



# MULTIDIMENSIONAL SPECKLE NOISE, MODELLING AND FILTERING RELATED TO SAR DATA

by

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**Ph.D. Dissertation**

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# Bibliography

- [1] J. S. Lee, M. R. Grunes, and G. de Grandi, "Polarimetric SAR speckle filtering and its impact for classification," *IEEE Trans. Geosci. Remote Sensing*, vol. 37, no. 5, pp. 2363 – 2373, Sept. 1999. (document), [1.1](#), [5.1](#), [5.5.2](#), [7.2](#), [7.4.1](#), [7.4.1](#), [7.4.1](#), [3](#), [7.5](#), [7.5.1](#), [7.3](#), [7.4](#), [7.5.1](#), [7.5.2](#), [8](#)
- [2] A. Rosenqvist, M. Imhoff, A. Milne, and C. Dobson, Eds., *Remote Sensing and the Kyoto Protocol: A Review of Available and Future Technology for Monitoring Treaty Compliance*. International Society for Photogrammetry and Remote Sensing (ISPRS), Oct. 1999. [1.1](#)
- [3] J. W. Goodman, "Some fundamental properties of speckle," *J. Opt. Soc. Am*, vol. 66, no. 11, pp. 1145 – 1149, Nov. 1976. [1.1](#), [2.1.4](#), [2.1.4](#), [2.1.6](#)
- [4] J. W. Goodman, *Statistical Optics*, John Wiley & Sons, New York, 1984. [1.1](#), [2.1.4](#), [2.1.4](#)
- [5] J. C. Dainty, J. W. Goodman, G. Parry, T. S. McKechnie, M. Fraçon, and A. E. Ennos, *Laser Speckle and Related Phenomena*, Springer-Verlag, Berlin, Germany, 1975. [1.1](#), [2.1.4](#), [2.2.3](#)
- [6] J. C. Curlander and R. N. McDonough, *Synthetic Aperture Radar: Systems and Signal Processing*, John Wiley & Sons, New York, 1991. [1.1](#), [2.1.1](#), [2.1.2](#), [2.1.2](#), [2.1.4](#)
- [7] C. Oliver and S. Quegan, *Understanding Synthetic Aperture Radar Images*, Artech House, Boston, USA, 1998. [1.1](#), [2.1.4](#), [2.1.4](#), [2.1.4](#), [2.2.3](#), [2.2.3](#), [2.2.3](#), [2.3.5](#), [2.3.6](#), [4.1](#), [5.1](#), [7.2](#)
- [8] J. S. Lee, "Speckle analysis and smoothing of synthetic aperture radar images," *Computer graphics and image processing*, vol. 17, pp. 24 – 32, 1981. [1.1](#), [2.1.4](#), [2.1.6](#)
- [9] J. S. Lee, "A simple speckle smoothing algorithm for synthetic aperture radar images," *IEEE Trans. Systems, Man and Cybernetics*, vol. SMC - 13, no. 1, pp. 85 – 89, Jan. 1983. [1.1](#), [2.1.4](#)
- [10] D. T. Kuan, A. A. Sawchuk, C. Strand T, and P. Chavel, "Adaptive noise smoothing filter for images with signal-dependent noise," *IEEE Trans. on Pattern Analysis and Machine Intelligence*, vol. PAMI - 7, no. 2, pp. 165 – 177, Mar. 1985. [1.1](#)
- [11] V.S. Frost, J.A. Stiles, K.S. Shanmugan, and J.C. Holtzman, "A model for radar images and its implications to adaptive digital filtering of multiplicative noise," *IEEE Trans. on Pattern Analysis and Machine Intelligence*, vol. 4, no. 2, pp. 157 – 166, Mar. 1982. [1.1](#)
- [12] A. Lopes, R. Touzi, and E. Nezry, "Adaptive speckle filters and scene heterogeneity," *IEEE Trans. Geosci. Remote Sensing*, vol. 28, no. 6, pp. 992 – 1000, Nov. 1990. [1.1](#), [2.1.6](#)
- [13] A. Lopes, E. Nezry, R. Touzi, and H. Laur, "Structure detection and adaptive speckle filtering in SAR images," *Int. J. Remote Sensing*, vol. 14, no. 9, pp. 1735 – 1758, 1993. [1.1](#), [2.1.4](#), [2.1.4](#)
- [14] L. C. Graham, "Synthetic interferometric radar for topographic mapping," *Proc. IEEE*, vol. 62, pp. 763–768, June 1974. [1.1](#), [2.2.1](#)

