Spectral and spatial quality analysis of pan-sharpening algorithms: A case study in Istanbul

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Abstract
In this paper, the performance of four different image pan-sharpening methods, the Brovey, the Gram-Schmidt (GS), the Intensity-Hue-Saturation (IHS) and the Principle Component Analysis (PCA), are investigated based on spectral and spatial distortions. In the study, the Brovey, the GS, the IHS, and the PCA pan-sharpening algorithms are applied to multispectral (MS) bands of Ikonos and QuickBird images. The spectral and spatial qualities of pan-sharpened images are tested using the Correlation Coefficient (CC), the Root Mean Square Error (RMSE), and the Structural Similarity Index (SSIM). A comparative performance analysis of the CC, the RMSE, and the SSIM shows that the PCA followed by the GS, the Brovey, and the IHS perform the best among all the techniques, except a swap in the PCA and the GS in the SSIM.

Keywords: Pan-sharpening, Brovey, Gram-Schmidt, Intensity-Hue-Saturation.

Introduction
The pan-sharpening of low resolution multispectral (MS) and high resolution panchromatic (PAN) satellite images is a very important concern for numerous remote sensing applications such as classification, segmentation, and object detection. An effective fusion technique is a useful tool not only for increasing the interpretability for human observers but also for improving the accuracy of photo-analysis, feature extraction, modeling and classification [Yang et al., 2012]. The general idea behind image sharpening is to preserve the spectral values of the MS image in the pan-sharpened image and to improve the spatial resolution simultaneously [Konus and Ehlers, 2007]. The pan-sharpened image quality is mostly associated with the existing algorithms. Different algorithms may lead to different pan-sharpening qualities [Zhang, 2004]. To date, numerous algorithms for image pan-sharpening have been developed in order to combine the spatial information of high resolution PAN image with the spectral information of a lower resolution MS image to produce a high resolution MS image. Some widely performed pan-sharpening algorithms in the remote sensing community are the Intensity-Hue-Saturation (IHS) [Schetsellar, 1998; Choi et al., 2000; Choi, 2006; Myungjin, 2006], the Principal Component Analysis (PCA) [Chavez
and Kwarteng, 1989; Shettigara, 1992; Vrabel et al., 1996; Shah, 2008; Yang and Gong, 2012], the Brovey transform [Earth Resource Mapping Pty Ltd., 1990; Chaves, 1991; Du et al., 2007; Bovolo et al., 2010], and the Gram-Schmidt (GS) [Laben et al., 2000]. These pan-sharpening techniques are performed on the pixel level because of the minimum information loss during the sharpening process, so the digital classification accuracy of the pixel level fusion is the highest [Zhang, 1999].

This study aims to analyze the performance of four different image pan-sharpening algorithms. In the study, the Brovey, the GS, the IHS, and the PCA pan-sharpening algorithms are applied to the MS bands of Ikonos and QuickBird images to produce better quality images with higher spectral and spatial resolution. The spectral and spatial qualities of the generated pan-sharpened images are tested statistically based on the Correlation Coefficient (CC), the Root Mean Square Error (RMSE), and the Structural Similarity Index (SSIM) of each pan-sharpened case.

Test Area and Image Data Sets
In order to conduct the study, a test region is selected which is located in the northeastern part of Sisli municipality, Istanbul (Fig. 1). The test area covers urban areas involving shadows, roads, vegetation and high-density built-up areas with different roof types such as concrete, brick and metal.

The area is within the zone 35 of Universal Transverse Mercator (UTM) projection system. The upper left and lower right coordinates of the study area are 662540.083N-4545136.409E and 665624.173N-4547385.612E respectively. In the study, the Ikonos image of July 2008 and the QuickBird image of April 2008 are used. The Ikonos data consist of low-resolution (4 m) MS (red (R), green (G), blue (B), near-infrared (NIR)) bands and high-resolution (1 m) PAN band. The size of the Ikonos image is 323x193 pixels for the MS and 1292x772 for the PAN with 16 bit pixel depth. The QuickBird data are composed of low resolution (2.4 m) MS (R, G, B, NIR) bands and high resolution (0.6 m) PAN band. The size of the QuickBird image is 538x322 pixels for the MS and 2152x1287 for the PAN with 16 bit pixel depth.

![Figure 1 - True color composite of the QuickBird image covering the study area.](image-url)
Method of the study
The method of the study consists of two main parts, which are the application of four different pan-sharpening algorithms to the MS bands of Ikonos and QuickBird image data and the quality check of the pan-sharpened images (Fig. 2).

Application of pan-sharpening algorithms
In this step, the MS bands of Ikonos and QuickBird images are pan-sharpened to high resolution PAN bands using four different methods.

