A Study Of Speckle Noise Reduction Filters for SAR Images

TIFOUTI Issam[#1], MERIANE Brahim[#1], RAHMOUNI Salah[#1] and MOUSSAOUI abdelkrim[#2]
[1#]*Higher School for professors Of Technological education, Skikda, Algeria.*
[2#]*Laboratory of Electrical Engineering of Guelma (LGEG), University 8th May 1945 Guelma, Algeria.*
[1] issam86@yahoo.fr.

***Abstract*— Synthetic Aperture Radar (SAR) imaging systems can provide valuable sources of earth observation data for various applications. Speckle noise can reduce the image quality of synthetic aperture radar (SAR) and complicate image interpretation. Reduction of speckle noise is one of the most important processes to increase the quality of the image. Several filters are widely used to enhance the quality of images by despeckling it. This paper compares six different speckle reduction filters such as Lee Filter, Frost Filter, Kuan Filter, Wiener Filter, Median Filter and SRAD (Speckle Reducing Anistrophic Diffusion) Filter that are applied to the SAR image. The statistical measures SNR, PSNR, SSIM, MSE, RMSE are compared and the results are tabulated to determine the filter that is well suited for SAR images. Finally the best filter has been proposed based on the statistical and experimental results.**

***Keywords*— Synthetic Aperture Radar (SAR), Speckle noise, Speckle Filtering, Statistical measures.**

I. INTRODUCTION

Synthetic Aperture Radar (SAR) images employ active sensors that detect microwave radiation, which has longer wavelength than visible light that is detected in passive sensors, such as the optical sensor. Therefore, the surface of the Earth can be observed at high resolution, regardless of weather conditions and sun phenomena [1]. The active sensor of SAR images is also used with satellites or unmanned aerial vehicles (UAVs), as the development of the active sensor technology applied to SAR images enabled high-resolution target detection and identification. SAR images are widely used in applications of a variety of fields, such as the military, agricultural, weather forecasting, and environmental analysis, etc. [2]. Due to the advantages of SAR images and their various applications, research on the technology behind SAR images is being actively conducted around the world (image enhancement [3–5], image classification [6,7], image segmentation [8,9], etc.).

Synthetic aperture radar (SAR) is a coherent imaging system [10]. Each pixel in SAR images represents the coherent addition of scatterers from a corresponding resolution cell. These scatterers interfere, either constructively or destructively, depending on the phase of the scatterers. As such, the resulting images exhibit bright and dark pixels and are uneven, even for homogeneous regions.

This phenomenon is called speckle noise and it often reduces the quality of images and complicates image interpretation [10,11]. Mathematically there are two basic models of noise: Multiplicative noise and additive noise. Multiplicative noise is image dependent, complex to model and difficult to remove. Whereas additive noise is systematic in nature and can be easily modeled and hence reduced easily [12]. Speckle noise is a multiplicative noise. It occurs in all coherent imaging systems, such as SAR (Synthetic Aperture Radar), satellite images, medical ultrasonic and photographic images [13]. The aim of the noise reduction techniques is to remove speckle noise and retaining the important features of the images without destroying useful diagnostic information.

I.1 ADDITIVE NOISE

The so called additive noise (AN) model is commonly found in acquiring images from digital devices [14]. Most of the literatures principally process with this type of image formation models. Let $f[m,n]$ be the original image, $f'[m,n]$ be the noise assimilate version and $\eta[m,n]$ be the noise function which returns values coming from an arbitrary distribution. Then the additive noise is given by the equation

$$f'[m,n] = f[m,n] + \eta[m,n] \quad (1)$$

Typically, $\eta[m,n]$ is symmetric about zero. Additive noise is independent of the pixel values in the original image.

I.2 SPECKLE NOISE

There are different noise types in real world. Multiplicative noise is common beside additive noise. Quality of images may degraded while images acquisition, transmission, and storage. The noise of the original record equipment, external perturbation, the defects of the imaging system and the movement of objects also cause the image noise. According to the assumption that imaging system is linear translation invariance system [15]. Speckle or multiplicative noise is a signal dependent form of noise which magnitude is related to the value of the original pixel. The mathematical expression for a multiplicative noise model is given by

$$f'[m,n] = f[m,n] + \eta[m,n] f[m,n] \quad (2)$$

$$f'[m,n] = f[m,n] + [1 + \eta[m,n]] \quad (3)$$

II. SOURCES OF NOISE IN DIGITAL IMAGES

The main source of noise in digital image processing arises during the image acquisition or transmission process. In general, noise is measured by the percentage of the corrupted image pixel. Depending on how the image has been created, there are several causes to add noise in the original image. The causes are:

