

Table of Contents

Introduction	xv
Chapter 1. The Physical Basis of Synthetic Aperture Radar Imagery	1
Jean-Marie NICOLAS and Sylvie LE HÉGARAT-MASCLE	
1.1. Electromagnetic propagation	1
1.1.1. The laws of propagation in homogenous media	1
1.1.1.1. Basic equations	1
1.1.1.2. Propagation equation solution	3
1.1.2. Propagation equation in heterogenous media	5
1.1.2.1. The permittivity variation case	6
1.1.2.2. The propagation equation in an absorbing medium	8
1.1.3. Application to satellite radars	8
1.2. Matter-radiation interaction	10
1.2.1. Theoretical backscattering models	10
1.2.1.1. Unbounded flat interface	10
1.2.1.2. Rayleigh scatterer	12
1.2.2. Phenomenological backscattering models	12
1.2.2.1. Rough interface	12
1.2.2.2. Scattering by a generic target	13
1.2.2.3. Scattering by a set of targets	13
1.3. Polarization	14
1.3.1. Definitions	14
1.3.2. Wave polarization	16
1.3.3. The BSA convention	18
1.3.4. Complex backscattering matrix S , Mueller matrix	19
1.3.4.1. Properties of \mathbf{M}	22
1.3.4.2. Other definitions of \mathbf{M}	23

Chapter 2. The Principles of Synthetic Aperture Radar	25
Jean-Marie NICOLAS and Frédéric ADRAGNA	
2.1. The principles of radar	26
2.1.1. Description of surveillance radars	26
2.1.2. Notion of resolution	29
2.1.3. Imaging radars	30
2.1.4. Synthetic Aperture Radar (SAR)	32
2.1.5. The radar equation	33
2.2. The SAR equations	35
2.2.1. The principle of pulse compression	35
2.2.2. Range resolution	38
2.2.3. Azimuth resolution	41
2.2.3.1. Principles	41
2.2.3.2. Application to the ERS-1 satellite	43
2.2.3.3. Taking platform motions into account	44
2.2.4. Transfer function of the SAR antenna	45
2.2.5. Range and azimuth samplings	46
2.2.5.1. Range sampling	46
2.2.5.2. Azimuth sampling	46
2.2.5.3. Choice of a PRF: theoretical constraints	47
2.2.6. Operation of a satellite SAR	47
2.2.6.1. Effects on radial quality	48
2.2.6.2. Effects on azimuth quality	49
2.2.6.3. The squint case	49
2.3. Acquisition geometry of SAR images	50
2.3.1. Sampling and resolution	51
2.3.1.1. Range	51
2.3.1.2. Azimuth	52
2.3.2. Radar geometry and ground geometry	53
2.3.2.1. Radar geometry	53
2.3.2.2. Ground geometry	53
2.3.3. Overlays, foreshortening and shadow	54
Chapter 3. Existing Satellite SAR Systems	57
Jean-Marie NICOLAS and Frédéric ADRAGNA	
3.1. Elements of orbitography	57
3.1.1. Remote sensing satellite orbits	58
3.1.1.1. Inclination	58
3.1.1.2. Period	58
3.1.1.3. Eccentricity	60
3.1.1.4. Sun-synchronism	60
3.1.1.5. Cycle	61
3.1.1.6. Phasing	61
3.1.1.7. Orbital drift and correction	61