Brovey Sharpening
The Brovey sharpening uses a mathematical combination of MS bands and high resolution PAN bands. In this process, each MS band in the color image is multiplied by a ratio of the high resolution PAN data divided by the sum of MS bands. The function automatically resamples three MS bands to the high-resolution pixel size using a nearest neighbor, bilinear or cubic convolution technique. The output RGB images will have the pixel size of the input high-resolution data [Vrabel, 1996; Bovolo et al., 2010]. The Brovey transform is defined as the equation [1],

$$DN_{fusedMSi} = \frac{DN_{bi}}{DN_{b_1} + DN_{b_2} + \ldots + DN_{b_n}} DN_{PAN} \quad [1]$$

Where DN is the digital number of that particular band and bi is the particular band of the MS image.

Gram-Schmidt (GS) Sharpening
The GS spectral sharpening method enhances the spatial resolution of the MS image by merging the high resolution PAN image with the low spatial resolution. The GS fusion simulates the PAN band from the lower spatial resolution spectral bands. In general, this is achieved by averaging the MS bands. As the next step, a GS transformation is performed for the simulated PAN band and the MS bands, where the simulated PAN band is employed as the first band. Then the high spatial resolution PAN band is replaced with the first GS
band. Finally, an inverse GS transform is applied to create the pan-sharpened MS bands [Laben et al., 2000].

**Intensity-Hue-Saturation (IHS) sharpening**
The IHS sharpening technique is usually used in image fusion to use the complementary nature of MS images [Choi et al., 2000; Te-Ming et al., 2004; Choi, 2006]. For the IHS sharpening, the R, G and B bands of the MS image are converted into IHS components. In this step, the histogram of the PAN image is matched with the intensity component of the MS images. The intensity component is replaced with the PAN image and an inverse transformation is performed to obtain a high resolution MS image. The output RGB images will have the pixel size of the input high-resolution data. The basic steps of the applied IHS procedure are given in Figure 3.

![Figure 3 - Basic steps of the applied IHS procedure.](image)

**Principle Component analysis (PCA)**
The PCA is a statistical technique that transforms a multivariate data set of correlated variables into a dataset of uncorrelated linear combinations of the original variables [Chavez et al., 1991]. For images, it creates an uncorrelated feature space that can be used for further analysis instead of the original MS feature space. The PC band 1 is replaced with the high resolution band [Shettigara, 1992], which is scaled to match the PC band 1, so no distortion of the spectral information occurs. Then, an inverse transform is performed. The MS data is automatically resampled to the high resolution pixel size using a nearest neighbor, bilinear or cubic convolution technique. After the fusion, the resulted image contains the character of high spatial resolution image and the high spectral resolution of the original image.

**Performance evaluation of the pan-sharpened images**
Images are subject to spectral distortions during pan-sharpening operations. The spectral quality of pan-sharpened images is determined according to the changes in colors of the fused images as compared to the MS reference images.
In this study, three methods (CC, RMSE and SSIM) have been used in order to determine the quality of the pan-sharpened images. Before the analysis, each MS image is resampled with the equivalent size of the corresponding PAN image.

**Correlation Coefficient (CC)**
The CC is a statistical measure of the strength and direction of a linear association between
two images. The CC between the original and the fused image is defined as the equation [2]:

\[
CC(A,B) = \frac{\sum_{m,n} (A_{m,n} - \mu_A)(B_{m,n} - \mu_B)}{\sqrt{\sum_{m,n} (A_{m,n} - \mu_A)^2 \sum_{m,n} (B_{m,n} - \mu_B)^2}}
\]  

[2]

Where \( \mu_A \) and \( \mu_B \) are the mean values of the images A and B, respectively. The CC should be as close to 1 as possible. The difference between correlations will show how much the spatial quality is maintained.

**Root Mean Square Error (RMSE)**

The RMSE is one of the most widely used methods for measuring the similarity between each band of the original and the fused image and defined as the equation [3]:

\[
RMSE = \frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} (x(i,j) - y(i,j))^2
\]  

[3]

Where \( x(i,j) \) represents the original (reference) image and \( y(i,j) \) represents the distorted (modified) image and i and j are the pixel position of the MxN image. The smaller the RMSE value is, the better the correspondence between the images becomes.

**Structural Similarity Index (SSIM)**

The SSIM index computes the quality of a distorted image by comparing the correlations in luminance, contrast, and structure locally between the reference and distorted images and averaging these quantities over the entire image.

