

Modulation Transfer Function in Optical and Electro-Optical Systems

Modulation Transfer Function in Optical and Electro-Optical Systems

Glenn D. Boreman

Tutorial Texts in Optical Engineering
Volume TT52

SPIE
PRESS

Bellingham, Washington USA

Tutorial Texts Series

- *Modulation Transfer Function in Optical and Electro-Optical Systems*, Glenn D. Boreman, Vol. TT52
- *Uncooled Thermal Imaging Arrays, Systems, and Applications*, Paul W. Kruse, Vol. TT51
- *Fundamentals of Antennas*, Christos G. Christodoulou and Parveen Wahid, Vol. TT50
- *The Basics of Spectroscopy*, David W. Ball, Vol. TT49
- *Optical Design Fundamentals for Infrared Systems, Second Edition*, Max J. Riedl, Vol. TT48
- *Resolution Enhancement Techniques in Optical Lithography*, Alfred Kwok-Kit Wong, Vol. TT47
- *Copper Interconnect Technology*, Christoph Steinbrüchel and Barry L. Chin, Vol. TT46
- *Optical Design for Visual Systems*, Bruce H. Walker, Vol. TT45
- *Fundamentals of Contamination Control*, Alan C. Tribble, Vol. TT44
- *Evolutionary Computation: Principles and Practice for Signal Processing*, David Fogel, Vol. TT43
- *Infrared Optics and Zoom Lenses*, Allen Mann, Vol. TT42
- *Introduction to Adaptive Optics*, Robert K. Tyson, Vol. TT41
- *Fractal and Wavelet Image Compression Techniques*, Stephen Welstead, Vol. TT40
- *Analysis of Sampled Imaging Systems*, R. H. Vollmerhausen and R. G. Driggers, Vol. TT39
- *Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnosis*, Valery Tuchin, Vol. TT38
- *Fundamentos de Electro-Óptica para Ingenieros*, Glenn D. Boreman, translated by Javier Alda, Vol. TT37
- *Infrared Design Examples*, William L. Wolfe, Vol. TT36
- *Sensor and Data Fusion Concepts and Applications, Second Edition*, L. A. Klein, Vol. TT35
- *Practical Applications of Infrared Thermal Sensing and Imaging Equipment, Second Edition*, Herbert Kaplan, Vol. TT34
- *Fundamentals of Machine Vision*, Harley R. Myler, Vol. TT33
- *Design and Mounting of Prisms and Small Mirrors in Optical Instruments*, Paul R. Yoder, Jr., Vol. TT32
- *Basic Electro-Optics for Electrical Engineers*, Glenn D. Boreman, Vol. TT31
- *Optical Engineering Fundamentals*, Bruce H. Walker, Vol. TT30
- *Introduction to Radiometry*, William L. Wolfe, Vol. TT29
- *Lithography Process Control*, Harry J. Levinson, Vol. TT28
- *An Introduction to Interpretation of Graphic Images*, Sergey Ablameyko, Vol. TT27
- *Thermal Infrared Characterization of Ground Targets and Backgrounds*, P. Jacobs, Vol. TT26
- *Introduction to Imaging Spectrometers*, William L. Wolfe, Vol. TT25
- *Introduction to Infrared System Design*, William L. Wolfe, Vol. TT24
- *Introduction to Computer-based Imaging Systems*, D. Sinha, E. R. Dougherty, Vol. TT23
- *Optical Communication Receiver Design*, Stephen B. Alexander, Vol. TT22
- *Mounting Lenses in Optical Instruments*, Paul R. Yoder, Jr., Vol. TT21
- *Optical Design Fundamentals for Infrared Systems*, Max J. Riedl, Vol. TT20
- *An Introduction to Real-Time Imaging*, Edward R. Dougherty, Phillip A. Laplante, Vol. TT19
- *Introduction to Wavefront Sensors*, Joseph M. Geary, Vol. TT18
- *Integration of Lasers and Fiber Optics into Robotic Systems*, J. A. Marszalec, E. A. Marszalec, Vol. TT17
- *An Introduction to Nonlinear Image Processing*, E. R. Dougherty, J. Astola, Vol. TT16
- *Introduction to Optical Testing*, Joseph M. Geary, Vol. TT15
- *Image Formation in Low-Voltage Scanning Electron Microscopy*, L. Reimer, Vol. TT12
- *Diazonaphthoquinone-based Resists*, Ralph Dammell, Vol. TT11
- *Infrared Window and Dome Materials*, Daniel C. Harris, Vol. TT10
- *An Introduction to Morphological Image Processing*, Edward R. Dougherty, Vol. TT9
- *An Introduction to Optics in Computers*, Henri H. Arsenaault, Yunlong Sheng, Vol. TT8
- *Digital Image Compression Techniques*, Majid Rabbani, Paul W. Jones, Vol. TT7
- *Aberration Theory Made Simple*, Virendra N. Mahajan, Vol. TT6
- *Single-Frequency Semiconductor Lasers*, Jens Buus, Vol. TT5