3.2. Polar orbiting SAR satellites	62
3.2.1. SEASAT	62
3.2.2. ERS	62
3.2.3. JERS	64
3.2.4. RADARSAT	64
3.3. Satellites in non-polar orbit	65
3.3.1. ALMAZ	65
3.3.2. Space shuttle use	66
3.3.2.1. Columbia: the SIR-A program (1982)	67
3.3.2.2. Challenger: the SIR-B program (1984)	67
3.3.2.3. Endeavour: the SIR-C program (1994)	68
3.3.2.4. Endeavour: the SRTM program (2000)	69
3.4. Other systems	69
3.5. Airborne SARs	70
3.5.1. Sandia	70
3.5.2. CCRS	70
3.5.3. CRL/NASDA	71
3.5.4. JPL's AIRSAR	71
3.5.5. PHARUS	72
3.5.6. DLR's E-SAR	72
3.5.7. Some remarkable military systems	72
Chapter 4. Synthetic Aperture Radar Images	75
FrédéricADRAGNA, Sylvie LE HÉGARAT-MASCLE and Jean-Marie NICOLAS	
4.1. Image data	76
4.1.1. Raw data	76
4.1.2. Complex single-look data	76
4.1.3. Multi-look data	78
4.1.4. Derivative products	79
4.1.5. Polarimetric data	80
4.1.5.1. SIR-C/X-SAR data	80
4.1.5.2. AirSAR data	81
4.1.5.3. Polarimetric synthesis and examples	82
4.2. Radiometric calibration	83
4.2.1. Scalar SAR data calibration	83
4.2.2. Calibration of SAR polarimetric data	84
4.3. Localization precision	85
Chapter 5. Speckle Models	87
Armand LOPÈS, René GARELLO and Sylvie LE HÉGARAT-MASCLE	
5.1. Introduction to speckle	87
5.2. Complex circular Gaussian model of single-look and scalar speckle	89
5.2.1. Random walk and Gaussian speckle conditions	90

5.2.1.1. Random walk in a complex plane	90
5.2.1.2. Fully developed speckle hypotheses	91
5.2.2. First order distributions: R radar reflectivity	92
5.2.2.1. Fully developed complex speckle distribution: radar reflectivity	92
5.2.2.2. Distributions of amplitude A, phase ϕ and intensity I	94
5.2.2.3. Multiplicative and additive speckle models	96
5.3. Complex circular multi-variate Gaussian model of vectorial or multi-look speckle	98
5.3.1. Joint distribution of single-look complex data	98
5.3.2. Spatial correlation and spectral properties of the single-look Gaussian speckle	99
5.3.3. Joint distribution of single-look detected data	104
5.3.4. Distributions of scalar multi-look data	105
5.3.4.1. Gamma and generalized Gamma distributions	107
5.3.4.2. Goodman distribution	110
5.3.4.3. Multi-look logarithmic data	112
5.3.4.4. Spectral and spatial properties of multi-look speckle	115
5.3.5. Multi-look vectorial distributions	115
5.3.5.1. Distribution of the variables derived from Σ_Z and the Wishart distribution	116
5.4. Non-Gaussian speckle models	125
5.4.1. Scalar product model and normalized texture	126
5.4.1.1. Normalized texture variable	126
5.4.1.2. Statistical properties of heterogenous area data	127
5.4.1.3. The Pearson system and K, U, B and W distributions	129
5.4.2. Non-Gaussian clutter	133
5.4.2.1. The lognormal distribution	134
5.4.2.2. Weibull distribution	134
5.4.2.3. Nagakami-Rice distribution	135
5.4.2.4. The partially developed speckle	135
5.5. Polarimetric radar speckle	136
5.5.1. The Gaussian model	136
5.5.2. The product model	137
5.5.3. Distributions of the phase difference and 2-amplitude ratio	138
5.5.4. Correlation of the co- and cross-polar channels	140
Chapter 6. Reflectivity Estimation and SAR Image Filtering	143
Armand LOPÈS, Florence TUPIN and Sylvie LE HÉGARAT-MASCLE	
6.1. Introduction	143
6.2. Estimations of reflectivity R	145
6.2.1. Bayesian estimation recap	145
6.2.1.1. The Kronecker function: $L(x, x') = 1 - \delta_{x, x'}$	146
6.2.1.2. The quadratic cost function: $L(x, x') = (x - x')^2$	146