1) If the image is scanned from a photograph made on film, the film grain is a source of noise. Noise can also be introduced by the scanner itself, or be the result of damage to the film.
2) If the image is captured in a digital format directly, then the mechanism for collection (the data) may introduce noise.
3) Electronic transmission of image data can also make noise [16-17].
4) When the emitted light from the object cannot enter into the device lenses and that's why noise is introduced into the image if the device sensor is not properly opened . Light levels and sensor temperature are major factors in making a noise.
5) Dynamic range is a parameter which is used in mapping a 3D view in the image plane. If this range is small then more intensity is gathered on the pixels which also make the picture noisy and if the dynamic range is high then the light intensity is scattered into a wide region which makes the picture noisy [17].

III. DENOISING

Denoising is the process of reducing noise in the images [18]. Conceptually, Noise reduction techniques are very similar regardless of the image being processed, however a prior knowledge of the characteristics of an expected signal can mean the implementations of these techniques varies, greatly depending on the type of signal. Image denoising is often used in several domains like SAR and satellite images processing applications, where an image was infected with noise but needs to be enhanced before it can be making observations or used. For this type of application we must to know something about the degradation process in order to develop a model. The inverse process can be applied to the image to restore it back to the original form when we have a model for the degradation process. Image denoising finds applications in fields such as photography where noise is made up of lots of small points that are created, astronomy where the resolution limitations are intense and in medical imaging where the physical requirements for two high quality imaging are needed to analyze appropriate for images. So denoising is a technique to remove the undesirable information from an image to make it more appropriate for the next steps of the image processing [13].

IV. PROPOSED METHODOLOGY

Our work is based on the use of different techniques for the reduction speckle noise of SAR and satellite images. Several filters are used for speckle reduction, some filters are best adapted for some specific class of images. The proposed work is a comparative study on the performance of the several filters such as Lee Filter, Frost Filter, Kuan Filter, Weiner Filter, Median Filter and SRAD Filter in removing the speckle noise from the input images. Statistical parameters like SNR, PSNR, SSIM, MSE, RMSE are calculated for the output images obtained from the filters to assess the quality of the images used. The images corresponding to the best statistical value are shown and results are discussed.

V. METHODS FOR SPECKLE FILTERING

Divers methods are available for image denoising of images which are corrupted by speckle noise includes filtering techniques like Median Filter, Lee Filter, Frost Filter, Kuan Filter, Wiener Filter, and SRAD Filter.

V.1 MEDIAN FILTER

Median filter is one of the popular methods to be employed to reduce impulse noise level from corrupted images [19]. The median filter is a spatial nonlinear filter which removes pulse or spike noise by replacing the middle pixel value in the window with the median value of its neighbors in the window [20]. The median filter is very effective in retaining the image details since they do not depend on values which are significantly different from typical values in the neighborhood [21]. The median filter works on successive image window in a manner similar to that of the linear filters, but the method employed does not use a weighted sum. Pixels in each window are sorted into ascending order and the pixel value in the middle is selected as the new value for a particular pixel. Advantage of this filter is it preserves the edges [20]. Disadvantage is the long time needed for computation of the median value for sorting N pixels.

V.2 LEE FILTER

The Lee filter [22], developed by Jong-Sen Lee, is an adaptive filter which changes its characteristics according to the local statistics in the neighborhood of the current pixel. The Lee filter is able to smooth away noise in flat regions, but leaves the fine details such as lines and textures unchanged. The Lee filter is designed to eliminate speckle noise while preserving edges and point features in radar imagery [23]. Lee Filter is based on multiplicative speckle model [24], this model is first approximated by a linear model. Then the minimum mean square error criterion is applied to the linear model [25]. The resulting grey level value R for the smoothed pixel is

$$R = I_c * W + I_m * (1 - W) \quad (4)$$

Where

$W = 1 - \frac{C_u^2}{C_i^2}, C_u = Sqrt\left(1/N_{look}\right), C_i = S/I_m$,

I_c is the centre pixel of filter window. I_m = mean value of intensity within window, S = standard deviation of intensity within window, the C_u above is the estimated noise variation coefficient. C_i is the image variation coefficient. W is a weighting function.

