Evaluation of Adaptive Filters for Speckle Reduction in RISAT-1 Data for Flood Mapping

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Abstract

Processing SAR images without reducing speckle would yield inaccurate and unreliable results. To overcome this problem, many researchers have worked on development of different speckle reduction techniques/filters. However, the choice of best speckle reduction filter is subjective to data and objectives of the study. So, this paper focuses on evaluating the performance of different speckle filters, which work on the principle of reducing speckle by statistically manipulating the value of target pixel considering the values of neighbouring pixels. Five filters comprising - Lee filter, Lee Sigma filter, Frost filter, Local Region filter and Gamma filter were examined for their efficiency in speckle reduction over RISAT-1 (MRS) data. The process of choosing an optimal filter is a trade-off between reduction of speckle and loss of useful data. So, the terms of trade-off were defined first. Since the aim of speckle reduction was to utilize the resulting filtered image for flood mapping, the specifications to determine the efficiency of the filter was defined accordingly. The specified characteristics of the filtered images were measured by Mean Square Error, Signal to Noise Ratio, Speckle Suppression Index, Speckle Mean Preservation Index and comparison of the change in Mean and Standard Deviation and also by close visual examination. The RISAT-1 data was filtered using all the five filters in three window sizes – 3×3, 5×5 and 7×7. The impact of various filters was studied on the entire image as well as water bodies separately. Keeping in mind that an efficient filter should reduce maximum speckle while preserving features and minimal loss of useful data, it was concluded that a single pass of Frost (7×7) is the most suited filter for RISAT-1 data intended for flood mapping application.

Key words: RISAT-1, Speckle, Adaptive Filters, Flood

1. Introduction

The drastic climatic variability has increased the occurrence of devastating flood events globally in recent times (Senthilnath et al., 2013). India being geographically located in tropical and sub-tropical climatic zone, gets affected by these climatic extremities more often than perceived in the planning and development phase in the past. Hence, there is urgent need for better adaptation and mitigation strategies against disasters like flood. Dynamic (in time and space)
mapping of flood extent is a prerequisite in any flood related study. Given to the inaccessibility of flood affected area during ongoing flood events, the mapping task can best be accomplished with the aide of remote sensing. In the past, optical remote sensing has been widely used to generate the flood extent maps, however, the overshadowing cloudy conditions brings the accuracy of flood mapping below the desirable/acceptable levels. Remote sensing system operating in the wavelength range of radio waves, popularly known as microwave remote sensing, has the capability of penetrating haze, light rain, and cloud. This makes microwave imaging suitable for monitoring of flood events even with cloudy conditions when optical data is not useful (Chunming et al., 2005).

Realizing the need for operational space based active microwave remote sensing system Indian Space Research Organization (ISRO) has launched it’s first indigenously built, multi-mode, multi-polarization Synthetic Aperture Radar (SAR) on-board RISAT-1 (Radar Imaging SAtellite -1), on 26 April 2012. Since its commissioning, data from RISAT-1 has been extensively used in monitoring rice acreage, retrieval of very high-resolution ocean surface winds, ocean wave spectra, detection of coastal and deep sea ships and flood mapping-monitoring (Chakraborty et al., 2013). However, like every coherent imaging systems, SAR also has an inherent problem of Speckle noise, commonly known as salt-and-pepper effect (Goodman, 1976; Arsenault and April, 1976; Lim and Nawab, 1981; Gagnon and Jouan, 1997).

RISAT-1 uses microwave radiation (‘C’ band) to illuminate the surface of Earth. An image is formed after the SAR system receives the coherent sum of reflected radiation at the antenna that is synthesized by the large motion of the sensor system (Qiu et al. 2004; Chakraborty et al., 2013). Active sensor of RISAT-1 transmits pulses coherently, such that the transmitted waves are oscillating in phase with one another, which interact minimally on their way to the target. After interaction with the target, these waves though still coherent in frequency but no longer remains coherent in phase. The main reason for this is the difference in distance the waves have to travel from source to target and back from different targets even in single ground resolution cell/pixel (Lillesand et al., 2004). Other reasons for this shift in phase could be the difference in surface roughness causing difference scattering mechanism (single or multiple bounce scattering), movement of synthesized antenna (Hervet et al., 1998). These out of phase waves generate stronger or weaker final signal (output) by constructively or destructively interfering with each other. These interferences produce a seemingly random pattern of brighter and darker pixels giving the radar images a distinctly grainy appearance known as ‘Speckle’ (Goodman, 1976; Lee et al., 1994; Lillesand et al., 2004). These speckles result in a SAR image that fails to have a constant mean radiometric level in homogeneous areas (Bruniquel and Lopes, 1997). The speckles generally have the characteristics of a random multiplicativc noise in the sense that the noise level increases with the average gray of a local area (Lee, 1983)

The presence of speckle in an image reduces the detectability of ground targets, obscures the spatial patterns of surface features, and decreases the accuracy of automated image classification (Sheng and Xia, 1996). It not only complicates visual image interpretation, but also makes automated digital image classification, an efficient technique of flood mapping, a difficult task. It is therefore essential that speckle is reduced before any further processing is carried out. There are several filters that have been developed to reduce the speckle from SAR images viz., Lee Filter (Lee, 1981), Frost Filter (Frost et al., 1982), Gama MAP Filter (Lopes et al., 1990). Each of these filters has its unique strengths and limitations. Speckle filters with good noise removal capabilities often tend to degrade the spatial and radiometric resolution of an original image and cause the loss of image detail (Qiu et al., 2004). The performance of noise suppression must be balanced with the filter’s effectiveness in order to preserve finer details (Xiao et al., 2003). Thus, the choice of which filter to use depends upon the requirements of the specific application and the characteristics of the dataset employed (Lee et al., 1994). Hence in the present study, the most preferred speckle filters are evaluated over RISAT-1 (MRS) data, intended for flood mapping application.