- [15] H.A. Zebker and R.M. Goldstein, "Topographic mapping from interferometric synthetic aperture radar observations," *Int. J. of Remote Sensing*, vol. 9, no. 5, pp. 857 – 872, 1988. [1.1](#)
- [16] H. Zebker, J.J. Van Zyl, and D. N. Held, "Imaging radar polarimetry from wave synthesis," *J. of Geophysical Research*, vol. 92, pp. 683 – 701, 1987. [1.1](#), [5.7](#), [7.5](#)
- [17] H. Zebker, J.J. Van Zyl, S.L. Durden, and L. Norikane, "Calibrated imaging radar polarimetry: Technique, examples and applications," *IEEE Trans. Geosci. Remote Sensing*, vol. 29, no. 6, pp. 942 – 961, Nov. 1991. [1.1](#), [5.7](#)
- [18] H. Zebker and J.J. Van Zyl, "Imaging radar polarimetry: A review," *Proc. IEEE*, vol. 79, no. 11, pp. 1683 – 1606, Nov. 1991. [1.1](#), [5.7](#)
- [19] A. Gabriel and R. Goldstein, "Crossed orbit interferometry: Theory and experimental results from SIR-b," *Int. J. Remote Sensing*, vol. 9, no. 5, pp. 857 – 872, 1988. [1.1](#), [2.2.1](#)
- [20] K. Sarabandi, "Deriation of phase statistics from the mueller matrix," *Radio Science*, vol. 27, no. 5, pp. 553 – 560, Sept. 1992. [1.1](#), [2.2.3](#), [5.2](#), [5.3](#), [7.3.1](#)
- [21] J. S. Lee, K. W. Hoppel, and S. A. Mango, "Intensity and phase statistics of multilook polarimetric and interferometric SAR imagery," *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 5, pp. 1017–1027, Sept. 1994. [1.1](#), [2.2.3](#), [2.2.3](#), [2.3.3](#), [2.3.5](#), [2.3.5](#), [5.2](#)
- [22] R. J. A. Tough, D. Blacknell, and S. Quegan, "A statistical description of polarimetric and interferometric synthetic aperture radar data," *Proc. R. Soc. Lond. A*, pp. 567–589, 1995. [1.1](#), [2.2.3](#), [2.2.3](#), [2.2.3](#), [2.2.3](#), [2.3.3](#), [2.3.5](#), [2.3.5](#), [5.2](#), [5.3](#), [B](#)
- [23] S. Mallat, *A Wavelet Tour of Signal Processing*, Academic Press, Inc., San Diego, USA, second edition, 1998. [1.1](#), [3.1](#), [3.2.4](#), [3.2.4](#), [3.3.2](#), [3.3.3](#), [3.3.4](#), [3.3.4](#), [3.3.4](#), [3.3.5](#), [3.3.5](#), [3.3.6](#), [3.4.1](#), [3.4.1](#), [4.3.2](#), [4.3.2](#), [4.3.3](#), [4.4](#), [6.5.1](#)
- [24] L. Prasad and S. S. Inyegard, *Wavelet Analysis with Applications to Image Processing*, CRC Press, Boca Raton, Florida, USA, 1997. [1.1](#), [3.1](#), [3.2.1](#), [3.2.2](#), [3.2.3](#), [3.2.3](#), [3.2.4](#), [3.2.4](#), [3.3.2](#), [3.3.3](#), [3.3.3](#), [3.3.3](#), [3.3.3](#), [3.3.3](#), [3.3.4](#), [3.3.4](#), [3.4.1](#), [3.4.1](#), [3.4.2](#)
- [25] P. P. Vaidyanathan, *Multirate Systems and Filter Banks*, Englewood Cliffs, NJ, USA, 1989. [1.1](#), [3.3.4](#), [3.4.1](#)
- [26] G. Sinclair, "The transmission and reception of elliptically polarized waves," *Proc. IRE*, vol. 38, pp. 148 – 151, 1950. [1.1](#), [2.3.3](#)
- [27] E. M. Kennaugh, "Effects of the type of polarization on echo characteristics," Tech. Rep., Antenna Laboratory, Ohio State University, 1951, Report 389-9. [1.1](#), [2.3.3](#)
- [28] J. R. Huynen, *Phenomenological Theory of Radar Targets*, Ph.D. thesis, Thecnical University, Delf, The Netherlands, 1970. [1.1](#), [7.5](#)
- [29] W.M. Boerner and M.B. El-Arini, "Polarization dependence in electromagnetic inverse problem," *IEEE Trans. Antennas and Propagation*, vol. 29, no. 2, pp. 262 – 271, 1981. [1.1](#)
- [30] R. C. Jones, "A new calculus for the treatment of optical systems i. description and discussion," *J. Opt. Soc. Amer.*, vol. 31, pp. 488 – 493, July 1941. [1.1](#), [2.3.1](#)
- [31] R. C. Jones, "A new calculus for the treatment of optical systems II. proof of the three general equivalence theorems," *J. Opt. Soc. Amer.*, vol. 31, pp. 493 – 499, July 1941. [1.1](#), [2.3.1](#)
- [32] R. C. Jones, "A new calculus for the treatment of optical systems III: The stokes theory of optical activity.," vol. 31, pp. 500 – 503, July 1941. [1.1](#), [2.3.1](#)

- [33] E. Krogager, *Aspects of Polarimetric Radar Imaging*, Ph.D. thesis, Technical University of Denmark, Electromagnetics Institute, Lyngby, Mar. 1993. [1.1](#)
- [34] S.R. Cloude, *Polarimetry: The Characterization of Polarimetric Effects in EM Scattering*, Ph.D. thesis, University of Birmingham, Faculty of Engineering, UK, Oct. 1986. [1.1](#)
- [35] E. Pottier, *Contribution de la Polarimétrie Dans la Discrimination de Cibles Radar, Applications à l'Imagerie Electromagnétique Haute Résolution*, Ph.D. thesis, IRESTE, Nantes, France, Dec. 1990. [1.1](#)
- [36] S. R. Cloude and E. Pottier, "A review of target decomposition theorems in radar polarimetry," *IEEE Trans. Geosci. Remote Sensing*, vol. 34, no. 2, pp. 498 – 518, Mar. 1996. [1.1](#), [2.3.3](#), [2.3.3](#), [2.3.4](#), [2.3.4](#), [2.3.4](#), [2.4](#), [2.4.2](#), [4.1](#), [7.5](#), [7.5](#)
- [37] L. M. Novak and M. C. Burl, "Optimal speckle reduction polarimetric SAR imagery," *IEEE Trans. Aerospace Electron. Systems*, vol. 26, no. 2, pp. 293 – 305, Mar. 1990. [1.1](#), [4.2.3](#), [5.1](#), [7.2](#)
- [38] Q. Lin and J. P. Allebach, "Combating speckle in SAR images: Vector filtering and sequential classification based in a multiplicative noise model," *IEEE Trans. Geosci. Remote Sensing*, vol. 28, no. 4, pp. 647 – 653, July 1990. [1.1](#)
- [39] J. S. Lee, M. R. Grunes, and S. A. Mango, "Speckle reduction in multipolarization, multifrequency SAR imagery," *IEEE Trans. Geosci. Remote Sensing*, vol. 29, no. 4, pp. 535 – 544, July 1991. [1.1](#), [5.1](#), [7.2](#)
- [40] S. Goze and A. Lopez, "A MMSE speckle filter for full resolution SAR polarimetric data," *J. Electromagn. Waves Appl.*, vol. 7, no. 5, pp. 717 – 737, May 1993. [1.1](#), [5.1](#), [7.2](#)
- [41] R. Touzi and A. Lopes, "The principle of speckle filtering in polarimetric SAR imagery," *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 5, pp. 1110 – 1114, Sept. 1994. [1.1](#), [7.2](#), [7.3](#)
- [42] S. R. Cloude and K. P. Papathanassiou, "Polarimetric SAR interferometry," *IEEE Trans. Geosci. Remote Sensing*, vol. 36, no. 5, pp. 1551–1565, Sept. 1998. [1.1](#), [2.2](#), [2.2.4](#), [2.4](#), [2.4.1](#), [2.4.2](#)
- [43] K. P. Papathanassiou, *Polarimetric SAR Interferometry*, Ph.D. thesis, The Faculty of Natural Sciences, Physics Department, Technical University Graz. Austria, 1999. [1.1](#), [2.4](#)
- [44] M. Coltelli, G. Fornaro, G. Franceschetti, R.N Lanari, M. Migliaccio, J. R. Moreira, K. P. Papathanassiou, G. Puglisi, D. Riccio, and M. Schuabisch, "SIR-C/X-SAR multifrequency multipass interferometry: A new tool for geological interpretation," *J. of Geophysical Research*, vol. 101, no. E10, pp. 23,127 – 23,148, Oct. 1996. [1.1](#), [2.2](#)
- [45] R. Lanari, G. Fornaro, D. Riccio, M. Migliaccio, K. P. Papathanassiou, J. R. Moreira, M. Schuabisch, L. Dutra, G. Puglisi, G. Franceschetti, and M. Coltelli, "Generation of digital elevation models by using SIR-C/X-SAR multifrequency two-pass interferometry: The etna case study," *IEEE Trans. Geosci. Remote Sensing*, vol. 34, no. 5, pp. 1097 – 1114, Sept. 1996. [1.1](#), [2.2](#), [2.4](#), [6.2.1](#)
- [46] R. N. Treuhaft, S. N. Madsen, M. Moghaddam, and J. J. Van Zyl, "Vegetation characteristics un underlying topography from interferometric data," *Radio Science*, vol. 31, pp. 1449 – 1495, Nov./Dec. 1996. [1.1](#), [2.4](#)
- [47] M. I. Skolnik, *Introduction to Radar Systems*, McGraw-Hill, Singapore, 1981. [2.1.1](#), [2.1.2](#), [2.1.2](#)
- [48] A. B. Carlson, *Communication Systems. Third Edition*, McGraw-Hill, Singapore, 1986. [2.1.1](#), [2.1.2](#), [2.1.2](#), [4.3.2](#)