V.3 FROST FILTER

Invented by Frost in 1982, is linear, convolutional filter used to remove the multiplicative noise from images [22]. Frost filter is an adaptive filtering approach based on local statistic about the target pixel. In homogenous regions frost filter acts as a mean filter and at edges filtering is inhibited completely. Despeckled pixel value is estimated by the weighting coefficient which decay from the filter centre when high contrast regions are filtered [26]. Thus despeckling is widely carried out by smoothing in homogeneous region, and lesser smoothing in regions with high contrast pixels and edges. The filter output is determined by

$$\hat{x}_s = \Sigma_{p \in \eta} k_p x_p \quad (5)$$

where x_p is noisy pixel of interest in the window k_p is given by

$$k_p = e^{(-KA_s^2 dis_{s,p})} / \Sigma_{p \in \eta} e^{(-KA_s^2 dis_{s,p})} \quad (6)$$

where K, damping coefficient, is selected such that $KA_s^2 \to 0$ at homogeneous regions and results in mean filter output and $KA_s^2 \to \infty$ (so large) at edges and results in less or no despeckling or smoothing.

$$A_s^2 = (1/|\eta_s|)\Sigma_{p \in \eta}(x_p - \bar{x}_s)^2 / (x_p - \bar{x}_s)^2$$
(7)

Where

$\bar{x}_s$ is the mean value of the intensity within the filter window η_s

$$dis_{s,p} = \sqrt{(i - i_p)^2 + (j - j_p)^2} \quad (8)$$

(i_p, j_p) is the grid coordinates of pixel s and (i_p, j_p) is the grid coordinates of pixel p.

V.4 KUAN FILTER

It was developed by Kuan and Nathan and Kurlander in 1987 [22]. Kuan performs spatial filtering on each individual pixel in an image using the grey level values in a square window surrounding each pixel. The dimensions of the filter must be odd from 3x3 to 11x11 pixels. All pixels are filtered. In order to filter pixels located near edges of the image, edge pixels are replicated to give sufficient data. The resulting grey level value R for the smoothed pixel is: [25]

$$R = C_p * W + I * (1 - W) \quad (9)$$

Where,

$C_u = 1/N_{look}, C_i = Var/I, W = (1 - C_u/C_i)/(1 + C_u)$

, i = Mean grey level in the filter window, C_p = central pixel in filter window, Var = Variance in filter window, N_{look} = Number of Looks.

V.5 WIENER FILTER

The aim of wiener filter is reduced the mean square error as much as possible [27]. The Wiener filter is designed by minimizing the MSE between the original image and filtered image. It can be applied to the image, adaptively, adaptation itself to the local image variance. When the variance is small, it performs more smoothing. When the variance is large, it performs low smoothing. Since the intensities of the pixels in the weld area follow a Gaussian distribution. The Wiener filter was selected for filtering of radiographic images of welds, because it is close to the matched filter in this case [28].

V.6 SRAD FILTER

SRAD is Speckle Reducing Anti Isotropic filter [29]. In the case of diffusion filtering the strength and direction of the diffusion are controlled by an edge detection function. It removes speckles by modifying the image via solving a Partial Differential Equation. It removes speckles and at the same time improves the edges. SRAD is proposed for speckled images without logarithmic compression. Just as lee and frost filters utilize the coefficient of variation in adaptive filtering, SRAD exploits the instantaneous coefficient of variation, which serves as edge detector in speckled images. The function produces high values at edges and presents low values in homogeneous regions. Thus it ensures the edge preserving and edge enhancing at the edges and mean preserving behavior in the homogeneous regions [30].

VI. ESTIMATION OF STATISTICAL PARAMETERS

To evaluate the performance of the proposed filters for removal speckle noise and to evaluate their comparative Performance. The parameters which are used in estimation of performance are Signal to Noise Ratio(SNR), Peak signal to noise ratio(PSNR), Mean Square Error(MSE), Root Mean Square Error(RMSE), Structural Similarity Index(SSIM).

VI.1 ESTIMATION OF SNR

SNR is a measurement of distortion. Especially in homogeneous regions, It exhibits the success of noise. It is calculated as:

$$SNR = 10\log_{10}\left(\frac{\sigma_g^2}{\sigma_e^2}\right) \quad (10)$$

where, σ_g^2 is the variance of the noise free image and σ_e^2 is the variance of error (between the original and denoised image). The value of SNR should be high for good quality image.

VI.2 ESTIMATION OF PSNR

PSNR is the ratio between maximum possible power of a signal and the power of corrupting noise that affects the reliability and quality of its representation. PSNR is calculated as

$$PSNR = 10\log_{10}\left(\frac{MAX^2}{MSE}\right) \quad (11)$$

Where MSE is mean square error and MAX is the maximum pixel value of image [31].

