Departament de Teoria
del Senyal i Comunicacions
UNIVERSITAT POLITÈCNICA DE CATALUNYA

MULTIDIMENSIONAL SPECKLE NOISE, MODELLING AND FILTERING RELATED TO SAR DATA

by

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Ph.D. Dissertation

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Barcelona, June 2, 2003

Chapter 1

Introduction

1.1 Radar Remote Sensing

Mankind has been always interested in his surrounding environment. Nowadays, this interest has caused the appearance of a wide spectra of technologies and techniques dedicated to gather and to analyze information about the Earth's properties and its dynamics. Among this bast amount of procedures, it exist a collection of technologies collectively known as Remote Sensing. The definition of Remote Sensing is not unique, but probably, the broadest definition is given by Charles Elachi in *Introduction to the Physics and Techniques of Remote Sensing*, where he defines Remote Sensing as the acquisition of information about an object without being in physical contact with it. This description does not actually specifies neither the type of information which is acquired nor the way it is acquired. More concrete definitions refer to Remote Sensing as the science of acquiring, processing and interpreting data that record the interaction between electromagnetic energy and matter.

In the last decades, Remote Sensing has arisen an enormous interest since it has been demonstrated as fundamental to monitor mankind's effects over the environment. This importance was ratified after the signature of the *Kyoto Protocol to the United Nations Framework Convention on Climate Change* in December 1997 and the holding of the more specific workshop *Remote Sensing and the Kyoto Protocol: A Review of Available and Future Technology for Monitoring Treaty Compliance* [2], which took place in October 1999 in the University of Michigan under the aegis of the International Society for Photogrammetry and Remote Sensing. As the name itself indicates, this workshop was convened to discuss how Remote Sensing technology could contribute to the information requirements raised by implementation of and compliance with the terms of the Kyoto Protocol.

There exist different ways in which Remote Sensing technologies can be classified. Indeed, this diversity has been always highlighted as a matter of complementarity and not as ranking of useful or useless technologies. A first classification can be established on the basis of the electromagnetic energy source. On the one hand, Remote Sensing technologies are classified as active when the illumination source is provided by the measuring system itself. On the other hand, passive Remote Sensing technologies are based on measuring the radiation emitted by the scene under analysis. A second classification divides the Remote Sensing technologies according to the system's working frequency. In this sense, systems are basically divided into microwave and optical systems. This thesis concerns the study of Synthetic Aperture Radars, also called SAR systems, which represent perhaps, the best example of active microwave systems.

The birth of the SAR technology can be established early in the 1950s, when it was demonstrated that the azimuth spatial resolution of a radar system could be drastically increased through a coherent recording and processing of the radar's echoes. The success of SAR systems is due to the fact that when mounted on orbital platforms, SAR systems are able to provide wide coverage, with high spatial resolution, independently of weather conditions and the day-night cycle. In this first period, the SAR systems were characterized for being very inflexible, since they operated basically in a single frequency, single polarization mode, able to provide two-dimensional, high resolution reflectivity maps of the imaged scene.

Despite the limitations derived from the fact of being single-channel systems, the increasing concern in SAR technology made possible a better understanding of this technology, from the different aspects associated with the physical sensor itself, to the requirements of the focusing process taking charge of the coherent combination of the different echoes producing the high-resolution reflectivity image. The first civilian SAR mission in space was the United State's SEASAT (L-band), which operated from early July to mid-September 1978. It was followed by the two Shuttle missions of one week duration each, SIR-A (L-band, November 1981) and SIR-B (L-band, October 1984). The activity in orbital SAR systems was increased with the launch of new platforms supported by national or international space agencies: KOSMOS (USSR; S-band; 1987-1989), ALMAZ (USSR; S-band; March 1991 to October 1992), ERS-1 (ESA; C-band; July 1991 to 1996) and J-ERS-1 (Japan; L-band; February 1992 to 1994).