2. Speckle Reduction Techniques and Performance Measures

There are two approaches to speckle reduction. The first approach involves techniques such as multiple-look processing, which averages together several independent images or “looks” of different portions of the available azimuth spectral bandwidth (synthetic aperture), or different polarization states of the same area during image formation (Lillesand et al., 2004). The second technique involves use of digital image processing techniques to smoothen the image after it has been formed as a result of pre-processing. Further, in the second technique, there are two major approaches which may be followed to reduce speckle. The first approach of digital filtering is achieved in the frequency domain by wavelet transformation (Gagnon and Jouan, 1997). The second approach is accomplished in the spatial domain, where noise is removed by averaging or statistically manipulating the values of neighboring pixels (Qiu et al., 2004). The present research focuses on the second approach wherein some of the commonly used speckle filters for SAR data have been evaluated for speckle reduction over RISAT-1 data.

Speckle filters working in spatial domain are generally categorised in to two categories. Low pass filters such as Mean or Median which generally tends to smoothen the images. The second type is adaptive filters, as indicated by their name, adapt to local variations in the image. Since adaptive filters consider local statistical properties they proved better efficiency as compared to low-pass smoothing
filters (e.g. Mean and Median filters). Adaptive filters perform much better than low-pass filters, in preservation of the image sharpness and details while suppressing the speckle noise (Schwan et al., 1995).

Following the assumption of the multiplicative characteristic of noise, many filters such as Lee filter, Frost filter, Gamma (MAP or Maximum A Posteriori) and Lee-sigma filter have been devised and applied in the past. All these adaptive filters aim to effectively reduce speckle in radar images without eliminating the finer details (Jensen, 2000). The detailed description of all the speckle filters is not in the scope of this paper, however, the basic formulation of the most preferred filters used to reduce the speckle from SAR data are briefly given here.

2.1. Mean Filter

Mean filter is a low-pass filter and simply averages the values in the moving window. It is the least satisfactory method of speckle noise reduction as it results in loss of detail and resolution (Mansourpour et al., 2006)

2.2. Median Filter

Low value and high value pixels in the SAR data correspond to destructive and constructive interference (Sheng and Xia, 1996). The Median filter effectively suppresses these extreme values. The Mean and Median filters meet with only limited success when applied to SAR data. One reason for this is the multiplicative nature of speckle noise, which relates the amount of noise to the signal intensity. The other reason is that they are not adaptive filters in the sense that they do not account for the particular speckle properties of the image (Qiu et al., 2004).

2.3. Lee Filter

Lee filter is based on the assumption that the mean and variance of the pixel of interest are equal to the local mean and variance of all pixels within the user-selected moving window (Lee, 1981). The filter removes the noise by minimizing either the mean square error or the weighted least square estimation (Qiu et al., 2004).

The formulation of Lee filter is (Lee, 1981)

\[ D_{out} = [Mean] + K[DN_{in} - Mean] \]  

Where,

\[ D_{out} = \text{filtered output} \]
\[ Mean = \text{average of pixels in moving window} \]
\[ DN_{in} = \text{unfiltered input} \]
\[ K = \frac{Var(x)}{[Mean]^2 + Var(x)} \]  

The Variance of \( x \) is defined as

\[ Var(x) = \frac{[\text{Variance within window} + \text{Mean within window}^2] - [\text{Mean within window}]^2}{\sigma^2 + 1} \]  

Lee filter, due to the use of a fixed sigma computed for the entire scene, blurs some of the low-contrast edges and linear features (Eliaison and McEwen, 1990). A refined version of this filter is the Lee-Sigma filter (Lee, 1983).

2.4 Lee-Sigma Filter

The Lee-Sigma filter is an effective alternative to the Lee filter and other sophisticated adaptive filters (Lee, 1983). It is based on the sigma probability of the Gaussian distribution. It first computes the sigma (Standard Deviation) of the entire scene and then replaces each central pixel in a moving window with the average of only those neighboring pixels that have an intensity value within a fixed sigma range of the central pixel (Lee, 1983 and Qiu et al., 2004).

The Standard Deviation of an image can be mathematically defined as:

\[ \text{Standard Deviation} = \frac{\text{Variation}}{\text{Mean}} = \text{Coefficient of Variation} = \sigma / \mu \]  

Based on an assumption that speckle has a Gaussian distribution, 95.5% of random samples would be within 2 standard deviation range. This would yield a theoretical value for Standard Deviation (SD) values of 0.52, 0.37, 0.30, 0.26 for 1, 2, 3, 4 looks respectively (ERDAS Field Guide). The filter averages the values within the moving window of only such pixels that are within a range corresponding to its number of looks. The coefficient of variance is calculated for the entire image and is used as an input parameter.

