A comparative study of noise removal from High Resolution Remote Sensing Images

Eng. Mohamed Ahmed Ali *
Dr. Fawzy Eltohamy*
Dr.Mahmoud Safwat*
Dr. Gouda I. Salama*
**** Egyptian Armed Forces***

ABSTRACT *Satellite imaging is one of the most attractive sources of information for the governmental agencies and the commercial companies since the lunch of high resolution commercial satellites. It is very important especially for the military applications. Satellite images may have unwanted signals (noise) in addition to useful information due to several reasons such as bad sensor function (detectors and electronics), and imaging environment. Several noise removal methods can be used to eliminate or reduce the effect of noise over the image before information extraction.*

In this paper a comparative study among four types of noise removal filters is carried out. The investigated filters are Median Filter, Wiener Filter, Average Filter and Bilateral Filter. These filters are applied on a test set of four high resolution remote sensing images acquired by different satellites (GeoEye.1, Ikonos, Spot.5 and World View2). The test images are contaminated by four types of noise: Salt and Pepper noise (SPN), Shot Noise (Poisson noise), Speckle Noise and Gaussian Noise. The results of applying the four filters are compared, evaluated and analyzed. The evaluation is conducted with the help of Mean Square Errors (MSE), Peak-Signal to Noise Ratio (PSNR), structural similarity index measure (SSIM), discrepancy(D) and Universal Image Quality Index (UIQI).

Keywords *Satellite Image noise, Average filter, Median filter, Wiener filter, Bilateral filter, PSNR, MSE, SSIM, Discrepancy – Universal Image Quality Index (UIQI) .*

INTRODUCTION

Noise can be introduced into the image during the image acquisition and transmission process. Due to noise some pixels values would not reflect the true intensities of the real scene. This means that the noises cause the degradation of image quality, therefore a noise reduction processes should be conducted before image analysis. The most commonly occurring types of noise are i) Impulse noise, ii) Additive noise (e.g. Gaussian noise) and iii) Multiplicative noise (e.g. Speckle noise) [1]. Several noise removal methods are published in literatures. They can be classified into spatial (image) domain methods and frequency domain methods. The performance of noise removal methods changes according to the noise type. A noise removal method can perform well with s specific noise type while not capable with another noise type. The study presented in this paper will illustrate this after applying the investigated filters on different types of noise.

The Used Set of High Resolution Remote Sensing Images

The data set used consists of four different types of images acquired by different satellites .Image-1 of GeoEye-1 satellite which is launched in September 2008. The satellite collects images at 0.5 meter panchromatic in the band (0.45 – 0.8) µm and 2 meter multispectral. Image-2 acquired by IKONOS satellite which collects panchromatic images with 1 meter resolution in the band (0.45 – 0.9) µm and multispectral imagery with 4 meter resolution at nadir. Image-3 acquired by spot5 satellite which has a 2.5 meter panchromatic in the band (0.519 – 0.73) µm resolution. Image-4 acquired by WorldView-2 satellite which is launched in October 2009 and considered the first high-resolution 8-band multispectral commercial satellite, operating at an altitude of 770 km. WorldView-2 provides images of 0.5 meter panchromatic in the band (0.45 – 0.8) µm and 2 meter multispectral [2].].Fig 1 shows the selected test set of image and Table (1) shows their characteristics.

Image-1 (GeoEye-1)	Image-2 (Ikonos)	Image-3 (Spot 5)	Image-4 (WorldView 2)

Figure (1) Tested set of images

TABLE 1
Characteristics of test set images

Image No.	Band (μm)	Resolution (m)	Image area	Sample size (pixels)
Image-1 (GeoEye-1)	Panchromatic (0, 45 – 0, 8)	0.5	Arizona, (USA)	512 x 512
Image-2 (Ikonos)	Panchromatic (0, 45 – 0, 8)	1	Vancouver (Canada)	512 x 512
Image-3 (Spot 5)	Panchromatic (0, 519 – 0, 73)	2.5	Shanghai, (China)	512 x 512
Image-4 (WorldView 2)	Panchromatic (0, 45 – 0, 8)	0.5	Colorado, (USA)	512 x 512

Remote sensing Image Noise types and sources

Image noise is generally regarded as an undesirable by-product of image capture. The main sources of noise in remote sensing digital image can be [3, 4]:

a) The imaging sensor (photo detector) and the environmental conditions during image acquisition.
b) Insufficient light levels and sensor temperature may introduce the noise in the image.
c) Interference in the transmission channel may also corrupt the image.

