

Optics Using MATLAB®

Tutorial Texts Series

- *Design and Fabrication of Diffractive Optical Elements with MATLAB®*, A. Vijayakumar and Shanti Bhattacharya, Vol. TT109
- *Energy Harvesting for Low-Power Autonomous Devices and Systems*, Jahangir Rastegar and Harbans S. Dhadwal, Vol. TT108
- *Practical Electronics for Optical Design and Engineering*, Scott W. Teare, Vol. TT107
- *Automatic Target Recognition*, Bruce J. Schachter, Vol. TT105
- *Design Technology Co-optimization in the Era of Sub-resolution IC Scaling*, Lars W. Liebmann, Kaushik Vaidyanathan, and Lawrence Pileggi, Vol. TT104
- *Special Functions for Optical Science and Engineering*, Vasudevan Lakshminarayanan and L. Srinivasa Varadharajan, Vol. TT103
- *Discrimination of Subsurface Unexploded Ordnance*, Kevin A. O'Neill, Vol. TT102
- *Introduction to Metrology Applications in IC Manufacturing*, Bo Su, Eric Solecky, and Alok Vaid, Vol. TT101
- *Introduction to Liquid Crystals for Optical Design and Engineering*, Sergio Restaino and Scott Teare, Vol. TT100
- *Design and Implementation of Autostereoscopic Displays*, Byoung-ho Lee, Soon-gi Park, Keehoon Hong, and Jisoo Hong, Vol. TT99
- *Ocean Sensing and Monitoring: Optics and Other Methods*, Weilin Hou, Vol. TT98
- *Digital Converters for Image Sensors*, Kenton T. Veeder, Vol. TT97
- *Laser Beam Quality Metrics*, T. Sean Ross, Vol. TT96
- *Military Displays: Technology and Applications*, Daniel D. Desjardins, Vol. TT95
- *Interferometry for Precision Measurement*, Peter Langenbeck, Vol. TT94
- *Aberration Theory Made Simple, Second Edition*, Virendra N. Mahajan, Vol. TT93
- *Modeling the Imaging Chain of Digital Cameras*, Robert D. Fiete, Vol. TT92
- *Bioluminescence and Fluorescence for In Vivo Imaging*, Lubov Brovko, Vol. TT91
- *Polarization of Light with Applications in Optical Fibers*, Arun Kumar and Ajoy Ghatak, Vol. TT90
- *Digital Fourier Optics: A MATLAB Tutorial*, David G. Voeltz, Vol. TT89
- *Optical Design of Microscopes*, George Seward, Vol. TT88
- *Analysis and Evaluation of Sampled Imaging Systems*, Richard H. Vollmerhausen, Donald A. Reago, and Ronald Driggers, Vol. TT87
- *Nanotechnology: A Crash Course*, Raúl J. Martín-Palma and Akhlesh Lakhtakia, Vol. TT86
- *Direct Detection LADAR Systems*, Richard Richmond and Stephen Cain, Vol. TT85
- *Optical Design: Applying the Fundamentals*, Max J. Riedl, Vol. TT84
- *Infrared Optics and Zoom Lenses, Second Edition*, Allen Mann, Vol. TT83
- *Optical Engineering Fundamentals, Second Edition*, Bruce H. Walker, Vol. TT82
- *Fundamentals of Polarimetric Remote Sensing*, John Schott, Vol. TT81
- *The Design of Plastic Optical Systems*, Michael P. Schaub, Vol. TT80
- *Fundamentals of Photonics*, Chandra Roychoudhuri, Vol. TT79
- *Radiation Thermometry: Fundamentals and Applications in the Petrochemical Industry*, Peter Saunders, Vol. TT78
- *Matrix Methods for Optical Layout*, Gerhard Kloos, Vol. TT77
- *Fundamentals of Infrared Detector Materials*, Michael A. Kinch, Vol. TT76
- *Practical Applications of Infrared Thermal Sensing and Imaging Equipment, Third Edition*, Herbert Kaplan, Vol. TT75
- *Bioluminescence for Food and Environmental Microbiological Safety*, Lubov Brovko, Vol. TT74
- *Introduction to Image Stabilization*, Scott W. Teare and Sergio R. Restaino, Vol. TT73
- *Logic-based Nonlinear Image Processing*, Stephen Marshall, Vol. TT72
- *The Physics and Engineering of Solid State Lasers*, Yehoshua Kalisky, Vol. TT71
- *Thermal Infrared Characterization of Ground Targets and Backgrounds, Second Edition*, Pieter A. Jacobs, Vol. TT70
- *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)*, Raghuveer Rao and Sohail Dianat, Vol. TT67

(For a complete list of Tutorial Texts, see <http://spie.org/publications/books/tutorial-texts>.)

