Anais XIV Simpósio Brasileiro de Sensoriamento Remoto, Natal, Brasil, 25-30 abril 2009, INPE, p. 7299-7305.

Performance evaluation of several adaptive speckle filters for SAR imaging

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Abstract. Speckle noise is a significant disturbing factor for SAR image processing. In this study the performance of eight adaptive speckle filter algorithms (Lee, Enhanced Lee, Frost, Enhanced Frost, Gamma, Kuan, Local Sigma and Bit Errors) with several moving window sizes was compared. A bi-polarized ALOS/PALSAR image covering an area in the north of Minas Gerais, Brazil, was used for this study. Three criteria were evaluated to test the ability of the filters to reduce speckle noise (Standard deviation To Mean ratio) and preserve the mean of a homogeneous land cover segment (Normalized Mean), and at the same time their ability to retain detailed edge information (Edge Index). In general, all speckle filters were able to preserve the mean of the homogeneous land cover segments to a satisfactory level. In particular the Enhanced Lee, Frost, Enhanced Frost and Gamma filter with a 7x7 window size were able to significantly suppress speckle noise, with speckle reduction rates up 70%. For the preservation of the edges again the Enhanced Lee, Frost, Enhanced Frost and Gamma filter performed best in the HH-polarized image, even showing enhancement of the edges. For the HV-polarized image most speckle filter algorithms resulted in slight edge blurring.

Keywords: adaptive speckle filters, remote sensing, synthetic aperture radar (SAR)

1. Introduction

An imaging radar generates a Synthetic Aperture Radar (SAR) image by transmitting a coherent electromagnetic wave and subsequently processing the backscattered signal from the ground objects. However, due to interference processes between scatterers speckle noise is introduced into the image. Speckle noise is a disturbing factor, because it limits the ability to correctly interpret SAR images, restricts edge abstraction, image segmentation, target recognition and classification, and it introduces uncertainty in ground surface parametric inversion (Huang and Liu, 2007). Therefore it is important to apply suitable speckle reduction methods prior to image processing, which are able to smooth speckle noise, while retaining as much detailed information as possible.

There are two types of speckle noise reduction techniques, according to Lee (1986). Multi-look processing reduces the spatial resolution to improve the radiometric resolution. This simple technique is able to remove speckle noise efficiently, but much edge information is lost. To suppress speckle noise in an uniform area, and to preserve edge information numerous adaptive speckle filter techniques were developed, for example, the Lee filter (Lee, 1980), the Enhanced Lee filter (Lopes et al., 1990), the Kuan filter (Kuan et al., 1985), the Frost filter (Frost et al., 1982), the Enhanced Frost filter (Lopes et al, 1990) and the Gamma MAP filter (Kuan et al, 1987).

In this study a comparison is made between several adaptive speckle filters (Lee, Enhanced Lee, Frost, Enhanced Frost, Gamma, Kuan, Local Sigma (Eliason and McEwen, 1990) and Bit Errors (Eliason and McEwen, 1990)) to investigate their ability to reduce speckle noise, without losing significant detailed edge information. The interest lay in the improvement of SAR images for segregation of different land cover classes (and not on enhancement of within-class texture), therefore this research was done on a land cover segment scale The performance of these filters was tested with criteria determining the ability of the filter to preserve the mean in an homogeneous land cover segment, suppress the speckle noise and preserve edge information. For this study a bi-polarization (HH/HV) ALOS/PALSAR image was used covering an area in the north of the state Minas Gerais, Brazil.

2. Adaptive speckle filters and performance criteria

With speckle reduction techniques the difficulty is to both suppress speckle noise in an uniform area, and preserve edges and linear features simultaneously. In many studies, the optimal trade-off between these objectives is tried to be obtained. In this research, the performance of eight different adaptive speckle filters was evaluated, these are:

1) Lee
2) Enhanced Lee
3) Frost
4) Enhanced Frost
5) Gamma
6) Kuan
7) Local Sigma
8) Bit Errors

