Evaluation of Several Speckle Filtering Techniques for ERS-1&2 Imagery

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ABSTRACT:

The speckle noise appearing in SAR images forms a main obstacle to analyse, interpret and classify SAR images for various remote sensing applications. To date, many filters have been developed for speckle reduction in SAR imagery. In this paper, the authers evaluate eight ready-made speckle filters, which are Moving Average Filter, Median Filter, Lee Filter, Enhanced Lee Filter, Frost Filter, Enhanced Frost Filter, Kuan Filter and Gamma MAP Filter, in order to test these filters with ERS-1&2 data and provide a guideline for users are interested in SAR applications. The evaluation has been done from three aspects, which are statistical model testing, quantitative evaluation and qualitative evaluation. The test results presented in this paper confirm that filtering techniques are helpful for SAR image applications.

1. Introduction

The earliest concept of speckle is introduced from the laser field[1], which indicated that the interference of the coherent and dephased reflected scatters will cause a peculiar granular pattern in the image due to the majority of surfaces being extremely rough on the scale of the wavelength. This concept is suitable to SAR speckle as the SAR system has a similar principal with the laser imaging system. Therefore, the SAR speckle is related with laser speckle both physically and mathematically so that the large amount of material on laser speckle is applicable to understand the phenomenon of SAR speckle.

For several decades, many mathematical models of SAR speckle noise have been deeply investigated [2][3], which took the speckle noise as a kind of multiplicative noise. By using the statistical properties of the SAR image, the probability density function(pdf) of a normalized multiplicative fading process can be expressed as an exponential pdf, which provide the fundamental theory for SAR speckle reduction techniques. Many speckle filtering techniques based on the speckle model of multiplicative noise are well developed.

In solution to the incoherence of SLAR systems, which are relatively immured to speckle due to performing an incoherent summation of N independent estimation of the radar backscatters with the same resolvable element, the multi-look algorithm[4] has been proposed to reduce the speckle noise. It is realized in the frequency domain by segmentation of the azimuth spectrum to form several independent single-look images and summation of these images to obtain a multi-look images. The drawback is that the speckle reduction is accompanied by loss of image resolution. The second category technique to reduce speckle noise is referred to the time domain algorithm, as it performs speckle filtering after a full resolution is processed. It has advantages over the conventional frequency domain multi-look technique due to the fact that it is much easier to compromise the balance between the image resolution and speckle reduction, and more flexible to filter the full resolution images with the different filters. Many speckle filters are well developed, such as Box Filter[4], Median Filter[5], Lee Filter[6], Enhanced Lee Filter[10], Frost Filter[8], Wiener Filter[11], Kuan Filter[11], GMAP[9], Geometric Filter[13] and so on.

The main goal of these speckle filters is to reduce speckle noise to a minimum, in order to achieve image quality as good as photography does. However, these filters still cannot meet the requirement of the purposes of easy interpretation and clear classification. The reason is that the properties of SAR speckle are more complicated to be modeled as an exponential distribution. In some cases, the statistical model violates this distribution. The different terrain and different SAR systems, for example, terrain size, terrain geometry, moisture, dielectric constant, wavelength, polarization, view angle and so on, will generate the different speckle noises. How to overcome it with one filter has become a difficult and long-term task that has been treated by many scientists. In spite of these deficiencies discussed above, the majority of image processing software packages have been formed according to the theory of these filtering algorithms. Currently, the common software packages, such as MICRO BRIAN, ILWIS, ERDAS,PCI,and ER Mapper are widely used in remote sensing and they include the different filters in them so as to meet the needs of different application purposes.

What we want to do now is to obtain more information from SAR speckle image data and to compare several speckle filtering algorithms in order to provide some results concerning ERS-1&2 image application. This paper is organized as follows,

(1) General review of speckle reduction techniques.

It will present the mathematics model of SAR speckle and the theoretical expression of several speckle filters. It includes a discussion on these filters.

(2) Analyzing the speckle properties for ERS-1&2 data.

Statistical results are obtained by testing ERS-1&2 images. The statistical results are show in this section and the detailed analyses concerning these test results are presented.

(3) Testing result analysis.

