PAN-SHARPENING OF MULTI-SPECTRAL SATELLITE IMAGES USING MULTI-SCALE TRANSFORM BASED TECHNIQUES FOR URBAN INFORMATION EXTRACTION

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ABSTRACT

This paper demonstrates the implementation and usefulness of multi-scale transform based pan-sharpening technique for urban information extraction. Multi-scale Transform (MST) based image analysis techniques overcome the shortcomings of the conventional Fourier-based, purely spatial and frequency based techniques. MST provides the efficient characterization of local spectral properties of non stationary image which is desirable for pan-sharpening. The pan sharpening techniques namely, Discrete Wavelet Transform (DWT), Stationary Wavelet Transform (SWT) and Non sub-sampled contour-let Transform (NSCT) techniques have been selected for the pan-sharpening of multispectral images of World View-2 and IKONOS sensors. The accuracy of the pan sharpening techniques has been evaluated by means of standard parameters, such as, Root Mean Square Error, Peak Signal-to-Noise Ratio, Correlation Coefficient, ERGAS and UIQI. Experimental analysis proves that NSCT based pan-sharpening technique gives good result in terms of urban information and have a good trade-off between the preservation of spectral information and the enhancement of spatial resolution.

Keywords- Pan-sharpening, Multi-scale Transform analysis, Non Sub-sampled Contour-let Transform.

1. INTRODUCTION

Pan-sharpening of multi-spectral (MS) satellite images using panchromatic (PAN) images aims at integrating the information acquired at different spatial and spectral resolutions. Pan-sharpening is applied to digital imagery in order to sharpen images or retain the individuality of the images with extended information content (Karathanassi et al. 2007). As far as, satellite pan-sharpening is concerned, the most challenging application is pan-sharpening of multi-spectral (MS) using panchromatic (PAN) images collected from different satellite sensor without introducing artifacts or inconsistencies, which may damage the quality of the pan-sharpened image. High spatial and spectral resolution images are necessary to perform various complex tasks in urban information extraction such as, heterogeneous forested areas or agricultural areas with a high degree of plot subdivision or to accurately delimit the area occupied by each land cover type, as well as, to locate different ground features and structures.

The diversity of datasets has contributed to the development of different types of pan-sharpening techniques and procedures for the implementation of pan-sharpening. Many pan-sharpening techniques based on color methods, statistical methods and multi-scale transform methods as well as software tools have been developed so far. Further, analysis of non-stationary image is a challenging job, as their spectral properties change with time. Such signals cannot be analyzed well by pure spatial domain and frequency domain representations. The MST based technique has been proven to be a powerful tool for analyzing and detection of spatial-scale characteristics of non-stationary images in a more comprehensive manner. MST-based image analysis methods, such as Discrete Wavelet Transform (DWT). and Non Sub-sampled Contour-let Transform (NSCT) to overcome the shortcomings of the traditional Fourier-based methods, Pyramid Transform, pyramid decomposition, pure spatial domain and frequency domain based techniques. However, the problem associated with DWT is that it suffers from poor directionality & lack of shift invariance due to aliasing between sub-bands [Yocky, 1995]. These limitations can be overcome by using some of DWT's extensions, such as the Stationary Wavelet Transform (SWT) which is translation invariant [Ranchin and Wald, 1993]. It is observed that SWT offers limited directional selectivity i.e., it does not resolve the problem of feature orientation. Thus, to resolve the limitation of DWT and SWT, Non Sub-sampled Contour-let Transform (NSCT) has introduced [Cunha et al. 2006]. This method possesses the property of shift-invariance and spatial-scale based local characterization of image representation. The remarkable properties of NSCT motivate its use in image processing applications. Therefore, in this study, pan-sharpening of World View-2 and IKONOS

PAN and MS datasets using MST based techniques have been carried out. The outputs are evaluated in objective and subjective performances.

Further, the comparison of performance of the selected pan-sharpening techniques in terms of different scenario is the central theme of this paper.

2. An overview of pan-sharpening techniques

2.1 Discrete Wavelet Transform (DWT) based pan-sharpening

In the DWT algorithm, the Low Pass (LP) and High Pass (HP) filters have been used for the decomposition of image. These filters divide the image into two bands i.e., LP and HP bands [Yocky, 1995]. The former performs an averaging operation to extract the average information of the image, whereas, the later performs a differencing operation to extract the lines, points and edges information. Thereafter, the output of filtering operation is decimated by 2. A 2-D transformation is achieved by performing two individual 1-D transforms, along row and column separately. This operation decomposes the image into four bands namely LL, LH, HL and HH respectively (Mallat, 1989; Gungor et al. 2008). The pan-sharpening procedure for the pan-sharpening of PAN and MS images using DWT can be summarized in section 2.3.

