

# POLARIMETRIC RADAR IMAGING

FROM BASICS TO APPLICATIONS



$|HV|$ ,  $|HH|$ ,  $|VV|$

$|HV|$ ,  $|HH-VV|$ ,  $|HH+VV|$

**JONG-SEN LEE • ERIC POTTIER**



CRC Press  
Taylor & Francis Group

TN958  
L478

# POLARIMETRIC RADAR IMAGING

FROM BASICS TO APPLICATIONS

---

**JONG-SEN LEE • ERIC POTTIER**



E2009002614



**CRC Press**

Taylor & Francis Group

Boca Raton London New York

---

CRC Press is an imprint of the  
Taylor & Francis Group, an **informa** business

CRC Press  
Taylor & Francis Group  
6000 Broken Sound Parkway NW, Suite 300  
Boca Raton, FL 33487-2742

© 2009 by Taylor & Francis Group, LLC  
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works  
Printed in the United States of America on acid-free paper  
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-13: 978-1-4200-5497-2 (Hardcover)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access [www.copyright.com](http://www.copyright.com) (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

**Trademark Notice:** Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

---

**Library of Congress Cataloging-in-Publication Data**

---

Lee, Jong-Sen.

Polarimetric radar imaging : from basics to applications / authors, Jong-Sen

Lee, Eric Pottier.

p. cm. -- (Optical science and engineering ; 143)

"A CRC title."

Includes bibliographical references and index.

ISBN 978-1-4200-5497-2 (hardcover : alk. paper)

1. Radar. 2. Polarimetry. 3. Radio waves--Polarization. 4. Remote sensing. I.

Pottier, Eric. II. Title. III. Series.

TK6580.L424 2009

621.3848--dc22

2008051280

---

Visit the Taylor & Francis Web site at  
<http://www.taylorandfrancis.com>

and the CRC Press Web site at  
<http://www.crcpress.com>

# POLARIMETRIC RADAR IMAGING

FROM BASICS TO APPLICATIONS

# OPTICAL SCIENCE AND ENGINEERING

*Founding Editor*

**Brian J. Thompson**

*University of Rochester*

*Rochester, New York*

1. Electron and Ion Microscopy and Microanalysis: Principles and Applications, *Lawrence E. Murr*
2. Acousto-Optic Signal Processing: Theory and Implementation, *edited by Norman J. Berg and John N. Lee*
3. Electro-Optic and Acousto-Optic Scanning and Deflection, *Milton Gottlieb, Clive L. M. Ireland, and John Martin Ley*
4. Single-Mode Fiber Optics: Principles and Applications, *Luc B. Jeunhomme*
5. Pulse Code Formats for Fiber Optical Data Communication: Basic Principles and Applications, *David J. Morris*
6. Optical Materials: An Introduction to Selection and Application, *Solomon Musikant*
7. Infrared Methods for Gaseous Measurements: Theory and Practice, *edited by Joda Wormhoudt*
8. Laser Beam Scanning: Opto-Mechanical Devices, Systems, and Data Storage Optics, *edited by Gerald F. Marshall*
9. Opto-Mechanical Systems Design, *Paul R. Yoder, Jr.*
10. Optical Fiber Splices and Connectors: Theory and Methods, *Calvin M. Miller with Stephen C. Mettler and Ian A. White*
11. Laser Spectroscopy and Its Applications, *edited by Leon J. Radziemski, Richard W. Solarz, and Jeffrey A. Paisner*
12. Infrared Optoelectronics: Devices and Applications, *William Nunley and J. Scott Bechtel*
13. Integrated Optical Circuits and Components: Design and Applications, *edited by Lynn D. Hutcheson*
14. Handbook of Molecular Lasers, *edited by Peter K. Cheo*
15. Handbook of Optical Fibers and Cables, *Hiroshi Murata*
16. Acousto-Optics, *Adrian Korpel*
17. Procedures in Applied Optics, *John Strong*
18. Handbook of Solid-State Lasers, *edited by Peter K. Cheo*
19. Optical Computing: Digital and Symbolic, *edited by Raymond Arrathoon*
20. Laser Applications in Physical Chemistry, *edited by D. K. Evans*
21. Laser-Induced Plasmas and Applications, *edited by Leon J. Radziemski and David A. Cremers*
22. Infrared Technology Fundamentals, *Irving J. Spiro and Monroe Schlessinger*

