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Aerial and Satellite Image Denoising using Least Square Weighted Regularization Method

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Abstract

Remotely sensed images are subjected to various types of noises. Noise interrupts the image information; hence noise removal is one of the important pre-processing steps in every image processing applications. Since both noise and edges contain high-intensity values, image denoising leads to smoothening of the edges thereby reducing the visual quality of the image. Hence, edge preserved image denoising is an ever-relevant topic. Over decades, several image denoising techniques were developed. Most of the denoising algorithms are very complex and time consuming. **Background/Objectives:** This paper introduces a novel image denoising technique based on least square weighted regularization. **Methods/Statistical Analysis:** The one-dimensional signal denoising introduced by14 is mapped into two-dimensional image denoising. The proposed method is experimented on a set of colored aerial and satellite images. The column-wise denoising of the image is performed first, followed by row-wise denoising. The performance of the proposed method is evaluated based on the standard quality metric peak signal-to-noise ratio and computational time. **Findings**: From the experimental results, it is observed that the proposed method outperforms the earlier denoising methods on the basis of time and complexity. **Applications/Improvements:** The proposed denoising technique can be adopted as a faster pre-processing step in most of the image processing applications.

Keywords: Least Square, Legendre-Fenchel, Peak Signal-to-Noise Ratio, Total Variation, Wavelet

1. Introduction

Digital image processing plays a key role in various applications like remote sensing, medical field, transmission and encoding, pattern recognition, microscopic imaging etc. This paper focuses on the remotely sensed color images, which are widely used in the geographical information system, astronomy and geoscience studies. Based on the platforms on which sensors are placed, the remotely sensed images can be grouped into aerial images and satellite images. Aerial images are obtained from the sensors mounted on aircraft whereas; satellite images are obtained from the sensors mounted on satellites. A wide variety of satellite imagery and aerial photography is available for use in various applications. But there is a shortcoming of the high chance of these images getting contaminated by noise during the process of data acquisition, transmission, reception and processing[1]. The presence of noise degrades the quality of the image. Because of such degradation, the analyst finds difficulty in separating the fine details from the image. In addition to this, it critically affects the computer-based analysis and quantitative measurement. Hence, noise removal has turned into an indispensable pre-processing practice in every image processing applications[2].

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Noise removal from an image will not end up with a unique solution. Since the original texture of the image could be noisy or have different unknown regularity features, the restoration of the noisy image will result in a number of solutions. The best solution for image denoising is the one which gives the better result without losing the image information[3]. One of the main criteria while denoising is, edge preservation which is the main challenge faced by researchers in recent days.

Over years, a great deal of research[4–6] has taken place in the field of image denoising. Partial Differential Equation (PDE) and variational based methods have gained popularity for image denoising[7,8], of which Total Variation (TV) model[9] is best known. Tikhonov model is formulated based on TV. One problem with Tikhonov regularization is the problem of over-smoothing by which the detailed information from an image can be lost. Another feasible and useful denoising technique is wavelet thresholding or shrinkage, pioneered by[10,11]. This method is comparatively efficient and easy to realize. Wavelet transform transforms the signal from time domain to time-scale domain. A threshold is selected according to the characteristic of the image, so as to reduce the noise. Here, threshold setting is a very crucial task. It is very difficult to accurately set the threshold for a better denoising. Higher the threshold, better the effect of denoising. But, the edges get blurred at the same time[12]. Next widely used denoising technique on remotely sensed images is Legendre-Fenchel Transformation. This method deals with the mapping of function from primal space to dual space[13]. While doing denoising, time is also a constraint. A best denoising technique is one which gives better results in a minimum time. To retain optimum time and preserve the novel information in the image, the least square weighted regularization was introduced. In[14] proposed One-Dimensional (1D) signal denoising using least square. This Least square denoising concept is extended to Two-Dimensional (2D) image denoising in this paper. The advantages of the proposed least square weighted regularization are its simplicity and fast processing.

This paper deals with denoising of aerial and satellite color images using least square weighted regularization technique. The quality of the denoised image is determined based on visual perception and Peak Signal to Noise Ratio (PSNR). A comparative study of different denoising techniques is performed depending on the PSNR values and time taken for denoising.