The Lee filter is a standard deviation based filter that calculates the new pixel values with statistics computed within individual filter windows. The Enhanced Lee filter is an adaptation of the Lee filter and also uses local statistics (coefficient of variation). Furthermore, each pixel is put into one of three classes: 1) homogeneous class, where the pixel value is replaced by the average of the filter window, 2) heterogeneous class, where the pixel value is replaced by a weighted average, or 3) point target class, where the pixel value is not changed. The Frost filter is an exponentially damped circularly symmetric filter, where a calculation based on the distance from the filter centre, the damping factor and the local variance determines the new pixel value. The Enhanced Frost filter is similar to the Frost filter, only like with the Enhanced Lee filter the pixels are first separated into the three classes. The Kuan filter transforms the multiplicative noise model into an additive noise model. This filter is similar to the Lee filter but uses a different weighting function. The Gamma filter is similar to the Kuan filter, but differs by assuming the data is gamma distributed. The local Sigma filter uses the local standard deviation to determine the valid pixels within the filter window, and subsequently replaces the filtered pixel value with the mean calculated using only the valid pixels within the filter box. The Bit Error filter is used to remove bit-error noise, which is usually caused by isolated pixels that have extreme values unrelated to the image scene. An adaptive algorithm is used to detect spike pixels with local statistics (mean and standard deviation), and replaces the filtered pixel value with the average of the valid neighbouring pixels.

These speckle filters were applied on both the HH- and HV-polarization image. In addition, for every speckle filter several moving window sizes (3x3, 5x5 and 7x7) were used to study the effect of the window size on the smoothing characteristics and edge preservation.

Because the objective of this study was to reduce speckle noise in order to improve separation of different land cover classes, and not to look at natural within-class variability, the speckle noise reduction approach was applied on a land cover segment scale. To achieve this, first a spatial subset of the original SAR image was automatically segmented with the SegSAR method (Sousa, 2005). This specialized radar hierarchical segmentation strategy uses “region growing” in the highest compression level and the “split and merge” technique is used in the intermediate levels. In addition, before the “split and merge” procedure a border refinement algorithm is applied to each level, to enhance the region frontier solution. From the obtained segmented image four homogeneous land cover segments with different mean intensity values, shape, size and orientation were selected for further performance evaluation of the speckle filters (Fig. 1).

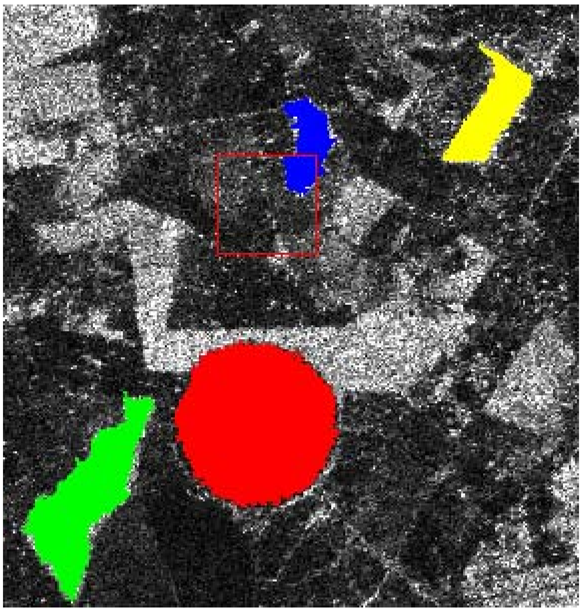

Fig. 1. Selected homogeneous land cover segments

To test the smoothing performance and the edge preservation ability of the speckle filters several criteria were addressed:

1) Normalized mean (NM), to examine the ability to preserve the mean of a homogeneous land cover segments (equation 1):

$$NM = \frac{M_{filtered}}{M_{original}} \quad (1)$$

Where $M_{filtered}$ and $M_{original}$ are the means of the land cover segments of the filtered and the original image, respectively. The closer NM is to 1, the better the filter is able to preserve the mean.

2) Standard deviation to mean (STM), to determine the ability to reduce speckle noise of a homogeneous land cover segment (equation 2):

$$STM = \frac{SD}{M} \quad (2)$$

Where a smaller STM indicates a better speckle reduction ability.