23. Single-Mode Fiber Optics: Principles and Applications, Second Edition, Revised and Expanded, *Luc B. Jeunhomme*
24. Image Analysis Applications, *edited by Rangachar Kasturi and Mohan M. Trivedi*
25. Photoconductivity: Art, Science, and Technology, *N. V. Joshi*
26. Principles of Optical Circuit Engineering, *Mark A. Mentzer*
27. Lens Design, *Milton Laikin*
28. Optical Components, Systems, and Measurement Techniques, *Rajpal S. Sirohi and M. P. Kothiyal*
29. Electron and Ion Microscopy and Microanalysis: Principles and Applications, Second Edition, Revised and Expanded, *Lawrence E. Murr*
30. Handbook of Infrared Optical Materials, *edited by Paul Klocek*
31. Optical Scanning, *edited by Gerald F. Marshall*
32. Polymers for Lightwave and Integrated Optics: Technology and Applications, *edited by Lawrence A. Hornak*
33. Electro-Optical Displays, *edited by Mohammad A. Karim*
34. Mathematical Morphology in Image Processing, *edited by Edward R. Dougherty*
35. Opto-Mechanical Systems Design: Second Edition, Revised and Expanded, *Paul R. Yoder, Jr.*
36. Polarized Light: Fundamentals and Applications, *Edward Collett*
37. Rare Earth Doped Fiber Lasers and Amplifiers, *edited by Michel J. F. Digonnet*
38. Speckle Metrology, *edited by Rajpal S. Sirohi*
39. Organic Photoreceptors for Imaging Systems, *Paul M. Borsenberger and David S. Weiss*
40. Photonic Switching and Interconnects, *edited by Abdellatif Marrakchi*
41. Design and Fabrication of Acousto-Optic Devices, *edited by Akis P. Goutzoulis and Dennis R. Pape*
42. Digital Image Processing Methods, *edited by Edward R. Dougherty*
43. Visual Science and Engineering: Models and Applications, *edited by D. H. Kelly*
44. Handbook of Lens Design, *Daniel Malacara and Zacarias Malacara*
45. Photonic Devices and Systems, *edited by Robert G. Hunsberger*
46. Infrared Technology Fundamentals: Second Edition, Revised and Expanded, *edited by Monroe Schlessinger*
47. Spatial Light Modulator Technology: Materials, Devices, and Applications, *edited by Uzi Efron*
48. Lens Design: Second Edition, Revised and Expanded, *Milton Laikin*
49. Thin Films for Optical Systems, *edited by Francoise R. Flory*
50. Tunable Laser Applications, *edited by F. J. Duarte*
51. Acousto-Optic Signal Processing: Theory and Implementation, Second Edition, *edited by Norman J. Berg and John M. Pellegrino*
52. Handbook of Nonlinear Optics, *Richard L. Sutherland*



