

OPTICAL IMAGING AND ABERRATIONS

PART II

WAVE DIFFRACTION OPTICS

SECOND EDITION

OPTICAL IMAGING AND ABERRATIONS

PART II

WAVE DIFFRACTION OPTICS

SECOND EDITION

Virendra N. Mahajan

**SPIE
PRESS**

Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Mahajan, Virendra N.

Optical imaging and aberrations / Virendra N. Mahajan. -- 2nd ed.

v. cm. -- (Press monograph ; 209)

Contents: -- pt. 2. Wave diffraction optics.

Includes bibliographical references and index.

ISBN 978-0-8194-8699-8 (pt. 2)

1. Aberration. 2. Imaging systems. 3. Geometrical optics. I. Title.

QC671.M36 2011

621.36--dc23

2011020047

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: +1 360.676.3290

Fax: +1 360.647.1445

Email: Books@spie.org

Web: <http://spie.org>

Copyright © 2011 Society of Photo-Optical Instrumentation Engineers

All rights reserved. No part of this publication may be reproduced or distributed in any form or by any means without written permission of the publisher.

The content of this book reflects the work and thought of the author(s). Every effort has been made to publish reliable and accurate information herein, but the publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Printed in the United States of America.

First printing



SPIE

In loving memory of my parents:

mother Shrimati **Sushila Devi**

and father Shri **Ram Chand**

FOREWORD TO THE FIRST EDITION

Three years ago Vini Mahajan published a book on the subject of Geometrical Images in the presence of aberrations. In this book, Mahajan extends this work to include the effect of wave optics. He continues his thorough tutorial on image formation with a detailed look at the approaches to calculating the form of images. Anyone interested in understanding the methods of predicting the light distribution to be expected in real imaging situations will find this book of interest.

The book begins with an exhaustive development of the basics of diffraction image formation. Mahajan covers the issues associated with the calculation of point-spread functions and discusses the accuracy of such calculations. He introduces the Optical Transfer Function as the Transform of the Point Spread Function and reviews the procedures involved in calculating the OTF. Asymptotic and approximate evaluations of the OTF are included, as are several examples throughout the book.

These approaches are then applied to some real examples of circular and annular apertures. In this discussion, Mahajan carries out in detail many of the classical computations for various image descriptors. This is a topic that is generally treated only lightly in most texts on the subject. Such issues as edge response and line spread function and encircled power are carefully considered. A good discussion of optimal balancing of aberrations is also provided. The treatment of aberration balancing and tolerances in annular pupils is unique in its completeness in this book.

Mahajan includes a detailed discussion of the effect of imaging with a Gaussian weighted aperture, a topic of much interest today. Finally the always-interesting subject of imaging through turbulence is discussed for both circular and annular pupils.

The completeness of the discussions regarding the calculation of image structure is thorough and detailed in this book. Mahajan includes in his discussion many of the “classical” computations of image quality functions that form the basis of the field today, but are seldom encountered in most texts on the subject. The student will have the opportunity to learn the details and limitations of the process. The experienced worker will find this volume useful as a reference in carrying out diffraction image calculations in a wide range of optical systems.

Tucson, Arizona
April 2001

R. R. Shannon

TABLE OF CONTENTS

PART II. WAVE DIFFRACTION OPTICS

Preface to the First Edition	xvii
Acknowledgments	xix
Preface to the Second Edition	xxi
Symbols and Notation.....	xxiii
 CHAPTER 1: IMAGE FORMATION	 1
1.1 Introduction	3
1.2 Rayleigh-Sommerfeld Theory of Diffraction and Huygens-Fresnel Principle	5
1.2.1 Rayleigh-Sommerfeld Formula	5
1.2.2 Fresnel and Fraunhofer Approximations	9
1.2.3 Transfer Function of Free Space	12
1.3 Gaussian Image	12
1.4 Diffraction Image	14
1.4.1 Pupil Function	14
1.4.2 Diffracted Wave	17
1.4.3 Incoherent PSF and Shift-Invariant Imaging of an Incoherent Object	22
1.5 Physical Significance of Incoherent PSF	24
1.6 Optical Transfer Function (OTF)	27
1.6.1 General Relations	27
1.6.2 Physical Significance of OTF	31
1.6.3 Properties of OTF	33
1.6.4 OTF Slope at the Origin	35
1.6.5 OTF in the Limit of Zero Wavelength	40
1.6.6 Geometrical OTF	41
1.6.7 Comparison of Diffraction and Geometrical OTFs	44
1.6.8 Determination of OTF	45
1.6.9 Significance of PTF	45
1.7 Asymptotic Behavior of PSF	45
1.7.1 Point-Spread Function	46
1.7.2 Encircled Power	47
1.8 PSF Centroid	50
1.8.1 Centroid in Terms of OTF Slope	50
1.8.2 Centroid Related to Wavefront Slope	51
1.8.3 Centroid Related to Wavefront Perimeter	52
1.9 Strehl Ratio	53
1.9.1 General Relations	53