Speckle is an effect inherent to all coherent measurement systems [3, 4, 5], and also to SAR [6, 7]. Since most of the times, the resolution cell dimensions are larger than the wavelength in which the system operates, it produces the returned echo from a particular resolution cell to be the result of the coherent addition of the echoes of the elementary scatterers inside the cell. This coherent addition can be constructive as well as destructive, producing the SAR image to present a noisy aspect. As one can deduce, speckle is a true electromagnetic measurement, since it is a function of the arrangement and properties of the elementary scatterers within the resolution cell. Because of the lack of knowledge of the internal structure of the wavefront leaving the resolution cell, it is necessary to analyze the speckle properties from an stochastic point of view. The statistics of concern are defined over an ensemble of resolution cells, all with the same *macroscopic* properties, but differing in the *internal* properties. This point of view of the imaging process allows to consider speckle as a disturbing factor [3, 4, 5, 6, 7, 8], that is, as a noise, since the reflectivity value of a particular resolution cell can not be predicted exactly in advance.

Speckle is often modelled, for single SAR imagery, as a multiplicative random noise process which is statistically independent of the scene [6, 7]. Hence, this disturbing signal has to be eliminated in order to have access to the average information. The reduction of speckle noise often involves an average process, generally known as multilook. The multilook reduces speckle noise according to the extend of the average process, but the most important disadvantage is that the spatial resolution is reduced by the same amount. Consequently, one can observe the existing trade-off between the reduction of speckle noise and the loss of the spatial properties of the SAR image. The speckle noise problem for single SAR imagery has been extensively studied and results concerning its reduction have been reported in the literature, where basic references are: J.S. Lee [8,9], D.T. Kuan [10], V.S. Frost [11] and A. Lopes [12,13]. One of the key aspects which has made possible to solve the speckle noise problem satisfactorily is the availability of the multiplicative speckle noise problem, that is, an expression which indicates where the useful information and the noise components are, and how they are combined. The increasing number of SAR missions made clear that speckle noise represents one of the main limitations of SAR technology.

SAR technology suffered a big breakthrough with the introduction of the concept of multidimensional SAR imagery. This concept is based on the idea of diversity, that is, on to acquire different SAR images, between which one or more imaging parameters vary. Multidimensional SAR imagery has made possible a large amount of new exciting applications. Indeed, it can be affirmed, that this process is still open nowadays, since multidimensional SAR data have been shown suitable for quantitative radar remote sensing applications.

A relevant multidimensional SAR data application is SAR interferometry, also referred as InSAR, in which two SAR images from the same Earth's surface area are acquired from slightly different positions. In 1974, L.C. Graham demonstrated that the phase difference between a pair of SAR images can be related with the terrain's relief [14]. These techniques were later extended by H.A. Zebker and R.M. Goldstein in [15], introducing digital image processing techniques on the basis of SAR images acquired with the JPL airborne AIRSAR sensor [16, 17, 18]. In 1988, it was demonstrated that this technique could be applied to satellite SAR images acquired on separate passes acquired over several days [19]. By combining several ERS-1 images with a Digital Elevation Model (DEM), in 1993 D. Massonet *et al.* demonstrated that SAR interferometry is a powerful tool to monitor the Earth's dynamics. At the same time, the different problems associated with SAR interferometry, as for instance: phase unwrapping, phase noise reduction or phase preservation in SAR image processing, were considered. In these early stages, SAR interferometry was based on the combination of SAR images acquired by already existing SAR systems. This technique reached his maturity with the launch of specific SAR interferometric sensors. The fist mission was the SIR-C/X-SAR, a joint venture between United States, Germany and Italy which flew a multi-frequency (L-, C- and X-band) SAR sensor onboard the Shuttle in an interferometric configuration. Another breakthrough for SAR interferometry was the launch, in 1995, of the ERS-2 system, a copy of the ERS-1 sensor, which flew in a tandem configuration. Additional interferometric SAR sensors, as the commercial system RADARSAT (Canada; C-band; November 1995 to 2000) or the already mentioned Japanese J-ERS help to the advance of this technique. The importance of SAR interferometry was finally demonstrated by the launch, in February 2000, of the NASA's Space Shuttle for the SRTM mission (Unites States, Germany and Italy; C- and X-band), with the objective to map the entire land surface.