53. Handbook of Optical Fibers and Cables: Second Edition, *Hiroshi Murata*
54. Optical Storage and Retrieval: Memory, Neural Networks, and Fractals, *edited by Francis T. S. Yu and Suganda Jutamulia*
55. Devices for Optoelectronics, *Wallace B. Leigh*
56. Practical Design and Production of Optical Thin Films, *Ronald R. Willey*
57. Acousto-Optics: Second Edition, *Adrian Korpel*
58. Diffraction Gratings and Applications, *Erwin G. Loewen and Evgeny Popov*
59. Organic Photoreceptors for Xerography, *Paul M. Borsenberger and David S. Weiss*
60. Characterization Techniques and Tabulations for Organic Nonlinear Optical Materials, *edited by Mark G. Kuzyk and Carl W. Dirk*
61. Interferogram Analysis for Optical Testing, *Daniel Malacara, Manuel Servin, and Zacarias Malacara*
62. Computational Modeling of Vision: The Role of Combination, *William R. Uttal, Ramakrishna Kakarala, Spiram Dayanand, Thomas Shepherd, Jagadeesh Kalki, Charles F. Lunskis, Jr., and Ning Liu*
63. Microoptics Technology: Fabrication and Applications of Lens Arrays and Devices, *Nicholas Borrelli*
64. Visual Information Representation, Communication, and Image Processing, *edited by Chang Wen Chen and Ya-Qin Zhang*
65. Optical Methods of Measurement, *Rajpal S. Sirohi and F. S. Chau*
66. Integrated Optical Circuits and Components: Design and Applications, *edited by Edmond J. Murphy*
67. Adaptive Optics Engineering Handbook, *edited by Robert K. Tyson*
68. Entropy and Information Optics, *Francis T. S. Yu*
69. Computational Methods for Electromagnetic and Optical Systems, *John M. Jarem and Partha P. Banerjee*
70. Laser Beam Shaping, *Fred M. Dickey and Scott C. Holswade*
71. Rare-Earth-Doped Fiber Lasers and Amplifiers: Second Edition, Revised and Expanded, *edited by Michel J. F. Digonnet*
72. Lens Design: Third Edition, Revised and Expanded, *Milton Laikin*
73. Handbook of Optical Engineering, *edited by Daniel Malacara and Brian J. Thompson*
74. Handbook of Imaging Materials: Second Edition, Revised and Expanded, *edited by Arthur S. Diamond and David S. Weiss*
75. Handbook of Image Quality: Characterization and Prediction, *Brian W. Keelan*
76. Fiber Optic Sensors, *edited by Francis T. S. Yu and Shizhuo Yin*
77. Optical Switching/Networking and Computing for Multimedia Systems, *edited by Mohsen Guizani and Abdella Battou*
78. Image Recognition and Classification: Algorithms, Systems, and Applications, *edited by Bahram Javidi*
79. Practical Design and Production of Optical Thin Films: Second Edition, Revised and Expanded, *Ronald R. Willey*

80. Ultrafast Lasers: Technology and Applications, *edited by Martin E. Fermann, Almantas Galvanauskas, and Gregg Sucha*
81. Light Propagation in Periodic Media: Differential Theory and Design, *Michel Nevière and Evgeny Popov*
82. Handbook of Nonlinear Optics, Second Edition, Revised and Expanded, *Richard L. Sutherland*
83. Polarized Light: Second Edition, Revised and Expanded, *Dennis Goldstein*
84. Optical Remote Sensing: Science and Technology, *Walter Egan*
85. Handbook of Optical Design: Second Edition, *Daniel Malacara and Zacarias Malacara*
86. Nonlinear Optics: Theory, Numerical Modeling, and Applications, *Partha P. Banerjee*
87. Semiconductor and Metal Nanocrystals: Synthesis and Electronic and Optical Properties, *edited by Victor I. Klimov*
88. High-Performance Backbone Network Technology, *edited by Naoaki Yamanaka*
89. Semiconductor Laser Fundamentals, *Toshiaki Suhara*
90. Handbook of Optical and Laser Scanning, *edited by Gerald F. Marshall*
91. Organic Light-Emitting Diodes: Principles, Characteristics, and Processes, *Jan Kalinowski*
92. Micro-Optomechanics, *Hiroshi Hosaka, Yoshitada Katagiri, Terunao Hirota, and Kiyoshi Ito*
93. Microoptics Technology: Second Edition, *Nicholas F. Borrelli*
94. Organic Electroluminescence, *edited by Zakya Kafafi*
95. Engineering Thin Films and Nanostructures with Ion Beams, *Emile Knystautas*
96. Interferogram Analysis for Optical Testing, Second Edition, *Daniel Malacara, Manuel Sercin, and Zacarias Malacara*
97. Laser Remote Sensing, *edited by Takashi Fujii and Tetsuo Fukuchi*
98. Passive Micro-Optical Alignment Methods, *edited by Robert A. Boudreau and Sharon M. Boudreau*
99. Organic Photovoltaics: Mechanism, Materials, and Devices, *edited by Sam-Shajing Sun and Niyazi Serdar Sarafci*
100. Handbook of Optical Interconnects, *edited by Shigeru Kawai*
101. GMPLS Technologies: Broadband Backbone Networks and Systems, *Naoaki Yamanaka, Kohei Shiimoto, and Eiji Oki*
102. Laser Beam Shaping Applications, *edited by Fred M. Dickey, Scott C. Holswade and David L. Shealy*
103. Electromagnetic Theory and Applications for Photonic Crystals, *Kiyotoshi Yasumoto*
104. Physics of Optoelectronics, *Michael A. Parker*
105. Opto-Mechanical Systems Design: Third Edition, *Paul R. Yoder, Jr.*
106. Color Desktop Printer Technology, *edited by Mitchell Rosen and Noboru Ohta*
107. Laser Safety Management, *Ken Barat*
108. Optics in Magnetic Multilayers and Nanostructures, *Štefan Višňovský*
109. Optical Inspection of Microsystems, *edited by Wolfgang Osten*