1.9.2	Approximate Expressions for Strehl Ratio	56
1.9.3	Determination of Strehl Ratio	58
1.10	Hopkins Ratio	59
1.11	Line- and Edge-Spread Functions (LSF and ESF)	61
1.11.1	Line-Spread Function	61
1.11.2	Edge-Spread Function	64
1.11.3	LSF and ESF in Terms of OTF	65
1.12	Shift-Invariant Imaging of a Coherent Object	67
1.12.1	Coherent Point-Spread Function	67
1.12.2	Coherent Transfer Function	70
1.13	Summary of Theorems.....	71
Appendix A: Fourier Transform Definitions		74
Appendix B: Some Frequently Used Integrals		75
References		76
Problems.....		78
CHAPTER 2: OPTICAL SYSTEMS WITH CIRCULAR PUPILS		79
2.1	Introduction	81
2.2	Aberration-Free System.....	82
2.2.1	Point-Spread Function.....	82
2.2.2	Encircled Power	87
2.2.3	Ensquared Power.....	88
2.2.4	Excluded Power.....	90
2.2.5	Optical Transfer Function.....	93
2.2.6	PSF and Encircled Power from OTF.....	96
2.3	Strehl Ratio and Aberration Tolerance.....	97
2.3.1	Strehl Ratio.....	97
2.3.2	Primary Aberrations	98
2.3.3	Balanced Primary Aberrations	99
2.3.4	Comparison of Approximate and Exact Results	101
2.3.5	Rayleigh's $\lambda/4$ Rule	102
2.3.6	Strehl Ratio for Nonoptimally Balanced Aberrations	103
2.4	Balanced Aberrations and Zernike Circle Polynomials	105
2.5	Defocused System	110
2.5.1	Point-Spread Function.....	111
2.5.2	Focused Beam	113
2.5.3	Collimated Beam.....	119
2.6	PSFs for Rotationally Symmetric Aberrations	121
2.6.1	Theory	122
2.6.2	Numerical Results	124

2.6.3	Gaussian Approximation.....	134
2.6.4	Summary of Results	135
2.7	Symmetry Properties of an Aberrated PSF	136
2.7.1	General Theory	137
2.7.2	Symmetry About the Gaussian Image Plane	138
2.7.3	Symmetry of Axial Irradiance	141
2.7.4	Symmetry in Sign of Aberration Coefficient	141
2.8	PSFs for Primary Aberrations	142
2.8.1	Defocus	142
2.8.2	Spherical Aberration Combined with Defocus.....	142
2.8.3	Astigmatism Combined with Defocus	144
2.8.4	Coma.....	148
2.8.5	2D PSFs	150
2.8.6	Comparison of Diffraction and Geometrical PSFs	157
2.9	Line of Sight of an Aberrated System	159
2.9.1	PSF and Its Centroid.....	159
2.9.2	Numerical Results	162
2.9.2.1	Wavefront Tilt	162
2.9.2.2	Primary Coma	162
2.9.2.3	Secondary Coma	165
2.9.3	Comments.....	168
2.10	Diffraction OTF for Primary Aberrations.....	169
2.10.1	General Relations	169
2.10.2	Defocus	172
2.10.3	Spherical Aberration.....	174
2.10.4	Astigmatism	174
2.10.5	Coma.....	176
2.11	Hopkins Ratio	182
2.11.1	Tolerance for Primary Aberrations	182
2.11.2	Defocus	182
2.11.3	Hopkins Ratio in Terms of Variance of Aberration Difference Function	185
2.11.4	Variance of Aberration Difference Function for Primary Aberrations	186
2.12	Geometrical OTF.....	187
2.12.1	General Relations	188
2.12.2	Radially Symmetric Aberration.....	189
2.12.3	Defocus.....	189
2.12.4	Spherical Aberration Combined with Defocus.....	190
2.12.5	Astigmatism Combined with Defocus	190
2.12.6	Coma.....	191
2.13	Incoherent Line- and Edge-Spread Functions.....	191
2.13.1	Theory	192