2.2 Stationary Wavelet Transform (SWT) based pan-sharpening

In order to resolve the problem of shift-variance associated with DWT, SWT based de-noising technique has been introduced (Holschneider and Tchamitchian, 1990; Starck and Murtagh, 1994). In SWT, the filter is up-sampled by adding zeros between the coefficients, thereby excluding the down-sampling step. In SWT, filter bank have been used for the decomposition of image, which in turn produces an approximation image and a detailed image, also called the wavelet plane. A wavelet plane contains the horizontal, vertical and diagonal information between 2^{j} and 2^{j-1} resolution. Further, the approximation image consists of equal number of rows and columns as the original image. This is due to the fact that the filters at each stage are up-sampled by adding zeros between the coefficients, which makes the size of the image equal.

The pan-sharpening procedure for the pan-sharpening of PAN and MS images using SWT can be summarized as follows:

i) To generate new panchromatic images, match histograms of PAN image to their corresponding MS image.
ii) Perform the second level wavelet transform only on the modified PAN image.
iii) The resulting wavelet planes of PAN are added directly to each MS images. Thus, eliminates the need for an inverse transform.

2.3 Non Sub-sampled Contour-let Transform (NSCT) based Pan-sharpening

The Contour-let Transform (CT) proposed by Do and Vetterli in 1998, is a real two-dimensional transform, which is based on non-separable filter banks and provides an efficient directional multi-resolution image representation. The CT decompose the image by first applying a multi-scale transform (the Laplacian pyramid transform), followed by a Direction Filter Banks (DFB) to gather the nearby basis functions at the same scale into linear structures. The contour-lets satisfy anisotropy principle and can capture intrinsic geometric structure information of images and offer better characteristics than DWT and SWT, especially for contours and edges.

However, due to the down sampling and up sampling, the CT lacks shift-invariance and thus results in ringing artifacts. Shift-invariance is just required in image processing applications, such as contour characterization, edge detection, pan-sharpening, etc. In order to reduce the frequency aliasing of contour-lets and enhance directional selectivity as well as shift-invariance, Cunha, Zhou, and Do proposed a novel method known as, NSCT, to overcome the impact of frequency aliasing of contour-lets. NSCT possess the property of shift-invariance and multi-directionality, which is required for the effective analysis of an image, particularly for image de-noising. In addition, it provides enhanced frequency selectivity and uniformity over CT. Further, it consists of two filter banks one is Non Sub-sampled Pyramid Filter Banks, provides multi-scale decomposition and other is Non Sub-sampled Directional Filter Banks, provides directional decomposition, which is used to divide Band Pass sub-bands in each scale into different directions.

The pan-sharpening procedure for the pan-sharpening of MS image with PAN using DWT/NSCT technique is described below:

i. Co-register both images and resample the MS image to make its pixel size equal to that of the PAN, in order to get perfectly matched images.
ii. Generate a new PAN image whose histogram matches that of the corresponding multi-spectral image.
iii. Employ DWT/NSCT mathematical decomposition procedure to the MS image and the corresponding new PAN image, and get low frequency sub-band and high frequency sub-bands coefficients.
iv. Fuse the MS image and the new PAN image coefficients generated in step *(iii)*, by using Optimum fusion rule.
v. Apply DWT/NSCT reconstruction with new coefficients to obtain the high resolution multi-spectral pan-sharpened image.

As a result, a new multispectral image with higher spatial resolution is obtained. This process is repeated for each individual multispectral and panchromatic band pair. Finally, all the new pan-sharpened bands are concatenated to form a new fused multispectral image. Here, the pan-sharpening rule considers a maximum value of coefficients, both for panchromatic and multi-spectral images. This rule can be mathematically represented as (Eq. 3).

$$W^F(x,y) = \begin{cases} W_{\dot{P}AN}(x,y)\,, if\ |W_{\dot{P}AN}(x,y)\,| > |W_{\dot{M}S}(x,y)| \\ W_{\dot{M}S}(x,y), \quad if\ |W_{\dot{P}AN}(x,y)\,| \le |W_{\dot{M}S}(x,y)| \end{cases} \qquad \text{... Eq(1)}$$

3 Criteria to evaluate the quality of the pan-sharpened images

Quantitative metrics such as, RMSE, PSNR, CC, ERGAS and UIQI have been used for the assessment of generated pan-sharpened images other than simple qualitative assessment of the pan-sharpened images [Wald, 1997]. The mathematical representation of these measures has been discussed below:

3.1 Quantitative analysis

The generated fused images are compared by using quantitative indicators in terms of coherence, structural similarity, and spectral information content. These indicators are capable of quantitatively summarizing the performance of the pan-sharpened image.