Trying the different speckle filters for ERS-1&2 imagery to evaluate the performance of speckle reduction by quantitative evaluation and qualitative evaluation. The comparison results are shown in tables and filtered images. The test results are discussed in detail.

2. Basic Principle of Speckle Theory and Filtering Techniques

2.1 Statistical Model for SAR speckled image

Much literature has been published concerning speckle characteristics and SAR image models[1][2][3]. Among them, the multiplicative model has proved to be one of the most accurate and suitable for SAR imagery.

A more realistic model for explaining a SAR image to simply measuring a patch of homogeneous area in a SAR image, can be expressed as

$$I(x,y) = R(x,y) \cdot S_n(x,y) \qquad (1)$$

where (x,y) are the spatial range and azimuth coordinates of the resolution cell center, $I(x,y)$ is the intensity of SAR image, $R(x,y)$ is a random process of radar reflectivity (unspeckled radiance) , $S_n(x,y)$ is model as speckle noise having a stationary random process with unit mean and variance proportional to the effective number of looks N and is statistically independent of $R(x,y)$.

Usually, SAR images are classified into two classes. One is 'homogeneous' and the other is 'heterogeneous'. In order to filter speckle in heterogeneous areas, some primary mathematical models have been established[9]. The most common one defined an N-look SAR image as having a Gamma distribution with mean value $R(x,y)$ and variance value $R^2(x,y)/N$ is expressed as follows,

$$p(I/R) = \frac{N^N I^{N-1}}{(N-1)!R^N} \cdot e^{-\frac{I}{R}N} \qquad (2)$$

For the homogeneous area, the pdf of SAR image is,

$$p(I) = p(I/R) = \frac{N^N I^{N-1}}{(N-1)!\bar{I}^N} \cdot e^{-\frac{I}{\bar{I}}N} \qquad (3)$$

However, for heterogeneous areas, the radar reflectivity $R(x,y)$ itself is a random process, so that the pdf of the intensity of SAR image have,

$$p(I) = \int_0^\infty p(I/R) \cdot p(R) \cdot dR \qquad (4)$$

Equation (3) demonstrates the general distribution for the homogeneous area, which is well accepted by scientists. However, to what kind of distribution the radar reflectivity $R(x,y)$ belongs, is still a dilemma. In fact, the main point of speckle filtering techniques is to recover $R(x,y)$ by means of the priori information about speckle pdf and image pdf.

2.2 Filtering techniques for speckle reduction

The speckle filtering techniques can be classified into two categories[6].The techniques in the first category are equivalent to applying a low-pass filter to the image, such as multi-look processing and the box filter. This step is taken as a part of preprocessing. The second category is to reduce speckle noise after the SAR image has been formed. It is considered as a part of the post-processing of SAR images. Here only the filters for the second category are discussed as follows,

Box Filter[4]: It is a typical low-pass filter, which can remove the noise with a high frequency spectrum as well as smoothing the details, such as the edges and points etc.

Median Filter[5]: It is a nonlinear filter and is derived from the maximum-likelihood (ML) estimation principle by assuming the signal to be contaminated by additive noise with a Laplace distribution. In some cases, it is much more efficient than most other filters.

Lee Filter[6][7]: It was derived from the minimum square error(MMSE) criteria by introducing the local statistics method in it. It was believed that it can reduce speckle noise while preserving the edges in the image.

Frost Filter[8]: It was also derived from the principle of MMSE. The filter kernel can vary with the local statistical value of the images so as to reduce the noise while at the same keeping the edges.

Kuan Filter[12]: It is derived from MMSE criteria under the assumption of a nonstationary mean and nonstationary variance(NMNV). It is quite similar to the Lee Filter in form. However, it is considered to be a a little more accurate than Lee Filter due to the fact that no approximation is required in the total derivation.

Enhanced Lee Filter[10]: Based on the Lee filter, A.Lopes modified it to improve the ability of preserving the edges in the image.

Enhanced Frost Filter[10]: The similar modification as Enhanced Lee Filter was introduced to the Frost Filter.

Gamma MAP Filter[9]: It is derived under the assumption of the image scene having a Gamma Distribution, which is believed more suitable to the realistic case.

The formula for these filters mentioned above is given in table 1.