The luminance between the two signals is determined with the mean intensity of the signals given in the equation [4]. The contrast is determined with the standard deviation presented in the equation [5]. Finally, the structure is determined with the correlation of the two presented in the equation [6]. This index was proposed by Wang et al. [2004]. The SSIM index values vary between 0 and 1. The values close to 1 show the highest correspondence with the original images.

\[
I(x,y) = \frac{(2\mu_x\mu_y + C_1)}{(\mu_x^2 + \mu_y^2 + C_1)}
\]  

[4]

\[
C(x,y) = \frac{(2\sigma_x\sigma_y + C_2)}{\sigma_x^2 + \sigma_y^2 + C_2}
\]  

[5]

\[
S(x,y) = \frac{(\sigma_{xy} + C_3)}{\sigma_x\sigma_y + C_3}
\]  

[6]

Where \( \mu_x \) and \( \mu_y \) are the sample means of x and y respectively, \( \sigma_x \) and \( \sigma_y \) are the sample variances of x and y respectively, and \( \sigma_{xy} \) is the sample correlation coefficient between x
and \( y \). \( x \) and \( y \) refer to a local window in the Image X and Y, respectively. The constants \( C_1 \), \( C_2 \) and \( C_3 \) are used to stabilize the algorithm when the denominators approach zero. The SSIM \((x,y)\) is a multiplication of these three components presented in the equation [7].

\[
SSIM(x,y) = \frac{(2\mu_x\mu_y + C_1) * (2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1) * (\sigma_x^2 + \sigma_y^2 + C_2)}
\] [7]

**Results and analysis**

**Application of pan-sharpening algorithms**

In this step, the MS bands of Ikonos and QuickBird images are pan-sharpened to the high resolution PAN band of each image using four different methods. The images obtained by the Brovey, the GS, the IHS and the PC based pan-sharpened MS bands of Ikonos and QuickBird images are depicted in Figure 4 (C, D, E, F) and Figure 5 (C, D, E, F), respectively.

![Figure 4](image)

**Figure 4** - (A) Original MS bands of Ikonos Image (B) PAN band of image (C) Brovey pan-sharpened image, (D) GS pan-sharpened image, (E) IHS pan-sharpened image and (F) PCA pan-sharpened image.

All the methods were computed in a notebook PC environment with Intel Core i3 CPU, 2.27 GHz, 4GB RAM, onboard display adapter, and 64 bit Win7 OS. The memory request and the processing speed to pan-sharpen the Ikonos image are 54.644 K / 2 seconds for the Brovey, 53.936 K / 15 seconds for the GS, 48.772 K / 4 seconds for the HIS, and 51.960
MB / 8 seconds for the PC. On the other hand, the memory request and the processing speed to pan-sharpen the QuickBird image are 61.784 K / 5 seconds for the Brovey, 63.944 K / 23 seconds for the GS, 56.676 K / 6 seconds for the HIS, and 64.272 MB / 14 seconds for the PC. The resulted pan-sharpened images are in the TIFF format and the dimensions of the pan-sharpened images are 5.67 MB for the Ikonos Brovey, 5.71 MB for the GS, 2.84 MB for the HIS, and 5.71 MB for the PC. On the other hand, the dimensions of the pan-sharpened images are 15.8 MB for the QuickBird Brovey, 15.8 MB for the GS, 7.91 MB for the HIS, and finally 15.8 MB for the PC. The visual comparison of the Brovey, the GS, the IHS and the PC-based pan-sharpened Ikonos and QuickBird images (Fig. 4 and 5 C, D, E, F) with the original MS bands of Ikonos (Fig. 4A) and QuickBird (Fig. 5A) images indicates that the pan-sharpened images have better spatial resolution than the original MS images. The visual comparison of each pan-sharpened outcome of the Ikonos and QuickBird gives similar results to the PAN image in terms of spatial quality. However, pan-sharpened images suffer from spectral distortions, which appear as color changes. The major difference in spectral quality is mostly noticeable in true color display. Looking at the zoomed pan-sharpened images in Figure 4 and Figure 5, it can be said that the image obtained by the Brovey and the IHS pan-sharpened images are similar to the GS and the PCA pan-sharpened images, though less sharp.

Figure 5 - (A) Original MS bands of QuickBird Image (B) PAN band of image (C) Brovey pan-sharpened image, (D) GS pan-sharpened image, (E) IHS pan-sharpened image and (F) PC pan-sharpened image.
Testing performance of pan-sharpening

Correlation Coefficient (CC)
The spectral quality of the spatially enhanced images is measured band by band through the correlation between the pixel value of the original images and the spatially enhanced images, depicted in the Table 1. The best correspondence between the fused and the original image data shows the highest correlation values. The PC pan-sharpening presents the best results for the CC in both the Ikonos and the QuickBird images with the mean of 0.56 and 0.64, respectively. The CC is lowest in the IHS with the means of 0.52 and 0.57 in the Ikonos and QuickBird images, respectively.