Library of Congress Cataloging-in-Publication Data

Boreman, Glenn D.

Modulation transfer function in optical and electro-optical systems / Glenn D. Boreman.

p. cm. — (Tutorial texts in optical engineering ; v. TT 52)

Includes bibliographical references and index.

ISBN 0-8194-4143-0

1. Optics. 2. Electrooptical devices. 3. Modulation theory. I. Title. II. Series.

TA1520 .B67 2001

621.36—dc21

2001031158

CIP

Published by

SPIE—The International Society for Optical Engineering

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: 360/676-3290

Fax: 360/647-1445

Email: spie@spie.org

WWW: www.spie.org

Copyright © 2001 The 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.

Printed in the United States of America.

Introduction to the Series

The Tutorial Texts series was initiated in 1989 as a way to make the material presented in SPIE short courses available to those who couldn't attend and to provide a reference book for those who could. Typically, short course notes are developed with the thought in mind that supporting material will be presented verbally to complement the notes, which are generally written in summary form, highlight key technical topics, and are not intended as stand-alone documents. Additionally, the figures, tables, and other graphically formatted information included with the notes require further explanation given in the instructor's lecture. As stand-alone documents, short course notes do not generally serve the student or reader well.

Many of the Tutorial Texts have thus started as short course notes subsequently expanded into books. The goal of the series is to provide readers with books that cover focused technical interest areas in a tutorial fashion. What separates the books in this series from other technical monographs and textbooks is the way in which the material is presented. Keeping in mind the tutorial nature of the series, many of the topics presented in these texts are followed by detailed examples that further explain the concepts presented. Many pictures and illustrations are included with each text, and where appropriate tabular reference data are also included.

To date, the texts published in this series have encompassed a wide range of topics, from geometrical optics to optical detectors to image processing. 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 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 processes and technologies under discussion.

During the past nine years, my predecessor, Donald C. O'Shea, has done an excellent job in building the Tutorial Texts series, which now numbers nearly forty books. It has expanded to include not only texts developed by short course instructors but also those written by other topic experts. It is my goal to maintain the style and quality of books in the series, and to further expand the topic areas to include emerging as well as mature subjects in optics, photonics, and imaging.

Arthur R. Weeks, Jr.
Invivo Research Inc. and University of Central Florida

TABLE OF CONTENTS

PREFACE / vii

CHAPTER 1 MTF IN OPTICAL SYSTEMS / 1

- 1.1 Impulse response / 1
- 1.2 Spatial frequency / 4
- 1.3 Transfer function / 7
 - 1.3.1 Modulation transfer function / 9
 - 1.3.2 Phase transfer function / 12
- 1.4 MTF and resolution / 16
- 1.5 Diffraction MTF / 18
 - 1.5.1 Calculation of diffraction MTF / 20
 - 1.5.2 Diffraction MTF for obscured systems / 25
- 1.6 Geometrical MTF / 26
 - 1.6.1 Effect of defocus on MTF / 27
 - 1.6.2 Effect of other aberrations on MTF / 27
 - 1.6.3 MTF and Strehl ratio / 28
- References / 29
- Further reading / 30

