Speckle Modeling and Turbo Filtering of PolSAR Images
Souhila BOUTARFA, Lynda BOUCHEMAKH and Youcef SMARA, Algeria

Key words: POLSAR images, speckle modeling, speckle filtering, Turbofilter, refined Lee filter, wavelet filtering, SWT

SUMMARY

SAR polarimetric radar images are affected by a granular noise called speckle, which degrades the quality of these images and makes it difficult to interpret. That is why polarimetric filtering is essential. The diagonal terms of the covariance matrix represent the intensity of the linear polarization and can be characterized by a multiplicative noise. The off-diagonal terms contain noise that cannot be characterized by a multiplicative or additive model.

In this paper, we are interested in modeling the speckle in the off-diagonal terms of the covariance matrix and filtering these terms with adjusting the filtering method already developed for the diagonal terms. Therefore, our objective is to adapt the filtering method called Turbofilter to filter PolSAR images containing noise that is not multiplicative or additive. The principle of Turbofilter is that it combines two complementary filters: the refined Lee filtering based on the estimation of the minimum mean square error MMSE and the wavelet filtering by using the stationary wavelet transform SWT. One filter can boost up the results of the other. We propose to optimize this method by adding a parameter in the calculation of the threshold in the wavelet filtering using multi-scale edge detection and the technique for improving the wavelet coefficients called SSC (sum of squared coefficients), this parameter will control the filtering effect and get a good compromise between smoothing homogeneous areas and preserving linear structures. The advantage of this algorithm is to use the advantages of both filters and to obtain images with well-reduced speckle and filtering all the elements of the covariance matrix, taking into account the noise type of each component.

Visual and statistical evaluation and a comparative study are performed to validate the obtained results according to the following criteria: best filtering in terms of smoothing homogeneous areas, preserving edges and conservation of the polarimetric information.
RÉSUMÉ

Les images radar SAR polarimétriques sont affectées par un bruit granulaire appelé speckle qui dégrade la qualité de ces images et rend difficile leur interprétation. C’est pour cela qu’un filtrage polarimétrique est primordial. Les termes diagonaux de la matrice de covariance $C$ représentent l’intensité de la polarisation linéaire et peuvent être caractérisés par un bruit multiplicatif. Les termes hors-diagonaux contiennent un bruit qui ne peut être caractérisé ni par un modèle multiplicatif ni additif.

Dans cette communication, nous nous intéressons à la modélisation du speckle dans les termes hors diagonaux de la matrice de covariance et de filtrer ces termes tout en leur adaptant la méthode de filtrage déjà élaboré pour filtrer les termes diagonaux caractérisées par un bruit multiplicatif. Donc, notre objectif est d’adapter la méthode de filtrage appelée Turbo pour filtrer les images PolSAR contenant un bruit qui n’est ni multiplicatif ni additif. Le principe du filtre Turbo est qu’il combine deux filtres complémentaires: le filtrage de Lee adaptatif basé sur l’estimation de l’erreur quadratique moyenne minimale (MMSE : Minimum Mean Square Estimation) et le filtrage en ondelettes en utilisant la transformée en ondelettes stationnaire SWT. Chaque filtre peut booster les résultats de l’autre. Nous proposons d’optimiser cette méthode en rajoutant un paramètre au niveau du calcul du seuil dans le filtrage par les ondelettes en utilisant la détection de bords multi-échelles et la technique d’amélioration des coefficients d’ondelettes appelée SSC (Sum of Squared Coefficients), ce paramètre permettra de mieux contrôler l’effet du filtrage et d’obtenir un bon compromis entre le lissage des zones homogènes et la préservation des structures linéaires. L’intérêt de cet algorithme est d’utiliser les avantages des deux filtres et d’obtenir des images avec un speckle bien réduit ainsi que de filtrer tout les éléments de la matrice de covariance tout en prenant en considération le type de bruit de chaque composante.

Une évaluation statistique et visuelle, ainsi qu’une étude comparative sont effectuées pour valider les résultats obtenus, selon les critères suivants : meilleur filtrage du point de vue lissage des zones homogènes, préservation des contours et conservation de l’information polarimétrique.