Table 1. The formula for several filters

Filter	Weighting Function	Filtering Formula
Box	$W(x,y)=\begin{cases}1 & \lvert x\rvert \le x_0 \quad \lvert y\rvert \le y_0 \\ 0 & otherwise\end{cases}$	$\hat{I} = I * W$
Median		$\hat{I} = \underset{\lvert x\rvert \le x_{00}, \lvert y\rvert y_0}{Median}(I(x,y))$
Lee	$W(x,y) = 1 - \frac{C_{si}^2}{C_I^2(x,y)}$	$\hat{I} = I \cdot W + \bar{I}(1-W)$
Frost	$W(x,y) = K_1 e^{-K_d C_I(x,y)\sqrt{x^2+y^2}}$	$\hat{I} = I * W$
Kuan	$W(x,y) = \frac{1 - C_{si}^2 / C_I^2(x,y)}{1 + C_{si}^2}$	$\hat{I} = I \cdot W + \bar{I}(1-W)$
Enh. Lee	$W(x,y) = e^{-K_d \frac{C_I(x,y) - C_{si}}{C_{\max} - C_I(x,y)}}$	$\hat{I} = \bar{I} \quad C_I \le C_{si}$ $\hat{I} = I \cdot W + \bar{I}(1-W)$ $C_{si} < C < C_{\max}$ $\hat{I} = I \quad C_I \ge C_{\max}$
Enh. Frost	$W(x,y) = K_1 e^{-K_d \frac{C_I(x,y) - C_{si}}{C_{\max} - C_I(x,y)}\sqrt{x^2+y^2}}$	$\hat{I} = \bar{I} \quad C_I \le C_{si}$ $\hat{I} = I * W \quad C_{si} < C < C_{\max}$ $\hat{I} = I \quad C_I \ge C_{\max}$
GMAP	where $k = \alpha - N - 1$ $\alpha = \frac{1 + C_{si}}{C_I^2 - C_{si}^2}$	$\hat{I} = \bar{I} \quad C_I \le C_{si}$ $\hat{I} = \frac{k\bar{I} + \sqrt{\bar{I}^2 k^2 + 4\alpha N \bar{I}}}{2\alpha}$ $C_{si} < C < C_{\max}$ $\hat{I} = I \quad C_I \ge C_{\max}$

Where C_{si} is standard speckle index, C_I is varied standard speckle index, N is the number of looks, $C_{\max}$ is the upper threshold and K_d is called damping factor.

3. Testing Statistical Model for ERS-1 and ERS-2 Images.

Several ERS-1 and ERS-2 single-look images and ERS-1 3-look images are chosen to test the statistical results for SAR images.

The testing is obtained from three aspects:

Speckle index: it is defined as follows,

$$c_{si} = \frac{\sigma}{\mu} \tag{5}$$

It is used as a measure of speckle reduction. The smaller that the speckle index is, the less speckle noise is left in the images. The standard speckle index for amplitude SAR images is related with the number of looks and is expressed as,

$$C_{si} = 0.523 / \sqrt{N} \tag{6}$$

There are three results shown in Fig.1 (a),(b),(c).