2.13.1.1	LSF from PSF	192
2.13.1.2	LSF from Pupil Function	192
2.13.1.3	Struve Ratio and Aberration Tolerances	193
2.13.1.3.1	Defocus	194
2.13.1.3.2	Astigmatism Combined with Defocus	195
2.13.1.4	LSF from OTF.....	196
2.13.1.5	ESF from OTF.....	198
2.13.2	Numerical Results	199
2.14	Miscellaneous Topics	205
2.14.1	Polychromatic PSF	205
2.14.2	Polychromatic OTF	208
2.14.3	Image of an Incoherent Disc	209
2.14.3.1	Gaussian Image	210
2.14.3.2	Diffraction Image	210
2.14.3.3	Numerical Results	213
2.14.4	Pinhole Camera	218
2.15	Coherent Imaging	222
2.15.1	Coherent Spread Function	222
2.15.2	Coherent Transfer Function	223
2.15.3	Coherent LSF	224
2.15.4	Coherent ESF	229
2.15.5	Image of a Coherent Disc	234
2.15.5.1	Diffraction Image	234
2.15.5.2	Numerical Results	235
2.15.6	Use of a Lens for Obtaining Fourier Transforms	238
2.15.7	Comparison of Coherent and Incoherent Imaging	241
2.15.7.1	Frequency Spectra of Images	241
2.15.7.2	Two-Point Resolution	245
2.16	Summary	253
	References	258
	Problems.....	262

CHAPTER 3: OPTICAL SYSTEMS WITH ANNULAR PUPILS 265

3.1	Introduction	267
3.2	Aberration-Free System.....	267
3.2.1	Point-Spread Function.....	267
3.2.2	Encircled Power	271
3.2.3	Ensquared Power.....	271
3.2.4	Excluded Power	272
3.2.5	Numerical Results	273
3.2.6	Optical Transfer Function.....	278

3.3	Strehl Ratio and Aberration Tolerance	287
3.3.1	Strehl Ratio	288
3.3.2	Primary Aberrations	289
3.3.3	Balanced Primary Aberrations	289
3.3.4	Comparison of Approximate and Exact Results	290
3.4	Balanced Aberrations and Zernike Annular Polynomials	297
3.5	Defocused System	304
3.5.1	Point-Spread Function	304
3.5.2	Focused Beam	305
3.5.3	Collimated Beam	309
3.6	Symmetry Properties of an Aberrated PSF	311
3.7	PSFs and Axial Irradiance for Primary Aberrations	314
3.8	2D PSFs	317
3.9	Line of Sight of an Aberrated System	328
3.9.1	PSF and Its Centroid	328
3.9.2	Numerical Results	329
3.9.2.1	Wavefront Tilt	329
3.9.2.2	Primary Coma	330
3.9.2.3	Secondary Coma	333
3.10	Summary	336
	References	339
	Problems	340

CHAPTER 4: OPTICAL SYSTEMS WITH GAUSSIAN PUPILS 341

4.1	Introduction	343
4.2	General Theory	344
4.3	Systems with Circular Pupils	346
4.3.1	Pupil Function and Transmitted Power	346
4.3.1.1	Gaussian Illumination on a Uniformly Transmitting Pupil	346
4.3.1.2	Uniformly Illuminated Pupil with Gaussian Transmission	348
4.3.2	Aberration-Free System	349
4.3.2.1	PSF	349
4.3.2.2	Focal-Point Irradiance and Optimum Beam Radius	353
4.3.2.3	OTF	354
4.3.3	Strehl Ratio, Aberration Balancing, and Zernike-Gauss Polynomials	355
4.3.3.1	Primary Aberrations: Standard Deviation and Tolerance	355
4.3.3.2	Balanced Primary Aberrations	357
4.3.3.3	Strehl Ratio for Primary Aberrations	359
4.3.3.4	Zernike-Gauss Circle Polynomials	369
4.3.4	Defocused System	372