The most common types of noise in the remote sensing images are as following: Amplifier noise (Gaussian noise), Salt-and pepper noise, Shot noise (Poisson noise), and Speckle noise.

Amplifier noise (Gaussian noise)

The standard model of amplifier noise is additive, Gaussian, independent at each pixel and independent of the signal intensity, Amplifier noise is a major part of the "read noise" of an image sensor, that is, of the constant noise level in dark areas of the image, and it's expressed mathematically as:

$$P(x) = 1/(\sigma\sqrt{2\pi}) * e(x-\mu)2 / 2\sigma 2 \; -\infty < 0 < \infty \qquad (1)$$

Where:
P(x) is the Gaussian noise in image; μ and σ are the mean and standard deviation respectively.

Salt-and-pepper noise

An image containing salt-and-pepper noise will have dark pixels in bright regions and bright pixels in dark regions. This type of noise can be caused by dead pixels, analog-to-digital converter errors; bit errors in transmission, etc. [5] this can be eliminated in large part by using dark frame subtraction and by interpolating around dark/bright pixels. Salt & pepper distribution noise can be expressed by:

$$P(x) = \begin{cases} P1, & x=A \\ P2, & x=B \\ 0, & \text{otherwise} \end{cases} \qquad (2)$$

Where:
p1, p2 are the Probabilities Density Function (PDF), p(x) is distribution salt and pepper noise in image and A, B are the arrays size image. Gaussian and salt & Pepper are called impulsive noise.

Poisson noise
Poisson noise or shot noise is a type of electronic noise that occurs when the finite number of particles that carry energy, such as electrons in an electronic circuit or photons in an optical device, is small enough to give rise to detectable statistical fluctuations in a measurement.

Speckle noise
Speckle noise is a granular noise that inherently exists in and degrades the quality of the active radar and synthetic aperture radar (SAR) images. Speckle noise in conventional radar results from random fluctuations in the return signal from an object that is no bigger than a single image-processing element. It increases the mean grey level of a local area. Speckle noise in SAR is generally more serious, causing difficulties for image interpretation. It is caused by coherent processing of backscattered signals from multiple distributed targets, it can be expressed by:

$$J = I + n*I \quad (3)$$

Where:
J is the distribution speckle noise image, I is the input image and n is the uniform noise image by mean o and variance v.

Concepts of Filters Used

Mean Filter:
The mean filter is a simple spatial filter .It is a sliding-window filter that replaces the centre value in the window. It replaces with the average mean of all the pixel values in the kernel or window. The window is usually square. The advantages of the mean filter are that Easy to implement and used to remove the impulse noise but its disadvantage that is it does not preserve details of image (Some details are removes of image with using the mean filter). [6]

Median Filter:
Median Filter is a simple and powerful non-linear filter which is based order statistics. It is easy to implement method of smoothing images. It is used for reducing the amount of intensity variation between one pixel and the other pixel. In this filter, we do not replace the pixel value of image with the mean of all neighbouring pixel values, we replaces it with the median value. Then the median is calculated by first sorting all the pixel values into ascending order and then replace the pixel being calculated with the middle pixel value. The advantages of the median filter are that Easy to implement and used for de-noising different types of noises and its disadvantage that its remove image details while reducing noise such as thin lines and corners also the Median filtering performance is not

satisfactory in case of signal dependant noise. To remove these difficulties different variations of median filters have been developed for the better results. [6]

Wiener Filter:

The purpose of the Wiener filter is to filter out the noise that has corrupted a signal. This filter is based on a statistical approach. Mostly all the filters are designed for a desired frequency response. Wiener filter deals with the filtering of an image from a different view. The goal of wiener filter is to reduce the mean square error as much as possible. The Fourier domain of the Wiener filter is: [6]

$$G(u,v) = \frac{H^*(u,v)}{|H(u,v)|^2 P_s(u,v) + P_n(u,v)} \quad (4)$$

Where:

