Comparison of Nine Fusion Techniques for Very High Resolution Data

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Abstract

The term "image fusion" covers multiple techniques used to combine the geometric detail of a high-resolution panchromatic image and the color information of a low-resolution multispectral image to produce a final image with the highest possible spatial information content while still preserving good spectral information quality.

During the last twenty years, many methods such as Principal Component Analysis (PCA), Multiplicative Transform, Brovey Transform, and IHS Transform have been developed producing good quality fused images. Despite the quite good visual results, many research papers have reported the limitations of the above fusion techniques. The most significant problem is color distortion. Another common problem is that the fusion quality often depends upon the operator's fusion experience and upon the data set being fused.

In this study, we compare the efficiency of nine fusion techniques and more specifically the efficiency of IHS, Modified IHS, PCA, Pansharp, Wavelet, LMM (Local Mean Matching), LMVM (Local Mean and Variance Matching), Brovey, and Multiplicative fusion techniques for the fusion of QuickBird data. The suitability of these fusion techniques for various applications depends on the spectral and spatial quality of the fused images.

In order to quantitatively measure the quality of the fused images, we have made the following controls. First, we have examined the visual qualitative result. Then, we examined the correlation between the original multispectral and the fused images and all the statistical parameters of the histograms of the various frequency bands. Finally, we performed an unsupervised classification, and we compared the resulting images.

All the fusion techniques improve the resolution and the visual result. The resampling method practically has no effect on the final visual result. The LMVM, the LMM, the Pansharp, and the Wavelet merging technique do not change the statistical parameters of the original images. The Modified IHS provokes minor changes to the statistical parameters than the classical IHS or than the PCA. After all the controls, the LMVM, the LMM, the Pansharp, and the Modified IHS algorithm seem to gather the more advantages in fusion panchromatic and multispectral data.

Introduction

Almost all the high-resolution (SPOT, Landsat, IRS, Ikonos, QuickBird, and Orbview) collect a high spatial resolution panchromatic (PAN) image and multiple (usually four) multispectral (MS) images with significant lower spatial resolution. The PAN images are characterized by very high spatial information content well-suited for intermediate scale mapping applications and urban analysis. The MS images provide the essential spectral information for smaller scale thematic mapping applications such as land-use surveys. It is of interest to note that most satellites do not collect high-resolution MS images directly, to meet this requirement for high-spatial and high-spectral resolutions.

There is a limitation to the data volume that a satellite sensor can store on board and then transmit to a ground receiving station. Usually the size of the PAN image is many times larger than the size of the MS images. The size of the PAN of Landsat ETM+ is four times greater than the size of an ETM+ MS image. The PAN image for Ikonos, QuickBird, SPOT5, and Orbview is sixteen times larger than the respective MS images. As a result, if a sensor collected high-resolution multispectral data, it could acquire fewer images during every pass.

Considering these limitations, it is clear that the most effective solution for providing high-spatial-resolution and high-spectral-resolution remote sensing images is to develop effective image fusion techniques.

The principal interest of fusing multi-resolution image data is to create composite images of enhanced interpretability (Welch and Ehlers, 1987; Kaczynski *et al*., 1995). The images should have the highest possible spatial information content while still preserving good spectral information quality (Cliché *et al*., 1985). Some authors stress the idea that the merging method used should not distort the spectral characteristics of the original MS data, ensuring that targets, which are spectrally separable in the original data, are still separable in the merged data set (Chavez *et al*., 1991). Such products not only allow a more accurate delineation of ground features, making them more useful for various applications (Vrabel, 1996), but also are more easily interpretable in terms of their original spectral signatures. Garguet-Duport *et al*. (1996) demonstrated that spectral information preservation is particularly well suited in the case of vegetation analysis, and its usefulness in urban mapping applications. Going one-step further, some authors even suggest that fused products with maximal spectral information preservation could ideally simulate MS images acquired at higher spatial resolutions (Vrabel, 1996; Wald *et al*., 1997).

Different merging methods have been proposed in the literature; using Principal Component Analysis (Chavez *et al*., 1991), Intensity-Hue-Saturation (IHS) transforms (Haydn *et al*., 1982; Carper *et al*., 1990), Brovey Transform

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(Gillespie *et al.*, 1987), Multiplicative Transform (Crippen, 1989), Wavelet Transform (Li *et al.*, 1995; Garguet-Duport *et al.*, 1996; Yocky, 1995 and 1996; Zhou *et al.*, 1998; Fanelli *et al.*, 2001), a statistics based fusion, currently implemented in the PCI Geomatica® software as special module, named Pansharp, (Zhang, 2002), Back Propagated Neural Networks (Del Carmen-Valdes and Inamura, 2001), High Pass Filters (HPF) (Schowengerdt, 1980), Smoothing Filters (Liu, 2000), or Local Mean Matching Method (De Béthune *et al.*, 1998). Recently, a Modified IHS was proposed (Siddiqui, 2003). Some of these methods have been compared for the fusion of ETM PAN and MS data (Vaiopoulos *et al.*, 2001; Nikolakopoulos, 2003).

In this paper, nine different fusion algorithms, IHS, Modified IHS, PCA, Pansharp, Wavelet, LMM (Local Mean Matching), LMVM (Local Mean and Variance Matching), Brovey and Multiplicative, were applied to QuickBird data set in order to assess the quality of the fused products.