Mots clé : Images POLSAR, Modelisation speckle, Filtre Turbo, Filtre de Lee, Filtre Ondelettes,
Speckle Modeling and Turbo Filtering of PolSAR Images

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1. INTRODUCTION

PolSAR radar imagery has the advantage, compared to optical imaging, can acquire data at night and under cloud cover. However, PolSAR images contain a specific noise called speckle. This noise impairs the readability of the radar images and is often the main cause of processing failure algorithms and information extraction. Also, many studies have been devoted to filtering these data to reduce speckle (Novak et al., 1990) (Lee et al., 1999) (Farage et al., 2007) (Alonso-González et al., 2013).

In this paper, we studied the specklenoise modeling in all elements of the covariance matrix\(C\) (Lee et al., 2009) and we noticed that these elements do not contain the same noise type i.e. multiplicative noise and that based on the work of Lee (Lee et al., 1999) and López-Martínez (López-Martínez et al., 2003). And we also studied the filtering method developed to treat these components that do not contain multiplicative noise unlike most methods, so we used the Turbo filtering for polarimetric SAR images proposed by Farage (Farage et al., 2008) to filter the diagonal elements of the covariance matrix in a manner and the other elements otherwise by adapting the filter relationship in order to treat a noise which is neither additive nor multiplicative. This method combines the refined Lee filter (Lee et al., 1999) with filtering by stationary wavelet transform SWT (Farage et al., 2007). Refined Lee filter is based on the estimation of the minimum mean square error MMSE in the detected aligned edges. Wavelet filtering applied the stationary wavelet transform SWT on noisy images using multi-scale edge detection and sum of squared coefficients SSC technique for the wavelet coefficients improvement.

We propose to optimize this method by adding a parameter in the calculation of the threshold in the wavelet filtering, this parameter will better control the filtering effect and get a good compromise between smoothing homogeneous areas and preserving edges. The purpose of the Turbo algorithm is to use the advantages of both filters and to obtain images with well reduced speckle. Its principle is that each filter can boost the results of the other. We have implemented this new method and compared the results with those of the two filters already developed, refined Lee filter and SWT filtering (Bouchemakh et al., 2008) (Boutarfa et al., 2010). And that, in order to determine its effectiveness in speckle reducing, according to the following criteria: best filtering in terms of smoothing homogeneous areas, preserving edges and conservation of the polarimetric information.

Two evaluation areas were considered in this study, image corresponding of Oberpfaffenhofen area located in Munich (Germany) in P-band airborne polarimetric mode (E-SAR) and image of an area located in Algiers (Algeria) in C-band spaceborne polarimetric mode (RADARSAT-2).
2. SPECKLE MODELING

The speckle model in polarimetric radar images is a multiplicative model (Lee, 1980)(Lee, 1981), represented by:

\[ y = v \times x \text{ with } (\sigma_v)^2 = \frac{1}{L} \text{ and } C_v = \frac{\sigma_v}{<v>} \]  

(1)

Where \( y \) is the original pixel of the observed signal, \( x \) is the filtered pixel that corresponds to the information that can be measured and \( v \) is a random process related to the speckle noise, which is multiplied to the signal, with a mean value \(<v> = 1\), \( L \) is the number of look, \((\sigma_v)^2\) is the speckle variance and \( C_v \) is the coefficient of variation of the speckle. The filtering purpose is to estimate the pixel \( x \) knowing the observed pixel \( y \).

The polarimetric filtering reduces the speckle in the elements of the covariance matrix \( C \) (eq.2) or the coherency matrix \( T \) (Lee et al., 2009). The diagonal terms of the covariance matrix represent the intensity of the linear polarization and can be characterized by a multiplicative noise. The off-diagonal terms contain a noise that cannot be characterized by a multiplicative or additive model (Lee et al., 1999).

In our study, we used the polarimetric covariance matrix \( C \) in the monostatic case which is written as follows:

\[
C = \begin{pmatrix}
|HH|^2 & HH, HV^* & HH, VV^* \\
HV, HH^* & |HV|^2 & HV, VV^* \\
VV, HH^* & VV, HV^* & |VV|^2
\end{pmatrix}
\]  

(2)

Where the superscript “\(^*\)” refers to the complex conjugate.

López-Martínez have developed a new formulation of the noise model in the off-diagonal images (López-Martínez et al., 2003). They demonstrated that these images are affected by a noise resulting from an addition of two noise types, multiplicative and additive, as shown in the following expression:

\[
HH \cdot VV^* = \psi N_C z_{nor} n_m e^{i \phi} + \psi \left| \rho \right| - N_C z_{nor} e^{i \phi} + \psi (n_{ar} + j n_{al})
\]  

(3)

where \( E \) is the expected value, \( _2F_1 \) is the Gauss hypergeometric function, \( N_C \) is a function of \( |\rho| \), \( z_{nor} \) is the normalized amplitude of the Hermitian product, \( n_m \) is the multiplicative noise, \( \rho \) is the coefficient of correlation, \( \phi \) is the phase value, \( n_{ar} \) and \( n_{al} \) are additive noise terms.