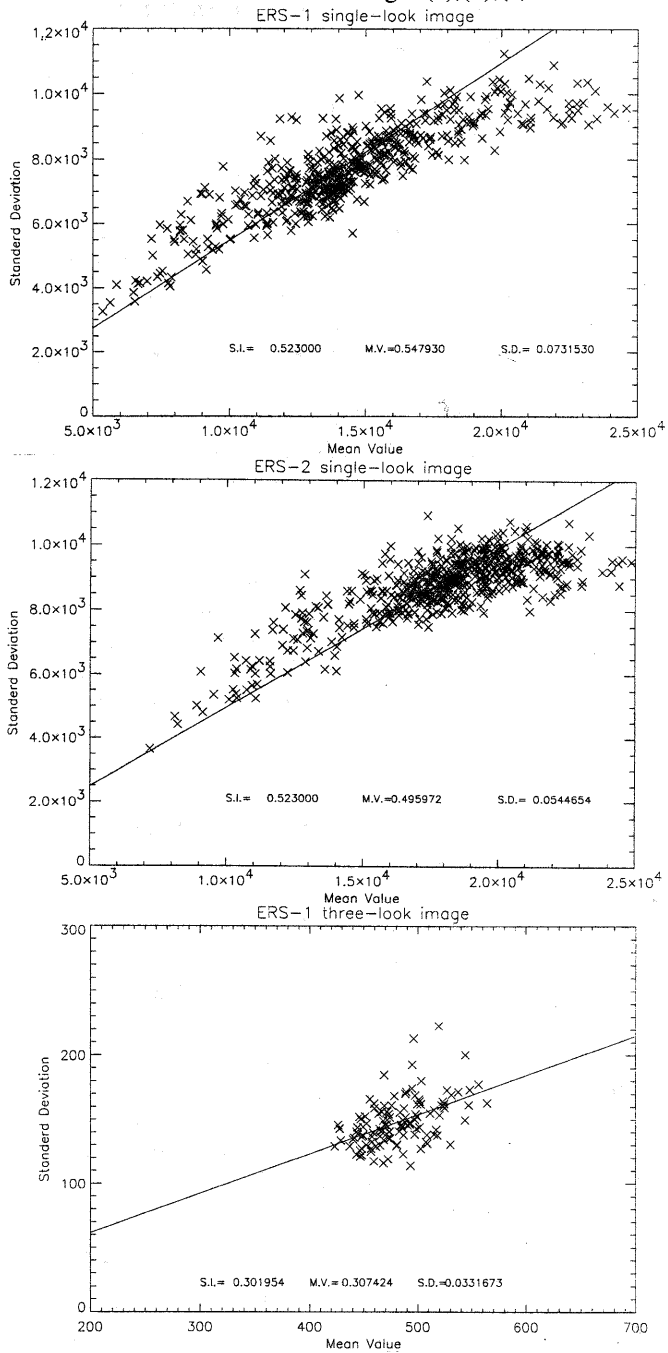

Fig.1(a). Speckle index for ERS-1 single-look image
(b). Speckle index for ERS-2 single-look image
(c). Speckle index for ERS-1 3-look image.

Fig.1(a) and (b) present the relationship between the mean value and standard deviation value for single-look ERS-1 and ERS-2 images. The linear fit is done and tested speckle index is presented in the figure. S.I represents the standard speckle index, M.V. represents the mean value of speckle index with raw data and S.D. is the standard deviation of speckle index. Fig.1(c) illustrates the results for a 3-look ERS-1 SAR image. The results coincide with the theoretical analysis. However, the speckle index changes with the intensity of the image. The lighter the image is, the smaller the speckle index is. From this result, we indicate that the a linear fit is not accurate enough.

Probability density function(pdf) of SAR images: In section 2, the statistical models of the SAR images are provided to have a Gamma distribution. Here we process a patch of homogeneous area in the ERS-1 and ERS-2 image to test the distribution of the SAR images. The tested results is shown in Fig.2,(a),(b). Fig.2(a) shows the pdf of a ERS-1 single-look image and Fig2.(b) shows the pdf of a ERS-2 single-look image. The results accord with the Gamma distribution. The slight deviation is due to the heterogeneous effect.

