

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

2.2	Polarization Ellipse	34
2.3	Jones Vector.....	37
2.3.1	Definition	37
2.3.2	Special Unitary Group $SU(2)$	38
2.3.3	Orthogonal Polarization States and Polarization Basis	40
2.3.4	Change of Polarimetric Basis	41
2.4	Stokes Vector.....	43
2.4.1	Real Representation of a Plane Wave Vector	43
2.4.2	Special Unitary Group $O(3)$	46
2.5	Wave Covariance Matrix	47
2.5.1	Wave Degree of Polarization	47
2.5.2	Wave Anisotropy and Wave Entropy	48
2.5.3	Partially Polarized Wave Dichotomy Theorem	49
	References	51

Chapter 3	Electromagnetic Vector Scattering Operators	53
3.1	Polarimetric Backscattering Sinclair S Matrix	53
3.1.1	Radar Equation	53
3.1.2	Scattering Matrix.....	55
3.1.3	Scattering Coordinate Frameworks.....	61
3.2	Scattering Target Vectors \underline{k} and $\underline{\Omega}$	63
3.2.1	Introduction.....	63
3.2.2	Bistatic Scattering Case	63
3.2.3	Monostatic Backscattering Case	65
3.3	Polarimetric Coherency T and Covariance C Matrices	66
3.3.1	Introduction.....	66
3.3.2	Bistatic Scattering Case	66
3.3.3	Monostatic Backscattering Case	67
3.3.4	Scattering Symmetry Properties.....	69
3.3.5	Eigenvector/Eigenvalues Decomposition.....	72
3.4	Polarimetric Mueller M and Kennaugh K Matrices	73
3.4.1	Introduction.....	73
3.4.2	Monostatic Backscattering Case	74
3.4.3	Bistatic Scattering Case	77
3.5	Change of Polarimetric Basis	80
3.5.1	Monostatic Backscattering Matrix S	80
3.5.2	Polarimetric Coherency T Matrix	83
3.5.3	Polarimetric Covariance C Matrix	84
3.5.4	Polarimetric Kennaugh K Matrix.....	84
3.6	Target Polarimetric Characterization	85
3.6.1	Introduction.....	85
3.6.2	Target Characteristic Polarization States	87
3.6.2.1	Characteristic Target Polarization States in the Copolar Configuration	88
3.6.2.2	Characteristic Polarization States in the Cross-Polar Configuration	88

3.6.3	Diagonalization of the Sinclair S Matrix	89
3.6.4	Canonical Scattering Mechanism	92
3.6.4.1	Sphere, Flat Plate, Trihedral	92
3.6.4.2	Horizontal Dipole.....	93
3.6.4.3	Oriented Dipole.....	94
3.6.4.4	Dihedral	95
3.6.4.5	Right Helix	96
3.6.4.6	Left Helix	97
	References	98
	Chapter 4 Polarimetric SAR Speckle Statistics.....	101
4.1	Fundamental Property of Speckle in SAR Images	101
4.1.1	Speckle Formation	101
4.1.2	Rayleigh Speckle Model.....	102
4.2	Speckle Statistics for Multilook-Processed SAR Images	105
4.3	Texture Model and K -Distribution	108
4.3.1	Normalized N -Look Intensity K -Distribution	108
4.3.2	Normalized N -Look Amplitude K -Distribution.....	109
4.4	Effect of Speckle Spatial Correlation	110
4.4.1	Equivalent Number of Looks	111
4.5	Polarimetric and Interferometric SAR Speckle Statistics	112
4.5.1	Complex Gaussian and Complex Wishart Distribution	112
4.5.2	Monte Carlo Simulation of Polarimetric SAR Data.....	114
4.5.3	Verification of the Simulation Procedure	115
4.5.4	Complex Correlation Coefficient.....	115
4.6	Phase Difference Distributions of Single- and Multilook Polarimetric SAR Data	116
4.6.1	Alternative Form of Phase Difference Distribution.....	120
4.7	Multilook Product Distribution.....	120
4.8	Joint Distribution of Multilook $ S_i ^2$ and $ S_j ^2$	121
4.9	Multilook Intensity and Amplitude Ratio Distributions.....	122
4.10	Verification of Multilook PDFs	125
4.11	K -Distribution for Multilook Polarimetric Data	130
4.12	Summary	135
	Appendix 4.A.....	136
	Appendix 4.B	138
	Appendix 4.C	140
	Appendix 4.D.....	140
	References	141
	Chapter 5 Polarimetric SAR Speckle Filtering	143
5.1	Introduction to Speckle Filtering of SAR Imagery	143
5.1.1	Speckle Noise Model.....	144
5.1.1.1	Speckle Noise Model for Polarimetric SAR Data.....	146