4.3.4.1	Pupil Function	372
4.3.4.2	PSF	373
4.3.4.3	Axial Irradiance	374
4.3.4.3.1	Focused Beam	374
4.3.4.3.2	Depth of Focus	379
4.3.4.3.3	Diffraction Focus	379
4.3.4.3.4	Collimated Beam	382
4.3.4.4	OTF	385
4.3.5	Balancing of Defocus Aberration with Spherical Aberration or Astigmatism	387
4.3.5.1	Focused Beam	387
4.3.5.2	Collimated Beam.....	392
4.3.6	Aberrated System	395
4.3.6.1	Spherical Aberration.....	395
4.3.6.2	Symmetry Properties of an Aberrated PSF	398
4.3.7	Weakly Truncated Gaussian Pupils and Beams	401
4.3.7.1	Pupil Function	401
4.3.7.2	PSF	402
4.3.7.3	Radius of Curvature of the Propagating Wavefront	407
4.3.7.4	Collimated beam	408
4.3.7.5	Beam Focusing and Waist Imaging by a Lens	410
4.3.7.6	OTF	414
4.3.7.7	Strehl Ratio, Aberration Balancing, and Zernike-Gauss Circle Polynomials.....	415
4.3.7.8	Beam Characterization and Measurement.....	419
4.4	Systems with Annular Pupils.....	421
4.4.1	Pupil Irradiance	422
4.4.2	Aberration-Free System	423
4.4.3	Strehl Ratio and Aberration Tolerance	425
4.4.4	Balanced Aberrations and Zernike-Gauss Annular Polynomials	425
4.4.5	Defocused System	429
4.4.5.1	PSF	429
4.4.5.2	Axial Irradiance	429
4.4.5.3	Collimated Beam.....	432
4.4.6	Symmetry Properties of an Aberrated PSF	433
4.5	Line of Sight of an Aberrated System	434
4.5.1	PSF and Its Centroid.....	434
4.5.2	Numerical Results	435
4.5.2.1	Wavefront Tilt	435
4.5.2.2	Primary Coma	435
4.5.2.3	Secondary Coma	436

4.6 Summary	438
References	441
Problems.....	444

CHAPTER 5: RANDOM ABERRATIONS 445

5.1 Introduction	447
5.2 Random Image Motion	447
5.2.1 Introduction	447
5.2.2 Transverse Image Motion	448
5.2.2.1 General Theory	448
5.2.2.2 Application to Circular Pupils	449
5.2.2.2.1 Theory	449
5.2.2.2.2 Gaussian Approximation	450
5.2.2.2.3 Numerical Results	451
5.2.2.3 Application to Annular Pupils	455
5.2.2.3.1 Theory	455
5.2.2.3.2 Numerical Results	456
5.2.3 Longitudinal Image Motion	459
5.2.3.1 Theory	459
5.2.3.2 Numerical results	460
5.3 Imaging through Atmospheric Turbulence	467
5.3.1 Introduction	467
5.3.2 Kolmogorov Turbulence	468
5.3.3 Mutual Coherence and Wave Structure Functions	470
5.3.4 Atmospheric Coherence Length	473
5.3.5 Phase Structure Function and Power Spectrum of Phase Fluctuations	477
5.3.6 Long-Exposure Image	478
5.3.6.1 Theory	478
5.3.6.2 Application to Circular Pupils	482
5.3.6.3 Application to Annular Pupils	486
5.3.7 Phase Aberration in Terms of Zernike Circle Polynomials	493
5.3.7.1 Zernike Circle Polynomials	493
5.3.7.2 Covariance and Variance of Zernike Expansion Coefficients	494
5.3.7.3 Aberration Variance and Approximate Strehl Ratio	497
5.3.7.4 Modal Correction of Aberration Function	500
5.3.8 Short Exposure Image	502
5.3.8.1 Angle-of-Arrival Fluctuations	502
5.3.8.1.1 Zernike Tilt Fluctuations	502
5.3.8.1.2 Centroid Fluctuations	503
5.3.8.2 Near-Field Imaging	507
5.3.8.2.1 Circular Pupils	507
5.3.8.2.2 Annular Pupils	514