110. Applied Microphotonics, *edited by Wes R. Jamroz, Roman Kruzelecky, and Emile I. Haddad*
111. Organic Light-Emitting Materials and Devices, *edited by Zhigang Li and Hong Meng*
112. Silicon Nanoelectronics, *edited by Shunri Oda and David Ferry*
113. Image Sensors and Signal Processor for Digital Still Cameras, *Junichi Nakamura*
114. Encyclopedic Handbook of Integrated Circuits, *edited by Kenichi Iga and Yasuo Kokubun*
115. Quantum Communications and Cryptography, *edited by Alexander V. Sergienko*
116. Optical Code Division Multiple Access: Fundamentals and Applications, *edited by Paul R. Prucnal*
117. Polymer Fiber Optics: Materials, Physics, and Applications, *Mark G. Kuzyk*
118. Smart Biosensor Technology, *edited by George K. Knopf and Amarjeet S. Bassi*
119. Solid-State Lasers and Applications, *edited by Alphan Sennaroglu*
120. Optical Waveguides: From Theory to Applied Technologies, *edited by Maria L. Calvo and Vasudevan Lakshminarayanan*
121. Gas Lasers, *edited by Masamori Endo and Robert F. Walker*
122. Lens Design, Fourth Edition, *Milton Laikin*
123. Photonics: Principles and Practices, *Abdul Al-Azzawi*
124. Microwave Photonics, *edited by Chi H. Lee*
125. Physical Properties and Data of Optical Materials, *Moriaki Wakaki, Keiei Kudo, and Takehisa Shibuya*
126. Microlithography: Science and Technology, Second Edition, *edited by Kazuaki Suzuki and Bruce W. Smith*
127. Coarse Wavelength Division Multiplexing: Technologies and Applications, *edited by Hans Joerg Thiele and Marcus Nebeling*
128. Organic Field-Effect Transistors, *Zhenan Bao and Jason Locklin*
129. Smart CMOS Image Sensors and Applications, *Jun Ohta*
130. Photonic Signal Processing: Techniques and Applications, *Le Nguyen Binh*
131. Terahertz Spectroscopy: Principles and Applications, *edited by Susan L. Dexheimer*
132. Fiber Optic Sensors, Second Edition, *edited by Shizhuo Yin, Paul B. Ruffin, and Francis T. S. Yu*
133. Introduction to Organic Electronic and Optoelectronic Materials and Devices, *edited by Sam-Shajing Sun and Larry R. Dalton*
134. Introduction to Nonimaging Optics, *Julio Chaves*
135. The Nature of Light: What Is a Photon?, *edited by Chandrasekhar Roychoudhuri, A. F. Kracklauer, and Katherine Creath*
136. Optical and Photonic MEMS Devices: Design, Fabrication and Control, *edited by Ai-Qun Liu*
137. Tunable Laser Applications, Second Edition, *edited by F. J. Duarte*
138. Biochemical Applications of Nonlinear Optical Spectroscopy, *edited by Vladislav Yakovlev*

139. Dynamic Laser Speckle and Applications, *edited by Hector J. Rabal and Roberto A. Braga Jr.*
140. Slow Light: Science and Applications, *edited by Jacob B. Khurgin and Rodney S. Tucker*
141. Laser Safety: Tools and Training, *edited by Ken Barat*
142. Polarimetric Radar Imaging: From Basics to Applications, *Jong-Sen Lee and Eric Pottier*

---

# Foreword

Remote sensing with polarimetric radar evolved from radar target detection along a thorny historical path over the past sixty years as was assessed in greatest detail during the two pioneering NATO ARWs<sup>\*†</sup> held in 1983 and 1988 during which more than 120 leading experts from Western Europe, North America, Japan and Northeast Asia were assembled to assess mathematical and physical methods of vector electromagnetic scattering and imaging, dealing with purely mathematical modeling; and where applied principles were tested against the first results on digital SAR imagery by employing the NASA-JPL AIRSAR polarimetric images.