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3. TURBO FILTER

A new approach to speckle reduction in polarimetric SAR images based on the iterative turbulence principle is proposed by Farage (Farage et al., 2008). The Turbofiltering is a combination of two complementary filters, each of the two filters can boost the results of the other by processing its residue image and retrieving useful information. Some filters, such as refined Lee filter (Lee et al., 1999), tend to get a very smooth image and other filters, such as wavelet filtering (Farage et al., 2007), tend to keep structural information, leaving some noise in the estimated image. Therefore, the interest of the Turbo algorithm is to use the advantages of both filters. We propose to optimize this method by adding a parameter in the calculation of the threshold in the wavelet filtering, this parameter will control the filtering effect and get a good compromise between smoothing homogeneous areas and preserving linear structures.

4. FILTERING BY WAVELET TRANSFORM

Wavelets are an effective tool for image processing applications. They can identify and analyze the discontinuities in the image at different levels. This property is used for filtering the wavelet coefficients before making the image reconstruction.

In what follows, we first recall the principle of the used wavelet transform, then we consider the principle of filtering by multi-scale edge detection and coefficients thresholding. The input image \( I_n \) used in the following sections is defined by:

\[
I_n = \begin{bmatrix}
HH, & HV, & VV, & \Re\{HH\}, & \Re\{HV\}, & \Re\{VV\}, & \Im\{HH\}, & \Im\{HV\}, & \Im\{VV\}
\end{bmatrix}
\]

Where \( \Re \) is the real part and \( \Im \) the imaginary part of the complex image.

4.1 Stationary Wavelet Transform SWT

The wavelet transform used in the filtering method is the stationary wavelet transform SWT (Farage et al., 2007). The SWT generates four images, three high frequency images called wavelet coefficients corresponding to the horizontal, vertical and diagonal directions noted by: \( W_h^j, W_v^j, W_d^j \), and an low-frequency image called approximate image noted by \( A^j \), bringing the highest percentage of information content among the four images. The transformation generates an equal number of wavelet coefficients at all scales. \( j \) represents the number of scale (\( j = 1, \ldots, J \)). The SWT transform is similar to the discrete wavelet transform DWT, except that the image is not decimated and in each level decomposition, the filters are up-
sampled by inserting zeros between each filter coefficient. Then, details images are the same size as the original image.

4.2 Filtering by Multi-Scale Edge Detection

To provide robustness to speckle filtering, the amplitude of the operator at level \( j \) is expressed as follows (Scharcanski et al., 2002):

\[
M_n^j = \sqrt{\sum_{x=n,v,d} W_x^j}
\]  

(5)

Where \( n \) is the number of the input image.

The procedure for classifying wavelet coefficients proposed by Farage (Farage et al., 2007) based on the SSC (Sum of Squared Coefficients) is given as follows:

\[
g^j = \begin{cases} 1 & \text{if } \sum_{n=1}^{N} (M_n^j)^2 > T \\ 0 & \text{otherwise} \end{cases}
\]

(6)

Where \( N \) is the total number of input images and \( T \) is the estimated threshold.

The edge coefficients tend to become larger at higher scales while the noise becomes smaller. If the image structures produce very large wavelet coefficients that must be preserved (Farage et al., 2007), a threshold is imposed as:

\[
g^j = \begin{cases} 1 & \text{if } ECM \{M_n^j\}_{1,2,3} > \sqrt{L + 2} \\ 0 & \text{otherwise} \end{cases}
\]

(7)

Where \( g^j \) is the binary mask at level \( j \). ECM (Enhancement Factor Method) is the improvement wavelet coefficients method by using the PCA (Principal Component Analysis) or the SSC (Sum of Squared Coefficients).

With:

\[
SSC = \sum_{n=1}^{N} (M_n^j)^2
\]

Another classification method of edge and non-edge coefficients is proposed by Dachasilaruk (Dachasilaruk, 2008). It is given by:

\[
g^j = \begin{cases} 1 & \text{if } (M^j)^2 > \sigma_v^j \\ 0 & \text{otherwise} \end{cases}
\]

(9)

With

\[
\sigma_v^j = \text{Median}(M^j)^2)/0.6745
\]

(10)

If \( g^j = 1 \), we have an edge and if \( g^j = 0 \), we haven’t any edges in the region.