Optics Using MATLAB[®]

Scott W. Teare

Tutorial Texts in Optical Engineering
Volume TT111

SPIE PRESS
Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Names: Teare, Scott W., author.

Title: Optics using MATLAB / Scott W. Teare.

Other titles: Tutorial texts in optical engineering ; v. TT 111.

Description: Bellingham, Washington : SPIE Press, [2017] | Series: Tutorial texts in optical engineering ; volume TT 111 | Includes bibliographical references and index.

Identifiers: LCCN 2016050697 | ISBN 9781510608313 (softcover ; alk. paper) | ISBN 1510608311 (softcover ; alk. paper) | ISBN 9781510608320 (pdf) | ISBN 151060832X (pdf) | ISBN 9781510608344 (Kindle) | ISBN 1510608346 (Kindle) | ISBN 9781510608337 (ePub) | ISBN 1510608338 (ePub)

Subjects: LCSH: Optics--Mathematics. | MATLAB.

Classification: LCC QC355.3 .T43 2017 | DDC 621.360285/53--dc23 LC record available at <https://lccn.loc.gov/2016050697>

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 © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE)

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. 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.

For updates to this book, visit <http://spie.org> and type “TT111” in the search field.

SPIE.

Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to cover 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 independently 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

<i>Preface</i>	<i>xi</i>
I MATLAB® Overview	1
1 Introduction to MATLAB	3
1.1 Getting Started with MATLAB	4
1.2 Anatomy of a Program	6
1.3 MATLAB Basic Functions and Operators	8
1.4 Simple Calculations using MATLAB	10
1.5 Vectorization and Matrix Indexing	12
1.6 MATLAB Scripts	13
1.7 MATLAB Functions	14
1.8 Practice Problems	16
References	16
2 Plotting Mathematical Functions	19
2.1 Mathematical Functions	19
2.2 Visualization Functions: <code>plot()</code>	25
2.3 Visualization Functions: <code>histogram()</code>	27
2.4 Visualization Functions: 3D plotting	30
2.5 Visualization Functions: <code>contour()</code> and <code>quiver()</code>	32
2.6 Visualization Function: <code>imagesc()</code>	35
2.7 Practice Problems	35
References	36
3 Curve Fitting and Statistics	37
3.1 Polynomial Synthesis and Curve Fitting	37
3.2 Polynomial Curve Fitting	41
3.3 Signal-to-Noise Ratio	44
3.4 Best Fit through the Data	47
3.5 Best Fit to the Data	49
3.6 Practice Problems	50
References	50

4	Data and Data Files	53
4.1	Text versus Binary	53
4.2	Writing Data Files	54
4.3	Generating Data to be Saved	57
4.4	Reading and Using Data Files	58
4.5	Binary MAT Files	59
4.6	Binary Image Files	60
4.7	Practice Problems	60
	References	61
5	Images and Image Processing	63
5.1	Image Files	63
5.2	Image Commands	66
5.3	Image Size and Super-pixels	67
5.4	Color Models and Conversions	70
5.5	Spatial Filtering	71
5.6	Practice Problems	78
	References	78
II	Optics Applications	79
6	Ray Optics and Glass Equations	81
6.1	Lensmaker's Equation and Spot Size	81
6.2	Paraxial Region and Snell's Law	84
6.3	Matrix Approach to Ray Tracing	85
6.4	Ray Tracing through Multiple Elements	89
6.5	Glass Equations	91
6.6	Practice Problems	94
	References	94
7	Spectrometers	95
7.1	Dispersion in a Material	95
7.2	Prisms	98
7.3	Gratings	100
7.4	Blazed Gratings	103
7.5	Grisms	104
7.6	Spectrometers and Monochrometers	106
7.7	Practice Problems	108
	References	108
8	Modulation Transfer Function and Contrast	109
8.1	Image Quality	109
8.2	Spatial Frequency and the Modulation Transfer Function	110
8.3	Point Spread Function	114
8.4	MTF Measurement	115