H*(u, v) = Complex conjugate of degradation function Pn (u, v) = Power Spectral Density of Noise Ps (u, v) = Power Spectral Density of non-degraded image H (u, v) = Degradation function [6]

Bilateral filter

Recently most popular denoising method is the bilateral filter [7]. The bilateral filter is a nonlinear weighted averaging filter and also the weights depend on both the spatial distance and the intensity distance with respect to the centre pixel. The main feature of the bilateral filter is its ability to preserve edges while doing spatial smoothing. The bilateral filter is a robust filter because of its range weight, pixels with different intensities. It averages local small details and ignores outliers. At a particular pixel location n, the bilateral filter output is calculated as follows,

$$\hat{I}(\mathbf{x}) = \frac{1}{C} \sum_{y \in N(x)} e^{\frac{-\|\mathbf{y}-\mathbf{x}\|^2}{2\sigma_d^2}} e^{\frac{-|I(\mathbf{y})-I(\mathbf{x})|^2}{2\sigma_r^2}} I(y) \quad (5)$$

Where:

σd and σr are parameters controlling the fall-off of weights in spatial and intensity domains, respectively, N(x) is a spatial neighborhood of pixel I (x) , and C is the normalization constant[8]

$$C = \sum_{y \in N(x)} e^{\frac{-\|\mathbf{y}-\mathbf{x}\|^2}{2\sigma_d^2}} e^{\frac{-|I(\mathbf{y})-I(\mathbf{x})|^2}{2\sigma_r^2}}$$

Quality Assessment of the filtered images

The quality of the output filtered images is evaluated using the following five metrics:

Root mean square error (RMSE)

It is the square root of the mean square error between the original and filtered image. It detects the difference between the filtered and the original image [9].

$$RMSE = \sqrt{\frac{1}{M \times N} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} (g(x,\ y) - f(x,\ y))^2} \qquad (7)$$

Where:
f(x,y)........ The original or input image.
g(x,y)....... The output image (the filtered image).
M x N .... The image size.

Peak signal to noise ratio (PSNR)
Peak signal to noise ratio is defined as [10, 11]:

$$PSNR = 10\log[\frac{X_{max}^{2}}{\frac{1}{MxN}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}(g(x,y)-f(x,y))^2}] \text{ [dB]} \qquad (8)$$

Where, Xmax is the maximum gray level (255 for 8-bit level) of the given input image .The PSNR is more commonly used than the RMSE, because people tend to associate the quality of an image with a certain range of PSNR. Table 2 illustrates the PSNR values and its indication [9].

TABLE 2
The Peak Signal to Noise Ratio and its description

PSNR	Description
Over 40 dB	Excellent image (i.e., being very close to the original)
Between 30 to 40 dB	Good image (i.e., the distortion is visible but acceptable)
Between 20 and 30 dB	Acceptable.
Lower than 20 dB	Unacceptable.

Structural Similarity Index Measure (SSIM)
The conventional methods PSNR and MSE do not always agree with the subjective viewing results in case of additive distortion. The SSIM gives good evaluation accuracy and simple mathematical formulation.
It is based on comparing the structures of the reference and the filtered images. The structural information in an image can be defined as those attributes that represent the structure of objects in the scene, independent of the average luminance and contrast.
Structural Similarity (SSIM) index between signals x and y is,
SSIM x, y = [l(x, y)]α. [c x, y]β. [s x, y]γ (9)
Where:
α > 0, β > 0 and γ > 0 are parameters used to adjust the relative importance of the three components. [11]

Discrepancy (D)

It is defined as:

$$D = \frac{1}{M * N} \sum_{i=1}^{M} \sum_{j=1}^{N} |O(i,j) - F(i,j)| \quad (10)$$

Where:

$O(i,j), F(i,j)$ are the pixel values at position (i, j) in the original images and the filtered images respectively. M and N are the numbers or rows and columns of the image respectively. It is known that the spectral quality of the image increases as (D) decreases. [12]

Universal Image Quality Index (UIQI)

The UIQI is designed by modeling image distortion as a combination of three factors; loss of correlation, radiometric distortion, and contrast distortion. It is defined by the following formula:

$$UIQI_i = \frac{4\sigma_{B_i^* F_i} \cdot \mu_{B_i^*} \cdot \mu_{F_i}}{\sigma^2_{B_i^*} + \sigma^2_{F_i} \left[\left(\mu_{B_i^*}\right)^2 + \left(\mu_{F_i}\right)^2 \right]} \quad (11)$$