Since then, pertinent mission-oriented textbooks have been scarce and the quest for developing a set of pertinent new research textbooks evolved. Instead, since about 1992 an ever increasing number of radar and SAR polarimetricists gathered at the annual IEEE-GRSS IGARSS symposia during which the Polarimetry Sessions were arranged as strings of consequential events creating quasi Mini-Polarimetry Workshops. We were all very involved in developing algorithms and tools for advancing polarimetric SAR imaging, polarimetric-interferometric imaging and polarimetric multimodal SAR tomography and holography utilizing the superb polarimetric imagery collected with the SIS-C/X-SAR shuttle missions of 1994, and from the increasing number of airborne fully polarimetric SAR sensors (AIRSAR of NASA-JPL, Convair C-580 of CCRS, E-SAR of DLR, RAMSES of ONERA, PiSAR of CRL (NICT)/NASDA (JAXA)).

No new textbooks were forthcoming because the focus was directed toward proofing the unforeseen capabilities of remote sensing applications using polarimetric imaging radar modalities first, and instead several mission-oriented programs such as the EU-TMR and EU-RTN collaboration on Radar Polarimetry, ONR-NICOP workshops on wideband interferometric sensing & surveillance sprung up, being more recently strengthened by the bi-annual EUSAR and the ESA-POLINSAR conferences, all of which the two authors of this valuable book polarimetric radar imaging contributed profoundly to advancing fundamental algorithm development as well as its diverse applications.

The urgent need for editing and publishing concise comprehensive textbooks on various specific topics of radar and SAR polarimetry and interferometry could no longer be delayed. It then became of top priority with the international group effort of advancing space-borne polarimetric SAR sensing, imaging and stress-change

---

<sup>\*</sup> Boerner, W-M. et al. (eds.), 1985, *Inverse Methods in Electromagnetic Imaging*, Proceedings of the NATO-Advanced Research Workshop (18–24 Sept. 1983, Bad Windsheim, FR Germany), Parts 1&2, NATO-ASI C-143, (1,500 pages), D. Reidel Publ. Co., Jan. 1985.

<sup>†</sup> Boerner, W-M. et al. (eds.), 1992, *Direct and Inverse Methods in Radar Polarimetry*, NATO-ARW, Sept. 18-24, 1988, Proc., Chief Editor, 1987-1991, (1,938 pages), NATO-ASI Series C: Math & Phys. Sciences, vol. C-350, Parts 1&2, D. Reidel Publ. Co., Kluwer Academic Publ., Dordrecht, NL, 1992 Feb. 15.

monitoring with the successful launching of the three national fully polarimetric SAR sensors: ALOS-PALSAR (L-Band) of JAXA/Japan, January 2006; RADARSAT-2 (C-Band) of CSA/MDA, Canada, December 2007; and TerraSAR-X (X-Band) of DLR/Astrium in Germany, June 2007. Whereas the currently available satellite fully polarimetric SAR sensors will be able to contribute toward highly improved global imaging and mapping of the terrestrial covers and become invaluable tools for global change detection, we now need to address the next more complex issue of quasi real-time monitoring of natural hazard regions for improving disaster reduction measures, which cannot be accomplished with the deployment of either airborne or satellite sensor platforms. This in turn requires the rapid development of differential repeat-pass Pol-In-SAR tomography for which airborne or satellite multimodal SAR imaging systems are not sufficient, and every effort must be made to developing fleets of high-altitude drone platforms equipped with multiband, multimodal fully polarimetric SAR sensors not only for defense missions but more so for regional environmental hazard monitoring and disaster control and also for detecting the onslaught of global change mechanisms.