3) Edge Index (EI), to examine the ability to preserve detailed edge information (equation 3):

$$EI = \frac{\Sigma\left|p_f(i,j) - p_f(i-1,j+1)\right|}{\Sigma\left|p_o(i,j) - p_o(i-1,j+1)\right|} \quad (3)$$

Where p_f (i, j) and p_o(i, j) are the filtered and the original pixel values, respectively, of the edges of the four selected land cover segments, with row number i and column number j. And p_f (i-1, j+1) and p_o(i-1, j+1) are neighbouring pixel values of the edges. When EI=1 the edge information is similar to the original image, edge blurring occurres for EI<1, and EI>1 indicates edge enhancement.

3. Speckle reduction and edge preservation evaluation

The smoothing characteristics for the four selected land cover segments and the edge preservation ability of every speckle filter for two different polarizations and three different window sizes are shown in table 1. Overall, all speckle filters are well capable of preserving the mean of a homogeneous segment for all tested window sizes and polarization modes. When looking at the speckle noise suppression ability a large variability can be observed between the different filters. For every land cover segment the ten STM ratios with the highest speckle noise reduction rates are highlighted in the table. In general, the Enhanced Lee, Frost, Enhanced Frost and Gamma filter with window size 7x7 all provided similar highest speckle reduction rates (50-70%, depending on the area). The same speckle filters, but with a window size of 5x5, also performed very well, with just marginally lower speckle reduction rates, but with a slightly better ability to preserve the mean of the homogeneous segment. The Local Sigma and Bit Errors filter show a relative poor speckle suppression performance. Overall, the influence of the polarization mode on speckle noise reduction is very small.

The Edge Index shows that many speckle filters are able to enhance the edges, in particular for the HH-polarization image. Again, the ten highest values of the EI are highlighted in table 1, indicating the good ability of the Enhanced Lee, Frost, Enhanced Frost and Gamma to enhance edges for the HH-polarization image. Although the EI for the HV-polarization image often indicates edge blurring, the EI values generally approximate 1, which means most edge information is retained. The window size appears to have a smaller influence on edge preservation.

Table 1. Smoothing and edge preservation characteristics of different adaptive filtering algorithms.

		Area I (red)		**Area II (green)**		**Area III (blue)**		**Area IV (yellow)**		
Filters	***Pol.***	*NM*	*STM*	*NM*	*STM*	*NM*	*STM*	*NM*	*STM*	*EI*
Original image	**HH**	**1,00**	**0,39**	**1,00**	**0,31**	**1,00**	**0,29**	**1,00**	**0,34**	**1,000**
	HV	**1,00**	**0,33**	**1,00**	**0,32**	**1,00**	**0,33**	**1,00**	**0,35**	**1,000**
Lee 3x3	HH	1,00	0,29	1,00	0,21	1,00	0,20	1,00	0,23	1,017
	HV	1,00	0,24	1,00	0,22	1,00	0,23	1,00	0,25	1,010
Lee 5x5	HH	1,01	0,27	1,00	0,19	1,00	0,19	1,00	0,21	1,002
	HV	1,01	0,22	0,99	0,20	0,99	0,21	0,99	0,22	0,989
Lee 7x7	HH	1,01	0,26	0,99	0,18	0,99	0,18	0,99	0,20	0,990
	HV	1,01	0,22	0,99	0,19	0,98	0,21	0,99	0,22	1,003
Enhanced Lee 3x3	HH	1,01	0,23	1,00	0,14	1,01	0,15	1,01	0,17	1,031
	HV	1,00	0,18	0,99	0,15	0,99	0,16	1,00	0,17	0,960
Enhanced Lee 5x5	HH	1,02	***0,19***	0,99	0,11	1,00	0,12	1,00	0,13	***1,044***
	HV	1,01	0,17	0,98	0,11	0,98	***0,13***	0,99	0,13	0,983
Enhanced Lee 7x7	HH	1,03	***0,18***	0,98	***0,09***	0,98	***0,11***	0,99	***0,11***	***1,040***
	HV	1,02	0,17	0,97	***0,10***	0,96	***0,13***	0,98	***0,11***	0,969