The usefulness of SAR interferometry lies on the concept of coherence between SAR images, that is, on how much both SAR images are correlated. For highly correlated SAR images, the speckle patterns of both images are very similar, producing the phase difference image to present a very low variance. The lower the coherence, the larger the difference between the speckle patterns and the larger the phase variance [20, 21, 22]. This phase variance, as it is consequence of speckle, is normally referred as phase noise. There exist two clear forms to decrease the influence of this noise term. The first consists of increasing the coherence by varying the different system parameters. When this is not feasible, signal processing techniques must be considered. In this direction, the wavelet analysis theory [23, 24, 25] has been demonstrated as a robust image processing technique when spatial resolution is main topic of concern. As it is presented later in this thesis, this new processing tool allows to reduce phase noise effects very efficiently. Additionally, it allows the retrieval of relevant information when the Hermitian product of a pair of SAR images is considered.

Electromagnetic waves are characterized by a vectorial nature, since the electric and magnetic fields are defined by a magnitude and a vector. This vectorial character is called polarization. Therefore, it is possible to define multidimensional SAR imagery on the basis of wave polarization. This is referred as SAR polarimetry or PolSAR.

The mathematical foundations of wave polarization were formally established in 1852 by J.C. Maxwell with the laws of macroscopic electromagnetics, despite previous works in optics studied the vectorial nature of light. In the same period, G. Stokes established the foundations to describe partially-polarized light, a concept which will be shown fundamental in this thesis. The first works conducted in radar polarimetry are due to G. Sinclair in 1946, where he introduced the concept of scattering matrix to describe the polarimetric properties of a given scatterer [26]. Major contributions came in the following years, among which it has to be pointed out the research carried out by E.M. Kennaugh defining the concept of optimal polarization [27], by J.R. Huynen with the idea of radar target phenomenology [28] and the critical analysis and the extension of these works performed by W.-M. Boerner [29]. The full development of radar polarimetry requires a complete understanding of the concept of partial polarization introduced by G. Stokes. Major research carried out in this topic was conducted by Müeller and R.C. Jones in the early 1940s concerning wave propagation, leading to the so-called Jones calculus, which has been also considered in radar scattering analysis [30,31,32].

In the last years, SAR polarimetry has been the objective of a significant number of researchers. The results derived from this growing interest have demonstrated the usefulness of polarimetric diversity in order to gather important information about the scattering process which occurs at the Earth's surface. As a result, spaceborne polarimetric SAR systems have been launched: as the SIR-C (United States; C- and L-band; April 1994) and ENVISAT (ESA; C-band with partial polarization; March 2002), or are planned missions: ALOS (Japan; L-band; scheduled for 2003), RADARSAT-2 (Canada; C-band; scheduled for 2004) or TERRASAR (Germany; L- and X-band; scheduled in 2005). Additionally, it is worth to mention that most of the advances in SAR technology have been possible as a consequence of the airborne SAR systems. This configuration makes possible to test, with a lower cost, new ideas which will become part of spaceborne SAR systems in the future. A few examples of these platforms are: E-SAR (DLR, Germany; P-, L- and S-band fully polarimetric; C-, X-band single polarization), AIRSAR (JPL, United States; P-, L- and C-band fully polarimetric), EMISAR (DDRS, Denmark; L- and C-band fully polarimetric), PHARUS (TNO-FEL, The Netherlands; C-band fully polarimetric), PISAR (NASDA/CRL, Japan; L- and X-band fully polarimetric), RAMSES (ONERA, France; P-, L-, S-, X-, Ku-, Ka-, W-band fully polarimetric) and SAR580 (CCRS, Canada; C- and X-band fully polarimetric).