- [49] G.L. Turin, “An introduction to digital matched filters,” *Proc. IEEE*, vol. COM-30, pp. 855 – 884, May 1976. [2.1.1](#), [2.1.2](#)
- [50] W. M. Brown, “Synthetic aperture radar,” *IEEE Trans. Aerospace Electron. Systems*, vol. AES-3, no. 2, pp. 217 – 229, Mar. 1967. [2.1.1](#)
- [51] C. Elachi, *Spaceborne Radar Remote Sensing: Applications and Techniques*, IEEE Press, New York, 1988. [2.1.1](#)
- [52] W. G. Carrara, R. S. Goodman, and R. M. Majewski, *Spotlight Synthetic Aperture Radar: Signal Processing Algorithms*, Artech House, Norwood, MA, 1995. [2.1.2](#)
- [53] K. Tomiyasu, “Conceptual performance of a satellite borne, wide swath synthetic aperture radar,” *IEEE Trans. Geosci. Remote Sensing*, vol. GE-19, pp. 108 – 116, 1981. [2.1.2](#)
- [54] A. Cardama, L. Jofre, J. M. Rius, J. Romeu, and S. Blanch, *Antenas*, Edicions UPC, Barcelona, Spain, 1993. [2.1.2](#)
- [55] F. T. Ulaby, R. K. Moore, and A. K. Fung, *Microwave Remote Sensing: Active and Passive*, vol. II, Artech House, Norwood, MA, 1986. [2.1.2](#), [2.1.3](#), [2.1.4](#), [2.1.4](#), [2.1.5](#), [2.3.3](#)
- [56] G. Franceschetti and R. Lanari, *Synthetic Aperture Radar Processing*, CRC Press, Boca Ratón, Florida, 1999. [2.1.2](#), [2.1.2](#)
- [57] S. N. Madsen, *Modelling, Analysis, and Applications Related to Synthetic Aperture Radar Data*, Ph.D. thesis, Technical University of Denmark, Nov. 1986. [2.1.2](#), [2.1.3](#), [2.1.3](#), [2.1.4](#), [2.1.4](#), [2.1.5](#)
- [58] F. K. Li and R. M. Goldstein, “Studies of multibaseline spaceborne interferometric synthetic aperture radars,” *IEEE Trans. Geosci. Remote Sensing*, vol. 28, no. 1, pp. 88 – 97, Jan. 1990. [2.1.2](#), [6.2.1](#)
- [59] P. Beckmann and A. Spizzichino, *The Scattering of Electromagnetic Waves from Rough Surfaces*, Artech House, Norwood, MA, 1987. [2.1.3](#), [2.1.4](#), [2.1.4](#), [2.1.4](#), [2.1.4](#)
- [60] J. A. Ogilvy, *Theory of Wave Scattering from Random Rough Surfaces*, Adam Hilger, New York, 1991. [2.1.3](#), [2.1.4](#)
- [61] A. D. Goldfinger, “Estimation of spectra from speckled images,” *IEEE Trans. Aerospace Electron. Systems*, vol. AES-18, no. 5, pp. 675 – 681, Sept. 1987. [2.1.3](#)
- [62] R. L. Mitchell, “Models of extended targets and their coherent radar images,” *Proc. IEEE*, vol. 62, no. 6, pp. 754 – 758, 1974. [2.1.3](#)
- [63] K. J. Langenberg, M. Brandfass, K. Mayer, T Kreutter, A. Brüll, P. Felinger, and D. Huo, “Principles of microwave imaging and inverse scattering,” *EARSel Advances in Remote Sinsing*, vol. 2, pp. 163 – 186, 1993. [2.1.3](#), [2.1.3](#)
- [64] K. J. Langenberg, *Applied Inverse Problems, in Basic Methods of Tomography and Inverse Problems*, Adam Hilger, Bristol, UK, 1987. [2.1.3](#)
- [65] N. Marechal, “Tomographic formulation of interferometric SAR for terrain elevation mapping,” *IEEE Trans. Geosci. Remote Sensing*, vol. 33, no. 3, pp. 726 – 739, May 1995. [2.1.3](#)
- [66] F. T. Ulaby, R. K. Moore, and A. K. Fung, *Microwave Remote Sensing: Active and Passive*, vol. III, Artech House, Norwood, MA, 1986. [2.1.4](#)
- [67] H. C. Van de Hulst, *Light Scattering by Small Particles*, Dover, New York, 1981. [2.1.4](#), [2.3.3](#)