2.5. Local Region Filter

The Local Region filter divides the kernel window into eight regions based on angular positions. For each of the region, the variance is calculated. The pixel of interest is replaced by the mean of region with least variance. For each region the Variance is calculated as follows (Nagao and Matsuyama, 1979)

\[ \text{Variance} = \frac{\sum (DN_{xy} - \text{Mean})^2}{n-1} \]  

The algorithm replaces the target pixel with mean of pixels with lowest variance in the window. A region with lowest variance is assumed to have pixels minimally affected by wave interference, yet very similar to the pixel of interest.

2.6. Frost Filter

The Frost filter replaces the pixels of interest with a weighted sum of the values within the moving window (Frost et al., 1982). The weighting factors decrease with distance from the pixel of interest and increase for the central pixels as variance within the window increases. This filter assumes multiplicative noise and stationary noise statistics (Frost et al., 1982; Qiu et al., 2004). It follows the following formula:
\[ DN = \sum_{n} ka e^{-\alpha|t|} \]  
(6)

Where,

\[ \alpha = \left( \frac{4}{\pi \sigma^2} \right)^{\frac{1}{2}} \frac{\bar{I}}{T} \]

\[ k = \text{normalized constant} \]

\[ \bar{I} = \text{local mean} \]

\[ \sigma = \text{local variance} \]

\[ \bar{\sigma} = \text{image coefficient of variation value} \]

\[ |t| = |X - X_0| + |Y - Y_0|, \text{and} \]

\[ n = \text{moving kernel size} \]

Frost filter needs to consider the influence of damping factor. Larger damping values preserve edges better but smooth less, and smaller values smooth more. A damping value of 0 results in the same output as a low pass filter. A larger damping factor produces less averaging. After application of the Frost filter, the filtered images show better sharpness at the edges (Lopes et al., 1990).

2.7. Gamma-MAP Filter

The Gamma-MAP (Maximum A Posteriori) filter was developed by Lopes et al., (1990). Prior knowledge of the probability density function of the scene is required before the filter can be applied. The filter tends to maximise the posterior probability of the original signal from the speckled signal. The scene reflectivity is assumed to be a Gamma distribution instead of a Gaussian distribution. It is based on a multiplicative noise model with non-stationary mean and variance parameters. However, the Gamma-MAP filter, like the Frost filter, will blur the edges (Qiu et al., 2004).

The Gamma-Map algorithm follows the following cubic equation (Frost et al., 1982)

\[ I^3 - \bar{I}^2 + \sigma (\bar{I} - DN) = 0 \]  
(7)

Where,

\[ I = \text{sought value} \]

\[ \bar{I} = \text{local mean} \]

\[ DN = \text{input value} \]

\[ \sigma = \text{original image variance} \]

2.8. Measuring Performance Efficiency of SAR Speckle Filters

There are several methods to quantitatively assess the performance of speckle filters according to different aspects such as noise reduction, edge preservation, feature preservation (Sheng and Xia, 1996). The results of these different measurements can be contradictory. Hence, different assessment methods should be used to find the optimum trade off among the different aspects of image quality assessment (Qiu et al., 2004). Although quantitative measures are often employed to compare different speckle suppression filters, visual inspection probably provides the best assessment of the performance of the speckle filter (Raouf and Lichtenegger, 1997).

Since the purpose of filtering SAR data in the present case is flood delineation, speckle reduction in water bodies, preservation of edges and linear structures were essential requirements. Following performance measures/methods were thus used to assess the performance of filters for the current study.

2.8.1. Mean Square Error (MSE)

MSE is the measure of the extent to which the output image differs from the input image. This helps indirectly to assess the feature preservation (Senthilnath et al., 2013).

\[ MSE = \frac{1}{K} \sum_{i=1}^{K} (I_o - I_f) \]

Where,

\[ I_f = \text{Filtered Image} \]

\[ I_o = \text{Original Image} \]

2.8.2. Signal to Noise Ratio (SNR)

The standard signal-to-noise ratio (SNR) is not adequate to evaluate the noise suppression in the case of multiplicative noise. Instead, a common way to achieve this in coherent imaging is to calculate the signal-to-noise \( (I_o/MSE) \) ratio, defined by Andrews and Hunt (1977) and; Starck et al. (1998) as

\[ SNR = 10 \log_{10} \left( \frac{\sum_{i=1}^{K} I_f^2}{\sum_{i=1}^{K} (I_o - I_f)^2} \right) \]  
(9)

Where \[ K = \text{Total number of pixels} \]

\[ I_f = \text{Filtered Image} \]

\[ I_o = \text{Original Image} \]

2.8.3. Speckle Suppression Index (SSI)

One of the measurements for speckle strength is the coefficient of variance, or the ratio of the standard deviation to the mean (Lee et al., 1994). It remains constant over homogeneous areas, where it is fully determined by the amount of speckle in the image (Hagg and Sties, 1996). The speckle suppression index (SSI) is the coefficient of variance of the filtered image normalized by that of the original image, which is defined as:

\[ SSI = \frac{\sqrt{\text{var}(R_f)}}{\text{mean}(R_f)} \times \frac{\text{mean}(R_o)}{\sqrt{\text{var}(R_o)}} \]  
(10)

Where \[ R_f = \text{Filtered image value} \]

\[ R_o = \text{Original noisy image value} \]
As a result of filtering the resultant image has lower variance because speckle is suppressed. SSI smaller than 1.0 indicates efficient speckle suppression (Sheng and Xia, 1996).