One of main characteristics of fully polarimetric radars is the possibility to decompose the scattering process from random media into elementary scattering processes. The roots of scattering decomposition where formulated in the J.R. Huynen's Ph.D. dissertation [28] on the basis of several works conducted in the past. A first type of decomposition techniques, called coherent decompositions, are based on decomposing the scattering matrix [33], whose main drawback is that they do not consider the effects of speckle noise, restricting their validity to those cases in which only a dominant scatterer is expected. The second type of decompositions, known as incoherent decompositions, whose foundations have to be found in the works of J.R. Huynen [28], S.R. Cloude [34] and E. Pottier [35], are more general since they decompose second moment polarimetric descriptors. The final idea behind these decompositions is to analyze the average scattering mechanism within random scattering media. A comprehensive description of the target decomposition techniques can be found in [36].

A polarimetric SAR system operates basically by acquiring a set of SAR images in an orthogonal polarization basis. Therefore, speckle noise will not only affect the properties of the SAR images, but also the polarimetric properties of the scattered waves. Hence, one can deduce that the concept of partial polarization is directly linked to the concept of speckle noise. Without loss of generality, it can be assumed that a radar system transmits a complete polarized wave, i.e., a wave whose polarization state is constant. If the same set of resolution cells employed to describe speckle noise for single SAR imagery is now considered, one can conclude that the polarization state of the scattered waves from each resolution cell will vary in a random way. Since the resolution cells are assumed homogeneous, it can be considered that the scattered waves have an average polarization state. Therefore, this makes feasible to define an average scattering mechanism, whose physical interpretation is pursued, as mentioned, by the incoherent target decomposition techniques.

As shown, speckle noise plays an important role in SAR polarimetry. Indeed, this problem represents the main topic of this thesis. Different approaches have been presented in the literature to solve the problem of speckle noise reduction in SAR polarimetry, as for instance: L.M. Novak and M.C. Burl [37], Q. Lin and J.P. Allebach [38], J.S. Lee [39], S. Goze and A. Lopes [40], R. Touzi and A. Lopes [41]. Considering the concept of average scattering mechanism, speckle noise reduction can be considered also as the process to estimate this average scattering mechanism [36]. Therefore, the polarimetric properties of this mechanism have to be retained by the noise reduction process. Additionally, since SAR imagery is characterized by a high spatial resolution, these properties have to be considered also when speckle noise is eliminated. All the techniques enumerated previously represent basically an extension of techniques already existing for single SAR images. Since polarimetric properties are not considered, these techniques do not preserve them. The approach presented in [1] by J.S. Lee *et al.* represents a first approach to filter

Polarimetric SAR data with the maintenance of the polarimetric, as well as the spatial properties of the SAR images. Despite it is still based on an extension of the multiplicative speckle noise model for single SAR imagery. This approach can be considered only as valid when all the polarimetric SAR images are uncorrelated [7]. All these approaches make clear that the speckle noise problem in SAR polarimetry, and in multidimensional SAR imagery to a greater extend, is still not solved, mainly, as a consequence of the lack of a suitable speckle noise model.

Multidimensional SAR imagery can be further extended by adding new information channels. In the last years, it has been demonstrated that it is possible to perform robust, model based, quantitative radar remote sensing by considering SAR interferometry together with SAR polarimetry, by means of the so-called polarimetric SAR interferometry, or PolInSAR [42,43]. The number of information channels can be increased by considering SAR systems operating in additional modes. A first form is to operate a SAR system in a multi-frequency mode, in order to make use of the frequency dependent behavior of scatterers, with the objective to increase the amount of information which can be retrieved about the scatterer itself [44, 45]. Multi-temporal configurations are also feasible to consider temporal effects or to monitor the evolution of a particular scatter or a given process taking place in the Earth's surface. An interesting extension of SAR interferometry, known a multi-baseline interferometry [46], is based on the possibility to acquire SAR images from more than a pair of positions. This idea can be brought to the extreme of acquiring a large amount of SAR images in the vertical dimension, making possible to construct three dimensional reflectivity images. As one can deduce, since the basis of all these ways of extending SAR imagery, collectively known as multidimensional SAR imagery, is based on the concept of synthetic aperture, they are affected by speckle noise.