- [68] L. J. Porcello, H. G. Massey, R. B. Innes, and J. M. Marks, "Speckle reduction in synthetic aperture radars," *J. Opt. Soc. Amer.*, vol. 66, no. 11, pp. 1305 – 1311, Nov. 1976. [2.1.4](#)
- [69] C. B. Burckhardt, "Speckle in ultrasound b-mode scans," *IEEE Trans. on Sonics and Ultrasonics*, vol. SU-25, no. 1, pp. 1 – 6, Jan. 1978. [2.1.4](#)
- [70] W. H. McCrea and F. J. W. Whipple, "Random paths in two and three dimensions," *Proc. Roy. Soc. Edinburgh*, vol. 60, pp. 281 – 298, 1940. [2.1.4](#)
- [71] J. L. Doob, L. S. Ornstein, G. E. Uhlenbeck, S. O. Rice, M. Kac, and S. Chandrasekhar, *Selected Papers on Noise and Stochastic Processes*, Dover publications, New York, 1954. [2.1.4](#), [4.5](#)
- [72] A. Papoulis, *Probability, Random Variables and Stochastic Processes*, McGraw-Hill, 1984. [2.1.4](#), [2.1.5](#), [2.2.3](#), [2.3.3](#), [2.3.3](#), [4.2.1](#), [4.2.3](#), [4.5](#), [A](#)
- [73] T. F. Bush Nad F. T. Ulaby, "Fading characteristics of panchromatic radar backscatter from selected agricultural targets," *IEEE Trans. Geosci. Electron.*, vol. 13, pp. 149 – 157, 1975. [2.1.4](#)
- [74] J. O. Hagberg, L. M. Ulander, and J. Askne, "Repeat-pass interferometry over forested terrain," *IEEE Trans. Geosci. Remote Sensing*, vol. 33, no. 2, pp. 331 – 340, Mar. 1995. [2.1.5](#), [2.4](#), [6.2.2](#), [6.6.2](#)
- [75] R. K. Raney, "Transfer function for partially coherent SAR systems," *IEEE Trans. Aerospace Electron. Systems*, vol. AES - 19, no. 5, pp. 740 – 750, Sept. 1983. [2.1.6](#)
- [76] D. Massonet and R. Rabaute, "Radar interferometry: Limits and potential," *IEEE Trans. Geosci. Remote Sensing*, vol. 31, no. 2, pp. 455 – 464, Mar. 1993. [2.2](#), [2.2.1](#)
- [77] F. T. Ulaby and C. Elachi, *Radar Polarimetry for Geoscience Applications*, Artech House, Norwood, MA, 1990. [2.2](#), [2.3.3](#), [5.2](#), [7.5](#), [7.5](#)
- [78] A. K. Gabriel, R. M. Goldstein, and H. A. Zebker, "Mapping small elevation changes over large areas: Differential radar interferometry," *J. Geophysical Research*, vol. 94, pp. 9183 – 9191, 1989. [2.2](#)
- [79] R. M. Goldstein, T. P. Barnett, and H. A. Zebker, "Remote sensing of ocean currents," *Science*, vol. 246, pp. 1282 – 1285, Dec. 1989. [2.2](#)
- [80] L. P. Orwig and D. N. Held, "Interferometric ocean surface and moving object relocations with a norden systems ku-band SAR," in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 92*, Houston, Texas, 1992, pp. 1598 – 1600. [2.2](#)
- [81] C. Prati and R. Rocca, "Limits to the resolution of elevation maps from stereo SAR images," *Int. J. Remote Sensing*, vol. 11, pp. 2215 – 2235, 1990. [2.2.1](#)
- [82] E. Rodriguez and J. M. Martin, "Theory and design of interferometric synthetic aperture radars," *IEE Proc.-F*, vol. 139, no. 2, pp. 147–159, Apr. 1992. [2.2.1](#), [6.2.1](#)
- [83] H. A. Zebker and R. M. Goldstein, "Topographic mapping from interferometric synthetic aperture radar obervations," *J. Geophysical Research*, vol. 91, no. B5, pp. 1079 – 1082, Apr. 1986. [2.2.1](#)
- [84] H. A. Zebker, C. L. Werner, P. A. Rosen, and S. Hensley, "Accuracy of topographic maps derived from ERS-1 interferometric SAR," *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 4, pp. 823 – 836, July 1994. [2.2.1](#)
- [85] D. C. Ghiglia and M. D. Pitt, *Two-Dimensional Phase Unwrapping: Theory, Algorithms, and Software*, Wiley & Sons, New York, USA, 1998. [2.2.1](#), [2.2.3](#), [6.2.1](#), [6.5.2](#)

- [86] F. Gatelli, A. M. Guarneri, F. Parizzi, P. Pasquali, C. Prati, and F. Rocca, "The wavenumber shift in SAR interferometry," *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 4, pp. 855–865, July 1994. [2.2.1](#), [2.2.4](#), [2.2.4](#), [4.3.1](#)
- [87] J. I. H Askne, P. B. G. Dammert, L. M. H. Ulander, and G. Smith, "C-band repeat-pass interferometric SAR observations of the forest," *IEEE Trans. Geosci. Remote Sensing*, vol. 35, no. 1, pp. 25 – 35, Jan. 1997. [2.2.2](#), [2.4](#)
- [88] L. M. H. Ulander and J. O. Hagberg, "Radiometric and interferometric calibration of ENVISAT-1 ASAR," Tech. Rep., Dept. of radio and space science, Chalmers University of Technology, Göteborg, Sweden. [2.2.2](#)
- [89] D. Just and R. Bamler, "Phase statistics of interferograms with applications to synthetic aperture radar," *Applied optics*, vol. 33, no. 20, pp. 4361 – 4368, July 1994. [2.2.3](#), [2.2.4](#), [2.2.4](#)
- [90] D. Middleton, *Introduction to Statistical Communications*, McGraw-Hill, New York, 1960. [2.2.3](#)
- [91] F. T. Ulaby, K. Sarabandi, and A. N Ashashibi, "Statistical properties of the mueller matrix of distributed targets," *IEE Proc. - F*, vol. 139, no. 2, pp. 136 – 146, Apr. 1992. [2.2.3](#), [2.3.3](#), [5.2](#)
- [92] H. A. Zebker and J. Villasenor, "Decorrelation in interferometric radar echoes," *IEEE Trans. Geosci. Remote Sensing*, vol. 30, no. 5, pp. 950–959, Sept. 1992. [2.2.4](#), [2.2.4](#)
- [93] C. Prati and F. Rocca, "Improving slant range resolution of stationary objects with multiple SAR surveys," *IEEE Trans. Aerospace Electron. Systems*, vol. 29, pp. 135 –144, Jan. 1993. [2.2.4](#)
- [94] J. S. Lee, K. P. Papathanassiou, T. L. Ainsworth, M. R Grunes, and A. Reigber, "A new technique for noise filtering of SAR interferometric phase images," *IEEE Trans. Geosci. Remote Sensing*, vol. 36, no. 5, pp. 1456–1465, Sept. 1998. [2.2.5](#), [4.2](#), [4.2](#), [4.2.4](#), [6.2.1](#), [6.3.1](#)
- [95] C. A. Balanis, *Advanced Engineering Electromagnetics*, John Wiley & Sons, New York, 1989. [2.3.1](#)
- [96] J. D. Jackson, *Electrodinámica Clásica*, Alhambra S.A., Madrid, Spain, 1966. [2.3.1](#)
- [97] "IEEE standard number 145-1983," *IEEE Trans. Antennas and Propagation*, vol. AP-31, no. 6, Nov. 1983. [2.3.1](#), [2.3.1](#), [2.3.3](#)
- [98] M. Born and E. Wolf, *Principles of Optics*, Pergamon Press, 4 & 5 Fitzroy Square, London W.1., UK, 1959. [2.3.1](#), [2.3.1](#), [2.3.1](#), [2.3.1](#)
- [99] C. Graves, "Radar polarization power scattering matrix," *Proc. IRE*, vol. 44, no. 5, pp. 248 – 252, 1956. [2.3.1](#)
- [100] E. Lüneburg, "Principles of radar polarimetry: The consimilarity transformation of radar polarimetry versus the similarity transformations in optical polarimetry," *IEICE Trans. on electronics (Special issue on Electromagnetic Theory)*, vol. E78-C, no. 10, pp. 1339 – 1345, 1995. [2.3.1](#), [2.3.7](#)
- [101] E. Lüneburg, *Direct and Inverse Electromagnetic Scattering*, chapter Radar Polarimetry: A Revision of Concepts, pp. 257 – 275, Pitman Research Notes in Mathematics Series 361, Addison wesley Longman, Harlow, U.K., 1996. [2.3.1](#)
- [102] G. G. Stokes, "On the composition and resolution of streams of polarized light from different sources," *Trans. Cambridge Philos. Soc.*, vol. 9, pp. 399 – 416, 1852. [2.3.1](#)
- [103] S. Chandrasekhar, *Radiative Transfer*, Dover, New York, 1960. [2.3.1](#)
- [104] H. Poincaré, *Théorie Mathématique de la Lumière*, Georges Carre, Paris, France, 1892. [2.3.1](#)