Frost 3x3	HH	1,01	0,23	1,00	0,14	1,01	0,15	1,01	0,17	***1,049***
	HV	1,00	0,19	0,99	0,15	0,99	0,16	1,00	0,17	0,955
Frost 5x5	HH	1,02	***0,19***	0,99	0,11	1,00	0,12	1,00	0,13	***1,037***
	HV	1,01	***0,17***	0,99	0,11	0,98	***0,13***	0,99	0,13	0,987
Frost 7x7	HH	1,03	***0,18***	0,98	***0,09***	0,99	***0,11***	0,99	***0,11***	1,029
	HV	1,02	***0,17***	0,98	***0,10***	0,97	***0,13***	0,98	***0,11***	0,969
Enhanced	HH	1,01	0,23	1,00	0,14	1,01	0,15	1,01	0,17	***1,034***
Frost 3x3	HV	1,00	0,19	0,99	0,15	0,99	0,16	1,00	0,17	0,969
Enhanced	HH	1,02	***0,19***	0,99	0,11	1,00	0,12	1,00	0,13	***1,044***
Frost 5x5	HV	1,01	0,17	0,98	***0,11***	0,98	0,13	0,99	***0,13***	0,980
Enhanced	HH	1,03	***0,19***	0,98	***0,09***	0,98	***0,11***	0,99	***0,11***	***1,047***
Frost 7x7	HV	1,02	0,17	0,97	***0,10***	0,96	***0,13***	0,98	***0,11***	0,967
Gamma 3x3	HH	1,01	0,23	1,00	0,14	1,01	0,15	1,01	0,17	***1,034***
	HV	1,00	0,19	0,99	0,15	0,99	0,16	1,00	0,17	0,969
Gamma 5x5	HH	1,02	***0,19***	0,99	0,11	1,00	0,12	1,00	0,13	***1,052***
	HV	1,01	0,17	0,98	0,11	0,98	0,13	0,99	***0,13***	0,980
Gamma 7x7	HH	1,03	***0,19***	0,98	***0,09***	0,98	***0,11***	0,99	***0,11***	***1,050***
	HV	1,02	0,18	0,97	***0,10***	0,96	***0,13***	0,98	***0,11***	0,960
Kuan 3x3	HH	1,01	0,26	1,00	0,16	1,01	0,17	1,01	0,19	1,006
	HV	1,00	0,20	1,00	0,17	1,00	0,20	1,00	0,20	0,971
Kuan 5x5	HH	1,01	0,26	1,00	0,18	1,00	0,18	1,00	0,20	0,992
	HV	1,01	0,22	0,99	0,19	0,99	0,20	0,99	0,21	0,994
Kuan 7x7	HH	1,02	0,24	0,99	0,17	0,99	0,17	0,99	0,19	0,979
	HV	1,01	0,21	0,99	0,18	0,98	0,20	0,99	0,20	1,019
Local Sigma	HH	1,00	0,36	1,00	0,28	1,00	0,27	1,00	0,30	1,017
3x3	HV	1,00	0,30	1,00	0,29	1,00	0,30	1,00	0,32	0,988
Local Sigma	HH	1,00	0,34	1,00	0,26	1,00	0,25	0,99	0,28	1,002
5x5	HV	1,00	0,28	0,99	0,27	0,99	0,29	0,99	0,30	0,981
Local Sigma	HH	1,00	0,33	0,99	0,25	0,99	0,24	0,99	0,28	1,002
7x7	HV	1,00	0,27	0,99	0,27	0,99	0,28	0,99	0,29	0,982
Bit Errors 3x3	HH	1,00	0,39	1,00	0,31	1,00	0,29	1,00	0,34	1,000
	HV	1,00	0,33	1,00	0,32	1,00	0,33	1,00	0,35	1,000
Bit Errors 5x5	HH	1,00	0,38	1,00	0,31	1,00	0,29	1,00	0,33	0,997
	HV	1,00	0,33	1,00	0,32	1,00	0,33	1,00	0,35	1,000
Bit Errors 7x7	HH	0,99	0,37	1,00	0,31	1,00	0,29	0,99	0,33	0,998
	HV	1,00	0,33	1,00	0,32	1,00	0,33	1,00	0,35	1,002

To demonstrate the smoothening effect of the speckle filters the non-smoothed original HH-polarization image and the same image smoothed by the Enhanced Frost filter (with window size 7x7) has been shown in figure 2. For convenience, also the edges of the selected homogeneous land cover segments are plotted on the image with a blue colour. First of all, it can be clearly seen that speckle noise is significantly reduced in the filtered image. Secondly, although the filtered image appears to be blurry within a land cover segment, differences between neighbouring land cover segments are visibly enhanced.