Organization of paper is as follows, introduction of basic concepts of least square weighted regularization technique in Section 2 followed by illustrations and explanations of the methodology in next section. The results are discussed in Section 4 and Section 5 concludes the paper.

2. Mathematical Background

2.1 Least Square Weighted Regularization Denoising

This Section deals with the least square weighted regularization algorithm for image denoising. The one-dimensional signal denoising using least square approach was proposed by[14]. The proposed method maps the one-dimensional signal denoising to two-dimensional image denoising using least square. The problem can be formulated as:

$$min_{\mathbf{x}} \| y - x \|_2^2 + \lambda \| \mathbf{D}x \|_2^2 \tag{1}$$

where 'y' is the noisy image, 'x' is the denoised image, λ >0 is the control parameter and 'D' is the second order differential matrix given by,

$$D = \begin{bmatrix} 1 & -2 & 1 & & & \\ & 1 & -2 & 1 & & \\ & & \ddots & & \ddots & \\ & & & 1 & -2 & 1 \end{bmatrix}$$

The coefficients in D matrix corresponds to the coefficients of the second order differential equation which is given by,

$$y(n) = x(n-1) - 2x(n) + x(n+1) \tag{2}$$

Then Dx in Equation (1) is the second-order difference of image x . The concept formulated in Equation (1) is to generate a denoised signal (1D) or image (2D) without losing the important structural features of the original image. The first term in Equation (1) corresponds to preserving the information of the input image. Minimization of the first term in Equation (1) forces x to be similar to noisy image y. The second term in the Equation (1) represents the squared L2-norm of second order derivative of output denoised signal. Minimization of the second term leads to the smoothing of x.

The least square formulation for the signal denoising is

$$x = [I + \lambda D^T D]^{-1} y \quad (3)$$

The trade-off between similarity and smoothing is controlled by λ. Higher the value of λ, smoother will be the denoised image. If λ is very small, less smoothing is achieved hence the denoised image will be same as input noisy image. Therefore, λ should be chosen such that, denoised image will be similar to the input image with the removal of noise.

3. Methodology

The proposed method deals with least square weighted regularization denoising technique performed on colored aerial and satellite images. The different planes of colored remotely sensed images are subjected to denoising separately. The block diagram of the proposed method is shown in Figure 1.

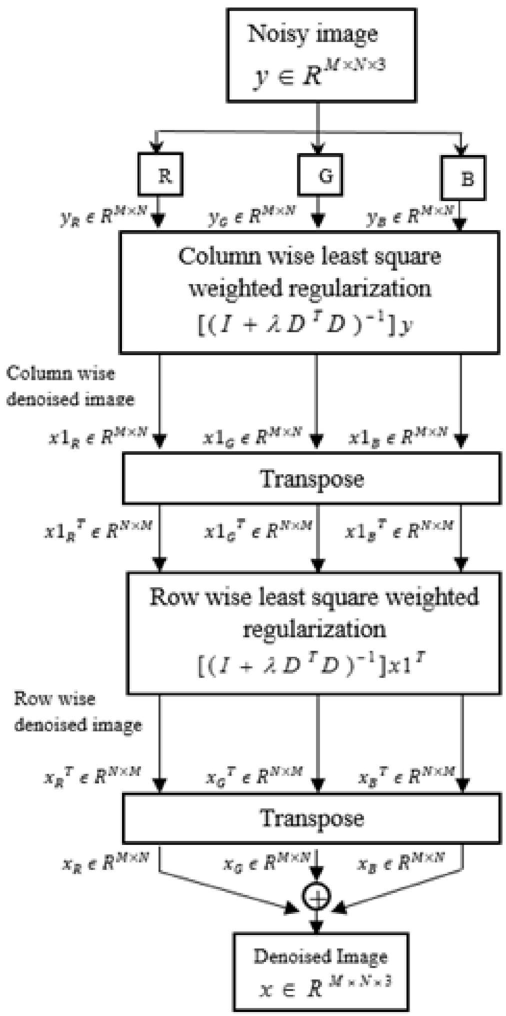

Figure 1. Block diagram of proposed method.

3.1 Algorithm

The algorithm of the proposed method is explained below.