- [105] R. M. A. Azzam and N. M. Bashara, *Ellipsometry and Polarized Light*, Elsevier Science, Amsterdam, 1987. [2.3.1](#), [2.3.3](#)
- [106] L. Tsang, J .A. Kong, and R. T. Shin, *Theory of Microwave Remote Sensing*, Wiley and Sons., New York, 1985. [2.3.3](#)
- [107] M. Borgeaud, R. T. Shin, and J. A. Kong, “Theoretical models for polarimetric radar clutter,” *J. Electromagn. Waves Appl.*, vol. 1, no. 1, pp. 73 – 89, 1987. [2.3.3](#)
- [108] S. R. Cloude, “Group theory and polarization algebra,” *Optik*, vol. 75, no. 1, pp. 26 – 36, 1986. [2.3.3](#), [7.5](#)
- [109] I. R. Joughin, D. P. Winebrenner, and D. B. Percival, “Probability density functions for multilook polarimetric signatures,” *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 3, pp. 562 – 574, May 1994. [2.3.3](#)
- [110] A. H. Nuttall, “High-order covariance functions for complex gaussian processes,” *IRE Trans. on Information Theory*, pp. 255 – 256, Apr. 1962. [2.3.3](#), [5.1](#), [5.2](#)
- [111] I. S. Reed, “On a moment theorem for complex gaussian processes,” *IRE Trans. on Information Theory*, pp. 194 – 195, Apr. 1962. [2.3.3](#), [5.1](#), [5.2](#)
- [112] A. Guissard, “Mueller and kennaug matrices in radar polarimetry,” *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 3, pp. 590 – 597, May 1994. [2.3.4](#)
- [113] Ridha Touzi, Armand Lopes, Jérôme Bruniquel, and Paris W. Vachon, “Coherence estimation for SAR imagery,” *IEEE Trans. Geosci. Remote Sensing*, vol. 37, no. 1, pp. 135 – 149, Jan. 1999. [2.3.5](#), [2.3.5](#), [4.2.3](#), [4.2.3](#), [6.2.2](#), [7.3.2](#), [7.3.2](#)
- [114] N. R. Goodman, “Statistical analysis based on a certain multivariate complex gaussian distribution (an introduction),” *Ann. Mathemat. Statist.*, vol. 34, pp. 152 – 177, 1963. [2.3.5](#), [2.3.5](#)
- [115] J. J. Van Zyl, H. A. Zebker, and C. Elachi, “Imaging radar polarization signatures: Theory and applications,” *Radio Science*, vol. 22, no. 4, pp. 529 – 543, Aug. 1987. [2.3.7](#), [7.5](#)
- [116] W. M. Boerner, “Optimal polarization concept in radar imaging,” in *Proc. ESA-EARSeL Workshop*. ESA, 1981. [2.3.7](#)
- [117] H. Mieras, “Optimum polarizations of simple compound targets,” *IEEE Trans. Antennas and Propagation*, vol. AP - 31, pp. 996 – 999, Nov. 1983. [2.3.7](#)
- [118] J. J. Van Zyl, C. H. Papas, and C. Elachi, “On the optimum polarizations of incoherently reflected waves,” *IEEE Trans. Antennas and Propagation*, vol. AP-35, no. 7, pp. 818 – 825, July 1987. [2.3.7](#)
- [119] A. B. Kostinski and W. M. Boerner, “On foundations of radar polarimetry,” *IEEE Trans. Antennas and Propagation*, vol. AP-34, no. 12, pp. 1395 – 1403, Dec. 1986. [2.3.7](#)
- [120] L. Sagüès Piella, *Surface and Volumetric Scattering Analysis of Terrains for Polarimetric and Interferometric SAR Applications*, Ph.D. thesis, Universitat Politècnica de Catalunya, Signal Theory and Communications Department, Barcelona, Spain, 2000. [2.4](#)
- [121] K. P. Papathanassiou and A. Reigber, “On the interferometric coherence: A multifrequency and multitemporal analysis,” in *FRINGE'96 Workshop*. ESA, 1996, pp. 319 – 330. [2.4](#)
- [122] A. Reigber, “Multitemporale analyze der koherenz von SAR daten,” M.S. thesis, Univ. Constance, Germany, 1997. [2.4](#)

- [123] S.R. Cloude, K. P. Papathanassiou, A. Reigber, and W. M. Boerner, “Multi-frequency polarimetric SAR interferometry for vegetation structure straction,” in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 00.* 2000, pp. 129 – 131, IEEE. [2.4](#), [2.4.2](#)
- [124] K. P. Papathanassiou, S. R. Cloude, A. Reigber, and W. M. Boerner, “Multi-baseline polarimetric SAR interferometry for vegetation parameters estimation,” in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 02.* 2000, pp. 2762 – 2764, IEEE. [2.4](#)
- [125] O. Stebler, E. Meier, and D. Nuesch, “Multi-baseline airborne pol-InSAR measurements for the estimation of scattering processes within vegetation media,” in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 01.* IEEE, 2001, pp. 3172 – 3174, IEEE. [2.4](#)
- [126] L. Saguès, J. M. López-Sánchez, X. Fàbregas, A. Broquetas, and A. J. Sieber, “Polarimetric radar interferometry for improved mine detection and surface clutter rejection,” *IEEE Trans. Geosci. Remote Sensing*, vol. 39, no. 6, pp. 1271 – 1278, June 2001. [2.4](#)
- [127] A. Cohen and J. Kovačvić, “Wavelets: The mathematical background,” *Proc. IEEE*, vol. 84, no. 4, pp. 514 – 522, Apr. 1996. [3.1](#)
- [128] N. Hess-Nielsen and M. V. Wickerhauser, “Wavelets and time-frequency analysis,” *Proc. IEEE*, vol. 84, no. 4, pp. 523–540, Apr. 1996. [3.1](#), [3.2.4](#), [3.2.4](#)
- [129] K. Ramchandran, M. Vetterli, and C. Herley, “Wavelets, subband coding and best bases,” *Proc. IEEE*, vol. 84, no. 4, pp. 541–558, Apr. 1996. [3.1](#), [3.3.6](#)
- [130] T. K. Sarkar and C. Su, “A tutorial on wavelets from an electrical engineering perspective, part 2: The continuous case.,” *IEEE Antennas and Propagation Magazine*, vol. 40, no. 6, pp. 36 – 49, Dec. 1998. [3.1](#)
- [131] T. K. Sarkar, C. Su, R. Adve, M. Salazar-Palma, L. Garcí-Castillo, and R. R. Boix, “A tutorial on wavelets from an electrical engineering perspective, part 1: Discrete wavelet techniques,” *IEEE Antennas and Propagation Magazine*, vol. 40, no. 2, pp. 49 – 68, Oct. 1998. [3.1](#), [3.3.3](#), [3.3.4](#)
- [132] M. Vetterli and C. Herley, “Wavelets and filter banks: Theory and design,” *IEEE Trans. Signal Process.*, vol. 40, no. 9, pp. 2207 – 2232, Sept. 1992. [3.1](#)
- [133] C. K. Chui, *An Introduction to Wavelets*, Academic Press, Inc., San Diego, USA, 1991. [3.1](#)
- [134] C. K. Chui, *Wavelets: A Tutorial in Theory and Applications*, Academic Press, Inc., San Diego, USA, 1992. [3.1](#)
- [135] I. Daubechies, *Ten Lectures on Wavelets, No 61 in CDMS-NSF Series in Applied Mathematics*, SIAM, Philadelphia, 1992. [3.1](#), [3.3.2](#), [3.3.3](#), [3.3.3](#), [3.4.1](#), [3.4.1](#), [3.4.1](#), [3.4.2](#), [6.5.2](#)
- [136] J. O. Strömberg, “A modified franklin system and higher order spline system on  $\mathbb{R}^n$  as unconditional basis for hardy spaces,” in *Conference on Harmonic Analysis*. Univ. of Chicago Press, 1981, pp. 475 – 494. [3.1](#)
- [137] A. Grossmann and J. Morlet, *Decomposition of Functions Into Wavelets of Constant Shape, and Related Transforms, in Mathematics and Physics, Lectures on Recent Results*, World Scientific Publishing, Singapore, 1985. [3.1](#)
- [138] A. Grossmann, J. Morlet, and T. Paul, “Transforms associated to square integrable group representations i. general results,” *J. Math. Phys.*, vol. 26, pp. 2473 – 2479, 1985. [3.1](#)
- [139] S. G. Mallat, “A theory for multiresolution signal decomposition: The wavelet representation,” *IEEE Trans. on Pattern Analysis and Machine Intelligence*, vol. 11, no. 7, pp. 674 – 693, July 1989. [3.1](#), [3.3.3](#), [3.3.4](#), [3.3.4](#), [3.3.5](#)