6.2.1.3. Notes on estimator behavior	147
6.2.2. Estimation of constant reflectivity R	148
6.2.2.1. Multi-look filters	148
6.2.2.2. Spatial filters	150
6.3. Single-channel filters with <i>a priori</i> knowledge of the scene	151
6.3.1. Linear MMSE filters	151
6.3.1.1. Lee and Kuan filters	151
6.3.1.2. Frost filter	152
6.3.2. Non-linear MMSE filters	154
6.3.2.1. T-linear filters	154
6.3.2.2. APE filters	155
6.3.3. Non-linear MAP filters	156
6.4. Multi-channel filters.	157
6.4.1. Intensity data	157
6.4.1.1. Homogenous channels	157
6.4.1.2. Textured channels	158
6.4.2. A general case: the linear vector MMSE	159
6.5. Polarimetric data filtering	161
6.5.1. Speckle reduction filters based on a combination of polarimetric channels	161
6.5.2. Polarimetric data restoration filters	165
6.6. Estimation of filter parameters	167
6.6.1. Formulae for statistical estimation	167
6.6.2. Choice of a calculation window	168
6.7. Filter specificities	169
6.7.1. Statistical evaluation of the various estimators	169
6.7.2. Results on an ERS-1 image	171
6.8. Conclusion	172
Chapter 7. Classification of SAR Images	175
Danielle DUCROT, Florence TUPIN and Sylvie LE HÉGARAT-MASCLE	
7.1. Notations	176
7.2. Bayesian methods applied to scalar images	177
7.2.1. Pixel-based Bayesian methods	179
7.2.1.1. Supervised methods	179
7.2.1.2. Unsupervised methods	180
7.2.2. Contextual Bayesian methods	181
7.2.2.1. Supervised methods	182
7.2.2.2. Unsupervised methods	184
7.2.3. Global Bayesian methods	185
7.2.3.1. Supervised methods	185
7.2.3.2. Unsupervised methods	186
7.3. Application of the Bayesian methods to ERS-1 time series	186
7.3.1. Pixel classification	188

7.3.1.1. The single-channel case	188
7.3.1.2. Multi-temporal contribution	188
7.3.1.3. Introduction of derived channels	189
7.3.1.4. Contribution of contextual classification methods	189
7.3.2. Radar and SPOT fusion, comparison with SPOT	191
7.3.3. Conclusion	192
7.4. Classification of polarimetric images.	192
7.4.1. Classification in three major backscattering mechanisms	193
7.4.1.1. The principle	193
7.4.1.2. Implementation and illustration of results	193
7.4.1.3. Conclusion	195
7.4.2. Entropy-based classification	195
7.4.2.1. The principle	195
7.4.2.2. Implementation and illustration of results	196
7.4.3. Polarimetric Bayesian classifications	198
7.4.3.1. The single-look Gaussian case	198
7.4.3.2. The multi-look Gaussian case	200
7.4.3.3. The product model case	201
7.4.4. Polarimetric non-Bayesian classifications	201
Chapter 8. Detection of Points, Contours and Lines	207
Florence TUPIN and Armand LOPÈS	
8.1. Target detectors	208
8.1.1. Intensity threshold	208
8.1.2. Ratio use	210
8.1.3. Other approaches	213
8.1.4. Conclusion	213
8.2. Contour detectors	214
8.2.1. Average ratio	215
8.2.2. Likelihood ratio	218
8.2.2.1. Use of detected data	218
8.2.2.2. Complex data use	219
8.2.3. Exponentially-balanced average ratio	221
8.2.4. Multi-directional case	225
8.3. Line detectors	225
8.3.1. Average ratio	226
8.3.2. Correlation with an ideal structure	227
8.4. Line and contour connection.	228
8.5. Conclusion	231
Chapter 9. Geometry and Relief	233
Frédéric ADRAGNA	
9.1. Radar image localization	233
9.1.1. Precision of orbital data	234