These phenomenal events made us arrive at the door-step of realizing polarimetric radar imaging, and an urgent specific textbook became in desperate need on assembling all of the succinct comprehensive basic theory, processing algorithms supplemented by hands-on digital processing tools, which is precisely and excellently treated in *Polarimetric Radar Imaging: From Basics to Applications* by the pioneering authors Jong-Sen Lee and Eric Pottier, supplemented by the PolSARpro tool box for verifying its numerous applications. This very concise book of some 400 pages covering basics to applications will serve as a fundamental hands-on textbook for years to come. This excellent book of 10 carefully selected chapters, so perfectly summarized in the introductory Chapter 1, will provide the basis for addressing those acute tasks confronting us with the expected increase in large-scale re-occurring floods or droughts with the associated crop failures, volcano eruptions and its impact on global changes, earthquakes and seaquakes with subsequent tsunami, and so on. This is a formidable task we can now start to address, and the basic methods of approach have herewith been established.

Therefore, we congratulate the authors for their diligence, oversight and sincere dedication for assembling such a well done and long overdue textbook on the basics and applications of polarimetric radar imaging. No one else could have performed a better job leading us closer to addressing the severe environmental stress changes our terrestrial planet is going to be submitted to from now into the future.

**Dr. Wolfgang-Martin Boerner**  
Professor Emeritus  
*The University of Illinois at Chicago*

---

# Acknowledgments

We would like to thank Professor Emeritus Wolfgang-Martin Boerner for writing the foreword of this book. His devoted involvement in polarimetric radar development, and his encouragement to fellow researchers, “polarimetry co-strugglers,” led to many advancements over the last 20 years and ultimately made this book a reality. We also would like to acknowledge Dr. Thomas Ainsworth, Naval Research Laboratory, and Professor Boerner for reading the chapters and providing valuable suggestions and Dr. Hab Laurent Ferro-Famil, University of Rennes-1, for his contribution to Chapter 9. We are most grateful for their help.

Many colleagues have contributed to the materials included in this book: Dr. Thomas Ainsworth, Dr. Dale Schuler, and Mitchell Grune, Naval Research Laboratory, United States; Dr. Laurent Ferro-Famil and Dr. Sophie Allain-Bailhache, University of Rennes-1, France; Professor Kun-Shan Chen and Professor Abel J. Chen, National Central University, Taiwan; Professor Wolfgang-Martin Boerner, University of Illinois at Chicago, United States; Dr. Gianfranco de Grandi, Joint Research Center, Italy; Dr. Konstantinos Papathanassiou and Dr. Irena Hajnsek, DLR, Germany; Dr. Ernst Krogager, DDRE, Denmark; Dr. Shane Cloude, AELc, Scotland; Dr. Yves-Louis Desnos, ESA—ESRIN, Italy; Dr. Carlos Lopez Martinez, UPC, Spain. We appreciate their collaborative efforts in many research projects, and we treasure their friendship. This book could not have been completed without their significant contributions.

Throughout this book, several polarimetric SAR imageries were used for illustration. In particular, the San Francisco data and several other datasets from JPL AIRSAR have been employed. DLR E-SAR imagery was used for forest and terrain classification and Danish EMISAR data were applied to polarimetric signature analysis of man-made structures. We appreciate receiving these valuable datasets and would like to thank the then team leaders: Dr. Jakob van Zyl, Dr. Yunjin Kim, Professor Alberto Moreira, and Dr. Soren Madsen.

This book was planned at the 2003 Pol-InSAR Workshop at ESA in Frascati, Italy, where we agreed to jointly write a polarimetric SAR book. Realizing the daunting task ahead, the writing stalled until the publisher encouraged us to meet the deadline. We appreciate Taylor & Francis, CRC Press, for their willingness to print so many color figures, and to save all color figures available for downloading at [http://www.crcpress.com/e\\_products/downloads/default.asp](http://www.crcpress.com/e_products/downloads/default.asp). The authors are also indebted to the Institute of Electrical and Electronics Engineers for permission to use material that has appeared in IEEE publications.

The first author, Jong-Sen Lee, would like to thank Professor Eric Pottier for his devoted effort and pleasant manner in making this book a concise and complete presentation. Eric is the recipient of the 2007 IEEE Education Award for his achievement in education and promotion of radar polarimetry and its applications. He is the best person to consult when one encounters a problem in radar polarimetry. His vast wisdom and high energy levels continue to inspire me and my colleagues.

