PolSAR Speckle Filtering Techniques and Their Effects On classification

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Abstract

In this paper the most significant and recent polarimetric SAR (PolSAR) speckle filters that have been developed so far are reviewed and the effects of them on classification and their ability to preserve polarimetric properties along with their strength in noise reduction are studied. For this purpose, the PolSAR filters such as refined Lee, intensity driven adaptive neighborhood (IDAN), scattering model base (SMB), speckle reduction anisotropic diffusion (SRAD), and a Non-Local PolSAR filtering are tested. These filters have been applied to a C-band multilook Polarimetric data taken by Radarsat-2 sensor over San Francisco Bay area, then the performance of the filters have been evaluated from various aspects: (1) land-use classification (2) speckle reduction level (3) edge preservation (4) polarimetric information maintenance.
KEY WORDS: polarimetric synthetic aperture radar (PolSAR), terrain classification, speckle filtering, polarimetry

I. Instruction

Speckle is noise-like because it is a true electromagnetic measuring and determined by the scattering process itself. Nevertheless, from the viewpoint of image processing speckle is considered as a disturbing factor that must be removed. Speckle existing in PolSAR data is due to the coherent nature of the SAR system. For reciprocal media, PolSAR data can be contained three correlated polarization channels: HH, VV and HV, where H and V indicate horizontal and vertical direction of polarized wave respectively. Speckle not only affects three intensity images, but also has effect on complex cross product terms. Speckle filtering should reduce speckle of whole covariance or coherency matrix.

Diagonal terms of covariance or coherency matrix that are three intensity images can be characterized by a multiplicative noise model but the off diagonal terms that are complex can be modeled by a combination of multiplicative and additive noise model [f1]. Speckle noise make mostly the explanation and analysis of images complex and also decrease the effectiveness of classification. Though, Speckle reduction is more difficult for polarimetric SAR than single-channel SAR because it must consider preserving the polarimetric properties, not to introduce cross-talk to deal with whole terms of covariance matrix for instance in a similar way. In addition, it is import not to degrade image quality.

Several scenario have been studied to reduce speckle noise in PolSAR data. According to the final objective, these PolSAR filtering algorithms can be divided into two groups. For first group, most important thing is to preserve spatial resolution even at expense of losing polarimetric information or introducing crass-talk between polarization channels. These approaches assume PolSAR data as a type of diversity. The second group tries to look at the issue from the perspective of spatial processing, thus it will be affecting the spatial resolution. This view does not allow the previous problem. It is clear that there is a trade-off between spatial resolution maintenance and the preservation of polarimertic properties [f2].

In early techniques of speckle reduction, the polarimetric information was not carefully preserved, and introduced some cross-talk between the channels. Novak and Burl are among the pioneers in polarimetric speckle filtering research [f3]. Moreover, Lee [f4], Goze and Lopes [f5] and Lopes and Sery [f6] proposed the filters that exploited statistical correlations between polarization channels, consequently all the terms of filtered covariance matrix will be totally correlated.

But recently many new speckle reduction techniques for PolSAR data are proposed that do not have problems of earlier despeckling approaches. Lee et al. [f1] proposed an alternative approach to preserve statistical characteristics between channels and avoid introducing cross-talk. Lee et al. also proposed a scattering model base (SMB) filter [f7] that would be more efficient than [1] in maintaining polarimetric properties. Yu et al. [8] outlined speckle reduction anisotropic diffusion (SRAD) filter using anisotropic diffusion technique and partial differential equation (PDE) approach that is edge-sensitive and adaptive. Vasile et al. [f9] proposed a new method, intensity driven adaptive neighborhood (IDAN), that is an extended idea of [2] filtering coherency matrix of polarimetric or interferometric SAR data. Chen et al. also recently provided a Non-Local PolSAR filter [f10] that was used as a test statistic based on complex Wishart distribution to decide the selection of homogeneous pixels.