5.3.8.3	Far-Field Imaging	518
5.3.8.4	Simulated Star Images.....	521
5.3.9	Lucky Imaging and Adaptive Optics.....	525
5.4	Summary	527
Appendix: Fourier Transform of Zernike Circle Polynomials.....		530
References		532
Problems.....		535
 BIBLIOGRAPHY		 537
REFERENCES FOR ADDITIONAL READING		539
INDEX		547

PREFACE TO THE FIRST EDITION

In Part I of this book, we discussed imaging based on ray geometrical optics. The aberration-free image of an object according to it is the exact replica of the object, except for its magnification. The aberration-free image of a point object is also a point. In reality, however, the image obtained is not a point. Because of diffraction of the object wave at the aperture stop, or equivalently, the exit pupil of the imaging system, the actual aberration-free image for a circular exit pupil is a light patch surrounded by dark and light rings. Geometrical optics is still assumed to hold from the object to the exit pupil in that rays are traced through the system to determine the shape of the pupil and the aberration across it. The determination of the characteristics of the diffraction image of an object formed by an aberrated system is the subject discussed in Part II. The emphasis of this part is on the numerical results on the effects of aberrations on a diffraction image and not on the formalism, exposition, or a critique of the variety of diffraction theories proposed over the years. It is a compilation of the works of masters like Nijboer, Hopkins, Barakat, and Fried with a sprinkling of my own work.

In Chapter 1, the diffraction theory of image formation is discussed. Starting with a brief account of the Rayleigh-Sommerfeld theory from a Fourier-transform standpoint, we derive the Huygens-Fresnel principle from it. We show that the diffraction image of a point object, called the point-spread function (PSF), is proportional to the modulus square of the Fourier transform of the complex amplitude across the exit pupil. It is shown that the diffraction image of an isoplanatic incoherent object is equal to the convolution of its Gaussian image and the diffraction PSF. The optical transfer function (OTF) of an imaging system, which is the Fourier transform of its PSF, is also discussed. The spatial frequency spectrum of the image of an isoplanatic object is shown to be equal to the product of the spectrum of the object and the OTF. The OTF based on geometrical optics is also considered, and an approximate expression valid for low spatial frequencies is given. A brief comparison of imaging based on diffraction and geometrical optics is given in terms of both the PSF and the OTF. The line of sight of a system is identified with the centroid of its PSF, which, in turn, is obtained in terms of the OTF or the aberration function. The line- and edge-spread functions are introduced and obtained in terms of the PSF or the OTF. Expressions for Strehl, Hopkins, and Struve ratios, useful for obtaining aberration tolerances, are derived. Finally, imaging of coherently illuminated objects is discussed. It is shown that the image of an isoplanatic coherent object is equal to the convolution of its Gaussian amplitude image and the coherent PSF of the imaging system. This chapter forms the foundation of Part II in that the fundamental relations derived in it, and stated as theorems, are used in the succeeding chapters to obtain some practical results for imaging systems with circular, annular, and Gaussian pupils. However, a reader need not read all of this chapter before attempting to read others.

Chapter 2 on systems with circular pupils starts with the aberration-free PSF and its encircled and ensquared powers. The effects of primary aberrations on its Strehl ratio are discussed, and aberration tolerances are obtained. Balanced primary aberrations are

considered and identified with Zernike circle polynomials. Focused and collimated beams are discussed, and the concept of near- and far-field distances is introduced. Aberrated PSFs and their symmetry properties are discussed, and a brief comparison is made with their counterparts in geometrical optics. The line of sight of an aberrated system, identified with the centroid of the PSF, is determined for primary aberrations. The OTF for these aberrations is also discussed, phase contrast reversal is explained, and aberration tolerances for a certain value of Hopkins ratio are given. Expressions for the geometrical OTF for primary aberrations are also given. Both incoherent and coherent line- and edge-spread functions are discussed, and aberration tolerances for a certain value of the Struve ratio are given. A brief comparison of incoherent and coherent imaging is given with special reference to the Rayleigh criterion of resolution. The Fourier-transforming property of wave propagation is illustrated in altering the image of an object by spatial filtering in the Fourier-transform plane.

