
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<tr>
<td>$W$</td>
<td>wave aberration</td>
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<tr>
<td>$\bar{v}_i$</td>
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<td>$\tau$</td>
<td>optical transfer function</td>
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<td>$\rho = r/a$</td>
<td>normalized radial coordinate</td>
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<td>$\theta$</td>
<td>polar angle of a position vector</td>
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<tr>
<td>$\phi$</td>
<td>polar angle of frequency vector</td>
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<td>Kronecker delta</td>
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<tr>
<td>$\Delta$</td>
<td>longitudinal defocus</td>
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<tr>
<td>$\Phi$</td>
<td>phase aberration</td>
</tr>
<tr>
<td>$r, \theta$</td>
<td>polar coordinates of a point</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>optical wavelength</td>
</tr>
<tr>
<td>$\xi, \eta$</td>
<td>spatial frequency coordinates</td>
</tr>
<tr>
<td>$\sigma_w$</td>
<td>standard deviation (wave)</td>
</tr>
<tr>
<td>$\sigma_\phi$</td>
<td>standard deviation (phase)</td>
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</table>
Anantaratnaprabhavya yasya himam na saubhagyavilopi jatam.
Eko hi doso gunasannipate nimajjatindoh kiranesvivankah.

The snow does not diminish the beauty of the Himalayan mountains which are the source of countless gems. Indeed, one flaw is lost among a host of virtues, as the moon’s dark spot is lost among its rays.

Kalidāsa Kumarasambhava 1.3