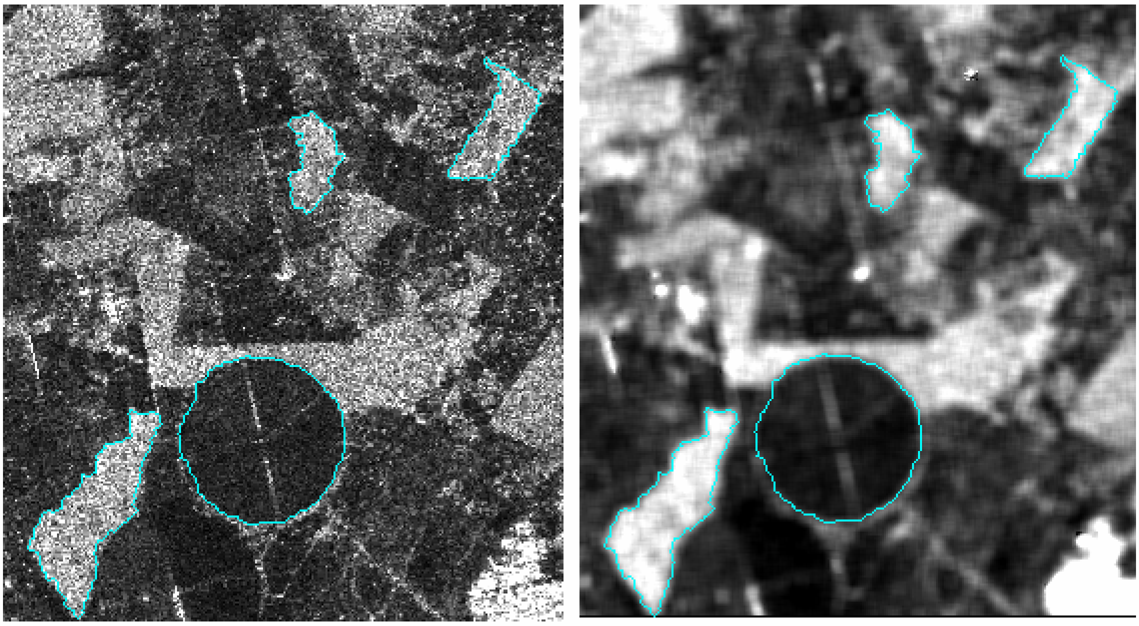

Fig. 2. Left: original HH-polarized SAR image; right: HH-polarized SAR image smoothed by the Enhanced Frost filter . In blue the edges of the selected homogeneous land cover segments.

4. Discussion and conclusions

The objective of this study was to compare the performance of eight different adaptive speckle filtering techniques for their ability to preserve the mean of a homogeneous land cover segment, reduce speckle noise and at the same time retaining the sharpness of the edges. A HH/HV-polarized SAR image and three performance criteria were used for the evaluation.

The results show that all speckle filters are able to preserve the mean of a homogeneous area to a satisfactory level. However, when looking at the speckle suppression, the Enhanced Lee, Frost, Enhanced Frost and Gamma filtering algorithm with moving window size of 7x7 outperform the other speckle filters significantly, with speckle reduction rates up to 70%. The Local Sigma and Bit Errors filters appear not to be able to significantly reduce speckle noise. The Edge Index shows that for the HH-polarized image again the Enhanced Lee, Frost, Enhanced Frost and Gamma speckle filter perform best in preserving and enhancing edges. For the HV-polarized image most speckle filter algorithms resulted in slight edge blurring.

It should be noted that the filter that's most suitable depends on the requirements of a particular application. In this study the focus was on differentiation and separation between different land cover segments. Therefore, smoothing of natural within-segment variability was not an issue and was not taken into account. However, when the interest of the study lies in texture analysis within a land cover segment, other speckle filters might have to be considered. For example, in recent years the use of wavelet transform techniques has been investigated and has been proven to be a useful tool in speckle noise reduction, enabling speckle smoothing on multiple resolution scales.

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