II. Speckle Filtering Techniques

A) PolSAR data

The scattering matrix of a medium that is measured by polarimetric radar can be written as

$$S = \begin{bmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{bmatrix} \qquad \text{Eq. 1}$$

Where h and v indicate the horizontal and vertical linear polarization and S_{hv} means wave transmitted horizontally and received vertically for instance. For reciprocal media$S_{hv} = S_{vh}$. The polarimetric scattering information can be represented by scattering vector like the Pauli basis (k) or lexicographic basis (Ω), as shown below.

$$k = \frac{1}{\sqrt{2}}[S_{hh} + S_{vv} \quad S_{hh} - S_{vv} \quad 2S_{hv}]^T \qquad \text{Eq. 2}$$

$$\Omega = [S_{hh} \quad \sqrt{2}S_{hv} \quad S_{vv}]^T \qquad \text{Eq. 3}$$

Where the superscript “T” denotes matrix transpose. The additional polarimetric information, covariance matrix C or the coherency matrix T and span can be obtained as follow:

$$C = \Omega\, \Omega^{*T}; \quad T = K\, K^{*T}; \quad Span = K^{*T}K = \Omega^{*T}\Omega \qquad \text{Eq. 4}$$

Where the superscript “*” refers to the complex conjugate.

B) Filtering approaches

Here are the filters that have been analyzed in this paper.

1. Box Filter

It is a simple averaging filter that replaces the center pixel in a square kernel by the mean value of kernel pixels. This filter has a good performance in reducing speckle in homogeneous area, but because of dealing similarly with all pixel in a kernel it degrades spatial resolution and also destroy the polarimetric properties.

2. Refined Lee Filter

Functionally [1] is similar to Lee filter [11] of single-channel SAR but there are an important difference between them. Refined Lee polarimetry filter such as its single-channel one uses a non-square and edged-aligned window that is based on local statistics. But in polarimetric case, the edged-aligned window and the weight filtering are determined by span image involving edges and features of all channels itself and the determined weight is applied on the elements of covariance matrix equally.

3. IDAN Filter

[9] proposed a new adaptive approach that is based on the local stationary assumption. It uses a new “windows growing” technique to form an adaptive neighborhood (AN) for each pixel. The proposed method uses only intensity

information to decide upon pixel selection to the AN. Early core of every AN is a seed pixel which is yielded by a median value in the 3×3 centered neighborhood. The main drawback of this method is its high computational complexity. The filtered pixel is computed in two ways: IDAN-LLMMSE and boxcar IDAN that LLMMSE approach has much better performance.

4. SRAD Filter

SRAD [8] is a partial differential equation (PDE) approach to reduce speckle noise. Its equation (PDE) is iteratively solved to smooth image. The SRAD method uses a diffusion coefficient that acts as edge-sensitive, where the magnitude of gradient of image is relatively large, the diffusion stops and where the magnitude of gradient of image is relatively small the diffusion occurs. The diffusion coefficient is calculated using the span image [12]. All element of the covariance matrix or the coherency matrix are filtered equally and separately by this coefficient.

5. SMD Filter

In [7] a centered pixel in a 9×9 moving window would be filtered by pixels that have similar scattering characteristic. It consist of three steps, first) by applying the Free and Durden decomposition finds pixels belong to which scattering category, second) unsupervised classification according to Wishart classifier is applied, third: pixels that are in same group and same scattering category are filtered by the LLMMSE approach.

6. Non-Local Filter [11]

Pixel selection for filtering can be expanded to global neighborhood rather than restricting to local neighborhood of an image. Every pixel in search area gets a weight that come from comparing its patch (neighborhood pixel that surrounding candidate pixel) with the patch of centered pixel to find homogeneous pixels. The method uses a statistic approach to calculate the similarity between the patches then compares by a threshold to decide whether to accept or not.