2.8.4. Speckle Mean Preservation Index (SMPI)

SSI is not reliable when sometimes mean value is overestimated due to the presence of extreme values in a comparatively smaller area of the image. Therefore, apart from SSI, one should also use SMPI (Speckle Suppression and Mean Preservation Index) to assess the performance of filters (Wang et al., 2012). Lower values of SMPI indicate better performance of the filter in terms of mean preservation and noise reduction. The equation of the SMPI is (Shamsoddini and Trinder, 2010):

\[
SMPI = Q \times \frac{\text{var}(I_f)}{\text{var}(I_o)}
\]

Where

\[
I_f = \text{Filtered Image}
\]

\[
I_o = \text{Original Image}
\]

\[
Q = 1 + |\text{mean}(I_o) - \text{mean}(I_f)|
\]

3. Methodology

The RISAT-1 (Mode: MRS) image depicting the part of South Madhepura, in Bihar, India (N25°31', E86°56') was used in the present study. This area comes under the category of highly prone area to the monsoon floods of Kosi River. The area is flat riverine terrain with mostly covered in agriculture interspersed with small villages comprising the cluster of houses.

One RISAT-1 image numbered 7021_1_6 dated 04 Aug. 2013, acquired in C-band (5.35 GHz) MRS mode was used in the present study for determining the optimal filter for speckle reduction for the purpose of flood delineation. The image was of Medium Resolution SCANSAR (MRS) Single Look Complex (SLC) in Level 1 in HH polarisation, incidence angle at 39.504º and nominal 8.33 m resolution. The subset images, henceforth termed as test images, of size 5674 × 4437 pixels representing the area of interest were used for evaluation. The one of subset image is shown in Figure 1.

Since the ultimate purpose of the speckle filtering was to accurately delineate flood, the complete evaluation was also carried out simultaneously on water bodies/water surface.

Figure 1. RISAT-1 test image used for evaluation of filters. (Subset from RISAT-1 scene number 7021_1_6 dated 04 Aug. 2013)

Figure 2. Extracted image for specific evaluation of water bodies. (Extracted from RISAT-1 scene number 7021_1_6 dated 04 Aug. 2013)
existing in the area in order to make a comparison and determine if there is any benefit accrued by this approach. The image of water bodies extracted out of scene 7021_1_6 dated 04 Aug. 2013, used for evaluation, is shown in Figure 2.

3.1. Pre-processing of RISAT-1 SLC Data

In a semi-automated process, The SLC data were imported and a multi-look image was generated using a cartographic size of 10 m and 4\textsuperscript{th} convolution cubic resampling. The multi-look image was radiometrically corrected, thereafter, the slant range was converted to ground range. An incidence angle image was generated and using this image and the ground range, backscatter image was generated. Finally, the backscatter image was geo-referenced and used to evaluate performance of various filters. The entire pre-processing was done using SARscape® which works as a plugin to ENVI.

3.2. Application of Filters

The Coefficient of Variation of the test image was measured and provided as a parameter in case of all filters except Local Region Filter since it does not consider global influences during the application of the filter. The test image was processed through following filters - Lee filter, Frost filter, Gamma (MAP or Maximum A Posteriori), Local Region filter and Lee-sigma filter. All the five filters were evaluated for three kernel sizes 3×3, 5×5 and 7×7 resulting in a total of fifteen images for evaluation. Henceforth each of this combination will be termed by name of filter window size i.e. Lee (3×3) or Lee (5×5). Similarly, the extracted water body/water surface image was also filtered using all the filters and three kernel sizes resulting in another set of fifteen images for evaluation.

3.3. Evaluation of Performance Efficiency of Filters

Each of the resulting 15×2 images was tested for performance in speckle suppression, feature preservation and loss of meaningful data using MSE, SNR, SSI, SMPI, examination of mean, standard deviation and also a close visual assessment. Models for each of the four measures i.e., MSE, SNR, SSI, SMPI were designed using model maker in ERDAS Imagine. The original test image and one of the respective thirty filtered images to be evaluated was used one at a time as image variables in ERDAS Imagine model maker to obtain the result. The mean and standard deviation was obtained using ERDAS Imagine built-in functions. The results for each measure with respect to each combination of filter and window size on test image and water surface image were recorded and a ranks were awarded to indicate a comparative performance.