VI.3 ESTIMATION OF MSE

The MSE is the cumulative square error between the synthesized image and the original image defined by [32]:

$$MSE = \sum_{0}^{m-1}\sum_{0}^{n-1}\left\| f(i,j) - g(i,j) \right\|^2 \quad (12)$$

VI.4 ESTIMATION OF RMSE

RMSE is a good measure of accuracy. A lower value for RMSE means lesser error and this result in a high value of PSNR. RMSE is a frequently used measure of the differences between values actually observed and the values predicted by an estimator or a model [33]. Its formula is given by

$$RMSE = \sqrt{MSE} \quad (13)$$

VI.5 ESTIMATION OF SSIM

This parameter is used for measuring the similarity between two images. The index is a reference to measure of image quality based on an initial distorted image as reference. The measurement should provide a good approximation to perceive image distortion. This parameter is defined as follows:

$$SSIM = \frac{\left(2\mu_x\mu_y + C_1\right)\left(2\sigma_{xy} + C_2\right)}{\left(\mu_x^2 + \mu_y^2 + C_1\right)\left(\sigma_x^2 + \sigma_y^2 + C_2\right)} \quad (14)$$

Where μ_x the average of x, μ_y the average of y, σ_x^2 the variance of x, σ_y^2 the variance of y, σ_{xy} the covariance of x and y, $C_1 = (k_1L)^2$, $C_2 = (k_2L)^2$ two variables to stabilize the division with weak denominator, L the dynamic range of the pixel values (typically this is $2^{\text{bit per pixel}}$ -1) and k_1=0.01 and k_2=0.03 by default.

The resultant SSIM index is a value between -1 and 1, and value 1 is only accessible in the case of two identical sets of data or better image quality [34].

VII. ALGORITHM FOR FILTER SELECTION

The input images are corrupted with uniformly distributed multiplicative noise. With three different values of standard deviation (σ) of the noise. Noisy images are filtered by using six filters such as Median Filter, Lee Filter, Frost Filter, Kuan Filter, Wiener Filter, and SRAD Filter. After the filtering, the images are saved for estimation of statistical measures. Statistical parameters such as SNR, PSNR, MSE, RMSE and SSIM are calculated for the filtered images obtained from each filter and we obtain six sets of statistical parameters, each set corresponding to a specific filter. Filtered image and statistical parameters corresponding to the best result obtained are given in the output after the comparison of the results for images.

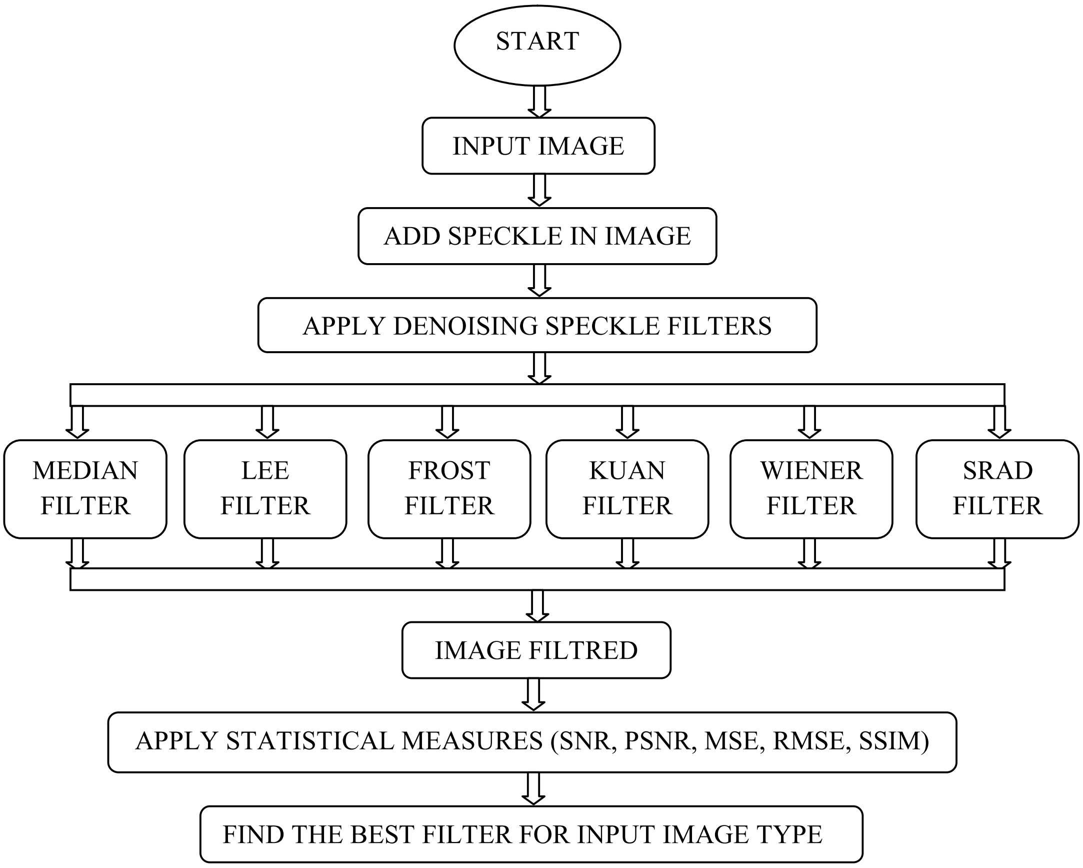


Fig. 1 Algorithm for Speckle noise reduction.