- A color image $I \in R^{M \times N \times 3}$ is read from respective folder.
- The image I is resized to 512 × 512 × 3.
- Image I is converted to noisy image $y \in R^{M \times N \times 3}$ by adding Gaussian noise.
- Red, green and blue planes are extracted from the color image as y_R , y_G and y_B respectively where each plane belongs to $R^{M \times N}$.
- The R plane is extracted from the image as $y_R \in R^{M \times N}$.
- Least square weighted regularization is applied on the image in R plane which denoises the columns of the image.
- The column wise denoised image $x1_R \in R^{M \times N}$ is then transposed to obtain $x1_R^T \in R^{N \times M}$.
- Now, least square regularization is applied on the trans-posed image $x1_R^T$ which will produce row wise denoised image $x_R^T \in R^{N \times M}$.
- The row wise denoised image x_R^T is then trans-posed to obtain the denoised image $x_R \in R^{M \times N}$.
- Steps (5 to 9) is repeated for green plane $y_G \in R^{M \times N}$ and blue plane $y_B \in R^{M \times N}$.
- The individual denoised planes x_R , x_G and x_B are concatenated to obtain denoised color image $x \in R^{M \times N \times 3}$.

4. Experimental Results and Analysis

This Section sets a brief description of the dataset used for the experiment, accuracy assessment measures and analysis of the least square weighted regularization denoising technique.

4.1 Dataset Description

A set of good resolution aerial and satellite color images are collected. The aerial images were obtained from the top flight photo webpage[15] and satellite images were obtained from Google earth. A total of ten images are used for denoising in which five are aerial images and five are satellite images.

The sample set of images used for this experiment is shown in shown in Figure 2. Aerial images are displayed from Figure 2(a) to Figure 2(c) and satellite images are displayed from

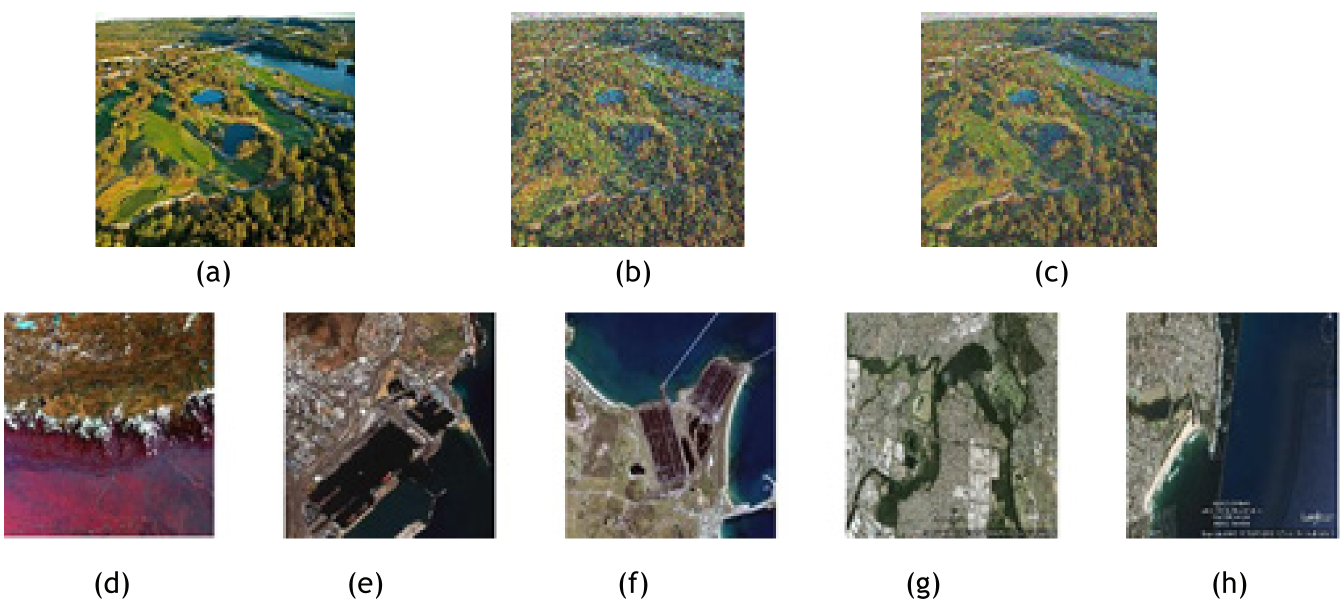

Figure 2. . Set of aerial images ((a) to (c)) and satellite images ((d) to (h)) used to experiment the proposed method of image denoising.