III. Analysis Procedures

The described filters in previous section were evaluated using a C-band multilook Polarimetric data acquired by Radarsat-2, over San Francisco Bay area. This scene contain sea surface, vegetation, road and city area as shown in figure 1. The performance of the filters with the following indexes is analyzed in this study:

- To evaluate the availability of the filtering techniques in speckle reduction equivalent number of looks (ENL) is used. ENL of the see surface is calculated. The higher value shows better denoising.

$$ENL = \frac{(mean^2)_{span\ image}}{variance_{span\ image}} \qquad \text{Eq. 5}$$

- To analyze the capability of a filter in preserving edge area such as water / land boundaries the edge-enhancing index (EEI) is used.

$$EEI = \frac{\sum|DN|_{filtered\ span\ image}}{\sum|DN|_{original\ span\ image}} \qquad \text{Eq. 6}$$

  DN is deference of pixel value on either side of the edge.

- There are many indicators to assess how well a filter is able to maintain polarimetric information. Statistical correlation is tested to see if it is preserved or not. The complex correlation coefficient between HH and VV using covariance matrix is calculated by

$$\rho = \frac{\langle S_{hh}S_{vv}^{*}\rangle}{\sqrt{\langle|S_{hh}|^2\rangle\langle|S_{vv}|^2\rangle}} \qquad \text{Eq. 7}$$

  For correct calculation of the parameter, a large number of samples should be used [1]. The magnitude of correlation coefficient $|\rho|$ is computed for comparison.

- Land-use classification plays an important role in PolSAR images especially in urban area. Speckle reduction enhances the performance of classification. We analyzed the effect of filtering methods on the classification by comparison of the kappa coefficient. The classification algorithm used here is based on the Bays maximum likelihood classification algorithm. The Wishart distribution has been verified using the multilook covariance matrix. Therefore, the distance measure is derived by

$$d(\bar{C}, \omega_m) = ln|C_m| + Tr(C_m^{-1}\bar{C}) \qquad \text{Eq. 8}$$

Where $\bar{C}$ is the multilook covariance matrix, ω_m is the mth class, C_m is the supposed covariance matrix for class m that can be obtained by averaging the training data. The image consists of four classes: sea surface, city area, road and vegetation. The coefficient of kappa using confusion matrix is computed for both original data and filtered data.

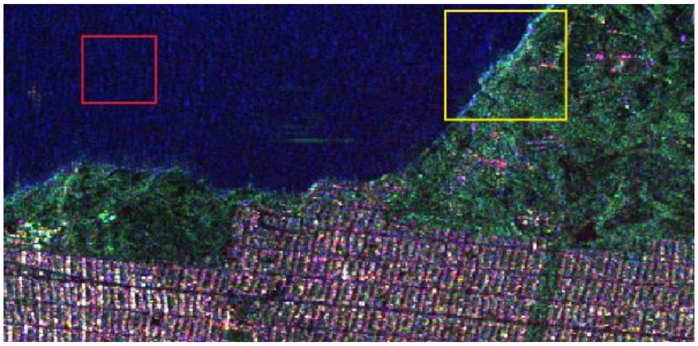

Figure 1. Pauli RGB 3-look PolSAR dataset from San Francisco Bay. Red and yellow rectangle shows process area of indices ELN and EEI, respectively.

IV. Implementation and Results

The dataset used in this paper is a PolSAR image in 3-look with 201×411 pixels, as can be seen in figure 1. All filtering methods that are described in section II are implemented on the dataset. The representative results that derived using applied filters are shown in figure 2.

Box filter and refined Lee are tested by a 5×5 and 7×7 window. SMB filter uses a 9×9 filter and is implemented by PolSARpro (v5.0) software. SRAD filter works with a speckle scale function which estimates the noise level at each iteration and a time step size of 0.05 during 300 iteration. The IDAN filter which uses region growing (RG) technique to find homogenous pixels filtering when stopping that either the number of selected pixels into AN area reach to a predefined upper limit N_{max} or none of the neighbor pixels verify the RG test as homogenous candidates. The N_{max} for SRAD filter is equal to 40 pixels here. The Non-Local filter uses a pretest approach based on complex Wishart distribution to determine similarity between patches and select homogenous pixels. In our implementation the "searching window" and "patch window" are set to be 15×15 and 3×3, respectively.