- [140] N. I. Akhiezer and I. M. Glazman, *Theory of Linear Operators in Hilbert Space*, Dover Publications, Inc., New York, USA, 1993. [3.2.1](#)
- [141] J. G. Proakis and D. G. Manolakis, *Digital Signal Processing. Principles, Algorithms and Applications*, Prentice-Hall, Inc., Upper Saddle River, New Jersey, USA, third edition, 1996. [3.2.2](#), [3.2.3](#), [4.3.2](#), [4.3.2](#)
- [142] D. Gabor, “Theory of communication,” *J. IEE*, vol. 93, no. III, pp. 429 – 457, 1946. [3.2.4](#)
- [143] R. J. Duffin and A. C. Shaeffer, “A class of nonharmonic fourier series,” *Trans. Amer. Math. Soc.*, vol. 72, pp. 341 – 366, 1952. [3.3.2](#)
- [144] C. Heil and D. Walnut, “Continuous and discrete wavelet transforms,” *SIAM Rev.*, vol. 31, pp. 628 – 666, 1989. [3.3.2](#)
- [145] I. Daubechies, “The wavelet transform, time-frequency localization and signal analysis,” *IEEE Trans. Information Theory*, vol. 36, pp. 961 – 1005, Sept. 1990. [3.3.2](#)
- [146] M. Frazier and B. Jawerth, “A discrete transform and decompositions of distribution spaces,” *J. Func. Anal.*, vol. 93, pp. 34 – 170, 1990. [3.3.2](#)
- [147] M. Holschneider, R. Kronland-Martinet, J. Morlet, and P. Tchmitchian, *Wavelets, Time-Frequency Methods and Phase Space*, chapter The interference structure of the Wigner distribution and related time-frequency signal representations, Elsevier, Amsterdam, 1993. [3.3.2](#)
- [148] G. Strang, “Wavelet transform versus fourier transform,” *Bull. Amer. Math. Soc.*, vol. 28, pp. 288 – 305, 1993. [3.3.3](#)
- [149] I. Daubechies, “Orthonormal bases of compactly supported wavelets,” *Comm. Pure Appl. Math.*, vol. 41, pp. 909–996, 1988. [3.3.3](#), [3.3.3](#), [3.4.1](#), [3.4.2](#)
- [150] S. Mallat, “Multifrequecy channel decompositions of images and wavelet models,” *IEEE Trans. Acoust. Speech Signal Process.*, vol. 37, pp. 2091 – 2110, 1989. [3.3.3](#)
- [151] A. Cohen, *Biorthogonal Wavelets: A Tutorial in Theory and Applicartions*, Academic Press, Inc., San Diego, USA, 1992. [3.3.3](#), [3.4.2](#)
- [152] S. Mallat, “Multiresolution approximations and wavelet orthonormal bases of  $\ell^2(\mathbb{R})$ ,” *Trans. Amer. Math. Soc.*, vol. 315, pp. 69 – 87, 1989. [3.3.3](#), [3.3.3](#), [3.3.3](#), [3.3.3](#)
- [153] Y. Meyer, *Wavelets and Operators*, Cambridge University Press, 1992. [3.3.3](#), [3.3.3](#), [3.3.3](#), [3.3.3](#)
- [154] M. Vetterli and Jelena Kovačević, *Wavelets and Subband Coding*, Englewood Cliffs, NJ, USA, 1995. [3.3.4](#)
- [155] Jelena Kovačević and Martin Vetterli, “Nonseparable multidimensional perfect reconstruction filter banks and wavelet bases for  $\mathbb{R}^n$ ,” *IEEE Trans. Information Theory*, Mar. 1992. [3.3.5](#)
- [156] R. R. Coifman, Y. Meyer, and M. V. Wickerhauser, *Wavelet Analysis and Signal Processing. In Wavelets and their Applications*, Jones and Barlett, Boston, USA, 1992. [3.3.6](#)
- [157] R. R. Coifman and M. V. Wickerhouser, “Entropy-based algoritms for best basis selection,” *IEEE Trans. Information Theory*, vol. 38, no. 2, pp. 713 – 718, Mar. 1992. [3.3.6](#)
- [158] J. M. Lina and M. Mayrand, “Complex daubechies wavelets,” *App. Comp. Harmonic Anal.*, vol. 2, pp. 219 – 229, 1992. [3.4.1](#)