8.5	Effect of Annular Optics on MTF	116
8.6	Image Transformation	120
8.7	Practice Problems	123
	References	123
9	Diffraction and Interference	125
9.1	Interference	126
9.2	Coherence	127
9.3	Diffraction	129
9.4	Young's Double-Slit Experiment	132
9.5	Michelson Stellar Interferometer	133
9.6	Mach-Zehnder Interferometer	136
9.7	Practice Problems	137
	References	138
10	Zernike Polynomials and Wavefronts	139
10.1	Wavefront Sensing in Adaptive Optics	139
10.2	Wavefront Aberrations	143
10.3	Zernike Polynomials	144
10.4	Wavefront Construction	150
10.5	Practice Problems	153
	References	153
	Further Reading	153
11	Polarization	155
11.1	Polarized Light	155
11.2	Double Refraction	158
11.3	The Jones Calculus: Polarizers	159
11.4	The Jones Calculus: Phase Retarders	162
11.5	The Mueller Calculus	165
11.6	Jones-to Mueller Transformation	168
11.7	Practice Problems	169
	References	170
12	Optical Interference Filters	171
12.1	Transfer Matrix for Thin Films	171
12.2	Antireflection Systems	173
12.3	High-Reflectance Systems	176
12.4	Bandpass Filters	179
12.5	Composite Filters	182
12.6	Index of Refraction Calculation	184
12.7	Practice Problems	185
	References	185

13 Metals and Complex Index of Refraction	187
13.1 Physical Vapor Deposition	187
13.2 Index of Refraction in Absorbing Media	189
13.3 Reflectivity of Metal Films	189
13.4 Absorption and Transmission in Metal Films	192
13.5 Impedance Matching	194
13.6 Practice Problems	200
References	200
III More with MATLAB®	203
14 User Interfaces	205
14.1 Simple User Interfaces	205
14.2 Built-In Interfaces	207
14.3 Graphical User Interfaces: GUIDE	210
14.4 Applications: App Designer	213
14.5 Zernike GUI Project	215
14.6 Practice Problems	217
References	218
15 Completing and Packaging Programs	219
15.1 P-Code	219
15.2 Publishing	221
15.3 Version Control	222
15.4 Interfacing with other Programming Languages	223
15.5 Object-Oriented Programming and More	226
References	227
<i>Bibliography</i>	229
<i>Index</i>	231

Preface

Optical engineers make use of a wide variety of commercial software tools in the design, development and testing of optical systems. These tools, no matter how excellent in their own right, can fall short of providing needed calculations. This need for flexibility and special calculations is the domain of user-programmable software.

Optics Using MATLAB[®] was written to tie a number of optical topics into programming activities with MATLAB and can act as a supplement to other textbooks or stand alone. The book is divided into three parts: Part I has five chapters focused on a wide range of basic programming fundamentals using MATLAB and includes topics such as curve fitting, image processing, and file storage. The eight chapters of Part II provide a review of a number of selected topics in optics and demonstrate how these can be explored using MATLAB scripts. Part III discusses how to use MATLAB to improve the usability of custom programs through graphical user interfaces and incorporating other programming languages.

The book was designed such that you can get started on any chapter that catches your attention and seek more specialized information from the earlier chapters as needed. Some examples of the topics in Part II are thin film filters, spectrometers, polarization, complex index of refraction, and wavefront sensing.

Optics Using MATLAB provides a functional overview of developing code using MATLAB that can be used to enhance and increase the understanding of optics topics though the use of visualization tools. This book is not meant to be a fundamental treatment of optics, but rather a complement to the many excellent books on optics, while providing an example-based approach to understanding the underlying optical questions.

I greatly appreciate all of the colleagues and friends who have both directly and indirectly helped me in preparing and writing this book, and I am grateful for their unswerving and unselfish support. I also appreciate the feedback from the many students who over the years have helped me refine my optics and electronics lectures and laboratories.

While I have benefited from the support of many individuals in preparing this work, any errors that remain in the text are mine to fix. I would

appreciate receiving any assistance in the form of comments and corrections. Please direct any correspondence to the author at scott.teare@nmt.edu.

I am most grateful for the support of SPIE for their interest in publishing this work as part of the *Tutorial Text* series and particularly the efforts of Senior Editor Dara Burrows, for putting this work into its final form.

Scott W. Teare
Socorro, New Mexico
December 2016