4. Results and Discussion

The detailed results of various performance measures for the test image (Figure 1) are described in subsequent sub-sections;

4.1. Mean Square Error

MSE value is an indicator of the extent of changes that the image has undergone as a result of the application of speckle filter. Table 1 shows the MSE of different filters with varying moving window sizes and the relative ranks of each combination based on MSE values. It is observed that Lee (7×7) and Frost (7×7) filters have very low MSE, indicating their effectiveness in the preservation of features. Local Region (7×7), Gamma MAP (7×7) and Lee Sigma (7×7) have the highest values indicating the poor performance in terms of the preservation of features.

4.2. Signal-to-Noise Ratio

SNR gives the strength of the pure signal or image, as compared to the noise present which is removed by the filter (Senthilnath et al., 2013). Table 2 shows the SNR values for all the filter and window size combinations applied on the test images. Higher the value of SNR better is the reduction of noise (Starck et al., 1998). It is seen that Lee filter is performing well, closely followed by Frost filter in all the moving window sizes. Frost (3×3) out performances all other combinations except Lee (3×3). However, one must keep in mind that, SNR is a global measure, thus it does not measure the local variations.

4.3. Speckle Suppression Index (SSI) and Speckle Mean Preservation Index (SMPI)

Tables 3 and 4 show SSI and SMPI values respectively along with the relative ranking of each filter combination. A lower value of SSI or SMPI indicates higher proficiency in the
Table 2. Signal-to-Noise Ratio and relative ranks of different speckle filter combinations

<table>
<thead>
<tr>
<th>SNR</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 × 3</td>
<td>5 × 5</td>
</tr>
<tr>
<td>Lee Sigma</td>
<td>10.592</td>
</tr>
<tr>
<td>Lee</td>
<td>16.139</td>
</tr>
<tr>
<td>Frost</td>
<td>15.250</td>
</tr>
<tr>
<td>Local Region</td>
<td>7.072</td>
</tr>
<tr>
<td>Gamma MAP</td>
<td>8.553</td>
</tr>
</tbody>
</table>

Table 3. Speckle Suppression Index values and relative ranks of different combinations

<table>
<thead>
<tr>
<th>SSI</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 × 3</td>
<td>5 × 5</td>
</tr>
<tr>
<td>Lee Sigma</td>
<td>0.828</td>
</tr>
<tr>
<td>Lee</td>
<td>0.894</td>
</tr>
<tr>
<td>Frost</td>
<td>0.904</td>
</tr>
<tr>
<td>Local Region</td>
<td>0.941</td>
</tr>
<tr>
<td>Gamma MAP</td>
<td>0.816</td>
</tr>
</tbody>
</table>

Table 4. Speckle Mean Preservation Index and relative ranks of different combinations

<table>
<thead>
<tr>
<th>SMPI</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 × 3</td>
<td>5 × 5</td>
</tr>
<tr>
<td>Lee Sigma</td>
<td>0.885</td>
</tr>
<tr>
<td>Lee</td>
<td>0.880</td>
</tr>
<tr>
<td>Frost</td>
<td>0.881</td>
</tr>
<tr>
<td>Local Region</td>
<td>0.790</td>
</tr>
<tr>
<td>Gamma MAP</td>
<td>0.743</td>
</tr>
</tbody>
</table>

reduction of speckle. A value of 0, currently not achievable by any of the existing methods, indicates 100% removal of speckle. A SSI or SMPI value of 1 indicates that no speckle reduction has taken place where as a value higher than one, which in reality no filter would produce, indicates that speckle has been added.

When the filters were evaluated over the test images, both SSI and SMPI gave consistent results. The SSI value reduces as the window size increases in case of all filters, indicating superior speckle suppression with an increase in the size of the moving window. The lowest SSI values, as well as SMPI values, corresponds to Lee Sigma (7×7) and Gamma-Map (7×7) filters which are indicative of the most effective speckle suppression in these respective combinations. The comparative performance of these very filters at 3×3 moving window size is indicative of another perspective. While Gamma-MAP was found to be less efficient in 3×3 window size as compared to 7×7 window size, it was still the most effective amongst all the filters in window size 3×3, however, Lee Sigma is the least effective amongst all the filters in 3×3 window size.

When the effectiveness of the filters was evaluated only on the water surface, which is homogenous and smooth, the values varied but ranking was only marginally different as compared to the evaluation based on entire images. The Gamma-MAP (7×7) was still the most effective with Lee Sigma (7×7) nearly as effective.

4.4. Performance Based on Changes in Mean and Standard Deviation

For quantitative evaluation of filters, the application of filters should ideally not bring about any change in Mean of target image while it should reduce the Standard Deviation (Mansourpour et al., 2006). Table 5 and Figures 3 to 5 shows a comparison between changes in Mean and Standard Deviations for various filters and window size combinations.