1.2 Scope and Organization of the Thesis

The scope of this thesis is the analysis and the elimination of speckle noise in multidimensional data, with special emphasis in Synthetic Aperture Radar applications. Accordingly, the research work of this thesis is divided into two main areas of study. The first part consists of the proposal of a novel speckle noise model for multidimensional SAR data on the basis of the scattering theory. The second part concerns its reduction, subjected to the preservation of the signal properties and the spatial resolution on the basis of the wavelet analysis theory. The organization of this thesis is as follows:

Chapter 2 is devoted to present the principles of SAR technology. The first part of the chapter contains a detailed derivation of the SAR impulse response and the SAR system model, as a basis for the stochastic description of SAR imagery. The multiplicative noise model for speckle is introduced next. The second part of the chapter establishes the basics of SAR interferometry. A geometric analysis permits to analyze the deterministic component of the interferometric phase, whereas from the detailed description of the interferometric SAR system model, one can characterize the stochastic component. The concept of coherence between a pair of SAR images is emphasized. This part ends with the derivation of the additive noise model for the interferometric phase. The last section of the chapter is focused on SAR polarimetry and polarimetric SAR interferometry. After describing the electromagnetic wave polarization, the scattering matrix, as well as its extension to describe random scattering media by means of second moments is examined in detail. The stochastic scattering process description is detailed next, where it is shown that the multidimensional speckle noise model can no be derived by extending the multiplicative noise model for SAR images. The chapter ends by presenting the basics of polarimetric SAR interferometry.

Chapter 3 is focused on a completely different topic from SAR, since it presents the principles of the wavelet analysis theory. Despite these two topics appear to be completely different, as it will be demonstrated in this thesis that they are, indeed, complementary. Essentially, the wavelet analysis theory will be shown as a suitable tool to consider those aspects of SAR imagery concerning spatial resolution maintenance. The first part of the chapter contains a brief description of the continuous, as well as the ideas behind the discrete wavelet transforms, with special attention to the admissibility condition of a wavelet function. Next, the multiresolution analysis is introduced. This concept represents perhaps, the most important advance in wavelet analysis theory, since it establishes the connection between continuous-time *orthogonal wavelets* and the world of digital signal processing. The multiresolution analysis allows to see the wavelet transform as a filter bank. Hence, it is employed to introduce the discrete wavelet transform, its fast calculation and the extension to the two-dimensional case. The arbitrary tiling of the time(space)-frequency plane is considered under the discrete wavelet packet transform. The chapter ends with a detailed description of different wavelet functions. These two chapters are devoted to present the theory in which this thesis is based on. The next four chapters represent the nucleus of this work.

In this thesis, multidimensional SAR data are considered under the covariance matrix representation. The Hermitian product of a pair of SAR images represents the basic building block of this formulation. In this direction, **Chapter 4** constitutes the first step towards the definition of a noise model for the Hermitian product of a pair of SAR images, as a basis for the multidimensional SAR speckle noise model. Chapter 4 begins with the presentation and quantitative validation of a novel noise model for the unit amplitude phasor whose argument consists on the phase difference of the Hermitian product of a pair of SAR images, named interferometric phasor, with special attention to SAR interferometry. One of the main outcomes of this analysis is the definition of a new coherence parameter which will be shown as fundamental for the multidimensional speckle noise model. The second part of Chapter 4 translates this noise model to the wavelet domain. On the one hand, the model in this new domain allows to determine the information contained in each complex wavelet coefficient. Therefore, it opens the door to analyze the interferometric phase in the wavelet domain. On the other hand, it is demonstrated that the wavelet transform itself can be considered as an interferometric phase noise filter. The chapter finishes with an example of the analysis of real SAR data in the wavelet domain.