- [159] X. Zhang, M. Desai, and Y. Peng, "Orthonormal complex filter banks and wavelets: Some properties and design," *IEEE Trans. Signal Process.*, vol. 47, no. 4, Apr. 1999. [3.4.1](#)
- [160] M. Vetterli, "Filter banks allowing perfect reconstruction," *Signal Proc.*, vol. 10, no. 2, pp. 219 – 244, Apr. 1986. [3.4.1](#), [3.4.1](#)
- [161] A. Cohen, I. Daubechies, and J. C. Feauveau, "Biorthogonal basis of compactly supported wavelets," *Commun. on Pure and Appl. Math.*, vol. 45, pp. 485 – 560, 1992. [3.4.1](#)
- [162] S. Mallat and W. L. Hwang, "Singularity detection and processing with wavelets," *IEEE Trans. Inform. Theory*, pp. 617 – 643, 1992. [3.4.1](#)
- [163] I. Daubechies, "Orthonormal bases of compactly supported wavelets II. variations on a theme.," *SIAM J. Math. Anal.*, vol. 24, pp. 499 – 519, 1993. [3.4.2](#)
- [164] O. Rioul and P. Duhamel, "A remez exchange algorithm for orthonormal wavelets," *IEEE Trans. on Circuits and Systems-II: Analog and Digital Signal Processing*, vol. 41, no. 8, pp. 550 – 560, Aug. 1994. [3.4.2](#)
- [165] S. R. Cloude and E. Pottier, "An entropy based classification scheme for land applications of polarimetric SAR," *IEEE Trans. Geosci. Remote Sensing*, vol. 35, no. 1, pp. 68 – 78, Jan. 1997. [4.1](#), [7.5](#)
- [166] F. M. Henderson and A. J. Lewis, Eds., *Principles & Applications of Imaging Radar. Manual of Remote Sensing*, vol. 2, John Wiley & Sons, Inc., New York, USA, 3th edition, 1998. [4.1](#)
- [167] C. H. Chen, Ed., *Information Processing For Remote Sensing*, World Scientific Publishing Co. Pte. Ltd., Singapore, 1999. [4.1](#), [5.1](#)
- [168] J. S. Lee, T.L. Ainsworth, M. R. Grunes, and R. M. Goldstein, "Noise filtering interferometric SAR images," in *SPIE European Symposium*, Rome, Italy, Sept. 1994, pp. 735 – 742. [4.2](#)
- [169] C. López-Martínez and X. Fábregas, "Modeling and reduction of SAR interferometric phase noise in the wavelet domain," *IEEE Trans. Geosci. Remote Sensing*, vol. 40, no. 12, pp. 2553 – 2566, Dec. 2002. [4.2](#), [4.2.1](#), [4.2.2](#), [4.2.2](#), [4.2.3](#), [4.2.3](#), [4.3](#), [4.3.2](#), [4.3.2](#), [4.3.3](#), [4.3.3](#), [4.4](#), [4.4](#), [4.4](#)
- [170] C. López-Martínez and F. X. Fàbregas-Cànovas, "SAR interferometric phase denoising. a new approach based on wavelet transform," *EUROPTO 2000*, vol. Proc. of Spie Vol. 4173, pp. 199–210, 25-29 Sept. 2000. [4.2.1](#), [4.2.2](#), [4.2.3](#), [4.3.1](#), [4.3.1](#)
- [171] I. M. Ryzhik I. S. Gradshteyn, A. Jeffrey, and D. Zwillinger, *Table of Integrals, Series and Products*, Academic Press, 5th edition, 1994. [4.2.1](#), [B](#), [B](#), [E](#)
- [172] G. Marsaglia, "A note on the construction of a multivariate normal sample," *IRE Trans. on Information Theory*, vol. IT-3, pp. 149, June 1957. [4.2.3](#), [4.2.3](#)
- [173] S. M. Kay, *Fundamentals of Statistical Signal Processing. Estimation Theory*, Prentice - Hall, Inc., Englewood Cliffs, NJ, USA, 1993. [4.2.3](#), [6.4.2](#), [6.4.2](#), [6.4.2](#), [7.4.1](#)
- [174] A. K. Jain, *Fundamentals of Digital Image Processing*, Prentice-Nall, Inc., Englewood Cliffs, NJ, USA, 1989. [4.3.1](#)
- [175] C. López-Martínez, X. Fábregas, and Madhukar Chandra, "High resolution coherence estimation," in *Proc. Open Symposium on Propagation and Remote Sensing URSI Commission-F*, Garmisch-Partenkirchen, Germany, Feb. 2002. [4.4](#), [6.6](#)
- [176] J. M. Shapiro, "Embedded image coding using zerotrees of wavelet coefficients," *IEEE Trans. Signal Process.*, vol. 41, no. 12, pp. 3445–3462, Dec. 1993. [4.4](#)

- [177] C. López-Martínez and X. Fàbregas, “SAR interferometric phase statistics in wavelet domain,” *IEE Electronic Letters*, vol. 38, no. 20, pp. 1207 – 1208, Sept. 2002. [4.5](#), [4.5](#), [4.5](#)
- [178] G. C. Canavos, *Probabilidad Y Estadística. Aplicaciones Y Métodos*, McGraw Hill, 1988. [4.5](#), [D](#)
- [179] T. W. Anderson, *An Introduction to Multivariate Statistical Analysis*, John Wiley & Sons, Inc., New York, USA, 2nd edition, 1984. [5.1](#), [5.2](#)
- [180] J. S. Lee, S. R. Cloude, K. P. Papathanassiou, M. R. Grunes, T. L. Ainsworth, and D. L. Shuler, “Speckle filtering of polarimetric SAR interferometry data,” Toronto, Canada, June 2002, pp. 832 – 834, Proc. Geosci. and Remote Sensing Symposium, IGARSS 02. [5.1](#)
- [181] K. Sarabandi, “ $\Delta k$ -radar equivalent of interferometric SAR’s: A theoretical study for determination of vegetation height,” *IEEE Trans. Geosci. Remote Sensing*, vol. 35, no. 5, pp. 1267 – 1276, Sept. 1997. [5.1](#), [5.7](#), [5.7](#)
- [182] C. López-Martínez and X. Fàbregas, “Polarimetric SAR speckle noise model,” *IEEE Trans. Geosci. Remote Sensing*, vol. 41, no. 10, pp. 2232 – 2242, Oct. 2003. [5.1](#)
- [183] C. López-Martínez, K. P. Papathanassiou, and X. Fàbregas, “Polarimetric and interferometric noise modelling,” in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 02*, Toronto, Canada, June 2002. [5.1](#), [5.5.3](#)
- [184] A. Lopes, R. Mougin, A. Beaudoin, S. Goze, E. Nezry, R. Touzi, M. A. Karam, and A. K. Fung, “Phase difference statistics related to sensor and forest parameters,” in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 92*, 1992, pp. 779 – 781. [5.3](#), [7.3.1](#)
- [185] R. Horn, “The DLR airborne SAR project E-SAR,” in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 96*, May 1996, pp. 1624 – 1628. [5.5.2](#)
- [186] R. Scheiber, “Single-pass interferometry with the E-SAR system of DLR,” in *Proc. of the European Conference on Synthetic Aperture Radar, EUSAR’98*, Friedrichshafen, Germany, May 1998, pp. 25 – 27. [5.7](#), [6.5.2](#), [6.5.2](#)
- [187] J. M. López-Sánchez, J. Fortuny-Guasch, A. J. Sieber, and K. Sarabandi, “Validation of the backscattered frequency correlation function for the inversion of biophysical parameters from natural targets,” in *Geosci. and Remote Sensing Symposium Proc.*, 1998, vol. 5, pp. 2390 – 2392. [5.7](#), [5.7](#)
- [188] C. López-Martínez and X. Fàbregas, “Multifrequency SAR polarimetric speckle noise model validation,” in *Proc. POLINSAR, Workshop on Applications of SAR Polarimetry and Polarimetric SAR Interferometry*. ESA, Jan. 2003. [5.7](#)
- [189] R. Bamler, N. Adam, G. W. Davidson, and D. Just, “Noise-induced slope distorsin in 2-d phase unwrapping by linear estimators with application to SAR interferometry,” *IEEE Trans. Geosci. Remote Sensing*, vol. 36, no. 3, pp. 913–921, May 1998. [6.2.1](#), [6.5.2](#)
- [190] M. S. Seymour and I. G. Cumming, “Maximum likelihood estimation for SAR interferometry,” *Proc. Geosci. and Remote Sensing Symposium, IGARSS 94*, pp. 2272–2275, 8-12 August 1994. [6.2.1](#), [6.2.2](#), [6.2.2](#)
- [191] B. Reeves, J. Homer, G. Stickley, D. Noon, and I.D. Longstaff, “Spatial vector filtering to reduce noise in interferometric phase images,” in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 99*, June 1999, pp. 260 – 263. [6.2.1](#)
- [192] J. S. Lee, “Digital image enhancement and noise filtering by use of local statistics,” *IEEE Trans. Pattern Anal. Machine Intell.*, vol. PAMI-2, pp. 165–168, Jan. 1980. [6.2.1](#), [7.2](#), [3](#)