Where:

$\sigma_{B_i^* F_i}$ is the covariance between the band of filtered images and the input (original) images, μ and σ are the mean and the standard deviation of the images. The dynamic range of UIQI is [-1, 1].The higher UIQI the better spectral quality image. [13]

Experimental Work & Results Evaluation

The filters were implemented using (MATLAB R2010b, 7.11.0) according to the following steps:
First, different types of noise are added to each one of the test original images to produce noisy images, tables (3-6) column 1,The Second, the four filters are used to filter the noisy image (The size of mean and median filters are a square window of size (3X3) ,Finally, comparing between resulting images depending on a quantitative measures: Peak Signal-to-Noise Ratio (PSNR), mean square error (MSE), (SSIM), (Discrepancy) and (Universal Image Quality Index) metrics to determine the best proper filter in each case. Tables 3, 4, 5 and 6 show the results of applying the four filters on the images suffered from Poisson noise, Gaussian noise, speckle and salt & paper noises respectively. From these tables we have the following:

In case of Poisson Noise

The Bilateral filter gives the best results using (PSNR, MSE) metrics while by using the (SSIM , Discrepancy and UIQI) metrics the Wiener filter gives more better results than the bilateral filter in images (1 and 4) with lightly difference.

In case of Gaussian noise

We get the best results using the Bilateral filter When using (PSNR, MSE) metrics, while by using (Discrepancy and UIQI) we get the best results using Wiener filter.

In case of Speckle noise

We found that the average filter gives the best results in images (1,2 and 4) using the five metrics while Wiener filter gives slightly good results more than the average filter in case of image (3) by using (MSE, PSNR and SSIM) metrics.

In case of Salt & Pepper noise

We found that approximately the median filter gives the best results in the four images using the five metrics.

