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MULTIDIMENSIONAL SPECKLE NOISE, MODELLING AND FILTERING RELATED TO SAR DATA

by

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Chapter 8

Conclusions and Future Work

After an extensive analysis of the literature, it was possible to conclude that the multidimensional speckle noise problem for SAR imagery could not be considered as to be completely solved due to the lack of a suitable noise model. This absence has been iteratively overcome by extrapolating the speckle theory from single-channel SAR imagery to the multidimensional case. Since this extension is not possible, all the techniques designed to reduce speckle effects on multidimensional SAR imagery based on this extension lead to a loss of the multidimensional data properties or to signal underfiltering. The work presented in this thesis proposes a solution to this problem since the knowledge of speckle has been gathered, reviewed, extended and applied to multidimensional SAR imagery. This work has been divided into two main areas of research. The first part has covered the theoretical analysis of the multidimensional speckle noise problem with the proposal of a novel noise model for multidimensional SAR imagery. The second part has dealt with the reduction of speckle noise effects in multidimensional SAR imagery. As it was presented in the Introduction, multidimensional SAR imagery speckle noise reduction is constrained by the maintenance of both: the multidimensional and the spatial properties. On the one hand, the proposed speckle noise model has made possible an optimum speckle noise reduction which preserves the properties of the signal. On the other hand, the spatial resolution is maintained on the basis of the wavelet analysis theory.

Within this work, multidimensional SAR imagery has been considered under the covariance matrix formulation. The usefulness of this representation lies in the fact that all the elements of this matrix are constructed as the complex Hermitian product of a pair of SAR images. Therefore, the multidimensional SAR imagery speckle noise model is derived as an extension of the Hermitian product speckle noise model, without this extension depending on the number of dimensions, i.e., the number of SAR images.

On the basis of the Gaussian scattering assumption, the complex Hermitian product phase, in the real plane, is described by an additive noise model. This idea is employed to derive a novel complex noise model for the unit amplitude phasor whose argument consist in the Hermitian product phase. For interferometric SAR data, this new phasor is referred as the interferometric phasor, whereas for a general Hermitian product it is referred as the phase difference phasor. A detailed study of the probability density functions associated with this phasor has made possible to identify noise sources, i.e., sources of randomness, and how they interact with useful information, i.e., the average signal value. As a result, a noise model for the interferometric phasor is proposed and extensively validated by means of simulated and real interferometric SAR data. Additionally, the model is demonstrated to be valid for single- and for multilook SAR imagery. An important result of this analysis has been the definition of the parameter N_c. It has been proved that it contains the same information as the coherence, but also the effect of the number of looks. As shown throughout this text, N_c is a key parameter. On the one hand, it allows to estimate the complex correlation coefficient ρ with high spatial resolution, but, on the other hand, it represents the basis over which the multidimensional speckle noise model is established for SAR data.

A deeper analysis of the noise model for the interferometric phasor has demonstrated the possibility to extract both: the true interferometric phase, as well as the interferometric coherence from the measured interferometric phase expressed in the complex plane. Since one of the main properties of SAR imagery is the high spatial resolution, this feature has to be preserved in any parameter derived from it. This is the reason why the discrete wavelet transform is considered to estimate the interferometric phase and the coherence. In order to have a complete knowledge of the interferometric phasor in the wavelet domain, it has been necessary to translate the interferometric phasor noise model from the original to this new domain. Once this translation has been obtained, it makes possible to identify the information contained in each complex wavelet coefficient. Thus, it is demonstrated that the amplitude of the wavelet coefficients contains basically coherence information, whereas the phase is determined by the interferometric phase. This fact allows to define the concept of modulated coherence as a complex phasor whose amplitude is N_c and the phase is given by the interferometric phase. A more careful analysis of the speckle noise model in the wavelet domain reveals that the wavelet transform improves the quality, in terms of signal to noise ratio, of the interferometric phase. This improvement is performed in such a way that the larger the number of wavelet scales, the larger the signal improvement. The signal to noise ratio increment is obtained at the expense of spatial resolution, but the most important conclusion is that the loss in spatial resolution can be recovered in the inverse transformation process, since the discrete wavelet transform is a lossless transform.

On the basis of the interferometric phasor noise model in the wavelet domain, a new algorithm to estimate both: the true interferometric phase and the interferometric coherence has been proposed. The working principle of this novel approach consist of the maintenance of the improving factor introduced by the wavelet transform in those wavelet coefficients which contain useful information, avoiding its loss in the inverse transform process. The effectiveness of this approach is demonstrated theoretically.