For the calculation of \( \sigma_v^j \), we propose to add in the equation (eq.10) a parameter \( \gamma \) which allows to control the filtering effect, therefore, to obtain a good compromise between smoothing homogeneous areas and preserving edges. The expression of \( \sigma_v^j \) becomes:
Once the masks are obtained, the wavelet coefficients are multiplied by the shrinkage function such as:

\[
(W_\epsilon^j) = g_\epsilon^j \times W_\epsilon^j \quad \epsilon = h, v, d
\]

Through the equation (12), we obtain the new filtered coefficients \( W_\epsilon^j \) that will be used in the inverse wavelet transform to obtain the filtered image.

The steps of the multi-scale edge detection filtering method are listed below:
- Apply the stationary wavelet transform SWT.
- Improve the wavelet coefficients \( M^j \) using the SSC technique on the input images.
- Classify the edge coefficients and no-edge coefficients, using the masking (eq. 9).
- Modify the wavelet coefficients by multiplying them by the mask \( g^j \) (eq. 12).
- Apply the inverse wavelet transform ISWT to produce the filtered images.

5. REFINED LEE FILTER

The refined Lee filter (Lee et al., 1999) is an adaptive filter based on the criterion of minimum mean square error MMSE (eq. 13), and the calculation of statistical parameters of the image. It considers the speckle as a multiplicative noise statistically independent of the scene. The estimated filtered pixel by the MMSE method is as follows:

\[
x = \bar{y} + b(\gamma - \langle \bar{y} \rangle)
\]

Where \( x \) is the estimated value of the filtered pixel, \( \bar{y} \) is the local average of unfiltered pixels and \( b \) is the adaptive filtering coefficient with a value between 0 and 1.

6. TURBO FILTER PRINCIPLE

The idea is to generate two components \( U_1 \) and \( U_2 \) from the original image \( I \) as shown in (Fig. 1) (Farage et al., 2008).
In Figure 1, the filter 1 is the wavelet filter; the filter 2 is the refined Lee filter; the output $Z_1$ represents the filtered image by Turbo SSC; the output $Z_2$ represents the image filtered by the Turbo Lee; the two components $U_1$ and $U_2$ are obtained from operators $\pi_1$ and $\pi_2$ as follows:

\begin{equation}
\mathcal{A}_{2,n}^\Delta \begin{cases} 
U_{2,n} = Z_{12,n}Z_{21,n} & \text{for diagonal terms} \\
U_{2,n} = \psi_n^\text{nor,n} Z_{12,n} e^{i\phi} & \text{for off-diagonal terms}
\end{cases}
\end{equation}

\begin{equation}
\mathcal{A}_{1,n}^\Delta \begin{cases} 
U_{1,n} = I_n / Z_{21,n} & \text{for diagonal terms} \\
U_{1,n} = \left| I_n / \psi_n^\pi \right| & \text{for off-diagonal terms}
\end{cases}
\end{equation}

Where $n$ is the input image number.

Two different filters are chosen in a way that their performances complement each other. The filter 1 (fig. 1) should have a tendency to reduce the noise with a good edge preservation, and must treat the noise of residue images to retrieve useful information. The filter 2 (fig. 1) should result in a speckle reduction with a good estimation of the polarimetric parameters. The output signals $Z_{12}$ and $Z_{21}$ are the exchanged information between the two filters to equilibrate the performance of the Turbo filter. At each iteration, $Z_{12}$ and $Z_{21}$ are estimated to improve the performance of each filter and to compensate their costs. The iterative process stops when change in $Z_{21}$ becomes small.

The steps of the Turbo filter method are:

- Apply SWT on the original image $I_n$ for the initialization, $Z_{21}$ is the low-frequency image $A'$. 
- Calculate the residue image $U_1$ from the operator $\pi_1$ (eq. 14) and apply the Filter 1 on $U_1$ and $I_n$.
- Calculate the residue image $U_2$ from the operator $\pi_2$ (eq. 15) and apply the Filter 2 on $U_2$ and $I_n$.
- Stop the iterations when change in $Z_{21}$ becomes small or go to step 2 for another iteration.