It is my greatest pleasure and honor to work with my best French friend on this joint adventure. I would also like to thank NRL management, especially Dr. Ralph Fiedler, for the unwavering support in my radar polarimetry research during the years before my retirement in 2006. I am indebted to Professor Larry Y.C. Ho, Harvard University, for guidance and help during the years of my graduate study. Finally, I would like to thank my beloved wife, Shu-Rong, for her love and company, and to remember my mother Yu-Yin Hu for raising me the best she could during the difficult years.

The second author, Eric Pottier, first met Dr. Jong-Sen Lee in 1995 during IGARSS'95 and he could never have imagined that someday he would have the great privilege and honor of writing this book with Dr. Jong-Sen Lee, who is recognized worldwide for his Lee filter that is today internationally used and applied as the standard reference for speckle filtering. Since 1995, Jong-Sen and I have worked closely together and have become friends. We have interacted on a regular basis on research matters dealing with polarimetric radar, and our greatest achievement was "Wishart— $H/A/\alpha$  Unsupervised Segmentation of PolSAR Data" that was awarded the best paper for "a very significant contribution in the field of synthetic aperture radar" during EUSAR2000. Because of his very pleasant manner of interaction, it has always been, it always is, and it will always truly be a pleasure and delight for me to interact with Jong-Sen, who is undoubtedly one of the truly outstanding international experts in the field of Pol-SAR and Pol-InSAR information processing today. It was a great honor for me to live and share the adventure of writing this book with Jong-Sen. Thank you *Shihan Söke Sensei* Jong-Sen.

I would also like to take this opportunity to dedicate this book to my three main polarimetric mentors. The first is Dr. J. Richard Huynen who helped me and explained to me the polarimetry philosophy. His personal support from the beginning, in my early PhD years, was a rare privilege. The second, where a special mention has to be made, is my great friend Dr. Shane R. Cloude with whom I have spent and lived my best polarimetric years from September 1993 to January 1996 when he joined me in Nantes. Supporting the local football team and creating the  $H/A/\alpha$  polarimetric target decomposition theorem were our two greatest achievements during this wonderful period. Lastly, my deepest gratitude and thanks go to Professor Wolfgang-Martin Boerner, *le grand migrateur*, for being the closest, the most critical, and the strongest supporter for 20 years. I am thankful for his continued friendship, assistance, permanent enthusiasm, and tireless encouragements. Finally, I would like to thank my beloved parents, Jacques and Bernadette, for their persistent support of my personal goals and permanent encouragement throughout my lifetime.

**Jong-Sen Lee**  
**Eric Pottier**



---

# Authors

**Jong-Sen Lee** received his BS from National Cheng-Kung University, Tainan, Taiwan in 1963, and his AM and PhD from Harvard University, Cambridge, Massachusetts, in 1965 and 1969, respectively. He is a consultant at the Naval Research Laboratory (NRL), Washington, DC after retiring from NRL in 2006. Currently, he is also a visiting chair professor at the Center for Space and Remote Sensing Research, National Central University, Taiwan. For more than 25 years, Dr. Lee has been working on synthetic aperture radar (SAR) and polarimetric SAR-related research. He has developed several speckle filtering algorithms that have been implemented in many GIS, such as ERDAS, PCI, and ENVI. Dr. Lee's professional expertise encompasses control theory, digital image processing, radiative transfer, SAR and polarimetric SAR information processing including radar polarimetry, polarimetric SAR speckle statistics, speckle filtering, ocean remote sensing using polarimetric SAR, supervised and unsupervised polarimetric SAR terrain, and land-use classification. He has published more than 70 journal papers, 6 book chapters, and more than 160 conference proceedings.

Dr. Lee is a life fellow of IEEE for his contribution toward information processing of SAR and polarimetric SAR imagery. He received the Best Paper Award (jointly with E. Pottier) and the Best Poster Award (jointly with D. Schuler) at the third and fourth European Conference on Synthetic Aperture Radar (EUSAR2000 and EUSAR2002), respectively. Upon his retirement, he was awarded the Navy Meritorious Civilian Service Award for his achievement in SAR polarimetry and interferometry research. He is an associate editor of *IEEE Transactions on Geoscience and Remote Sensing*.