Chapter 5 contains the main contribution of this thesis, since the multidimensional speckle noise model for SAR imagery is presented within the chapter. The bases over which this model is derived are presented at the beginning of the chapter. The suitability of the covariance matrix formulation is first justified. Next, the results derived in Chapter 4 are generalized to consider the phase difference of a general Hermitian product of a pair of SAR images. The following part of the chapter consists on a complete and detailed study of the Hermitian product statistics, leading to the derivation of a novel speckle noise model for the Hermitian product. Since all the covariance matrix entries consist of Hermitian products, the multidimensional speckle noise model is straightforwardly derived and quantitatively validated. In a first stage, the model's robustness is validated by means of simulated and real multidimensional SAR data. In the last part of Chapter 5, the proposed model is validated with SAR data acquired at P-, L-, C- and X-band. This validation allows to extend the noise model to consider SAR images acquired at different frequencies.

The following two chapters concern the usage of the proposed speckle noise models to estimate relevant information and to reduce its effects. **Chapter 6** is focused on exploiting the results derived in Chapter 4. The first part of the chapter contains a brief description of the state of the art concerning interferometric phase noise filtering and coherence estimation. The interferometric phase noise model in the wavelet domain serves as a basis to define a novel algorithm to reduce the interferometric phase noise and to estimate coherence information. The second part of the chapter is devoted to study and to present the filer's performance with respect to the interferometric phase noise reduction problem. The proposed algorithm is quantitatively compared with existing techniques by means of simulated interferometric data. In addition, the filter's performance is studied by means of several real interferometric phases. The properties concerning the spatial resolution maintenance are analyzed with detail. The characteristics of the proposed algorithm, with respect to its capability to estimate coherence information are analyzed in the last part of Chapter 6. The capability to estimate the coherence with high spatial resolution is specially considered.

Chapter 7 represents the synthesis of the ideas and concepts which have been presented and validated in the previous chapters. The chapter is focused, mainly, on speckle noise reduction in polarimetric SAR data, despite all the ideas can be easily exported to SAR data with a higher dimensionality. A brief revision of existing techniques to reduce speckle noise effects in polarimetric SAR data is presented in the first part of the chapter. The following part extends the results obtained in Chapter 6, concerning the estimation of the complex coherence coefficient for SAR interferometry, to a general pair of complex SAR images. Consequently, the multidimensional SAR imagery correlation structure can be estimated with high spatial resolution. Thanks to the availability of the Hermitian product speckle noise model defined in Chapter 5, the linear minimum square error filter (LMMSE) is derived, making clear that optimal speckle noise reduction for the Hermitian product of a pair of SAR images has to consider the complex correlation coefficient between SAR images. The ideas behind the LMMSE approach are extended to filter multidimensional SAR imagery, under the covariance matrix representation. Hence, since speckle is reduced according to the multidimensional correlation structure, the elements of the covariance matrix are processed differently. The main contribution of this new approach is that it demonstrates that the covariance matrix properties can be preserved perfectly, despite its elements are processed differently. This novel approach is validated by using simulated and real PolSAR data. As it will be presented, the polarimetric properties of the multidimensional SAR data are perfectly maintained in all the cases. The availability of the multidimensional speckle noise model, and its application to remove speckle noise, will be employed at the end of the chapter to introduce novel principles for optimum filtering of polarimetric speckle noise, and by extension, the elimination of multidimensional speckle noise.

Finally, **Chapter 8** summarizes the obtained results and draws the main conclusions which come out from this dissertation research study.