In a first stage, the performance of this novel algorithm with respect to interferometric phase noise reduction is tested by means of simulated and real interferometric SAR data. As a general result, it is demonstrated that this algorithm is able to estimate the interferometric phase preserving the spatial resolution and the spatial details, even for low coherence areas. The use of simulated interferometric phase data has allowed to perform a precise quantitative analysis of the algorithm's performance, showing that it overcomes already existing interferometric phase filters. In addition, the algorithm is tested with real interferometric phases. These tests have permitted to define several criteria that a wavelet filter needs to fulfill in order to be suitable for interferometric phase noise reduction. One can conclude that wavelet filters with a relatively large number of vanishing moments avoid the appearance of processing artifacts and allow to extend filtering to lower coherence areas than in the case of shorter filter. It is also proved that the number of vanishing moments is not a key factor determining the capability to reduce phase residues. A special case of study, with respect to the maintenance of the spatial resolution, has been phase noise reduction in urban areas. As it comes out from the obtained results, the proposed algorithm is able to maintain all the image details. The reason behind this capability has to be found first, in the ability of the discrete wavelet transform to represent these details, but also in the way the signal is processed in this domain. Since the algorithm does not eliminate any wavelet coefficient, but only increases the contribution of those containing useful information, it produces that the possible useful information contained in the noise coefficients is still incorporated to the inverse transformation process.

In a second stage, the capability of the algorithm to estimate the coherence information, through N_c, is also considered. On the basis of the multiresolution analysis performed by the discrete wavelet transform, the proposed algorithm is able to estimate the interferometric coherence with more spatial resolution than the standard multilook approach. A direct consequence of this new coherence estimation algorithm is that the estimated coherence map contains more image details. Since this novel approach reduces the spatial resolution losses when the interferometric coherence is estimated, it could be of special interest for high spatial resolution applications. As it demonstrated, an important characteristic of this novel interferometric coherence estimator is that it is unbiased with respect to the topographic phase component. This consequence is due to the fact that the coherence is estimated through the parameter N_c.

It is worth to mention that the main potential of the wavelet analysis theory for interferometric SAR imagery analysis lies in the fact that it performs a correct signal estimation without the necessity of any type of external help. This can be observed by considering the two main issues which determine the characteristics of any complex correlation coefficient estimation process. Since SAR imagery is inhomogeneous, it is required to analyze it locally. With the use of the wavelet analysis theory, it is not necessary to design a process to analyze locally the signal, since the wavelet transform itself provides this facility. In addition, as the wavelet transform increases the useful signal quality, i.e., it reduces speckle noise effects, it is not necessary to reduce it in the wavelet domain. The only task to perform, as it has been done, is to maintain the improving factor introduced by the transformation process in order to avoid its loss in the inverse transformation.

Since under the Gaussian scattering assumption, the complex Hermitian product probability density function does not depend on the type of information it contains, the noise model for the interferometric phasor can be extended to a general phase difference phasor. In this sense, the algorithm defined to estimate the interferometric complex correlation coefficient can be also extended to estimate this coefficient for a general complex Hermitian product. This extension has been validated for polarimetric SAR data. As it happens for interferometric SAR data, in this case, the estimated complex correlation coefficient is characterized by presenting a high spatial resolution.

The speckle noise model for a general complex Hermitian product of a pair of SAR images is constructed on the basis of the noise model for the phase difference phasor, to which, the Hermitian product amplitude is incorporated. As a result, the Hermitian product is divided into three additive components. A detailed study of these components allows to identify, again, noise sources, i.e., sources of randomness, and how them corrupt the useful information content, i.e., the mean value of the Hermitian product. This intermediate result can be considered already as a speckle noise model for the Hermitian product, but additional simplifications permit to define a linear speckle noise model for the complex Hermitian product. In conclusion, the Hermitian product speckle noise is due to two different noise mechanisms. On the one hand, speckle noise presents a real, homogeneous, multiplicative noise component which introduces noise only over the Hermitian product amplitude. On the other hand, speckle noise presents a complex, inhomogeneous, additive noise component which introduces noise both, in the amplitude and the phase of the complex Hermitian product. The inhomogeneity of this noise component is due to the fact that the standard deviation of the real and imaginary parts of this additive noise component are function of the coherence characterizing the Hermitian product, in such a way that, the lower the coherence, the larger the standard deviation.