7. EXPERIMENTAL RESULTS

7.1 Speckle Model Validation

In our work, according to the study of Lee et al. (Lee et al., 1999), we tested the statistical characteristics of diagonal and off-diagonal terms by plotting the scatter of the standard...
deviation versus the mean, employing a moving window of size 5×5 pixels of RADARSAT-2 images corresponding to Algiers area (Algeria). In Figure 2, the intensities images $|HH|^2$, $|HV|^2$ and $|VV|^2$, show the characteristics of a multiplicative noise. The real and imaginary parts are more difficult to characterize, they show the characteristics of a noise that is not multiplicative.

![Figure 2. The scatter plotting of the standard deviation versus the mean.](image1)

(a) $|HH|^2$, (b) $|HV|^2$, (c) $|VV|^2$, (d) $\Re\{HH \cdot VV^*\}$, (e) $\Im\{HH \cdot VV^*\}$.

By using the new formulation of the noise model (eq.3) developed by López-Martínez (López-Martínez et al., 2003). We plotted the scatter of the standard deviation versus the mean in both parts multiplicative and additive of the off-diagonal terms corresponding to RADARSAT-2 images of Algiers area (Algeria). Indeed, the results in figure 3 show that the off-diagonal terms have a noise resulting from a sum of two noise types: additive and multiplicative noise.
Figure 3. The scatter plotting of the standard deviation versus the mean.
(a) Multiplicative part of $\Re\{HH \cdot VV^*\}$, (b) Additive part of $\Re\{HH \cdot VV^*\}$,
(c) Multiplicative part of $\Im\{HH \cdot VV^*\}$, (d) Additive part of $\Im\{HH \cdot VV^*\}$.

The following section presents the different results obtained by the Turbo filtering considering the speckle modeling in all polarimetric covariance matrix elements.

### 7.2 Filtering Results

The filters tests are made on extracted images from two single-look POLSAR complex images, one is airborne corresponding to the region of Oberpaffenhofen in Germany acquired by E-SAR sensor in 2001 (P-band) and the other corresponding to the area of Algiers in Algeria acquired by RADARSAT-2 in April 2009 (C-band). The evaluation of each filter is based on the following main criteria: Ability to smooth the homogeneous areas, ability to preserve edges and especially preserving the polarimetric information.

#### 7.2.1 Visual Evaluation

The results are shown in (fig. 4,5) for Algiers region and (fig. 6,7) for Munich area.

![Figure 4. Images of Algiers region](image1)

(a) Original $\text{Span}$, (b) Lee $\text{Span}$, (c) SSC $\text{Span}$, (d) Turbo Lee $\text{Span}$, (e) Turbo SSC $\text{Span}$,
(f) Original $|HH \cdot VV^*|$, (g) Lee $|HH \cdot VV^*|$, (h) SSC $|HH \cdot VV^*|$, (i) Turbo Lee $|HH \cdot VV^*|$, (j) Turbo SSC $|HH \cdot VV^*|$.
Figure 5. Zoom images of Algiers region. (a) Original Span, (b) Lee Span, (c) SSC Span, (d) Turbo Lee Span, (e) Turbo SSC Span, (f) Original $[HH \cdot VV *]$, (g) Lee $[HH \cdot VV *]$, (h) SSC $[HH \cdot VV *]$, (i) Turbo Lee $[HH \cdot VV *]$, (j) Turbo SSC $[HH \cdot VV *]$.

Figure 6. Images of Munich region. (a) OriginalSpan, (b) LeeSpan, (c) SSCSpan, (d) Turbo LeeSpan, (e) Turbo SSCSpan, (f) Original $[HH \cdot VV *]$, (g) Lee $[HH \cdot VV *]$. 
According to the above figures, we see that the filtered images by Turbo Lee are well smoothed and the filtered images by Turbo SSC present a good compromise between smoothing homogeneous areas and preserving linear structures, details of objects appear clearer than in the other filtered images.

### 7.2.2 Statistical Evaluation

**Evaluation in Homogeneous regions:** The evaluation performance of each filter in terms of smoothing is performed on homogeneous areas of size 20×20 pixels extracted from the images before and after filtering. This evaluation is done by calculating the equivalent number of looks ENL (Bouchemakh et al., 2008). A good filtering in homogeneous areas is represented by an increase value of ENL.

The statistical results are shown in the following table:

<table>
<thead>
<tr>
<th>Table 1. ENL values in Span images.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Original Span</td>
</tr>
</tbody>
</table>
From tables 1 and 2, overall, the statistical evaluation of the obtained results of Turbo filter showed a great ability to preserve edges and smooth homogeneous areas. Thus, these results follow the conclusions of visual evaluation.