VIII. EXPERIMENTAL RESULTS

In this section we discussed the experimental results. These results have been obtained by applying reduction filters described above to SAR image., these image were filtered using Lee, Frost, Kuan, Wiener, Median and SRAD Filter, by using 3x3 windows size.

To compare the efficiency of each filter. Performance measurements of the reduction filters performed for each de-speckle image.

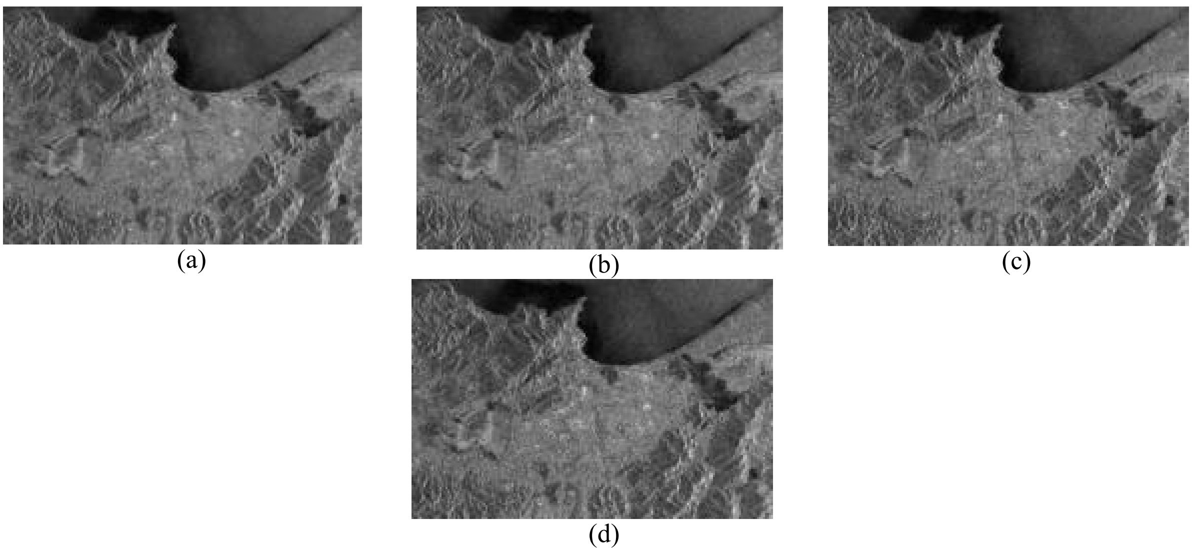


Fig. 2 (a) Original SAR Image (b) Noisy image with SD 0.01, (c) Noisy image with SD 0.02, (d) Noisy image with SD 0.03.

TABLE 1: RESULTS OF SAR IMAGE WITH STANDARD DEVIATION 0.01

FILTER	SSIM	SNR	PSNR	MSE	RMSE
LEE	0.9698	14.6065	26.5538	144.9090	12.0378
FROST	0.9158	15.9066	19.7958	686.9136	26.2090
KUAN	0.9155	16.2624	24.2879	244.1707	15.6260
WIENER	0.9479	17.6198	27.1892	125.1869	11.1887
MEDIAN	0.9231	16.1448	24.2921	243.9336	15.6184
SRAD	0.9153	16.5684	25.9815	165.3211	12.8577