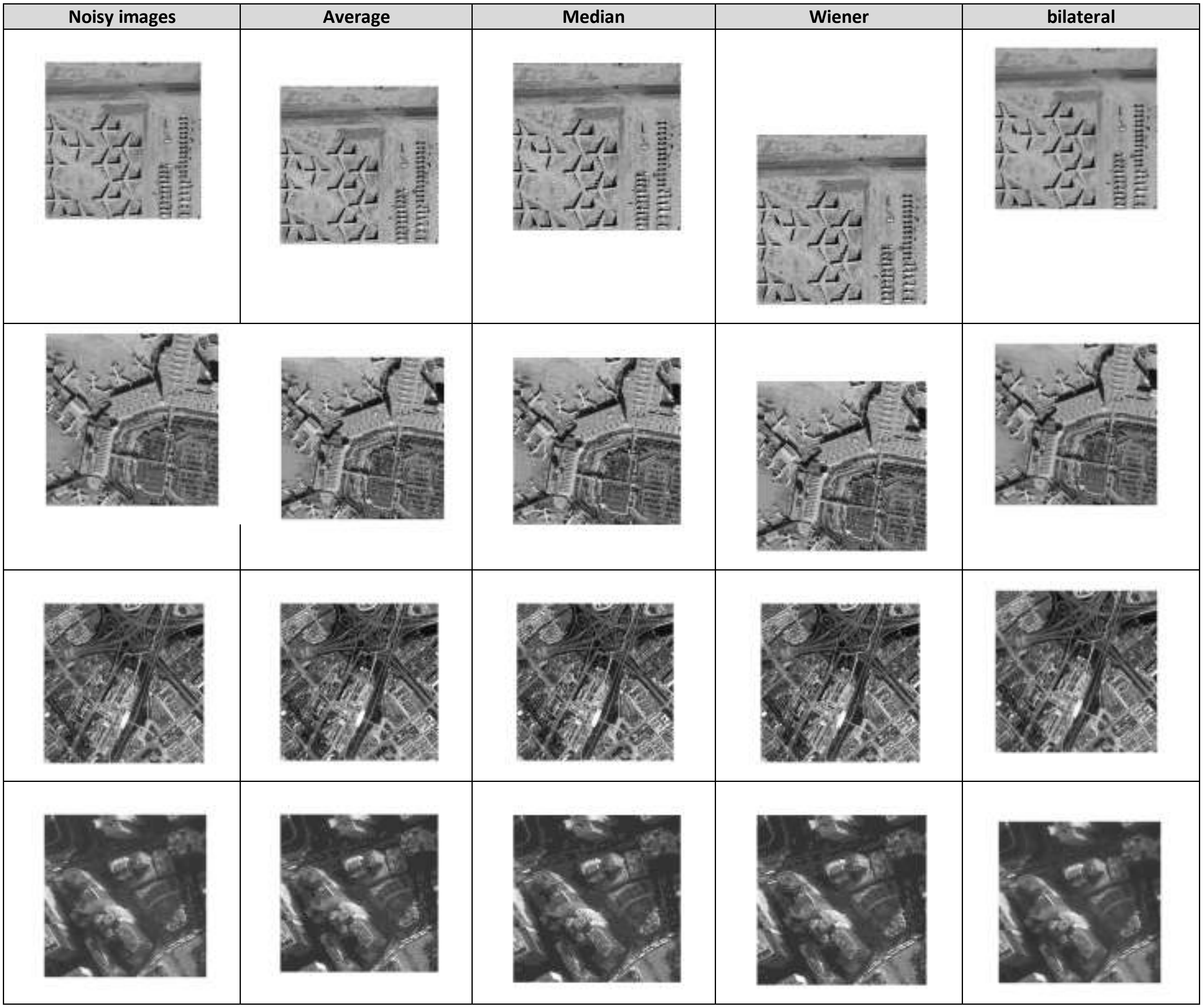

Fig (2) images contaminated by Poisson noise (column 1) and the filtered images after applying the 4 filters

TABLE III
RESULTS FOR POISSON NOISE

Filter type	Satellite images	Resolution [m]	Objective fidelity criterion				
			MSE	PSNR	SSIM	D	UIQI
Average	GeoEye-1	.5	132.0502	26.9234	0.9373	3.0816	0.9920
	Ikonos	1	184.0873	25.4806	0.9497	3.7686	0.9790
	Spot 5	2.5	312.3322	23.1846	0.9428	5.3750	0.9756
	WV2	.5	71.5219	29.5864	0.9548	2.1860	0.9932
Median	GeoEye-1	.5	96.8387	28.2703	0.9341	2.6302	0.9941
	Ikonos	1	153.5116	26.2694	0.9515	3.4662	0.9818
	Spot 5	2.5	259.6449	23.9870	0.9538	4.7110	0.9791
	WV2	.5	58.9664	30.4248	0.9497	2.0575	0.9939
Wiener	GeoEye-1	.5	50.0346	31.1381	0.9485	2.2373	0.9959
	Ikonos	1	80.9107	29.0507	0.9686	2.6892	0.9892
	Spot 5	2.5	167.7836	25.8833	0.9651	4.0924	0.9858
	WV2	.5	33.5370	28.7994	0.9652	1.5925	0.9971
Bilateral	GeoEye-1	.5	46.6644	31.4409	0.9235	2.4863	0.9950
	Ikonos	1	46.1169	31.4922	0.9710	3.0221	0.9907
	Spot 5	2.5	54.7600	30.7462	0.9853	3.0997	0.9930
	WV2	.5	33.2950	30.4496	0.9543	2.5392	0.9968

Noisy images	Average	Median	Wiener	bilateral
				
				
				

Fig (3) images contaminated by Gaussian noise (column 1) and the filtered images after applying the 4 filters