The assessment of the performance of the filters for suppressing speckle noise over selected homogenous area base on ENL index and testing the edge preservation criterion based on EEI index is given in table 1. In figure 1 red rectangle shows the selected homogenous area and yellow rectangle represents the selected edged area which are used in calculating of ENL and EEI, respectively. The best performance in noise reduction is related to the Non-Local and Box7 filters and then, the IDAN filter is placed in next order. The highest EEI value is belong to the SMB and Non-Local filters with the amount of 0.70 and then, the refined Lee filter is placed in next order.

In this study, the magnitude (|ρ|), namely the coherence, is evaluated just between copolar of HH and VV. Three different sample areas consisting of vegetation, city area and ocean are selected, then, the coherence of each area is estimated. Finally, the average value of three sample areas is used as the coherence. We do it for the all filtered images and the original image and results are given in table 1. As can be seen, the magnitude of the SRAD, refined Lee, SMB and Non-Local approaches have the nearer amount to original image. So, it is indicated that they are efficient in maintaining polarimetric properties.

The Wishart classifier which is one of the most widely used method for classification of polarimetric data is used in this paper to assess the effects of the filtering methods on classification. Therefore, four classes including water, vegetation, building and road are defined for this image. Table 2 presents the number of train and test samples for each class. Table 3 shows the accuracy assessment including producer's accuracy (PA), user's accuracy (UA) and overall accuracy (OA) of every filtered image and noisy image. PA, UA and OA metrics derive from error or confusion. OA is simply the sum of the major diagonal (i.e., the correctly classified sample units) divided by the total number of sample units in the error matrix. According to the results (table 3), Box7 and IDAN filter have the best and worst OA, respectively comparing to OA of original image. The refined Lee filter also has satisfying performance.

Table 1. Speckle noise reduction, edge and coherency preservation for filtered image.

Filters	**ENL**	**EEI**	**|ρ|**
Original image	28.66	--	0.148
Box 5	159.02	0.42	0.125
Box 7	238.13	0.28	0.124
Refined Lee 5	78.71	0.69	0.157
Refined Lee 7	100.34	0.69	0.157
IDAN	166.04	0.25	0.307
SRAD	140.28	0.67	0.141
SMB 9	122.82	0.70	0.137
Non-Local	308.75	0.70	0.138

Table 1. The number of train and test samples of classes of San Francisco Bay dataset.

	Water	**Vegetation**	**Building**	**Road**
# Train samples	189	170	150	138
# Test samples	378	340	299	276

Table 3. The accuracy assessment results of the noise reduction methods implemented on San Francisco Bay dataset (%).

	Original image	Box5	Box7	Refined Lee5	Refined Lee7	IDAN	SRAD	SMB 9	Non-Local
Mean PA	67.59	80.84	79.00	83.06	85.61	87.59	83.03	83.56	82.30
Mean UA	67.23	80.75	78.99	82.47	84.49	87.53	82.51	82.30	81.51
OA	69.76	82.38	80.91	83.91	86.16	88.63	84.15	84.38	83.15