The filters, Gamma MAP (7×7), Local Region (7×7) and Lee Sigma (7×7) were most effective in reducing the Standard Deviation but at a considerable cost of change in Mean thereby implying that the filters have reduced speckle considerably but have also caused considerable loss of meaningful data. On the contrary, Frost (7×7) filter made the least change in the Mean while reducing the Standard Deviation moderately at 25.95%. Lee (7×7) provides a fair balance by reducing the Standard Deviation by 22.90% without seriously affecting the Mean. Its performance is just next to Frost (7×7) filter in terms of reduction of Standard Deviation at the cost of 0.88% change in Mean.
Table 5. Mean and Standard Deviation changes on application of filters

<table>
<thead>
<tr>
<th>Filter</th>
<th>Mean</th>
<th>SD</th>
<th>Percent Change - Mean</th>
<th>Percent Change - SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfiltered Image</td>
<td>0.113</td>
<td>0.131</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1  Gamma MAP 7 X 7</td>
<td>0.092</td>
<td>0.065</td>
<td>18.58%</td>
<td>50.38%</td>
</tr>
<tr>
<td>2  Local Region 7 X 7</td>
<td>0.089</td>
<td>0.066</td>
<td>21.24%</td>
<td>49.62%</td>
</tr>
<tr>
<td>3  Lee Sigma 7 X 7</td>
<td>0.099</td>
<td>0.068</td>
<td>12.39%</td>
<td>48.09%</td>
</tr>
<tr>
<td>4  Gamma MAP 5 X 5</td>
<td>0.096</td>
<td>0.077</td>
<td>15.04%</td>
<td>41.22%</td>
</tr>
<tr>
<td>5  Lee Sigma 5 X 5</td>
<td>0.102</td>
<td>0.081</td>
<td>9.73%</td>
<td>38.17%</td>
</tr>
<tr>
<td>6  Local Region 5 X 5</td>
<td>0.095</td>
<td>0.088</td>
<td>15.93%</td>
<td>32.82%</td>
</tr>
<tr>
<td>7  Gamma MAP 3 X 3</td>
<td>0.102</td>
<td>0.096</td>
<td>9.73%</td>
<td>26.72%</td>
</tr>
<tr>
<td>8  Frost 7 X 7</td>
<td>0.112</td>
<td>0.097</td>
<td>8.88%</td>
<td>23.95%</td>
</tr>
<tr>
<td>9  Lee 7 X 7</td>
<td>0.112</td>
<td>0.101</td>
<td>8.88%</td>
<td>22.96%</td>
</tr>
<tr>
<td>10 Lee Sigma 3 X 3</td>
<td>0.107</td>
<td>0.103</td>
<td>5.31%</td>
<td>21.37%</td>
</tr>
<tr>
<td>11 Frost 5 X 5</td>
<td>0.111</td>
<td>0.104</td>
<td>1.77%</td>
<td>20.61%</td>
</tr>
<tr>
<td>12 Lee 5 X 5</td>
<td>0.112</td>
<td>0.106</td>
<td>0.88%</td>
<td>19.08%</td>
</tr>
<tr>
<td>14 Frost 3 X 3</td>
<td>0.110</td>
<td>0.115</td>
<td>2.65%</td>
<td>12.21%</td>
</tr>
<tr>
<td>13 Lee 3 X 3</td>
<td>0.111</td>
<td>0.115</td>
<td>1.77%</td>
<td>12.21%</td>
</tr>
<tr>
<td>15 Local Region 3 X 3</td>
<td>0.106</td>
<td>0.115</td>
<td>6.19%</td>
<td>12.21%</td>
</tr>
</tbody>
</table>

The performance of various filters was also measured on extracted water surface images. The method of measurement was exactly the same as that followed for the test images. The values of different measures are shown in Table 6. Also shown alongside Table 7 is the change in rankings between the test images and the water bodies.

From Table 7, it is observed that there is an insignificant change in performance efficiency of filters when tested specifically for water bodies. This indicates that the observations and deductions based on measures comprising MSE, SNR, SSI and SMPI will equally apply to water bodies as well. A comparison of the change in Mean and Standard Deviation was also carried out for water bodies, the results summarised in Table 8 shows that Frost (7×7) filter, has not changed the Mean of the filtered image as compared to original water body image while it reduced the Standard Deviation by 42.86%. Even when the test images were considered, Frost (7×7) filter had resulted in a minimal change in Mean (0.88%), while reduction Standard Deviation by 25.95%. Other filters who have not changed the Mean of the filtered image are Frost (7×7) filter, Lee (7×7) filter, Lee (5×5) filter with the change of standard deviation of 28.57%. The performance of Frost (7×7) filter in terms of reduction of Standard Deviation and preservation of Mean over water body, an area of interest for the present study, is far superior compared to all other filters.
Table 6. Measured values for different filter and window sizes for water bodies only

<table>
<thead>
<tr>
<th></th>
<th>MSE</th>
<th>Rank</th>
<th>Change in Ranking [Full Image - River Subset]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 × 3</td>
<td>5 × 5</td>
<td>7 × 7</td>
</tr>
<tr>
<td>Lee Sigma</td>
<td>0.000027</td>
<td>0.000046</td>
<td>0.000054</td>
</tr>
<tr>
<td>Lee</td>
<td>0.000009</td>
<td>0.000005</td>
<td><strong>0.000001</strong></td>
</tr>
<tr>
<td>Frost</td>
<td>0.000014</td>
<td>0.000008</td>
<td>0.000002</td>
</tr>
<tr>
<td>Local Region</td>
<td>0.000032</td>
<td>0.000078</td>
<td>0.000096</td>
</tr>
<tr>
<td>Gamma MAP</td>
<td>0.000056</td>
<td>0.000023</td>
<td>0.000033</td>
</tr>
</tbody>
</table>

Table 7. Change in performance rankings between full image and extracted water bodies.