TABLE IV
RESULTS FOR GAUSSIAN NOISE

Filter type	Satellite images	Resolution [m]	Objective fidelity criterion				
			MSE	PSNR	SSIM	D	UIQI
Average	GeoEye-1	.5	170.8049	25.8058	0.8777	3.7318	0.9879
	Ikonos	1	222.1299	24.6647	0.9144	4.3775	0.9733
	Spot 5	2.5	356.6540	22.6083	0.9236	5.7617	0.9729
	WV2	.5	112.4676	27.6205	0.8477	3.2237	0.9912
Median	GeoEye-1	.5	161.5838	26.0468	0.8593	3.7230	0.9854
	Ikonos	1	225.9253	24.5912	0.9045	4.5103	0.9721
	Spot 5	2.5	348.3309	22.7109	0.9251	5.7022	0.9741
	WV2	.5	126.9676	27.0939	0.8193	3.4601	0.9909
Wiener	GeoEye-1	.5	111.0649	27.6750	0.8849	3.2154	0.9888
	Ikonos	1	149.4433	26.3860	0.9289	3.7154	0.9800
	Spot 5	2.5	243.1387	24.2723	0.9431	4.8520	0.9810
	WV2	.5	95.0214	28.3526	0.8448	3.0550	0.9929
Bilateral	GeoEye-1	.5	109.4437	27.7389	0.8389	4.7868	0.9598
	Ikonos	1	128.5596	27.0398	0.9137	5.5824	0.9618
	Spot 5	2.5	153.1960	26.2783	0.9566	5.5979	0.9782
	WV2	.5	101.8653	28.0505	0.7963	5.1883	0.9874