***i.* Root Mean Square Error (RMSE)**

RMSE is one of the most usable, accurate and effective metric for the estimation of quality of image when reference image is available [Karathanassi et al. 2007].

$$RMSE = \sqrt{\sum_{i=1}^{M}\sum_{j=1}^{N}\frac{\left(F(i,j) - R_o(i,j)\right)^2}{m \times n}} \qquad \text{... (2)}$$

where m, n indicate the size of the image is $m \times n$. $F(i,j)$ and $R_o(i,j)$, indicate the pan-sharpened and reference image. Smaller the value of RMSE, lesser is the difference between the images.

***ii.* Peak Signal-to-Noise Ratio (PSNR)**

PSNR is one of the most well-known full reference metric, used to quantify the deformation of the generated fused image. The value of PSNR should be large for better output

$$\text{PSNR} = 10 \log\left(\frac{255}{\text{RMSE}}\right)^2 \qquad \text{... (3)}$$

***iii.* Correlation Coefficient (CC)**

The Correlation Coefficient of two images is often used to indicate their degree of correlation. Comparing the original image with the fused image, one can find the degree of differences. If the correlation coefficient of two images approaches one, it indicates that the fused image and original image match perfectly. The correlation coefficient is given by

$$corr(x,y) = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}(x(i,j) - \overline{x})(y(i,j) - \overline{y})}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}(x(i,j) - \overline{x})^2 \sum_{i=1}^{m}\sum_{j=1}^{n}(y(i,j) - \overline{y})^2}} \qquad \text{... (4)}$$

where $x(i,j)$ and $y(i,j)$ the elements of the image x and y, respectively. $\overline{x}$ and $\overline{y}$ stand for their mean values. High amount of the correlation shows that the spectral characteristic of the multispectral image has been preserved well.

***iv.* Relative Dimensionless Global Error (ERGAS)**

Wald et al. (1997) proposed an error index that offers a global spectral quality of a pan-sharpened image. This error is called ERGAS, which means relative dimensionless global error in synthesis. This index measures a distortion, and thus must be as small as possible and is given by:

$$ERGAS = 100\frac{l_{PAN}}{l_{MS}}\sqrt{\frac{1}{N}\sum_{i=1}^{n}\frac{RMSE^2(L_i)}{M_i^2}} \qquad \text{... (5)}$$

where l_{PAN} is the resolution of the panchromatic image, l_{MS} the resolution of the multispectral image, N the number of spectral bands (L_i) involved in the pan-sharpening, M_i the mean radiance of each spectral band and RMSE the root mean square error computed. MD and SD are Mean Difference and Standard Deviation respectively.

$$RMSE^2(L_i) = MD^2(L_i) + SD^2(L_i) \quad \dots(6)$$

v. Universal Image Quality Index (UIQI)

Wang and Bovik proposed a method to model any image distortion via a combination of three factors: loss of correlation, luminance distortion, and contrast distortion and named it as Universal Image Quality Index (UIQI). The mathematical representation of UIQI is given below:

$$UIQI = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \frac{2\overline{xy}}{(\bar{x}^2 + \bar{y}^2)} \frac{2\sigma_x \sigma_y}{(\sigma_x^2 + \sigma_y^2)} \quad \dots(7)$$

This quality index models any distortion as a combination of three different factors as represented by (Eq. 7), where first term represents the loss of correlation, second component represents luminance distortion while, the last component is contrast distortion.

The pan-sharpened image which will best preserve the spectral, spatial, and structural similarity information of the original image is the one that has satisfied the following conditions *i.e.* for a good pan-sharpening of images assessed, the following conditions must be satisfied (Table 1).

Table 1 The ideal and error value of different quantitative indicators

S. No.	Metric	Ideal Value	Error Value
1	Root Mean Square Error (RMSE)	0	> 0
2	Peak Signal-to-Noise Ratio (PSNR)	NA	> 1
3	Correlation Coefficient (CC)	1	> -1 and < 1
4	Relative Dimensionless Global Error (ERGAS)	0	> 1
5	Universal Image Quality Index (UIQI)	1	> 0 and < 1

4 Data Set

The above aforementioned methods are evaluated by performing pan-sharpening on datasets acquired by World View-2 and IKONOS.