**Eric Pottier** received his MSc and PhD in signal processing and telecommunication from the University of Rennes 1, in 1987 and 1990, respectively, and the habilitation from the University of Nantes in 1998. From 1988 to 1999 he was an associate professor at IRESTE, University of Nantes, Nantes, France, where he was the head of the polarimetry group of the electronic and informatic systems laboratory. Since 1999, he has been a full professor at the University of Rennes 1, France, where he is currently the deputy director of the Institute of Electronics and Telecommunications of Rennes (IETR—CNRS UMR 6164) and also head of the image and remote sensing group—SAPHIR team. His current research and education activities are centered on the topics of analog electronics, microwave theory, and radar imaging with an emphasis on radar polarimetry. His research covers a wide spectrum from radar image processing (SAR, ISAR), polarimetric scattering modeling, supervised/unsupervised polarimetric segmentation and classification to fundamentals and basic theory of polarimetry.

Since 1989, Dr. Pottier has helped more than 60 research students to graduation (MSc and PhD) in radar polarimetry covering areas from theory to remote sensing applications. He has chaired and organized 31 sessions in international

conferences and was a member of the technical and scientific committees of 21 international symposia or conferences. He has been invited to give 36 presentations at international conferences and 16 at national conferences. He has 7 publications in books, 38 papers in refereed journals, and more than 250 papers in conference and symposium proceedings. He has presented advanced courses and seminars on radar polarimetry to a wide range of organizations (DLR, NASDA, JRC, RESTEC, ISAP2000, IGARSS03, EUSAR04, NATO-04, PolInSAR05, IGARSS05, JAXA06, EUSAR06, NATO-06, IGARSS07, and IGARSS08).

He received the Best Paper Award (jointly with J.S. Lee) at the third European Conference on Synthetic Aperture Radar (EUSAR2000) and the 2007 IEEE GRS-S Letters Prize Paper Award. He is also the recipient of the 2007 IEEE GRS-S Education Award “in recognition of his significant educational contributions to geoscience and remote sensing.”

# Contents

Foreword ..... xix  
Acknowledgments..... xxi  
Authors..... xxiii

**Chapter 1 Overview of Polarimetric Radar Imaging ..... 1**

1.1 Brief History of Polarimetric Radar Imaging ..... 1  
    1.1.1 Introduction..... 1  
    1.1.2 Development of Imaging Radar..... 2  
    1.1.3 Development of Polarimetric Radar Imaging ..... 2  
    1.1.4 Education of Polarimetric Radar Imaging ..... 4  
1.2 SAR Image Formation: Summary ..... 5  
    1.2.1 Introduction..... 5  
    1.2.2 SAR Geometric Configuration..... 6  
    1.2.3 SAR Spatial Resolution ..... 8  
    1.2.4 SAR Image Processing ..... 9  
    1.2.5 SAR Complex Image..... 10  
1.3 Airborne and Space-Borne Polarimetric SAR Systems..... 13  
    1.3.1 Introduction..... 13  
    1.3.2 Airborne Polarimetric SAR Systems ..... 14  
        1.3.2.1 AIRSAR (NASA/JPL)..... 14  
        1.3.2.2 CONVAIR-580 C/X-SAR (CCRS/EC) ..... 16  
        1.3.2.3 EMISAR (DCRS)..... 16  
        1.3.2.4 E-SAR (DLR)..... 16  
        1.3.2.5 PI-SAR (JAXA-NICT)..... 17  
        1.3.2.6 RAMSES (ONERA-DEMR)..... 17  
        1.3.2.7 SETHI (ONERA-DEMR) ..... 18  
    1.3.3 Space-Borne Polarimetric SAR Systems ..... 19  
        1.3.3.1 SIR-C/X SAR (NASA/DARA/ASI)..... 19  
        1.3.3.2 ENVISAT-ASAR (ESA)..... 19  
        1.3.3.3 ALOS-PALSAR (JAXA/JAROS) ..... 20  
        1.3.3.4 TerraSAR-X (BMBF/DLR/Astrium GmbH) ..... 21  
        1.3.3.5 RADARSAT-2 (CSA/MDA)..... 22  
1.4 Description of the Chapters ..... 22  
References ..... 28

**Chapter 2 Electromagnetic Vector Wave and Polarization Descriptors ..... 31**

2.1 Monochromatic Electromagnetic Plane Wave..... 31  
    2.1.1 Equation of Propagation ..... 31  
    2.1.2 Monochromatic Plane Wave Solution ..... 32