9.1.2. Distance localization	234
9.1.3. Azimuth localization	235
9.1.4. Three-dimensional point localization from radar imaging	237
9.1.5. Moving targets	238
9.2. Geometric corrections	239
9.2.1. Geometric corrections with DTM	239
9.2.2. Image registration	240
9.2.2.1. Case of images obtained from identical orbits	240
9.2.2.2. Images acquired from different incidences	241
9.2.2.3. Images obtained in opposite direction orbits (ascending/descending)	241
Chapter 10. Radargrammetry	243
Henri MAÎTRE	
10.1. Stereovision principles: photogrammetry	243
10.1.1. Principles	243
10.1.2. Stereovision methods	244
10.2. Principles of radargrammetry	245
10.2.1. Lateral vision effects	246
10.2.2. Geometric reconstruction	249
10.2.2.1. Disparity/altitude relation in the general case	249
10.2.2.2. Simplified disparity/altitude relations	250
10.2.3. Matching	251
10.2.3.1. Correlation	251
10.2.3.2. Pyramidal approach	254
10.2.4. Geometry effects connected with radar viewing	255
10.2.5. Filling of hidden parts and non-matched areas	257
10.3. Results of radargrammetry	257
10.4. Conclusion	259
Chapter 11. Radarclinometry	261
Henri MAÎTRE	
11.1. Radarclinometry equation	262
11.1.1. Shape from shading	262
11.1.2. Shape from shading and radar	263
11.1.3. Radarclinometry equation	263
11.2. Resolution of the radarclinometry equation	265
11.2.1. Wildey approach	265
11.2.2. Frankot and Chellappa approach	266
11.2.3. Resolution of radargrammetry equation without <i>a priori</i> knowledge	267
11.2.3.1. Inversion of equation [11.6]	268
11.2.3.2. Regularization	268

11.3. Determination of unknown parameters	271
11.3.1. Determination of σ^o	271
11.3.2. Determination of backscattering distribution	272
11.4. Results	273
11.5. Radarpolarimetry	276
11.6. Conclusion	278
Chapter 12. Interferometry	279
Frédéric ADRAGNA and Jean-Marie NICOLAS	
12.1. Interferometry principle	280
12.1.1. Phase and interference	280
12.1.2. Construction of an interferometric product	281
12.1.3. What type of information does the interferogram carry?	282
12.2. Interferogram modeling	283
12.2.1. Statistical laws of interferograms	283
12.2.2. Estimation of empirical coherence	284
12.3. Geometric analysis of data	285
12.4. Applications of interferometry	288
12.4.1. Elevation measurement	288
12.4.1.1. Limitations	290
12.4.1.2. Precisions	291
12.4.2. Land movement measurement: differential interferometry	291
12.4.3. Use of coherence	292
12.4.3.1. Implementation	293
12.5. Limitations of interferometry imaging	294
12.5.1. Temporal change limitations	294
12.5.2. Limitations due to geometry	294
12.5.3. Effects of atmospheric propagation	297
12.5.3.1. Troposphere case	298
12.5.3.2. Ionosphere case	299
12.5.4. Role of signal-to-noise ratio	299
Chapter 13. Phase Unwrapping	301
Emmanuel TROUVÉ and Henri MAÎTRE	
13.1. Introduction	301
13.1.1. Corrected phase shift	302
13.1.2. Residue detection	304
13.2. Preprocessing of InSAR data	305
13.2.1. Analysis of local frequencies	306
13.2.1.1. Modeling	306
13.2.1.2. Direct estimation method	307
13.2.1.3. Confidence measure	309
13.2.1.4. Multi-scale implementation	310
13.2.2. Interferogram filtering	312

13.2.2.1. Two different approaches	312
13.2.2.2. Fringe pattern compensation	313
13.2.3. Detection of non-unwrappable areas	317
13.3. Phase unwrapping methods.	319
13.3.1. Local methods	320
13.3.1.1. Placing the cuts	321
13.3.1.2. Finding a mask	321
13.3.2. Least squares.	322
13.3.2.1. Considering disturbances	323
13.3.2.2. Minimization algorithms.	325
13.3.3. Green's functions	326
13.3.4. Conclusion	329
Chapter 14. Radar Oceanography	331
Jean-Marc LE CAILLEC and René GARELLO	
14.1. Introduction to radar oceanography.	331
14.2. Sea surface description	334
14.2.1. Division of the sea spectrum into different scales	334
14.2.2. Reflection of electromagnetic waves from the sea surface	336
14.3. Image of a sea surface by a real aperture radar	337
14.3.1. Tilt modulation	337
14.3.2. Hydrodynamic modulation	341
14.4. Sea surface motions	344
14.5. SAR image of the sea surface	345
14.5.1. Quasi-linear approximation of the SAR spectrum image	345
14.5.2. Modeling of non-linearities	348
14.6. Inversion of the SAR imaging mechanism	352
14.6.1. SAR spectrum inversion	352
14.6.2. Underwater topography inversion	353
Bibliography	357
List of Authors	377
Index	379