- [193] D. E. Carrasco, *Sar Interferometry for Digital Elevation Model Generation and Differential Applications*, Ph.D. thesis, Universitat Politècnica de Catalunya, Barcelona, Spain, 1998. [6.2.1](#), [6.2.1](#), [6.4](#)
- [194] R. Goldstein and C. Werner, "Radar ice motion interferometry," *Proc. of the third ERS Symposium, Florence, Italy*, pp. 969–972, Mar. 1997. [6.2.1](#), [6.3.1](#)
- [195] A. L. Bezerra Candeias, J. C. Mura, L. V. Dutra, and J. R. Moreira, "Interferogram phase noise reduction using morphological and modified median filters," in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 95*, July 1995, pp. 166– 168. [6.2.1](#)
- [196] A. B. Suksmono and A. Hirose, "Adaptive noise reduction of InSAR images based on a complex-valued MRF model and its application to phase unwrapping problem," *IEEE Trans. Geosci. Remote Sensing*, vol. 40, no. 3, pp. 699 – 709, Mar. 2002. [6.2.1](#)
- [197] E. J. M. Rignot and J. J. Van Zyl, "Change detection techniques for ERS 1 SAR data," *IEEE Trans. Geosci. Remote Sensing*, vol. 31, no. 4, pp. 896 – 906, July 1993. [6.2.2](#), [6.6.2](#)
- [198] J.S. Lee, A.R. Miller, and K.W. Hoppel, "Statistics of phase difference and product magnitude of multi-look processed gaussian signals," *Waves in Random Media*, vol. 4, pp. 307 – 319, 1994. [6.2.2](#)
- [199] A. Monti Guarnieri and Claudio Prati, "SAR interferometry: A "quick and dirty" coherence estimator for data browsing," *IEEE Trans. Geosci. Remote Sensing*, vol. 35, no. 3, pp. 660 – 669, May 1997. [6.2.2](#), [6.2.2](#), [6.2.2](#)
- [200] C. López-Martínez, X. Fàbregas-Cànoves, and M. Chandra, "SAR interferometric noise reduction using wavelet transform," *IEE Electronic Letters*, vol. 37, no. 10, pp. 649–651, May 2001. [6.4.1](#)
- [201] G.W. Wornell, *Signal Processing with Fractals: A Wavelet Based Approach*, Prentice Hall, Inc, Englewood Cliffs, N.J., U.S., 1996. [6.4.2](#)
- [202] R. Scheiber, A. Reigber, A. Ulbricht, K. P. Papathanassiou, R. Horn, S. Buckreuss, and A. Moreira, "Overview of interferometric data acquisition and processing modes of the experimental airborne SAR system of DLR," in *Proc. Geosci. and Remote Sensing Symposium, IGARSS 99*, 1999, vol. 1, pp. 35 –37. [6.5.2](#), [6.5.2](#)
- [203] M. Zink and R. Bamler, "X-SAR radiometric calibration and data quality," *IEEE Trans. Geosci. Remote Sensing*, vol. 33, no. 4, pp. 840 – 847, July 1995. [6.5.2](#)
- [204] M. D. Pitt and J. S. Shipman, "Least-squares two-dimensional phase unwrapping using FFT's," *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 3, pp. 706 – 708, May 1994. [6.5.2](#)
- [205] R. Goldstein, H. A. Zebker, and C. L. Werner, "Satellite radar interferometry: Two dimensional phase unwrapping," *Radio Sci.*, vol. 23, pp. 713–720, 1988. [6.5.2](#)
- [206] M. Costantini, "A novel phase unwrapping method based on network programming," *IEEE Trans. Geosci. Remote Sensing*, vol. 36, no. 3, pp. 813 – 821, May 1998. [6.5.2](#)
- [207] G. W. Davidson and R. Bamler, "Multiresolution phase unwrapping for SAR interferometry," *IEEE Trans. Geosci. Remote Sensing*, vol. 37, no. 1, pp. 163 – 174, Jan. 1999. [6.5.2](#)
- [208] W. Xu and I. Cumming, "A region-growing algorithm for InSAR phase unwrapping," *IEEE Trans. Geosci. Remote Sensing*, vol. 37, no. 1, pp. 124 – 134, Jan. 1999. [6.5.2](#)
- [209] A. Lopés and F. Séry, "Optimal speckle reduction for the product model in multilook polarimetric SAR imagery and the wishart distribution," *IEEE Trans. Geosci. Remote Sensing*, vol. 35, pp. 632 – 647, May 1997. [7.2](#)

- [210] J. S. Lee, "Refined filtering of image noise using local statistics," *Comput., Vis., Graph., Image processing*, vol. 15, pp. 380 – 389, 1981. [7.2](#), [3](#)
- [211] J. Schou and H. Skriver, "Restoration of polarimetric SAR images using simulated annealing," *IEEE Trans. Geosci. Remote Sensing*, vol. 39, no. 9, pp. 2005 – 2016, Sept. 2001. [7.2](#)
- [212] C. López-Martínez and X. Fábregas, "Model based SAR polarimetric speckle noise filter," in *Proc. POLINSAR, Workshop on Applications of SAR Polarimetry and Polarimetric SAR Interferometry*. ESA, Jan. 2003. [7.4.3](#)
- [213] I. Bronshtein and K. Semendiaev, *Manual de Matemáticas Para Ingenieros Y Estudiantes*, Editorial Mir, Madrid, Spain, 1993. [A](#), [A](#)
- [214] M. S. Spiegel and L. J. Stephens, *Schaum's Outline of Statistics*, McGraw-Hill, third edition, 1998. [D](#)