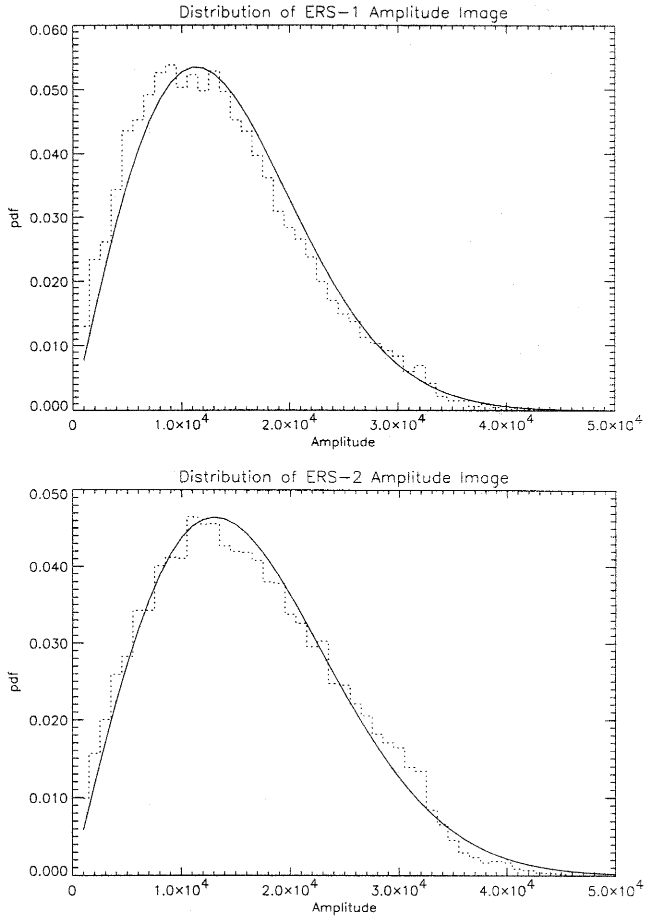

Fig.2 (a). pdf of a ERS-1 single-look image
(b).pdf of a ERS-2 single-look image

pdf of speckle index: It demonstrates the variation of speckle index for any one SAR image and illustrates the characteristics of a heterogeneous image. Fig.3(a) shows the pdf of speckle index for an ERS-1 image. Several curves are overlapped in this figure to show that the speckle index is changing with the variation of the terrain. The pdf of speckle index can be approximated as the Gaussian distribution for the homogeneous area. However, for the heterogeneous area, the pdf of speckle index is a complicated function and needs to be investigated (Ref. Fig.3 (b)).

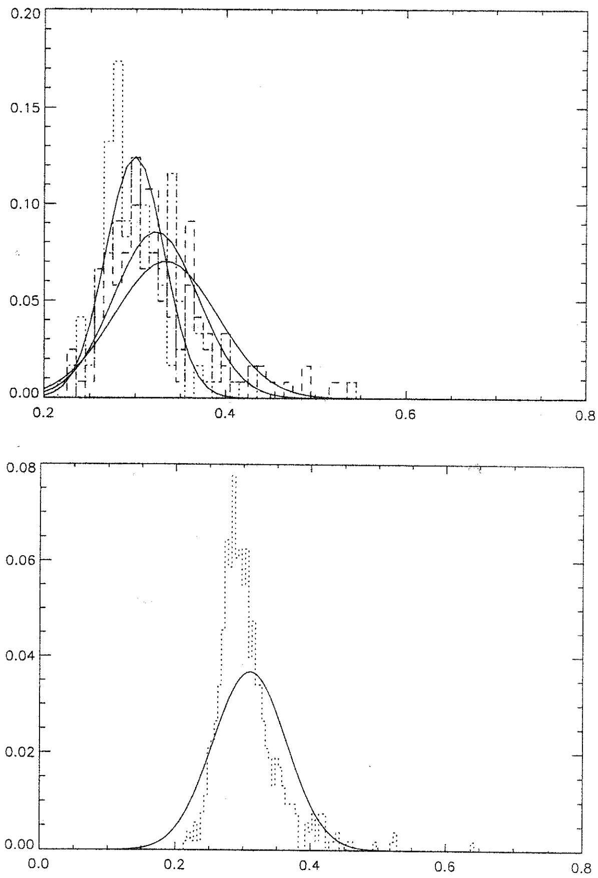

Fig.3 (a) the pdf of speckle index for different areas
(b) the pdf of speckle index for a heterogeneous area

4. Evaluation of Filtering Techniques

Both quantitative evaluation and qualitative evaluation have been made to evaluate the filtering techniques for ERS-1&2 imagery.

Quantitative Evaluation:
The performance of evaluating eight filters for 3-look ERS-1 images by computing the mean value, standard deviation and speckle index is shown in table 2. The window size of filtering is 7 by 7. The pixel number for statistical value is 400. The testing was done in a HP workstation using the PCI software package. From the average statistical data, the Box Filter, Frost Filter, Lee Filter, and Kuan filter have a good performance to keep the mean value of the tested area. Median Filter, Enhanced Lee Filter, Enhanced Frost Filter and GMAP Filter make a small amount of change in the mean value. Box filter is the best one to reduce speckle noise for SAR images.

Table 2. Mean, standard deviation and speckle index processed by 8 filters.