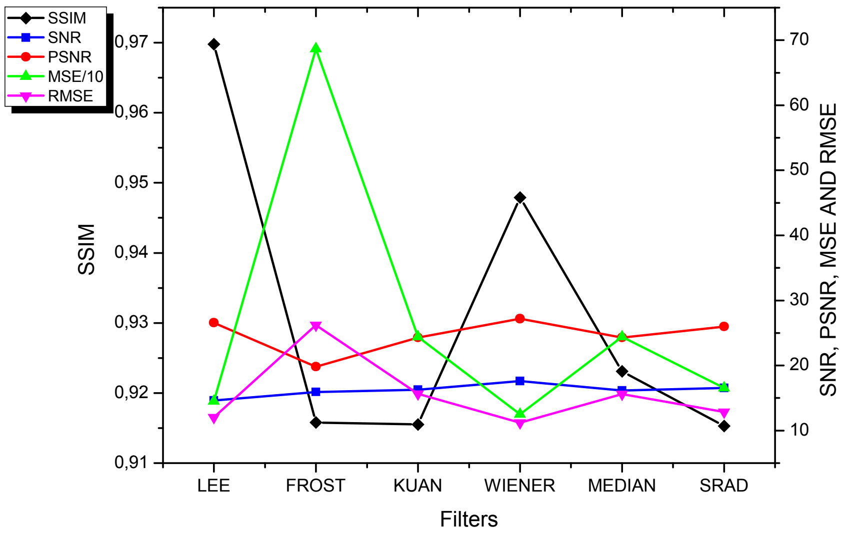


Fig. 3 Graph for SAR image with standard deviation 0.01

TABLE 2: RESULTS OF SAR IMAGE WITH STANDARD DEVIATION 0.02

FILTER	SSIM	SNR	PSNR	MSE	RMSE
LEE	0.9682	14.4279	26.4020	150.0668	12.2502
FROST	0.9125	15.8473	19.7756	690.1175	26.2701
KUAN	0.9154	16.1841	24.3347	241.5522	15.5419
WIENER	0.9432	17.3178	26.7524	138.4324	11.7657
MEDIAN	0.9177	15.6845	24.1048	254.6829	15.9588
SRAD	0.9170	16.4808	25.9349	167.1052	12.9269

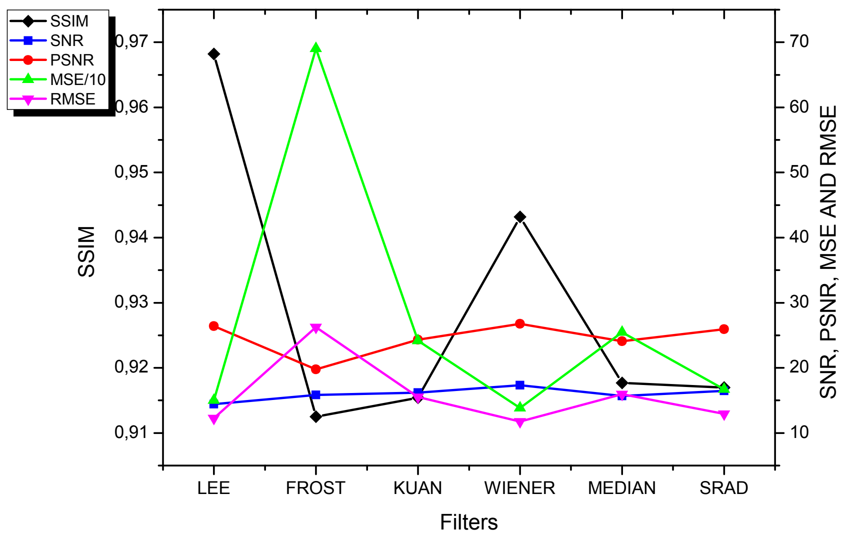


Fig.4 Graph for SAR image with standard deviation 0.02

TABLE 3: RESULTS OF SAR IMAGE WITH STANDARD DEVIATION 0.03

FILTER	SSIM	SNR	PSNR	MSE	RMSE
LEE	0.9669	26.2507	14.2973	155.3838	12.4653
FROST	0.9086	19.7533	15.7897	693.6705	26.3376
KUAN	0.9105	24.2738	16.1060	244.9628	15.6513
WIENER	0.9393	26.3738	17.1560	151.0430	12.2900
MEDIAN	0.9112	23.9210	15.4211	265.6959	16.3002
SRAD	0.9173	25.7858	16.2745	172.9399	13.1507