CHAPTER 2 MTF IN ELECTRO-OPTICAL SYSTEMS / 31

- 2.1 Detector footprint MTF / 31
- 2.2 Sampling / 35
 - 2.2.1 Aliasing / 35
 - 2.2.2 Sampling MTF / 41
- 2.3 Crosstalk / 51
- 2.4 Electronic-network MTF / 53
- 2.5 Conclusion / 55
- References / 56
- Further reading / 57

CHAPTER 3 OTHER MTF CONTRIBUTIONS / 59

- 3.1 Motion MTF / 59
- 3.2 Vibration MTF / 60
- 3.3 Turbulence MTF / 62
- 3.4 Aerosol-scattering MTF / 65
- References / 67
- Further reading / 68

CHAPTER 4 MTF MEASUREMENT METHODS / 69

- 4.1 Point-spread function (PSF) / 70
- 4.2 Line-spread function (LSF) / 71
- 4.3 Edge-spread function (ESF) / 73
- 4.4 Comparison of PSF, LSF, and ESF / 76
- 4.5 Noise targets / 76
 - 4.5.1 Laser speckle MTF test / 77
 - 4.5.2 Random-transparency MTF test / 78
- 4.6 Bar-target MTF measurement / 79
- References / 84

CHAPTER 5 PRACTICAL MEASUREMENT ISSUES / 85

- 5.1 Cascade properties of MTF / 85
- 5.2 Quality of auxiliary optics / 89
- 5.3 Source coherence / 90
- 5.4 Correcting for finite source size / 91
- 5.5 Correcting for the image-receiver MTF / 94
 - 5.5.1 Finite pixel width / 94
 - 5.5.2 Finite sampling interval / 95
- 5.6 Summary of instrumental MTF issues / 96
- 5.7 Increasing SNR in PSF, LSF, and ESF tests / 96
 - 5.7.1 Object- and image-plane equivalence / 96
 - 5.7.2 Averaging in pixelated detector arrays / 99
 - 5.7.3 Potential pitfalls / 100
- 5.8 MTF testing observations / 101
- 5.9 Use of computers in MTF measurements / 101
- 5.10 Representative instrument designs / 102
 - 5.10.1 Example #1: visible ESF / 102
 - 5.10.2 Example #2: infrared line response / 103
 - 5.10.3 Example #3: visible square-wave response / 104
 - 5.10.4 Example #4: bar-target response / 106
- References / 106
- Further reading / 107

INDEX / 109

PREFACE

I first became aware that there was such a thing as MTF as an undergraduate at Rochester, scurrying around the Bausch and Lomb building. There was, in one of the stairwells, a large poster of the Air Force bar target set. I saw that poster every day, and I remember thinking...gee, that's pretty neat. Well, more than 25 years later, I still think so. I have had great fun making MTF measurements on focal-plane arrays, SPRITE detectors, scanning cameras, IR scene projectors, telescopes, collimators, and infrared antennas. This book is an outgrowth of a short course that I have presented for SPIE since 1987. In it, I emphasize some practical things I have learned about making MTF measurements.

I am grateful for initial discussions on this subject at Arizona with Jack Gaskill and Stace Dereniak. Since then, I have had the good fortune here at Central Florida to work with a number of colleagues and graduate students on MTF issues. I fondly recall discussions of MTF with Arnold Daniels, Jim Harvey, Didi Dogariu, Karen MacDougall, Marty Sensiper, Ken Barnard, Al Ducharme, Ofer Hadar, Ric Schildwachter, Barry Anderson, Al Plogstedt, Christophe Fumeaux, Per Fredin, and Frank Effenberger. I want to thank Dan Jones of the UCF English Department for his support, as well as Rick Hermann, Eric Pepper, and Marshall Weathersby of SPIE for their assistance and enthusiasm for this project. I also appreciate the permissions granted for reproductions of some of the figures from their original sources.

Last but surely not least, I want to thank Maggie Boreman – my wife, main encourager, and technical editor. Once again, Meg, you have wrestled with my occasionally tedious exposition and transformed it, if not into poetry, then at least into prose. Thanks.

GDB
Cocoa Beach
15 March 2001