Figure 2(d) to Figure 2(h). For analysis, the aerial and satellite images are labelled in tables as Image 1, Image 2, Image 3, Image 4 and Image 5. In the experiment, all the ten images are resized to 512 ×512 × 3.

4.2 Accuracy Assessment Measures

In this paper, subjective assessment is done based on the visual interpretation. In addition to this, the comparison of the PSNR[16] and time factor comes under objective measurement.

Improving the visual quality can be subjective, since quality of an image could vary from person to person. In this work, in-built command for PSNR calculation in Matlab is used.

Time factor is the major constraint in solving large problems, particularly in case of the aerial and satellite images which contain huge amount of information. Such real time images take longer duration for processing than the normal test images. Time factor of the process is directly proportional to the computational complexity of the algorithm. Efficient algorithms which minimizes the processing time can be used to solve this problem.

4.3 Results and Discussions

In this experiment, Gaussian noise is added to the image with constant zero mean and different variance values. Different variance values chosen are 0.005, 0.01, 0.05, 0.1, 0.25 and 0.5. Least square weighted regularization technique is implemented on these noisy images for different values of λ. The experiment is conducted for following λ values: 0.5, 2, 5, 10, 20, 25 and 30. At each noise level, the PSNR of the denoised image is calculated for different values of λ. PSNR improvement is calculated by taking the difference between PSNR of denoised image and PSNR of the noisy image. PSNR of the denoised image (DI_PSNR) and noisy image (NI_PSNR) for various noise levels using least square weighted regularization method is depicted in Table 1. The DI_PSNR in Table 1 is the PSNR of the denoised image corresponding to the highest PSNR improvement.

From this Table, it can be inferred that the maximum PSNR improvement obtained for aerial and satellite images are 8.7593 dB and 9.6578 dB respectively. Image 3 from the set of aerial images and Image 4 from the set of satellite images produced highest PSNR improvement. The PSNR values obtained for these two images for different values of λ at each noise levels using proposed method (least square weighted regularization) are tabulated in Table 2. It is observed that, for a particular noise level, initially the PSNR increases with increase in λ value and then decreases gradually.

The proposed method is compared with other denoising techniques namely Legendre-Fenchel, wavelet thresholding and total variation. The comparison is done based on the PSNR values obtained and the time taken for denoising. The comparison of PSNR obtained using proposed least square weighted regularization technique with other existing denoising techniques on aerial Image 3 and satellite Image 4 at all noise levels is shown in Table 3.

It is observed that the PSNR obtained using least square weighted regularization technique is comparable with the PSNR obtained using other techniques. The output images are also compared based on visual perception. From the analysis of the denoised images, it is observed that the output image obtained by total variation denoising has lost the detail information of the image.

The denoised image is visually poor in case of the wavelet denoising. The Legendre-Fenchel denoised outputs and least square denoised outputs were comparable. But the highlight lies in the time elapsed for computation. The images obtained after denoising of a sample aerial image (Image 3) at noise level 0.25 using different techniques are shown in Figure 3.

To ascertain the effectiveness of the proposed method the elapsed time observed for different existing denoising techniques is recorded. Higher delay in denoising technique indicates the high complexity of algorithm. The time taken by different techniques for denoising of images at noise level 0.1 is shown in Table 4. From the analysis of Table 4, it is observed that the delay is higher for Total variation denoising when compared to other techniques. The time taken by wavelet thresholding is less than Legendre-Fenchel techniques. Of all the methods, least square weighted regularization technique took the minimum time for denoising, indicating the simplicity of the algorithm. From Table 4, the average of the time elapsed for each technique is computed and is represented graphically in Figure 4. It is observed from Figure 4 that