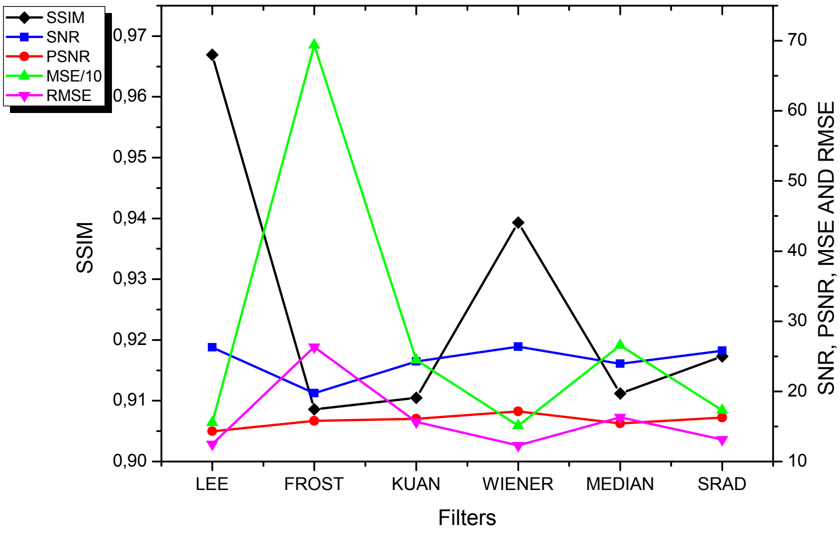
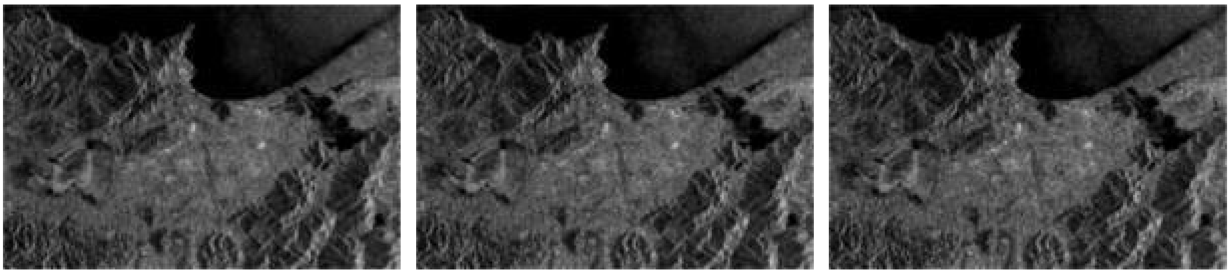
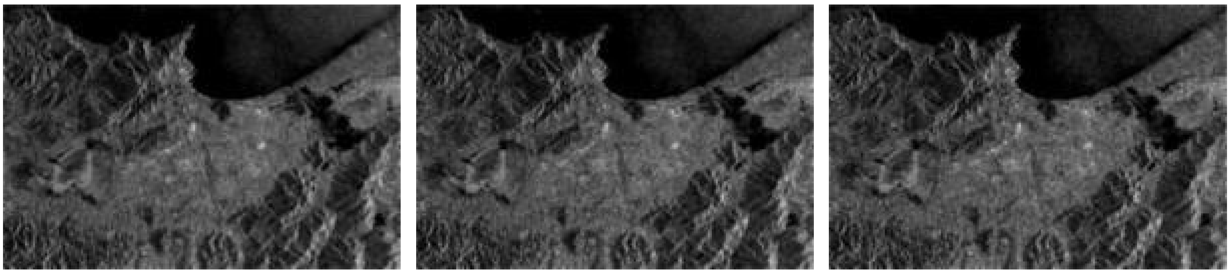


Fig.5 Graph for SAR image with standard deviation 0.03



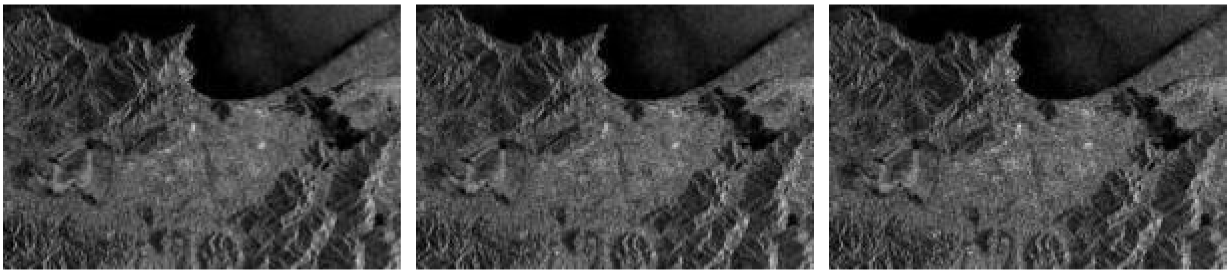
(a) (b) (c)

Fig. 6 Speckle noise reduction using Frost filter, (a) Denoised image for SD 0.01, (b) Denoised image for SD 0.02, (c) Denoised image for SD 0.03.