Table 2 : Data used

Features	**World View-2 (DS-I)**		**IKONOS (DS-II)**	
	Wavelength (μm)	**Band Number**	**Wavelength (μm)**	**Band Number**
MS Image –Spectral Bands and Range	Green (0.51-0.58)	3	Green (0.52-0.59)	2
	Red (0.63-0.69)	5	Red (0.63-0.69)	3
	NIR-1 (0.77-0.89)	7	NIR-1 (0.77-0.89)	4
PAN Spectral Range	(0.447-0.808)		(0.50-0.75)	
SR- MS image	1.84 m		4 m	
SR-PAN image	0.46 m		1 m	
Location	Uttarakhand, India		Naples, USA	
PAN and MS Image Size	512 × 512			

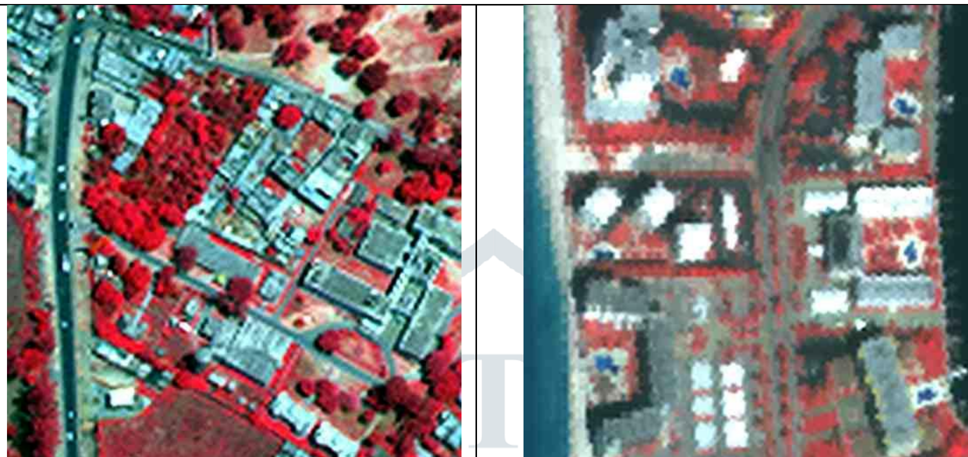
Note: SR-Spatial Resolution

All images are radio metrically calibrated. The MS and PAN images are co-registered for each dataset. Datasets corresponding to different land use variety have been selected, in order to examine the effect of different kinds of spatial (structures with diverse shapes and sizes) and spectral characteristics. Further, all imageries have different characteristics in terms of spectral bands and range, spatial and radiometric resolutions, size, location and date of acquisition. These characteristics are summarized in Table 2.

i. **Dataset-I (DS-I)*:*** This belongs to a cluster of trees, water bodies, bridge, bare land, and man-made buildings.

ii. **Dataset-II (DS-II):** This belongs to an area representing urban features such as manmade buildings, roads having different characteristics and pattern, and an area of sea.

The sample imageries used for the experiments are shown in Figs. 1 and 2 respectively.



(a) (b)

Fig. 1 False color composite (FCC) imagery of the datasets. (a) World View-2 scene—DS-I. (b) IKONOS scene—DS-II.

(a) (b)

Fig. 2 Panchromatic imagery of the datasets. (a) World View-2 scene—DS-I. (b) IKONOS scene—DS-II

5. Evaluation of Results and Discussion

In this study, thorough analysis of comparison of performance of pan sharpening techniques has been carried out, both visually and quantitatively for different datasets of World View-2 and IKONOS.

5.1 Visual analysis of the fused images

A visual comparison of the pan-sharpened images is used for the qualitative assessment, since it is a simple, yet an effective technique for assessing advantages and disadvantages of any pan-sharpening techniques. The pan sharpening techniques are applied to different datasets. The pan-sharpened images have been visually evaluated in terms of color radiometry, the outline of the roads, the outline of building roofs, the detailed patterns of trees, and water bodies. For visualization purposes, fusion techniques have been categorized from “Good” to “Poor”. In general, it is observed that, the entire pan-sharpened images exhibit improved geometric detail.

Considering all the datasets, the pan-sharpened images generated by NSCT technique using MPR (Fig. 5(a & b)), exhibit good spatial resolution as well as spectral quality when compared to the original MS data. This is followed by SWT (Fig. 4(a & b)) and DWT (Fig. 3(a & b)).

As a general observation, it is seen that the NSCT technique works well in terms of urban information extraction and gives a good trade-off between the enhancement of spatial resolution and preservation of spectral information.

(a) (b)

Fig. 3. DWT pan-sharpening results for datasets (a) DS-I, (b) DS-II

(a) (b)

Fig. 4. SWT pan-sharpening results for datasets (a) DS-I, (b) DS-II.