Systems with annular pupils are given a cursory look at best in books where imaging is discussed. Our Chapter 3 is written in a manner similar to Chapter 2 where, for example, the balanced aberrations are identified with the Zernike annular polynomials. Although the propagation of Gaussian beams is discussed in books on lasers, their treatment is generally limited to the weakly truncated aberration-free beams. In Chapter 4, we consider the effect of arbitrary truncation of beams with and without aberrations. The balanced aberrations in this case are identified with the Zernike-Gauss polynomials. It is shown, for example, that the pupil radius must be at least three times the beam radius in order to neglect beam truncation without significant error.

Finally, random aberrations are considered in Chapter 5. The effect of random image motion is considered first, and expressions and numerical values of time-averaged Strehl ratio, PSF, and encircled power are given for systems with circular and annular pupils. The random aberrations introduced by atmospheric turbulence when a wave propagates through it, as in astronomical observations by a ground-based telescope, are discussed; and expressions for time-averaged PSF and OTF are obtained. The aberration function for Kolmogorov turbulence is expanded in terms of the Zernike polynomials, and auto-correlation and cross-correlation of the expansion coefficients are given. The atmospheric coherence length is defined, and it is shown that the resolution of a telescope cannot exceed that of an aberration-free telescope of this diameter. Both the short- and long-exposure images are considered.

As in Part I, each chapter ends with a set of problems. It is hoped that they will acquaint the reader with application of the theory in terms of some practical examples. References for additional reading are given after the Bibliography. These references represent the author's collection as the editor of Milestone Series 74 entitled *Effects of Aberrations in Optical Imaging*, published by SPIE Press in 1993.

ACKNOWLEDGMENTS

It is a great pleasure to acknowledge the generous support I have received over the years from my employer, The Aerospace Corporation, in preparing this book. My special thanks go to the senior vice president Mr. John Parsons, for his continuous interest and encouragement in this endeavor. I thank Mr. John Hoyem for preparing the figures and Mr. Victor Onouye for some figures as well as the final composition. My thanks also go to Dr. Rich Boucher for computer generating the 2D PSFs and Mr. Yunsong Huang for numerical analysis and computer plotting. The Sanskrit verse on p. xxv was provided by Professor Sally Sutherland of the University of California at Berkeley.

I am grateful to Dr. P. Mouroulis and Professor Emeritus D. Schroeder for their careful review of the manuscript. I also benefited from the comments made by many friends and colleagues over the years. Included among them are Dr. Bill Swantner, Professor A. Walther, Professor A. Marathay, and Professor J. Harvey. Of course, any shortcomings or errors in the book are my responsibility. I also thank Professor R. R. Shannon for writing the Foreword to both Parts of this book.

I thank my sister Pushpa and brother Devinder for encouraging me to study physics. I can not say enough about the constant support I have received from my wife Shashi over the many years it has taken me to complete this two-part book. I dedicate this book to my departed parents who brought and nourished me in this world.

Finally, I would like to thank SPIE Press Senior Editor Dara Burrows for meticulously editing the book and SPIE Press Manager Tim Lamkins for facilitating the publication of this Second Edition. It has been a pleasure to work with them, especially because of their cooperative spirit and quality support.

El Segundo, California
April 2011

Virendra N. Mahajan

PREFACE TO THE SECOND EDITION

Ten years have passed since the publication of the first edition in April 2001. Many of the typographical errors were corrected in the Second Printing that took place after 3 years in 2004. Only a small amount of new material, approximately 11 pages, was added at that time. It included Appendix B in Chapter 1, Gaussian OTF in Chapter 4, and an extension of the discussion of the short-exposure image in Chapter 5. Additional corrections were made in the e-version of the book in 2009, and the discussion of Zernike circle, annular, and Gauss polynomials was streamlined utilizing an abbreviated notation with emphasis on their orthonormal form. However, a considerable amount of new material amounting to another 88 pages has been added in this Second Edition. Besides correction of some residual typographical errors, a Summary section has been included in Chapters 2, 3, and 5 for consistency with Chapters 1 and 4. Any compound references have been split into single ones. The new material is primarily in Chapters 4 and 5.