<table>
<thead>
<tr>
<th></th>
<th>MSE</th>
<th>SNR</th>
<th>SSI</th>
<th>SMPI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 × 3</td>
<td>5 × 5</td>
<td>7 × 7</td>
<td></td>
</tr>
<tr>
<td>Lee Sigma</td>
<td>10.825</td>
<td>6.287</td>
<td>4.531</td>
<td>4</td>
</tr>
<tr>
<td>Lee</td>
<td><strong>15.726</strong></td>
<td>12.182</td>
<td>10.682</td>
<td>1</td>
</tr>
<tr>
<td>Local Region</td>
<td>7.462</td>
<td>3.130</td>
<td>1.596</td>
<td>8</td>
</tr>
<tr>
<td>Gamma MAP</td>
<td>8.696</td>
<td>4.429</td>
<td>2.699</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 8. Mean and Standard Deviation changes on water bodies only.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Mean</th>
<th>SD</th>
<th>Percent Change - Mean</th>
<th>Percent Change - SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfiltered Image</td>
<td>0.008</td>
<td>0.007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma MAP 7 × 7</td>
<td>0.006</td>
<td>0.003</td>
<td>25.00%</td>
<td>57.14%</td>
</tr>
<tr>
<td>Frost 7 × 7</td>
<td>0.008</td>
<td>0.004</td>
<td>0.00%</td>
<td>42.86%</td>
</tr>
<tr>
<td>Lee Sigma 5 × 5</td>
<td>0.007</td>
<td>0.004</td>
<td>12.50%</td>
<td>42.86%</td>
</tr>
<tr>
<td>Gamma MAP 5 × 5</td>
<td>0.007</td>
<td>0.004</td>
<td>12.50%</td>
<td>42.86%</td>
</tr>
<tr>
<td>Lee Sigma 7 × 7</td>
<td>0.007</td>
<td>0.004</td>
<td>12.50%</td>
<td>42.86%</td>
</tr>
<tr>
<td>Local Region 5 × 5</td>
<td>0.007</td>
<td>0.004</td>
<td>12.50%</td>
<td>42.86%</td>
</tr>
<tr>
<td>Local Region 7 × 7</td>
<td>0.006</td>
<td>0.004</td>
<td>25.00%</td>
<td>42.86%</td>
</tr>
<tr>
<td>Frost 5 × 5</td>
<td>0.008</td>
<td>0.005</td>
<td>0.00%</td>
<td>28.57%</td>
</tr>
<tr>
<td>Gamma MAP 3 × 3</td>
<td>0.007</td>
<td>0.005</td>
<td>12.50%</td>
<td>28.57%</td>
</tr>
<tr>
<td>Lee 5 × 5</td>
<td>0.008</td>
<td>0.005</td>
<td>0.00%</td>
<td>28.57%</td>
</tr>
<tr>
<td>Lee Sigma 3 × 3</td>
<td>0.007</td>
<td>0.005</td>
<td>12.50%</td>
<td>28.57%</td>
</tr>
<tr>
<td>Frost 3 × 3</td>
<td>0.008</td>
<td>0.006</td>
<td>0.00%</td>
<td>14.29%</td>
</tr>
<tr>
<td>Lee 3 × 3</td>
<td>0.008</td>
<td>0.006</td>
<td>0.00%</td>
<td>14.29%</td>
</tr>
<tr>
<td>Local Region 3 × 3</td>
<td>0.007</td>
<td>0.006</td>
<td>12.50%</td>
<td>14.29%</td>
</tr>
</tbody>
</table>
When the test image, earlier filtered using Frost (7×7), were subjected to second iteration pass of the same filter and window size combination, the average change in Mean as compared to original unfiltered images is shown in Table 9. The gain of reduced Standard Deviation is not commensurate with the loss of data as indicated by the enhanced change in Mean. On an average 31.3% change in SD was achieved with only 5.31% change in Mean by applying Frost (7×7) in two successive iterations, whereas it is clear for combined analysis of Tables 5 and 9 that to achieve the same or higher level of change in SD around 9 to 21% change in Mean has to be tolerated if any other combination of filter is applied. This proves the superiority of Frost (7×7) filter in terms of preservation of Mean and change in SD during speckle filtering process.