Table 1 - CC for the pan-sharpened images in comparison with the original MS bands of Ikonos and QuickBird image.

|                  | CC of Ikonos band |                  | CC of QuickBird band |
|------------------|-------------------|------------------|----------------------|
|                  | Brovey | GS  | IHS | PC | Brovey | GS  | IHS | PC |
| Red              | 0.42   | 0.55| 0.40| 0.56| 0.76   | 0.62| 0.41| 0.64|
| Green            | 0.54   | 0.54| 0.53| 0.54| 0.61   | 0.63| 0.57| 0.63|
| Blue             | 0.65   | 0.56| 0.64| 0.56| 0.46   | 0.65| 0.73| 0.65|
| Mean             | 0.54   | 0.55| 0.52| 0.56| 0.61   | 0.63| 0.57| 0.64|

Root Mean Square Error (RMSE)
The spectral quality of the pan-sharpened images is measured band by band with the RMSE. The pixel values of the original images and the pan-sharpened images are presented in Table 2. The results of the RMSE are similar to those of the CC. The RMSE produces again the best results for the PC in both the Ikonos and the QuickBird images with the means of 48.12 and 48.73, respectively. The RMSE are the highest in the IHS with the means of 83.73 and 65.61 in the Ikonos and QuickBird images, respectively (Tab. 2).

Table 2 - RMSE for the fused images in comparison with the original MS bands of Ikonos and QuickBird image.

|                  | RMSE of Ikonos |                  | RMSE of QuickBird |
|------------------|----------------|------------------|-------------------|
|                  | Brovey | GS  | IHS | PC | Brovey | GS  | IHS | PC |
| Red              | 55.62  | 47.77| 85.68| 47.49| 59.34 | 49.41| 57.18| 48.67|
| Green            | 48.68  | 48.55| 80.04| 48.47| 52.90 | 49.23| 62.62| 48.99|
| Blue             | 42.14  | 48.26| 85.46| 48.41| 41.55 | 48.42| 77.04| 48.52|
| Mean             | 48.81  | 48.19| 83.73| 48.12| 51.26 | 49.02| 65.61| 48.73|

Structural Similarity Index (SSIM)
The structural information from the original MS bands of the Ikonos and QuickBird images is permanently lost in the pan-sharpened images, and they give lower SSIM values (Tab. 3). All the applied pan-sharpened algorithms give the mean SSIM index values between 0.11 and 0.66, which confirms the fact that there is only a slight similarity with the original MS image. As seen in Table 3, the mean SSIM index rate indicates that the PC and GS pan-sharpened images provide the highest structural similarity to the original MS bands of
the Ikonos and the QuickBird images. The IHS algorithm has the most distortions with the mean SSIM of 0.11 and 0.18 for the Ikonos and QuickBird images, respectively. On the other hand, the SSIM is the highest in the GS and the PC with the means of 0.55 and 0.53 for the Ikonos and 0.66 for the QuickBird image, respectively.

Table 3 - SSIM for the pan-sharpened images in comparison with the original MS bands of Ikonos and QuickBird image.

|          | SSIM of Ikonos |          | SSIM of QuickBird |
|----------|----------------|----------|-------------------|
|          | Brovey  | GS    | IHS   | PC    | Brovey  | GS    | IHS   | PC    |
| Red      | 0.28    | 0.43  | 0.08  | 0.44  | 0.31    | 0.57  | 0.18  | 0.6   |
| Green    | 0.47    | 0.47  | 0.12  | 0.46  | 0.61    | 0.65  | 0.22  | 0.64  |
| Blue     | 0.54    | 0.75  | 0.12  | 0.7   | 0.97    | 0.76  | 0.13  | 0.74  |
| Mean     | 0.43    | 0.55  | 0.11  | 0.53  | 0.63    | 0.66  | 0.18  | 0.66  |

**Discussions and conclusions**

In this study, the performance of the Brovey, the GS, the IHS and the PC pan-sharpening algorithms are tested with the Ikonos and QuickBird data sets, which cover the same test area. A qualitative and quantitative comparison is used to evaluate the spectral and spatial performance of the proposed pan-sharpening methods.

The proposed PCA pan-sharpening method achieves the best spectral quality in all bands when compared to the GS, the Brovey and the IHS methods. The visual and spectral analysis of the fused images indicates that the results generated with the PCA followed by the GS preserve the spectral and spatial information of the objects in original images better than the results generated by the Brovey and the IHS methods. The results of the statistical comparisons also show that the image pan-sharpening methods performed with the PCA and the GS are spectrally better.

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