5.2	Filtering of Single Polarization SAR Data	147
5.2.1	Minimum Mean Square Filter	149
5.2.1.1	Deficiencies of the Minimum Mean Square Error (MMSE) Filter.....	150
5.2.2	Speckle Filtering with Edge-Aligned Window: Refined Lee Filter	150
5.3	Review of Multipolarization Speckle Filtering Algorithms	152
5.3.1	Polarimetric Whitening Filter	153
5.3.2	Extension of PWF to Multilook Polarimetric Data	156
5.3.3	Optimal Weighting Filter.....	157
5.3.4	Vector Speckle Filtering	158
5.4	Polarimetric SAR Speckle Filtering.....	160
5.4.1	Principle of PolSAR Speckle Filtering	160
5.4.2	Refined Lee PolSAR Speckle Filter	161
5.4.3	Apply Region Growing Technique to PolSAR Speckle Filtering ...	165
5.5	Scattering Model-Based PolSAR Speckle Filter	166
5.5.1	Demonstration and Evaluation.....	169
5.5.2	Speckle Reduction	170
5.5.3	Preservation of Dominant Scattering Mechanism	172
5.5.4	Preservation of Point Target Signatures	174
	References	175

Chapter 6 Introduction to the Polarimetric Target Decomposition Concept 179

6.1	Introduction	179
6.2	Dichotomy of the Kennaugh Matrix K	181
6.2.1	Phenomenological Huynen Decomposition.....	181
6.2.2	Barnes–Holm Decomposition	185
6.2.3	Yang Decomposition	188
6.2.4	Interpretation of the Target Dichotomy Decomposition	191
6.3	Eigenvector-Based Decompositions	193
6.3.1	Cloude Decomposition.....	195
6.3.2	Holm Decompositions	195
6.3.3	van Zyl Decomposition.....	198
6.4	Model-Based Decompositions	200
6.4.1	Freeman–Durden Three-Component Decomposition	200
6.4.2	Yamaguchi Four-Component Decomposition	206
6.4.3	Freeman Two-Component Decomposition	208
6.5	Coherent Decompositions	213
6.5.1	Introduction	213
6.5.2	Pauli Decomposition.....	214
6.5.3	Krogager Decomposition	215
6.5.4	Cameron Decomposition	219
6.5.4.1	Scattering Matrix Coherent Decomposition.....	219
6.5.4.2	Scattering Matrix Classification	221
6.5.5	Polar Decomposition.....	224
	References	225

Chapter 7	<i>H/A/$\bar{\alpha}$</i> Polarimetric Decomposition Theorem.....	229
7.1	Introduction	229
7.2	Pure Target Case	229
7.3	Probabilistic Model for Random Media Scattering	230
7.4	Roll Invariance Property	232
7.5	Polarimetric Scattering $\bar{\alpha}$ Parameter	234
7.6	Polarimetric Scattering Entropy (H)	237
7.7	Polarimetric Scattering Anisotropy (A).....	237
7.8	Three-Dimensional $H/A/\bar{\alpha}$ Classification Space	239
7.9	New Eigenvalue-Based Parameters	247
7.9.1	SERD and DERD Parameters.....	247
7.9.2	Shannon Entropy.....	249
7.9.3	Other Eigenvalue-Based Parameters.....	251
7.9.3.1	Target Randomness Parameter.....	251
7.9.3.2	Polarization Asymmetry and the Polarization Fraction Parameters.....	252
7.9.3.3	Radar Vegetation Index and the Pedestal Height Parameters	254
7.9.3.4	Alternative Entropy and Alpha Parameters Derivation.....	255
7.10	Speckle Filtering Effects on $H/A/\bar{\alpha}$	257
7.10.1	Entropy (H) Parameter.....	257
7.10.2	Anisotropy (A) Parameter	259
7.10.3	Averaged Alpha Angle ($\bar{\alpha}$) Parameter	259
7.10.4	Estimation Bias on $H/A/\bar{\alpha}$	259
References	262	
Chapter 8	PolSAR Terrain and Land-Use Classification	265
8.1	Introduction	265
8.2	Maximum Likelihood Classifier Based on Complex Gaussian Distribution.....	266
8.3	Complex Wishart Classifier for Multilook PolSAR Data	267
8.4	Characteristics of Wishart Distance Measure	268
8.5	Supervised Classification Using Wishart Distance Measure	271
8.6	Unsupervised Classification Based on Scattering Mechanisms and Wishart Classifier	274
8.6.1	Experiment Results	276
8.6.2	Extension to $H/\bar{\alpha}/A$ and Wishart Classifier	279
8.7	Scattering Model-Based Unsupervised Classification	281
8.7.1	Experiment Results	284
8.7.1.1	NASA/JPL AIRSAR San Francisco Image.....	284
8.7.1.2	DLR E-SAR L-Band Oberpfaffenhofen Image	286
8.7.2	Discussion	288