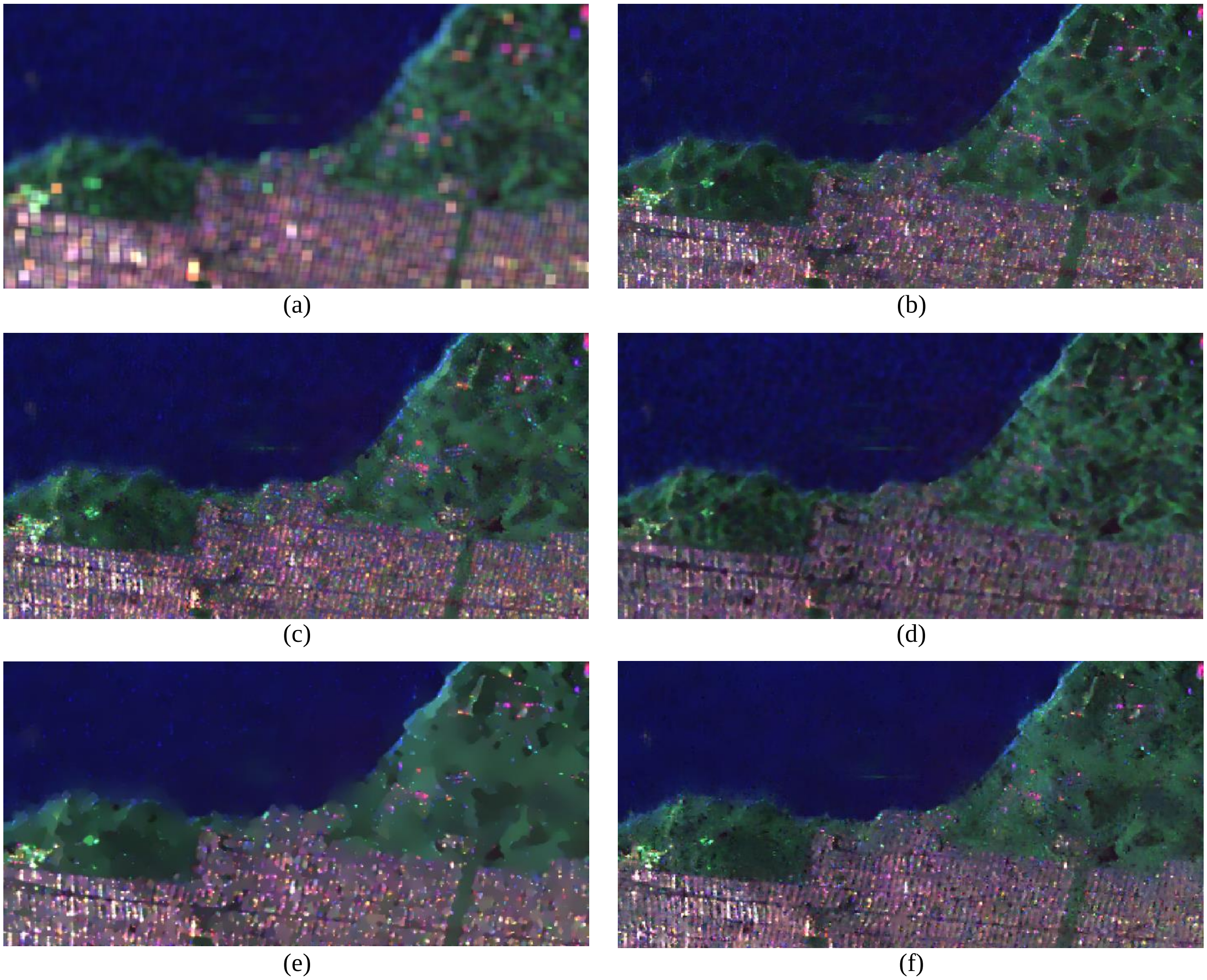

Figure 2. Comparison speckle reduction of filtering algorithms: (a) Box7 filter. (b) Refined Lee7 filter. (c) SMB algorithm. (d) IDAN filter. (e) SRAD speckle reduction technique. (f) Non-Local algorithm.