Table 1. Peak Signal-To-Noise Ratio (PSNR) of denoised image (di_psnr) and noisy image (ni_psnr) for various noise levels applied on test images using proposed method (least square weighted regularization

Image	Noise level											
	0.005		0.01		0.05		0.1		0.25		0.5	
	NI _PSNR (dB)	DI _PSNR (dB)	NI _PSNR (dB)	DI _PSNR (dB)	NI _PSNR (dB)	DI _PSNR (dB)	NI _PSNR (dB)	DI _PSNR (dB)	NI _PSNR (dB)	DI _PSNR (dB)	NI _PSNR (dB)	DI _PSNR (dB)
Aerial Image												
Image1	23.9501	28.7527	21.1489	27,1859	14.8809	22.1454	12.2877	19.6462	9.29515	16.2108	7.62934	13.9708
Image2	23.1224	25.6343	20.2646	24.8211	14.0528	21.319	11.709	19.7542	9.1653	17.4546	7.82738	15.8945
Image3	23.1142	26.0819	20.2133	25.1566	13.9509	21.7753	11.607	20.1269	**9.14757**	**17.907**	7.83822	16.2465
Image4	23.3431	28.8225	20.5635	27.3463	14.5574	23.6143	12.0025	21.3472	9.24517	17.7599	7.713	15.4323
Image5	23.3815	24.9507	20.5459	24.3383	14.266	20.9035	11.8423	19.1946	9.2042	16.5269	7.75963	14.8698
Satellite Image												
Image1	23.1444	24.5098	20.2427	23.9833	14.047	221.3005	11.671	19.8239	9.15322	17.6971	7.82561	16.0001
Image2	23.3653	25.2549	20.6036	24.5631	14.2946	21.1273	11.8408	19.4136	9.2001	16.848	7.7832	15.1573
Image3	23.2588	26.9782	20.3789	25.8444	14.0855	22.1126	11.7059	20.378	9.1639	17.7526	7.8068	15.9334
Image4	23.045	25.919	20.123	25.062	13.683	21.92	11.366	20.582	**9.0572**	**18.715**	7.8813	17.376
Image5	23.1676	26.8007	20.3825	25.7272	14.27	22.3366	11.8256	20.3767	9.1809	17.5115	7.7902	15.6204

Table 2. The PSNR values obtained for aerial image 3 and satellite image 4 for different values of λ at each noise levels using proposed method (least square weighted regularization)

Image	Noise level	NI_PSNR (dB)	DI _PSNR (dB)						
			Lambda						
			0.5	2	5	10	20	25	30
Aerial Image3	0.005	23.11423	26.08194	24.05972	22.75498	21.83334	21.18226	20.98489	20.82734
	0.01	20.21334	25.15661	23.70198	22.47347	21.74218	21.12224	20.93214	20.77977
	0.05	13.9509	21.33788	21.77529	21.34934	20.97935	20.56	20.41916	20.30273
	0.1	11.60701	19.30568	20.10053	20.12689	19.97097	19.72271	19.62899	19.54848
	0.25	9.147567	16.65175	17.562	17.85506	**17.90701**	17.85475	17.82063	17.7875
	0.5	7.838217	15.12644	15.76648	16.10668	16.22082	16.2465	16.23988	16.22987
Satellite Image4	0.005	23.04534	25.91942	23.96604	22.82416	22.0702	21.39311	21.18795	21.02408
	0.01	20.12297	25.06155	23.69075	22.68775	21.98622	21.33949	21.14132	20.98245
	0.05	13.68291	21.46182	21.92032	21.63663	21.26363	20.82868	20.68145	20.55938
	0.1	11.36645	19.42715	20.48811	20.5821	20.43215	20.16646	20.06394	19.97536
	0.25	9.057244	16.89527	18.24663	18.63682	**18.71498**	18.6596	18.61987	18.58079
	0.5	7.881	15.51424	16.72682	17.17683	17.33441	17.37568	17.36904	17.35738

Table 3. Comparison of PSNR using existing denoising techniques and the proposed method (least square weighted regularization) on aerial image 3 and satellite image 4