8.8	Quantitative Comparison of Classification Capability: Fully Polarimetric SAR vs. Dual- and Single-Polarization SAR.....	291
8.8.1	Supervised Classification Evaluation Based on Maximum Likelihood Classifier.....	292
8.8.1.1	Classification Procedure	292
8.8.1.2	Comparison of Crop Classification	293
	References	299

Chapter 9 Pol-InSAR Forest Mapping and Classification 301

9.1	Introduction	301
9.2	Pol-InSAR Scattering Descriptors	303
9.2.1	Polarimetric Interferometric Coherency T_6 Matrix.....	303
9.2.2	Complex Polarimetric Interferometric Coherence	307
9.2.3	Polarimetric Interferometric Coherence Optimization.....	308
9.2.4	Polarimetric Interferometric SAR Data Statistics	313
9.3	Forest Mapping and Forest Classification	314
9.3.1	Forested Area Segmentation	314
9.3.2	Unsupervised Pol-InSAR Classification of the Volume Class... 314	314
9.3.3	Supervised Pol-InSAR Forest Classification	318
Appendix 9.A.....	Derivation of Optimal Coherence Set Statistics	320
References	321	

Chapter 10 Selected Polarimetric SAR Applications 323

10.1	Polarimetric Signature Analysis of Man-Made Structures	323
10.1.1	Slant Range of Multiple Bounce Scattering	324
10.1.2	Polarimetric Signature of the Bridge during Construction.....	325
10.1.3	Polarimetric Signature of the Bridge after Construction	329
10.1.4	Conclusion	332
10.2	Polarization Orientation Angle Estimation and Applications.....	333
10.2.1	Radar Geometry of Polarization Orientation Angle	333
10.2.2	Circular Polarization Covariance Matrix	334
10.2.3	Circular Polarization Algorithm.....	336
10.2.4	Discussion	339
10.2.5	Orientation Angles Applications.....	342
10.3	Ocean Surface Remote Sensing with Polarimetric SAR	345
10.3.1	Cold Water Filament Detection	345
10.3.2	Ocean Surface Slope Sensing	346
10.3.3	Directional Wave Slope Spectra Measurement	347
10.4	Ionosphere Faraday Rotation Estimation	350
10.4.1	Faraday Rotation Estimation.....	351
10.4.2	Faraday Rotation Angle Estimation from ALOS PALSAR Data.....	353

10.5	Polarimetric SAR Interferometry for Forest Height Estimation.....	354
10.5.1	Problems Associated with Coherence Estimation	357
10.5.2	Adaptive Pol-InSAR Speckle Filtering Algorithm.....	358
10.5.3	Demonstration Using E-SAR Glen Affric Pol-InSAR Data	358
10.6	Nonstationary Natural Media Analysis from PolSAR Data Using a 2-D Time-Frequency Approach	362
10.6.1	Introduction.....	362
10.6.2	Principle of SAR Data Time-Frequency Analysis	362
10.6.2.1	Time-Frequency Decomposition	362
10.6.2.2	SAR Image Decomposition in Range and Azimuth...	363
10.6.2.3	Analysis in the Azimuth Direction	364
10.6.2.4	Analysis in the Range Direction	365
10.6.3	Discrete Time-Frequency Decomposition of Nonstationary Media PolSAR Response.....	365
10.6.3.1	Anisotropic Polarimetric Behavior.....	365
10.6.3.2	Decomposition in the Azimuth Direction	366
10.6.3.3	Decomposition in the Range Direction.....	368
10.6.4	Nonstationary Media Detection and Analysis	369
	References	375
	Appendix A: Eigen Characteristics of Hermitian Matrix	379
	Reference.....	384
	Appendix B: PolSARpro Software: The Polarimetric SAR Data Processing and Educational Toolbox	385
B.1	Introduction	385
B.2	Concepts and Principal Objectives	385
B.3	Software Portability and Development Languages	387
B.4	Outlook	388
	Index.....	391