The analysis of the performance of all the filters in terms of MSE, SNR, SSI and SMPI does not give single filter as the best suitable filter for the purpose of speckle reduction in the present study. Gamma-MAP filter performances well in terms of SSI and SMPI, however, its performance in terms of speckle reduction and feature preservation is far inferior compared to Frost (7×7) or Lee (7×7) filters. Gamma-MAP filter in all the three window size (i.e. 3×3, 5×5, and 7×7) changes the Mean of original image and waterbody image considerably compared to the changes brought in Mean by Frost (7×7) filter. However, since the objective of this speckle filtering was to use these SAR images for waterbody or flood mapping, the performance of filters on water body and that too in terms of reduction of Standard Deviation while preserving the Mean of the original image are most important. MSE indicates the success of filter in terms of preservation of features, which are important in flood mapping. The performance of Lee (7×7) and Frost (7×7) is far better in preservation of features in the filtered images. The selection of key statistical measure for finalizing the best suitable speckle filter is also subjective. In the present case, the performance of the filter in terms of preservation of mean, preservation of features and reduction of Standard Deviation over water body are considered as key criteria for finalizing the choice of best suitable filter. It can be reasonably inferred that using these yardsticks Frost (7×7) performance better than other filters in terms of speckle reduction with least loss of original data (Mean and feature preservation). Performance of Frost filter can be further be improved in terms of SNR and SSI by reducing the damping factor. Smaller damping factor will make image smoother, however, in that case, the performance in terms of feature preservation and Mean preservation will degrade. Lee (7×7) filter also performance at par with Frost (7×7) filter, however, its performance in terms of speckle reduction over waterbody with zero change in the Mean is poor compared to Frost (7×7) filter.

### 4.5. Visual Examination

Although quantitative measures are often employed to compare different speckle suppression filters, visual inspection probably provides the best assessment of the performance of the speckle filter (Raouf and Lichtenegger, 1997). Hence, the Visual examination was carried out by observation of chosen pixels with a view to ascertain removal of speckle, contamination due to alteration, loss of details and preservation of features. Figures 6 (a to k) shows a preview of the unfiltered test image (scene 7021_1_6) and its filtered outputs from 3×3 and 7×7 window size combinations of all the filters.

It is observed that regardless of which filter is used, 3×3 window size retains the edges much better than window size 7×7. Larger window size results in loss of edges. Lee, Lee Sigma and Frost retained edges as well as finer details. It was not possible to grade them visually since the variation was not perceivable. Local Region and Gamma MAP clearly resulted in the loss of edges and details.

Higher window size reduced the speckle more effectively as compared to smaller window size but make the image smooth. Local Region, Gamma MAP, Lee Sigma appeared to reduce speckle most effectively. Other filters did reduce the speckle but not to the extent of Local Region and Gamma MAP filters. The filters which reduced speckle effectively also resulted in considerable loss of meaningful data. Frost (7×7) appears to a reasonable trade-off between the degree of speckle reduction and data loss.

### 5. Conclusion

Speckle reduction aimed at effective flood delineation was the key consideration in the study. Effective speckle reduction implies that, while the speckle should be removed there should be minimal loss of meaningful data, in the process speckle filtering the features should be preserved.

MSE values indicate that Frost (7×7) is the second best options for preservation of features, after Lee (7×7). The reason for effective feature preservation in Frost filter is that this filter adapts to the local statistics by replacing the pixel of interest by a weighted factor which decreases with distance from the pixel of interest. SNR values indicate that the Frost

<table>
<thead>
<tr>
<th>Filter</th>
<th>Percent change - Mean</th>
<th>Percent Change - SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Pass</td>
<td>2nd Pass</td>
<td>1st Pass</td>
</tr>
<tr>
<td>Frost 7×7</td>
<td>0.88%</td>
<td>5.31%</td>
</tr>
</tbody>
</table>

Table 9. Mean and Standard Deviation changes on second pass.
Evaluation of Adaptive Filters for Speckle Reduction in RISAT-1 Data for Flood Mapping

Figure 6 (a to k) Preview of unfiltered and filtered images of 3X3 and 7X7 window size
was not as effective in noise reduction as the other filters, however, Frost (7×7) was better than its (3×3) counterpart. Performance of Lee Sigma and Gamma-MAP filters were better in terms of SSI and SMPI, however, these filter cause unacceptable loss of meaningful data in terms of change in value Mean original image after filtering. With minimal loss of data and yet reducing speckle effectively, Frost (7×7) was found to be the most optimal filter.

With increase in filter window size from 3×3 to 7×7 the loss of actual data also increases, the trade-off between speckle reduction and data loss is optimal at 7×7 window size as indicated by SSI and SMPI values wherein Frost (7×7) is found to be more effective in speckle reduction while preserving the mean as compared to Frost (3×3). The optimal choice of Frost (7×7) by trade-off is further established by comparison of the change in Mean and Standard Deviation for the entire image and only for water bodies.

Visual examination was found to be consistent with measured values. Within same window sizes, Frost filter was found to be most effective in retaining edges and finer details in the image even though, Frost (3×3) performed better than Frost (7×7). But since speckle reduction with the minimal loss was a major objective, Frost (7×7) out performed Frost (3×3).

The results of water surface were too aligned to those of the test images. For water bodies, the Frost (7×7) filter makes no change in the mean while reducing standard deviation by approximately 43%. The second pass of Frost (7×7) filter did increase the percentage change in standard deviation but also resulted in the considerable change in Mean, hence a single pass of Frost (7×7) is a better option.

By examining the results of various measures for effectiveness in speckle reduction it can be reasonably inferred that Frost (7×7) filter provides an optimal choice for feature preservation, retention of edges and reduction of speckle with minimal loss of meaningful data.

The final conclusion has been drawn that since the choice of filter is subjective characteristics of data, objective of the study, it is been found that a single pass of Frost (7×7) is the most suited filter removal speckle noise from RISAT-1 (MRS) data intended for flood mapping/delineation studies.

References