Image	Noise level	DI_PSNR			
		Wavelet	Total Variation	Legendre-Fenchel	Least Square
Aerial Image3	0.005	23.9777	22.4237	25.9243	**26.0819**
	0.01	23..4817	22.3246	25.6156	**25.1566**
	0.05	21.7853	21.4695	22.4208	21.7753
	0.1	19.8963	20.381	20.6966	20.1269
	0.25	17.7191	18.111	18.2244	17.907
	0.5	16.5325	16.4801	16.4772	16.2399
Satellite Image4	0.005	23.6282	22.4925	25.0587	**25.919**
	0.01	23.212	22.4094	24.8814	**25.062**
	0.05	21.7916	21.6197	22.2182	21.92
	0.1	20.6288	20.7195	20.8352	20.582
	0.25	18.4258	18.9044	18.918	18.715
	0.5	17.2375	17.5731	17.5986	17.376

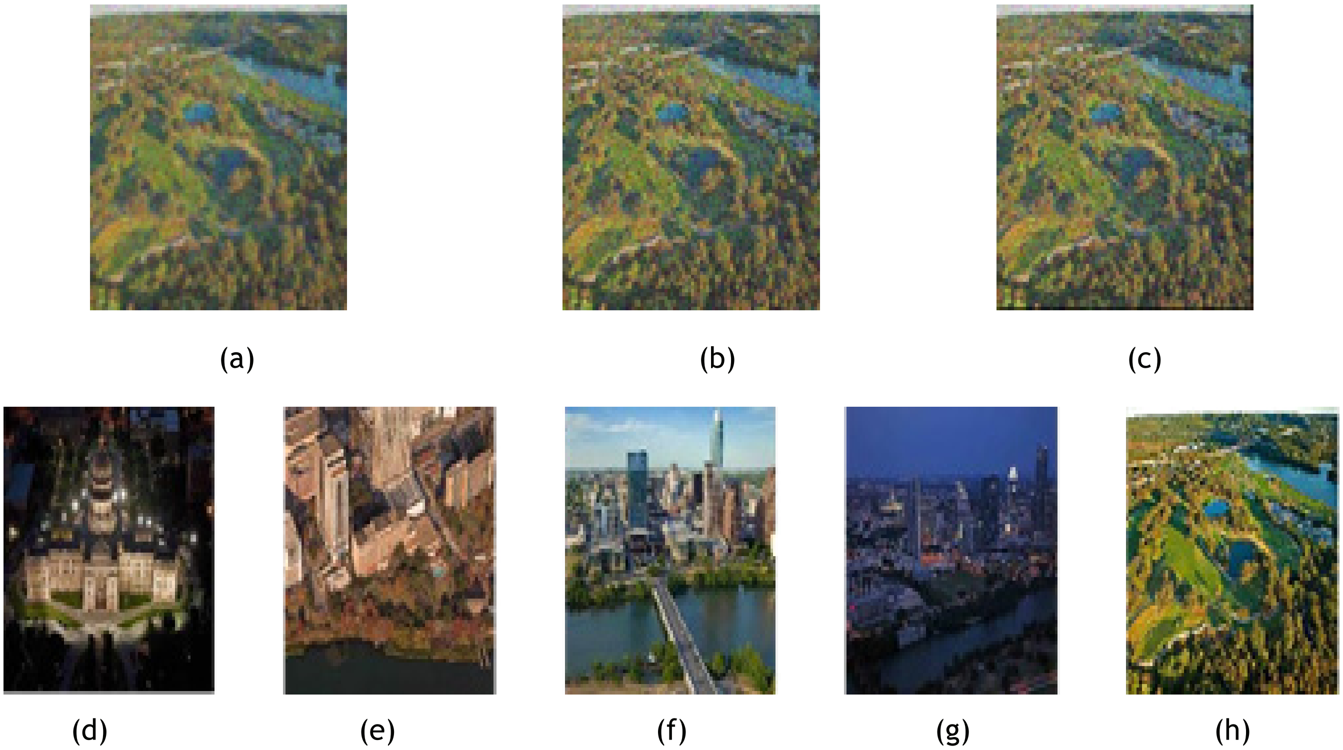

Figure 3. . Denoising using different techniques on aerial image 5. (a) Original image. (b) Noisy image with noise level 0.25. (c) Wavelet thresholding. (d) Total variation. (e) Legendre-Fenchel. (f) Least square weighted regularization.