Filter	M.V.	S.D.	Speckle Index
Original	187.54	57.94	0.309
Box	186.42	18.94	0.102
Median	186.84	19.08	0.102
Lee	186.42	18.94	0.102
Frost	186.44	19.17	0.103
Kuan	186.42	18.94	0.102
Enh. Lee	194.29	19.86	0.102
Enh. Frost	194.30	19.36	0.100
G-MAP	192.21	20.89	0.109

In order to test the performance of filtering techniques for a different types of area, Table 3 is made below. Several test areas were selected, such as ocean, coastal line, etc. and testing results present the ability of filtering homogeneous areas and heterogeneous areas. The speckle index is chosen as a criteria to measure the reduction of speckle noise by these filters. The homogeneous and heterogeneous areas were measured by the speckle index. From Table 3, for the heterogeneous areas, the speckle index is relatively higher. The GMAP filter is much more efficient for reducing the noise while keeping the edges.

Table 3 Speckle index test for different terrain.

Filter	*From*	*homo-geneous*	*to*	*Hetero-geneous*
Original	0.309	0.312	0.328	0.464
Box	0.105	0.121	0.142	0.228
Median	0.112	0.123	0.152	0.220
Lee	0.105	0.121	0.142	0.228
Frost	0.107	0.122	0.145	0.235
Kuan	0.104	0.121	0.142	0.228
Enh. Lee	0.112	0.125	0.152	0.328
Enh.Frost	0.107	0.125	0.147	0.301
GMAP	0.126	0.128	0.167	0.384

Qualitative Evaluation:

The qualitative evaluation was made by visual interpretation. A 3-look ERS-1 image with the size of 256 by 256 pixels was selected to test the performance of the filters. The test results is shown in Fig.4. Fig4(a) is the original image, which is an agricultural land area. Fig4.(b) illustrates the Box Filter filtered image. The speckle is reduced dramatically. However, the image also became blurred. The Median filter is slightly superior to the Box Filter for keeping edges(ref. Fig.4(c)). The Lee filter improves the ability of preserving edges compared with the box filter while reducing speckle noise(Fig.4.(d)). The Kuan Filter and Frost Filter are similar to the Lee Filter. Enhanced Lee Filter and Enhanced Frost Filter make improvements on reducing speckle noise at the edges. However, it cannot remedy sharp spot noise. GMAP Filter ptoved to be much better for filtering speckle noise while preserving the edges. From a visual interpretation point of view, it is the best one.