**Evaluation in Heterogeneous regions:** The best filter in terms of edge preservation is the one giving the highest coefficient of variation $C_{vg}$ (Bouchemakh et al., 2008) calculated from three heterogeneous areas of size $10 \times 10$ pixels. The results are illustrated in the following table:

<table>
<thead>
<tr>
<th>Areas</th>
<th>Original</th>
<th>Turbo Lee</th>
<th>Turbo SSC</th>
<th>Lee</th>
<th>SSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algiers</td>
<td>intensity</td>
<td>2.66</td>
<td>7.26</td>
<td>5.28</td>
<td>7.70</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>0.64</td>
<td>1.08</td>
<td>1.17</td>
<td>3.19</td>
</tr>
<tr>
<td>Munich</td>
<td>intensity</td>
<td>2.17</td>
<td>16.12</td>
<td>11.47</td>
<td>8.73</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>0.49</td>
<td>3.93</td>
<td>12.35</td>
<td>5.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Areas</th>
<th>Original</th>
<th>Turbo Lee</th>
<th>Turbo SSC</th>
<th>Lee</th>
<th>SSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algiers</td>
<td>intensity</td>
<td>1.07</td>
<td>8.56</td>
<td>4.53</td>
<td>7.00</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>0.50</td>
<td>1.27</td>
<td>1.19</td>
<td>4.36</td>
</tr>
<tr>
<td>Munich</td>
<td>intensity</td>
<td>1.98</td>
<td>14.19</td>
<td>13.12</td>
<td>9.08</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>0.30</td>
<td>3.48</td>
<td>14.19</td>
<td>4.50</td>
</tr>
</tbody>
</table>

**Table 2. ENL values in $HH \cdot VV$ images.**

<table>
<thead>
<tr>
<th>Areas</th>
<th>Original</th>
<th>Turbo Lee</th>
<th>Turbo SSC</th>
<th>Lee</th>
<th>SSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algiers</td>
<td>intensity</td>
<td>1.51</td>
<td>1.28</td>
<td>1.81</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>0.65</td>
<td>0.85</td>
<td>1.15</td>
<td>1.52</td>
</tr>
<tr>
<td>Munich</td>
<td>intensity</td>
<td>0.24</td>
<td>0.40</td>
<td>0.35</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>0.54</td>
<td>0.31</td>
<td>0.46</td>
<td>0.50</td>
</tr>
</tbody>
</table>

**Table 3. $C_{vg}$ values in Span images.**

<table>
<thead>
<tr>
<th>Areas</th>
<th>Turbo Lee</th>
<th>Turbo SSC</th>
<th>Lee</th>
<th>SSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algiers</td>
<td>intensity</td>
<td>2.01</td>
<td>1.30</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>0.75</td>
<td>1.89</td>
<td>1.05</td>
</tr>
<tr>
<td>Munich</td>
<td>intensity</td>
<td>0.21</td>
<td>0.99</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>0.56</td>
<td>1.88</td>
<td>1.46</td>
</tr>
</tbody>
</table>

**Table 4. $C_{vg}$ values in $HH \cdot VV$ images.**
From tables 3 and 4, we note that the best global result in terms of edge preservation in the two cases intensity and complex filtering is given by the Turbo filter. We also note that the statistical results join well the conclusions of the visual evaluation.

8. CONCLUSION

The new formulation of the speckle noise model allows to study the noise characteristics of the off-diagonal PolSAR covariance matrix terms and also to know better the used data for the treatment in order to achieve a better result.

According to the results obtained in the evaluation, we concluded that the Turbo filter provides clear images with much reduced speckle and presents a good compromise between smoothing homogeneous areas and preserving edges. And that thanks to the principle of this method which consists in joining together the advantages of the two filters: the refined Lee filter and wavelet filtering. Thus, images are sharper, which makes it possible to properly interpret the data and extract information. The filtered images will be used in various applications such as classification. However, the selection and adjustment of parameters is not obvious, we had to do several tests to obtain a good compromise between smoothing homogeneous areas and preserving edges.

ACKNOWLEDGEMENTS

We thank the Canadian Space Agency for the provision of RADARSAT-2 polarimetric data of Algiers region (Algeria), in C-band of 11 April 2009, as well as the private company Aerosensing for the provision of ESAR airborne polarimetric data of Munich area, in P-band of 2001.

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**BIOGRAPHICAL NOTES**

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