Table 4. Elapsed time analysis of existing denoising techniques and the proposed technique (least square weighted regularization) on datasets with noise level 0.1

Image name	Elapsed time Observed for Wavelet thresholding Model (in seconds)	Elapsed time Observed for Total variation Model (in seconds)	Elapsed time Observed for Legendre-Fenchel Model (in seconds)	Elapsed time Observed for Least square Model (in seconds)
Aerial image 1	2.759269	29.82942	9.129666	1.76908
Aerial image 2	3.092319	27.8156	7.343646	1.613279
Aerial image 3	2.949316	24.29108	10.0103	1.687476
Aerial image 4	3.145498	28.78749	8.935084	1.754755
Aerial image 5	2.908367	17.14077	8.056981	1.288224
Satellite image 1	2.593634	26.97416	9.593775	1.575704
Satellite image 2	3.023679	28.04517	8.286205	1.695089
Satellite image 3	2.939757	32.91017	10.5683	1.49726
Satellite image 4	3.338535	28.57667	8.113363	1.656212
Satellite image 5	3.496402	26.11813	11.62114	1.910706

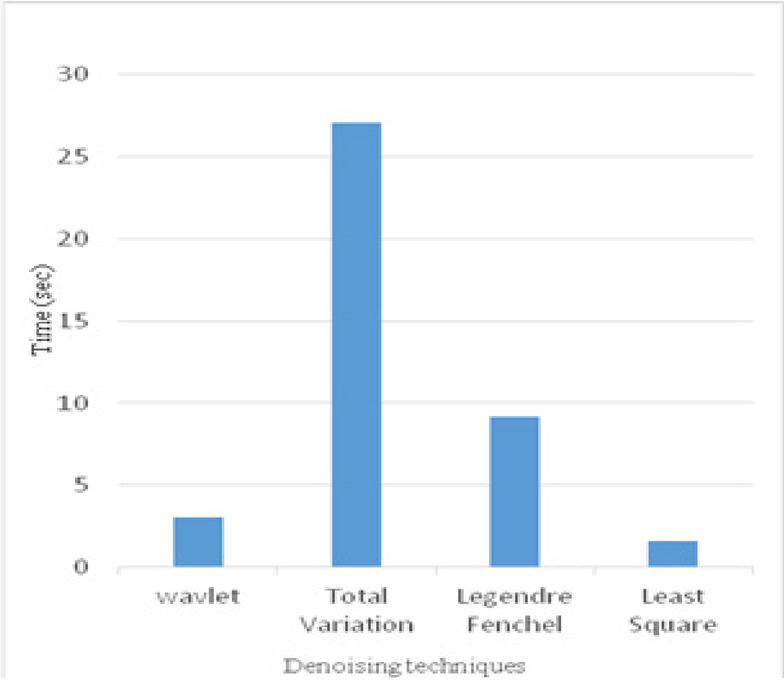

Figure 4. Graphical analysis of elapsed time of existing denoising techniques and the least square weighted regularization (proposed technique).

Table 5. Comparison of existing denoising techniques and the least square weighted regularization (proposed technique)

	PSNR (dB)	**Visual Perception**	**Computational Time (seconds)**
Total Variation	comparable	high smoothening	very high
Wavelet thresholding	comparable	slight smoothening	Less
Legendre-Fenchel	comparable	average smoothening	High
Least Square	comparable	average smoothening	Least

least square weighted regularization technique is computationally fast compared to other techniques.

From the experiment conducted, it is observed that all the denoising techniques give comparable PSNR values. Hence, the comparison of different methods is done based on the visual perception and the time elapsed. The comparison of TV, wavelet thresholding, Legendre-Fenchel and least square weighted regularization techniques is given in Table 5.

5. Conclusion

Denoising of satellite and aerial images using least square weighted regularization method is proposed in this paper. A set of remotely sensed images are collected and simulated with different noise levels. The experiment is conducted on these images for different values of λ λ . The proposed method is also compared with other existing denoising methods. Experimental analysis shows that least square weighted method is simple and computationally very fast and outperforms existing methods based on time factor.

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