The nature of the final speckle component for the complex Hermitian product results from the combination of the multiplicative and the additive speckle components, which is determined by the complex correlation coefficient which characterizes the complex Hermitian product. On the one hand, the homogeneous multiplicative noise component is multiplied by the complex modulated coherence term. Thus, the contribution of this speckle component to the Hermitian product real and imaginary parts is determined by the real and the imaginary parts of the complex modulated coherence term respectively, which is quantitatively similar to the complex correlation coefficient. On the other hand, the contribution of the additive speckle terms for the real and imaginary parts of the Hermitian product is only determined by the coherence value. Consequently, for low coherence areas, the Hermitian product speckle noise is dominated by an additive behavior. For coherences with medium and high values, the situation is more complex. In this case, the speckle noise nature depends also on the average phase difference through its influence on the real and imaginary parts of the modulated coherence term which multiply the multiplicative speckle component. Therefore, whenever the real or the imaginary parts of the modulated coherence term are zero, the real or the imaginary parts of the Hermitian product are dominated by the additive speckle component. An important consequence of this dependence is that the nature of speckle noise differs between the real and imaginary parts of the Hermitian product. Finally, regardless the phase difference dependence, and measuring the importance of the different Hermitian product terms affected by the two noise mechanisms in standard deviation terms, it has been demonstrated that the multiplicative speckle term can be considered as dominant for the Hermitian product real and imaginary parts only for coherences higher than 0.675. Below this value, speckle is dominated by an additive behavior.

The Hermitian product speckle noise model has been derived for a general Hermitian product. Therefore, it is able to determine the speckle noise nature for the diagonal and the off-diagonal covariance matrix entries. As it has been demonstrated, this novel noise model can be considered as a generalization of the multiplicative speckle model for the SAR images intensity. On the other hand, the multidimensional speckle model for a set of SAR images can be obtained straightforwardly by extending the noise model to all the covariance matrix elements. A practical consequence of this novel multidimensional noise model, is that it permits to process multidimensional SAR data without the difficulty associated with the complex Wishart probability density function.

An important objective of this work has been to test the validity and robustness of the multidimensional speckle noise model. In a first stage, the noise model has been tested with simulated multidimensional SAR data. This test has allowed to validate the different expressions which characterize the noise model. In a second stage, the model has been extensively tested, in a quantitative way, with real multidimensional SAR data. Specifically, the speckle noise model is tested with: polarimetric, polarimetric interferometric and multi-frequency SAR data. The use of least squares regression analysis allows to conclude that the novel noise model is able to explain the speckle behavior for multidimensional SAR data in different situations, confirming therefore, the model robustness. The use of polarimetric SAR data has evidenced the inhomogeneity of speckle noise for the Hermitian product, but also, the fact that it presents different behaviors for the real and the imaginary parts of the Hermitian product, as a consequence of the average phase difference dependence. This dependence acquires its maximum relevance in the case of polarimetric interferometric SAR data, since in this case, it is demonstrated that the speckle noise behavior is controlled by the terrain's relief. The proposed model has been also proved to be valid for a wide range of frequencies, as confirmed by tests in: P-, L-, C- and X-bands. This analysis is taken as a basis to conclude that the multidimensional speckle model can be extended to SAR images acquired at different frequencies.

The availability of the multidimensional noise model has permitted to derive the linear minimum square error estimator (LMMSE) for the complex Hermitian product. The final expression of this estimator has been derived on the basis of several simplifications, making its practical use to be difficult. Nevertheless, despite the approximations, the LMMSE filter expression permits to extract two important conclusions concerning the optimum filtering of the complex Hermitian product. First, this filtering has to be done in accordance with the complex correlation coefficient. Second, to approximate the speckle noise model by a fully multiplicative noise model leads to signal underfiltering. If the filtering concept behind the LMMSE approach is extended to all the covariance matrix entries, it is clear that they have to be filtered according to the particular complex correlation coefficient which characterizes each matrix entry. Hence, from a point of view of a multidimensional SAR signal, one can conclude that the speckle noise in the covariance matrix has to be eliminated according to the data's correlation structure.

The concept of filtering the elements of the covariance matrix in a different way, but in accordance with the proposed multidimensional speckle noise model, represents an advance with respect to the previous ideas and principles concerning multidimensional SAR imagery filtering. As demonstrated, to process multidimensional data on the basis of this approach does not damage the multidimensional signal properties. In the case of polarimetric SAR data, it has been proved that despite the covariance matrix elements are processed differently, the polarimetric properties are perfectly preserved. Even, since this approach considers the additive speckle component, it leads to a larger noise reduction with the consequent reduction of the biases of the different polarimetric indicators as: coherences, entropy or anisotropy among others.