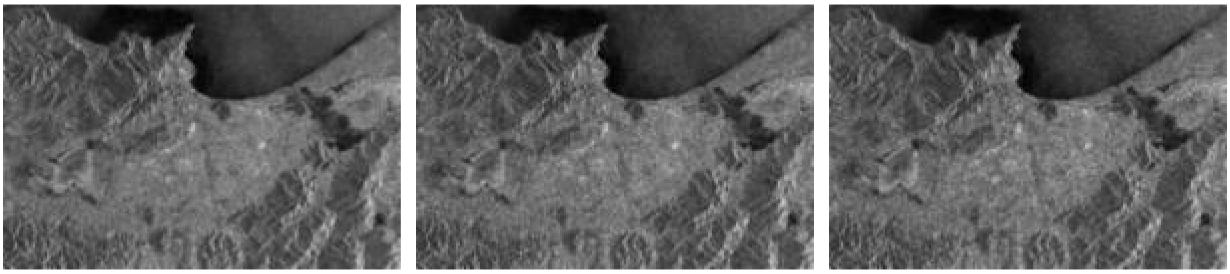
(a) (b) (c)

Fig. 7 Speckle noise reduction using Kuan filter, (a) Denoised image for SD 0.01, (b) Denoised image for SD 0.02, (c) Denoised image for SD 0.03.



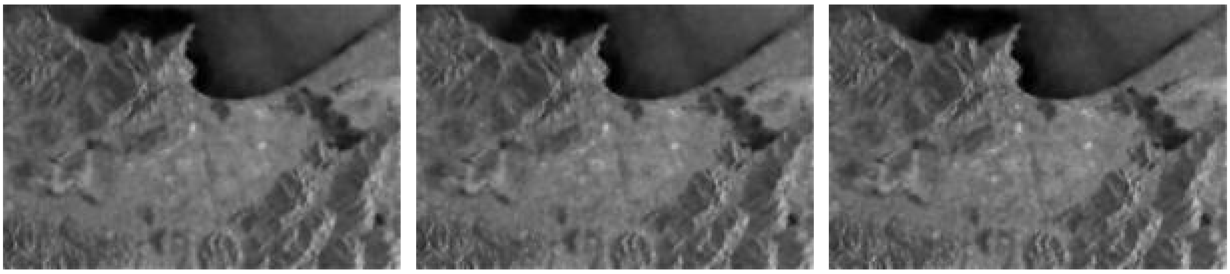
(a) (b) (c)

Fig. 8 Speckle noise reduction using Lee filter, (a) Denoised image for SD 0.01, (b) Denoised image for SD 0.02, (c) Denoised image for SD 0.03.



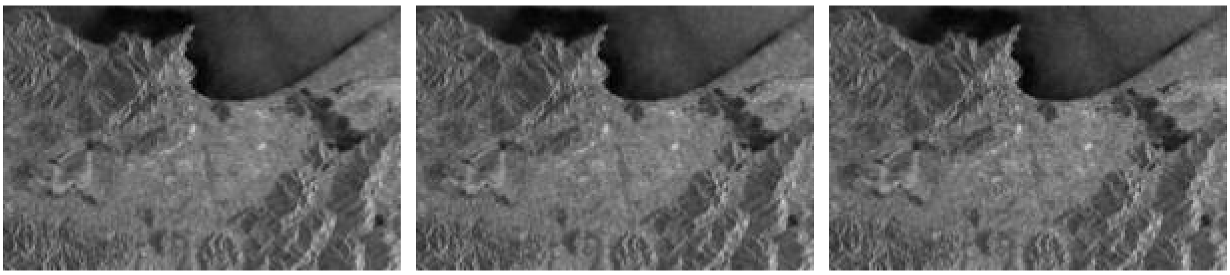
(a) (b) (c)

Fig. 9 Speckle noise reduction using Median filter, (a) Denoised image for SD 0.01, (b) Denoised image for SD 0.02, (c) Denoised image for SD 0.03.



(a) (b) (c)

Fig. 10 Speckle noise reduction using SRAD filter, (a) Denoised image for SD 0.01, (b) Denoised image for SD 0.02, (c) Denoised image for SD 0.03.



(a) (b) (c)

Fig. 11 Speckle noise reduction using Wiener filter, (a) Denoised image for SD 0.01, (b) Denoised image for SD 0.02, (c) Denoised image for SD 0.03.

By analyzing above results we can infer that Wiener and Lee give optimal result.

IX. CONCLUSION

The filter is used to reduce speckle noise and preserve image features like edges and so on. Hence we proposed an algorithm that takes the decision automatically, for SAR and satellite images, the filter must be used, because this algorithm selects the best filter among the different filters used and which gives optimal results among the different results produced by different filtering techniques. We Studied six Different types of filters with different type of Standard Deviation of noise. Out of six filters used, Lee and Wiener Filter gives best results for SAR Images.

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