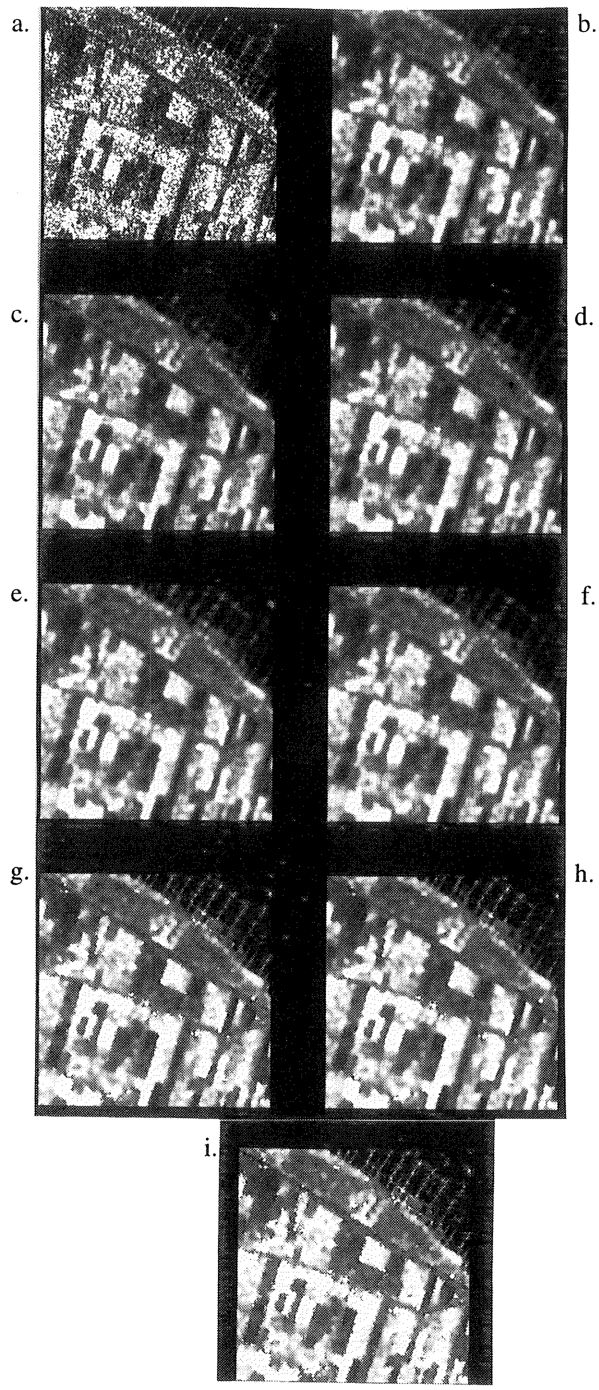

Fig.4, (a) Original ERS-1 3-look image.(b). Box Filter. (c). Median Filter. (d). Lee Filter. (e). Frost Filter. (f). Kuan Filter. (g). Enhanced Lee Filter. (h). Enhanced Frost Filter.(i). GMAP Filter.

In order to evaluate the performance of the filters with different window size and different damping factors, which are parameters available in the PCI software package, we take the Frost Filter as an example. The tested results are shown in Fig.5. From Fig.5, we conclude that speckle noise decreases as the window size increases. The damping factor influences the sharp edges. The larger the damping factor, the sharper the edges are preserved. The number of looks also influence the final filtered image(Ref.Fig.5(g),(h)).

a. b.

c. d.

e. f.

g. h.

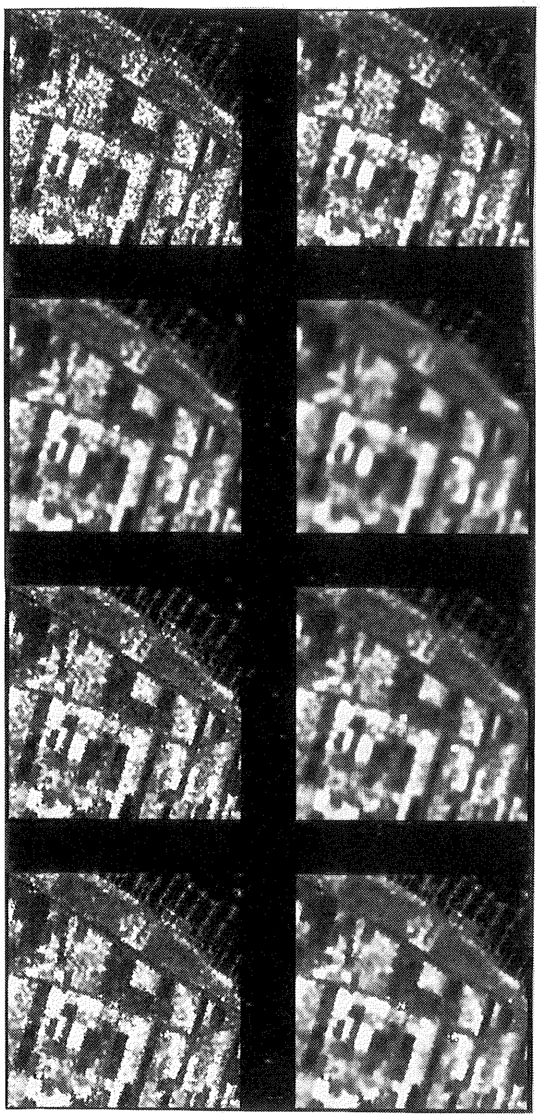

Fig.5, (a). window size 3X3, (b), window size 5X5,(c), window size 7X7, (d). window size 11X11, (e) window size 7X7, damp=0.1, (f). window size 7X7,damp=10.(g). window size 11X11, damp=10. (h). window size 11X11, damp=5.

5. Conclusion

In this paper, the primary results of evaluating filtering techniques have been made by using PCI software. The results indicate the performances of these filter are dependent on the window size, the number of looks, and the filtered areas. The performances of the Lee Filter, Frost Filter, Kuan Filter are similar. The GMAP filter is superior to the other filters in terms og visual interpretation. The further research will focus on detailed evaluation and design of speckle filters.

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