V. Conclusion

If we summarized the results, it could be said that Box filter was just good in decreasing speckle noise but it degrade the spatial resolution and edges (figure 2). Although, refined Lee7 and SMB9 filters were suitable in all criteria, they reduce less speckle level toward Box filter but they did not blurred the image, smear edge features and deny polarimetric scattering properties and the Refined Lee7 was better in classifying. The Non-Local filter was very effective in speckle noise reduction in homogenous area along with well protection of edge characteristic and coherence (similar to SMB9) in PolSAR image. Lower OA of the IDAN filter toward other approaches indicated that it could not be the best choice as preprocessing step in classifying. But, it did not have the restriction of SMB filter in selecting neighborhood pixels that have the same scattering characteristic in a local area. From different aspect, the SRAD and refined Lee7 filters taken a higher score because they were efficient in noise reduction, preserving edge and polarimetric information and also enhanced the accuracy of classification simultaneously, especially refined Lee filter. Finally, all noise reduction methods were proper in improving OA of the image classification, even Box filter. In addition, they improved the mean PA and mean UA of image classification. And we could conclude that there was a direct relation between classification accuracy and further noise reduction.

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Speckle is noise-like because it is a true electromagnetic measuring determined by the scattering process itself. Nevertheless, from the viewpoint of image processing speckle is considered as a disturbing factor that must be removed. Speckle noise make mostly the explanation and analysis of images complex and also decrease the effectiveness of classification. Speckle existing in PolSAR data is due to the coherent nature of the SAR system. For reciprocal media, PolSAR data can be contained three correlated polarization channels: HH, VV and HV, where H and V indicate horizontal and vertical direction of polarized wave respectively. Speckle not only affects three intensity images, but also has effect on complex cross product terms. Speckle filtering should reduce speckle of whole covariance or coherency matrix. Diagonal terms of covariance or coherency matrix that are three intensity images can be characterized by a multiplicative noise model but the off diagonal terms that are complex can be modeled by a combination of multiplicative and additive noise model. It is necessary that PolSAR filters deal with whole terms of covariance matrix for instance in a similar way, preserve the polarimetric properties and not to introduce cross-talk between channel. In addition, it is important not to degrade image quality. So, speckle reduction is more difficult for polarimetric SAR image than single-channel SAR image.

Several scenarios have been studied to reduce speckle noise in PolSAR data. According to the final objective, PolSAR filtering algorithms can be divided into two groups. For first group, most important thing is to preserve spatial resolution even at expense of losing polarimertic information or introducing crass-talk between polarization channels. These approaches assume PolSAR data as a type of diversity. The second group tries to look at the issue from spatial processing perspective, thus it will affect the spatial resolution. This view prevents previous problems from occurring. It is clear that there is a trade-off between spatial resolution maintenance and the preservation of polarimertic properties.

In this paper the most significant and recent PolSAR filters that have been developed so far are reviewed and the effects of these filters on classification and their ability to preserve polarimetric properties along with their strength in noise reduction are studied. For this purpose PolSAR filters such as refined Lee, intensity driven adaptive neighborhood (IDAN), Sigma Lee, scattering model base (SMB), speckle reduction anisotropic diffusion (SRAD), and a nonlocal PolSAR filtering are used. These filters have been applied to a C-band multilook Polarimetric data taken by Radarsat-2 sensor over San Francisco Bay area, then the performance of the filters have been evaluated from various aspects: (1) land-use classification plays an important role in PolSAR images especially in urban area. Speckle reduction enhances the performance of classification. We analyzed the effect of filtering methods on the classification by comparison of the overall accuracy. The employed classification algorithm is based on the complex Wishart distribution of the multilook covariance matrix. The Wishart distribution has been verified using polarimetric SAR data. Based on the maximization of Wishart density function, a simple distance measure, named as Wishart distance, is derived. After classifying using Wishart distance, the overall accuracy for both different filtered data and original data is calculated. (2) To evaluate the availability of the filtering techniques in speckle reduction equivalent number of looks (ENL) is used. ENL of the sea surface is calculated and the higher value shows better denoising. (3) To analyze the capability of a filter in preserving edge area such as water / land boundaries the edge-enhancing index

(EEI) is used. (4) Finally, there are many metrics about polarimetric information evaluation to assess how well a filter is able to maintain polarimetric information. Here, the magnitude of complex correlation coefficient is computed to see if the statistical correlation is preserved or not.