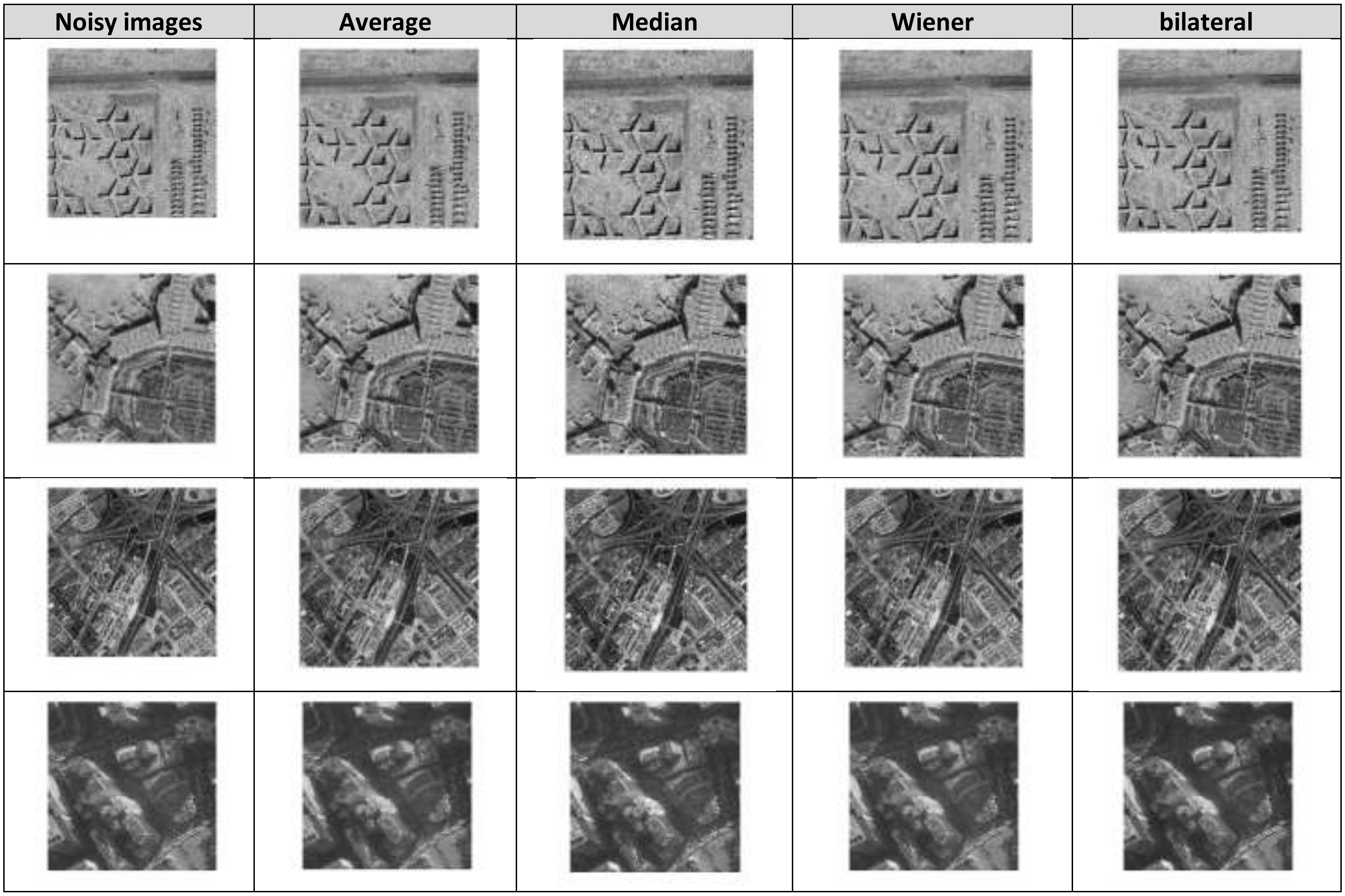

Fig (4) images contaminated by Speckle noise (column 1) and the filtered images after applying the 4 filters

TABLE V
RESULTS FOR SPECKLE NOISE

Filter type	Satellite images	Resolution [m]	Objective fidelity criterion				
			MSE	PSNR	SSIM	D	UIQI
Average	GeoEye-1	.5	**286.7062**	**23.5564**	**0.7680**	5.5021	0.9592
	Ikonos	1	**308.5672**	**23.2373**	**0.8580**	5.6549	0.9482
	Spot 5	2.5	**423.7504**	**21.8597**	**0.9116**	6.7764	0.9642
	WV2	.5	**139.9098**	**26.6723**	**0.8536**	3.6196	0.9873
Median	GeoEye-1	.5	**486.8936**	**21.2565**	**0.6926**	7.6610	0.9183
	Ikonos	1	**464.6416**	**21.4596**	**0.8136**	7.6951	0.9264
	Spot 5	2.5	511.1086	21.0457	0.8956	8.4781	0.9544
	WV2	.5	216.3898	24.7784	0.7751	4.7618	0.9803
Wiener	GeoEye-1	.5	293.7629	23.4508	0.7604	5.6596	0.9430
	Ikonos	1	312.2105	23.1863	0.8577	5.6793	0.9418

	Spot 5	2.5	364.2405	22.5169	0.9270	6.2409	0.9643
	WV2	.5	185.5247	25.4468	0.8501	3.8649	0.9770
Bilateral	GeoEye-1	.5	1100.0	17.7169	0.6908	11.5026	0.8456
	Ikonos	1	852.8286	18.8222	0.8238	9.7921	0.8973
	Spot 5	2.5	662.3058	19.9202	0.9245	8.4211	0.9414
	WV2	.5	379.5546	22.3381	0.8292	7.5892	0.9647