Fig. 5. NSCT pan-sharpening results for datasets (a) DS-I, (b) DS-II.

(a)

(b)

Table 3 shows the qualitative assessment of each technique for the different type of dataset. It is observed that NSCT yields the best results in terms of urban information i.e., outline of building roof, outline of road, etc.

However, the intensity of colour in the pan-sharpened images generated by NSCT technique using MPR is lighter when compared to the original MS image. This is followed by SWT and DWT using the same pan-sharpening rule. However, the pan-sharpened image generated by DWT (Fig. 3(a & b)), pan-sharpening technique yields lower spatial quality. This is due to the sub-sampling process involved in DWT technique, leading to the introduction of artifacts. Another factor affecting the performance of DWT technique in terms of spatial quality is due to the limited directional selectivity *i.e.* horizontal, vertical and diagonal directions possess by the technique. This deteriorates the visual quality of the pan-sharpening result. The comparison results of different pan-sharpening techniques on the basis of visual object detection are listed in Table 3.

Table 3 Comparison of pan-sharpening techniques on the basis of visual object detection

Datas et	**pan-sharpenin g Rule**	**pan-sharpening Method**	**C R**	**OB R**	**T**	**OR**	**V R**	**ES**
DS-I	**MAX**	DWT	A	A	A	A	B A	A
		SWT	A A	G	G	G	G	AA
		NSCT	**G**	**G**	**G**	**G**	**G**	**G**
DS-II		DWT	A	A	A	A	B A	A
		SWT	A A	G	G	AA	G	AA
		NSCT	**A A**	**G**	**G**	**G**	**G**	**G**

Thus, visually, it can be inferred that the NSCT pan-sharpening technique using Maximum Pan-Sharpening Rule for pan-sharpening works well in terms of urban information extraction and gives a good trade-off between the enhancement of spatial resolution and preservation of spectral information, followed by SWT and DWT based pan-sharpening techniques.

5.2 Statistical analysis to estimate the quality of the pan-sharpened images

Table 4 shows the results of the various parameters of accuracy assessment for pan-sharpened images generated using different pan-sharpening techniques. Quantitative indicators such as RMSE, PSNR, CC, ERGAS and UIQI are used to estimate the spectral and structural properties of the generated pan-sharpened image.

Table 4. Assessment of accuracy of pan-sharpened image with respect to original data

Datase t	**Technique**	**Accuracy Assessment Parameters**				
		PSNR	**RMS E**	**CC**	**ERGA S**	**UIQ I**
DS-I	**DWT**	22.09	19.96	0.93	5.2808	0.91
	SWT	23.02	15.18	0.94	4.9989	0.86
	NSCT	23.95	15.85	0.95	4.6149	0.91
DS-II	**DWT**	25.36	13.75	0.95	3.2279	0.95
	SWT	26.27	12.59	0.97	2.9531	0.94
	NSCT	26.46	12.11	0.97	2.9217	0.95

Table 4 clearly shows that the performance of NSCT technique using MPR is best amongst all the techniques, as explained by correlation coefficient values i.e. each band of the pan-sharpened image has been well correlated with the bands of the original MS image, followed by the SWT and DWT pan-sharpening techniques. Ideally, the value of ERGAS should close to zero, however, studies generally show that the value of ERGAS ranges between 2 to 4. Hence, the value of ERGAS obtained for all the dataset, is an indicator of good pan-sharpening quality of MS with PAN using NSCT technique, when compared to other techniques. Amongst all the pan-sharpening techniques, pan-sharpened images generated by DWT based pan-sharpening technique gives the least desirable result, when compared to NSCT and SWT techniques. This is due to the fact that DWT suffers from shift-variance property, which causes large error in the image reconstruction process, while NSCT and SWT techniques possess the property of shift-invariance.

Thus, statistically, it is found that irrespective of the datasets, NSCT based pan-sharpening technique is best in preserving the urban related information efficiently, when compared to other techniques.

6. Conclusion

This paper aims in presenting the comparison of performance of various multi-scale transform based pan-sharpening techniques in terms of different scenario. The experimental results show that the property of shift-invariance and multi-directionality of NSCT based pan-sharpening technique provides the best result, both in terms of qualitatively and quantitatively parameters. Further, quantitatively analysis shows that NSCT pan-sharpening technique provides better pan-sharpening results in terms of well-known global indexes, and is best in preserving the urban related information efficiently, when compared to the SWT and DWT techniques.

Finally, it can be concluded from this study is that the analysis of urban related information can be analyzed effectively by using NSCT based pan-sharpening technique, in comparison to other pan-sharpening techniques.

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