In Chapter 4, a Gaussian pupil obtained by apodization is compared with that of a Gaussian beam. The optimum value of the Gaussian radius relative to that of the pupil to yield the maximum focal-point irradiance is derived. The discussion of the standard deviation, aberration balancing, and Strehl ratio for primary aberrations for different values of the ratio of the beam and pupil radii has been expanded. It is shown that the approximate expression for Strehl ratio in terms of the aberration variance is not suitable for very narrow Gaussian beams. The aberration-free OTF has been extended to that of a defocused system. The problem of balancing defocus aberration with spherical aberration or astigmatism is discussed, illustrating that an aberrated beam can yield a higher axial irradiance in a certain defocused region than its aberration-free focal-point value. The PSFs aberrated by spherical aberration are considered to illustrate the loss of advantage of the Gaussian pupil in reducing the secondary maxima when the aberration is present. The characterization of the width of a multimode beam compared to that of a Gaussian beam is discussed briefly.

In Chapter 5, the effect of random transverse image motion on the PSF has been supplanted by a discussion of the effect of random longitudinal defocus. The coherence length of atmospheric turbulence is calculated for the Hufnagel-Valley model of the refractive index structure parameter, for both looking up and down through the atmosphere. The angle of arrival of the light wave propagating through turbulence is discussed for both the Zernike tilt as well as the centroid of the PSF, showing that they are nearly equal. A brief discussion of lucky imaging is also given, where better quality short-exposure images are selected, aligned, and added to obtain a high-quality image.

El Segundo, California
April 2011

Virendra N. Mahajan

SYMBOLS AND NOTATION

a	pupil radius	r_0	atmospheric coherence diameter
a_i	aberration coefficient	\vec{r}_i	image point position vector
A	amplitude	\vec{r}_p	pupil point position vector
A_i	peak aberration coefficient	R	radius of reference sphere
B_d	defocus coefficient	Re	real part
B_t	tilt coefficient	$R_n^m(\rho)$	Zernike radial polynomial
D	pupil diameter	S	Strehl ratio
\mathcal{D}	structure function	S_{en}	area of entrance pupil
F	focal ratio	U	complex amplitude
ESF	edge transfer function	S_{ex}	area of exit pupil
H	Hopkins ratio	W	wave aberration
I	irradiance	x, y	rectangular coordinates of a point
Im	imaginary part	z	optical axis, axial distance
k	wavenumber	$Z_n^m(\rho, \theta)$	Zernike circle polynomial
l	distance, log amplitude	\vec{v}_i	image spatial frequency vector
LSF	line spread function	\vec{v}_o	object spatial frequency vector
m_p	pupil magnification	v	normalized spatial frequency
M	magnification	τ	optical transfer function
MCF	mutual coherence function	Ψ	phase transfer function
MTF	modulation transfer function	$\rho = r/a$	normalized radial coordinate
OTF	optical transfer function	θ	polar angle of a position vector
P	object point	ϕ	polar angle of frequency vector
P'	Gaussian image point	ϵ	obscuration ratio
P_{ex}	power in the exit pupil	$\delta(\cdot)$	Dirac delta function
P_i	image power	η	relative irradiance
$P(\cdot)$	pupil function	Φ	phase aberration
PSF	point-spread function	r, θ	polar coordinates of a point
PTF	phase transfer function	λ	optical wavelength
r	radial coordinate	ξ, η	normalized frequency coordinates
r_c	radius of circle	σ_W	standard deviation of wave aberration

अनन्तरत्नप्रभवस्य यस्य हिमं न सौभाग्यविलोपि जातम् ।
एको हि दोषो गुणसन्निपाते निमज्जतीन्दोः किरणेष्विवाङ्कः ॥

Anantaratnaprabhavasya yasya himaṃ na saubhāgyavilopi jātam |

Eko hi doṣo gūṇasannipāte nimajjātīndoḥ kiraṇesvivāṅkaḥ ||

The snow does not diminish the beauty of the Himālayan 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.

Kālidāsa *Kumārasambhava* 1.3