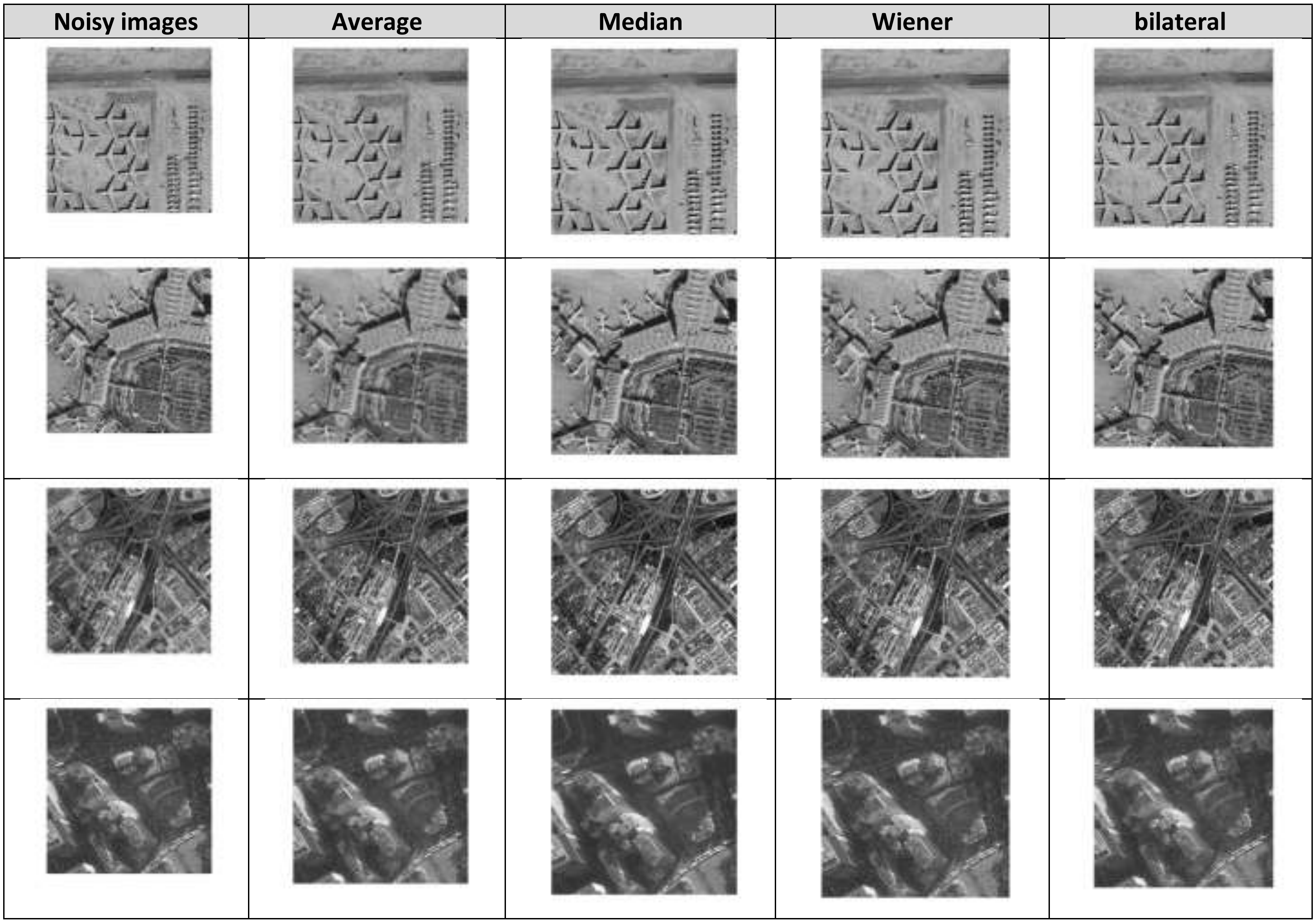

Fig (5) images contaminated by Salt & Pepper noise (column 1) and the filtered images after applying the 4 filters

TABLE VI

RESULTS FOR SALT & PEPPER NOISE

Filter type	Satellite images	Resolution [m]	Objective fidelity criterion				
			MSE	PSNR	SSIM	D	UIQI
Average	GeoEye-1	.5	196.6247	25.1944	0.8539	4.1480	0.9893
	Ikonos	1	256.5437	24.0392	0.8944	4.5453	0.9712
	Spot 5	2.5	397.0759	22.1421	0.9085	5.7088	0.9708
	WV2	.5	141.1499	26.6340	0.8109	2.6570	0.9906
Median	GeoEye-1	.5	87.2534	28.7230	0.9656	1.8140	0.9956
	Ikonos	1	146.9325	26.4596	0.9656	2.7519	0.9855
	Spot 5	2.5	264.8416	23.9009	0.9543	4.1954	0.9797
	WV2	.5	50.7917	31.0729	0.9753	1.4773	0.9948
Wiener	GeoEye-1	.5	300.5576	23.3515	0.8156	3.6646	0.9856
	Ikonos	1	357.3606	22.5997	0.8780	4.0051	0.9736
	Spot 5	2.5	444.4801	21.6523	0.9099	4.9280	0.9701
	WV2	.5	363.0158	22.5315	0.7362	2.4808	0.9764
Bilateral	GeoEye-1	.5	302.5596	23.3227	0.7309	4.0925	0.9764
	Ikonos	1	298.4476	23.3821	0.8427	3.6193	0.9772
	Spot 5	2.5	330.2386	22.9425	0.9055	3.5773	0.9784
	WV2	.5	294.9812	23.4329	0.6797	2.6958	0.9778

Conclusion

In this paper, comparative study among four different noise removal filters is conducted. The experimental results proved that we can use Bilateral filter to remove (Poisson - Gaussian) noises from high resolution satellite images also in some cases we can use the Wiener filter for the same type of noises .In case of reduction the effect of speckle noise we can use the Average filter and in some cases the Wiener filter may be used. Finally we can use the Median filter perfectly in case of Salt and Pepper noise removal from high resolution satellite images with preserving the detailed features.

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