Despite the LMMSE approach is not considered directly, the concepts behind it have been practically implemented leading to the definition of a novel approach to filter multidimensional SAR data. This idea is based on a two-step process: the first step eliminates the additive speckle components on the basis of the data's correlation structure, whereas the second step eliminates the multiplicative speckle term. A first implementation of this procedure has considered the use of the multilook approach to estimate the data's correlation structure for the additive speckle noise elimination and for the filtering of the multiplicative noise component. In summary, the proposed algorithm outperforms clearly the standard multilook approach as a consequence of the larger noise reduction, without corrupting the polarimetric information, despite the covariance matrix entries are differently processed. This implementation presents the drawback that speckle noise is reduced at the expense of spatial resolution. Therefore a more advanced approach has been studied. In this case, the data's correlation structure is estimated by means of the algorithm based on the wavelet analysis theory which has been defined in this thesis. As proved, the information derived with this algorithm permits to eliminate the additive speckle noise without spatial resolution losses. The multiplicative speckle noise term is eliminated by means of the LMMSE filtering approach presented by J.S. Lee *et al.* [1], which is specifically defined to reduce multiplicative noise without corrupting the signal's spatial properties. As shown, this approach is able to reduce polarimetric speckle noise optimally without the loss neither the spatial nor the polarimetric properties of the signal. All these results have permitted to introduce new principles concerning the definition and implementation of an optimum polarimetric SAR data filter. These novel principles are basically introduced as a direct consequence of the multidimensional SAR speckle noise model which has been derived in this thesis.

The research started in this thesis represents a first step towards a better understanding of speckle noise in multidimensional SAR imagery. The implications of the theory and results presented here suggest some directions in which further efforts should be addressed.

First of all, a natural way to extend the research performed in this thesis is to include the multidimensional speckle noise model in SAR imagery processing. A first point which has to be taken into account is to extend the research on multidimensional speckle noise reduction. As it has been demonstrated, the noise reduction is constrained to the availability of a reliable estimation of the complex correlation coefficients. Consequently, further research is needed in this direction. Nevertheless, the ideas and concepts presented in this thesis can be employed to different SAR imagery processing procedures, as for instance, signal classification. Another important field of application of these novel models is the improvement of the estimation of the different parameters associated with SAR imagery. In this direction, the model can help to reduce the estimation biases of these parameters, specially in those areas with low signal quality.

Another point which needs further research is the extension of the multidimensional SAR speckle noise model to the case of textured areas. In this case, multidimensional SAR data are characterized by the K-distribution probability density function, which consist of a complex Wishart distribution multiplied by a Gamma distribution accounting for the texture. Therefore, the model presented in this text can be considered as a starting point to define a noise model for the K-distribution. Since signal texture is a signal property characterized by a relatively high spatial resolution, it could be interesting to analyze multidimensional speckle noise reduction, in these situations, by means of the wavelet analysis theory.

The extension of the use of the wavelet analysis theory to process multidimensional SAR imagery is an interesting topic of supplementary research. As it has been shown in this thesis, the wavelet analysis theory represents an efficient alternative to consider the high spatial resolution of SAR imagery. The wavelet transform has been considered through the Mallat Algorithm. Since this is not the only alternative to calculate this transform, different alternatives have to be considered. These differ basically on the way the space-frequency plane is divided. In this sense, arbitrary tailings controlled by the signal being transformed, named *best basis selection*, seem to be promising. In these situations, the signal itself determines in which areas spatial resolution is a priority in front of signal averaging. Another important improvement which should be considered is the use of non-subsampled wavelet transforms, since these alternatives can improve the maintenance of spatial resolution.

Another important application of the wavelet transform is the possibility to work within the transformed domain in order to perform additional processing, and not only noise reduction. The noise model for the interferometric phasor in the wavelet domain represents a first step into this direction. Since, the coarse approximation wavelet band can be considered basically as a multilook, it is necessary to articulate new ways to combine this information with the rest of wavelet detail bands. In this sense, an interesting point of research is to determine which type of information can be extracted from the inter-scale relations.

Finally, since the wavelet analysis theory is a representant of the most general theory of multi-resolution analysis, different multi-resolution techniques should be considered to study and process SAR imagery. All these techniques fit with the necessity of taking into account the high spatial resolution of SAR imagery.