The data set corresponds to a (1000 pixel × 1000 pixel) portion of a QuickBird PAN image (0.7 m resolution) and four QuickBird MS channels (2.8 m resolution). The final fused images have 0.7 m spatial resolution, and they are produced by one of the nine different fusion techniques that were previously mentioned. The nearest neighbor and the cubic convolution resampling methods were applied.

In order to quantitatively measure the quality of the fused images, we have made the following controls. First, we have examined the visual qualitative result. Then, we examined the correlation between the original MS and the fused images and all the statistical parameters of the histograms of the various frequency bands. Finally, we performed an unsupervised classification, and we compared the result images.

Fusion Techniques Used in this Study

Since the launch of SPOT1 (providing high-resolution (10 m) PAN images and low-resolution (20 m) MS images) in 1986, many fusion algorithms have been presented. Some are very simple, based on algebra functions, and others are quite sophisticated based on wavelet theory.

The simplest fusion technique used in this study is the Multiplicative. This method applies a simple multiplicative algorithm, which integrates the two-raster images. As it is computationally simple, it is generally the fastest method and requires the least system resources. However, the resulting merged image does not retain the radiometry of the input multispectral image. Instead, the intensity component is increased, making this technique good for highlighting urban features (which tend to be higher reflecting components in an image).

The basic procedure of the Brovey Transform first multiplies each MS band by the high-resolution PAN band, and then divides each product by the sum of the MS bands. The Brovey Transform was developed to visually increase contrast in the low and high ends of an images histogram (i.e., to provide contrast in shadows, water, and high reflectance areas such as urban features). Consequently, the Brovey Transform should not be used if preserving the original scene radiometry is important. However, it is good for producing RGB images with a higher degree of contrast in the low and high ends of the image histogram and for producing "visually appealing" images. Since the Brovey Transform is intended to produce RGB images, only three bands at a time should be merged from the input multispectral scene (ERDAS Imagine®, 2003).

In the IHS fusion, an RGB color composite of bands (or band derivatives) such as ratio is transformed into Intensity-Hue-Saturation color space. The intensity component is replaced by the PAN image, the hue and saturation bands are resampled to the high-resolution pixel size using a nearest neighbor, bilinear, or cubic convolution technique, and the scene is reverse transformed. The technique integrally merges the two data sets (Parcharidis *et al.*, 2001; ENVI, 2004)

The PCA transform converts intercorrelated MS bands into a new set of uncorrelated components. The first component also resembles a PAN image. It is, therefore, replaced by a high-resolution PAN for the fusion. The PAN image is fused into the low-resolution MS bands by performing a reverse PCA transform (Zhang, 2004). Modified IHS was proposed by (Siddiqui, 2003). The modified IHS method is a vast improvement over traditional IHS for fusing satellite imagery that differs noticeably in spectral response. The modified HIS method was designed to produce an output that approximates the spectral characteristics of the input MS bands while preserving the spatial integrity of the PAN data. The technique works by assessing the spectral overlap between each MS band and the high-resolution PAN band and weighting the merge based on these relative wavelengths. Therefore, it works best when merging images (and bands) where there is significant overlap of the wavelengths. As such, it may not produce good results when merging SAR imagery with optical imagery, for example.

The LMM (Local Mean Matching) and the LMVM (Local Mean and Variance Matching), methods were specifically designed in order to minimize the difference between the fused image and the low-resolution MS channels (De Béthune *et al.*, 1997), hence to preserve most of the original spectral information of the low-resolution channels. These filters apply normalization functions (Joly, 1986) at a local scale within the images in order to match the local mean and/or local mean and variance values of the PAN image with those of the original low-resolution spectral channel. The small residual differences remaining correspond to the high spatial information stemming from the high-resolution PAN image. This type of filtering drastically increases the correlation between the fused product and the low-resolution channel. By adjusting the filtering window sizes, we can control the amount of spectral information preserved in the fused product.

The wavelet algorithm used is a modification of the work of (King *et al.*, 2001) with extensive input from (Lemeshewsky, 1999 and 2002). Fusing information from several sensors into one composite image can take place on four levels: signal, pixel, feature, and symbolic. This algorithm works at the pixel level. The results of pixel level fusion are primarily for presentation to a human observer/analyst (Rockinger and Fechner, 1998). However, in the case of PAN/multi-spectral image sharpening, it must be considered that computer-based analysis (e.g., supervised classification) could be a logical follow-on. Thus, it is vital that the algorithm preserve the spectral fidelity of the input dataset. In this wavelet fusion, the high-resolution image is first decomposed through several iterations until a low-resolution low-pass image is generated plus all the corresponding high-pass images derived during the recursive decomposition. This low-resolution, low-pass image, derived from the original PAN image, can be replaced with the low-resolution MS image, and the whole wavelet decomposition process reversed using the high-pass images derived during the decomposition to reconstruct a high-resolution multispectral image. The approximation component of the high spectral resolution image and the horizontal, vertical, and diagonal components of the high spatial resolution image are fused into a new output image. If all of the above calculations are done in a mathematically rigorously way (histomatch and resample before substitution, etc.) one can derive a MS image that has the high-pass (high frequency) details from PAN image (ERDAS Imagine, 2003).

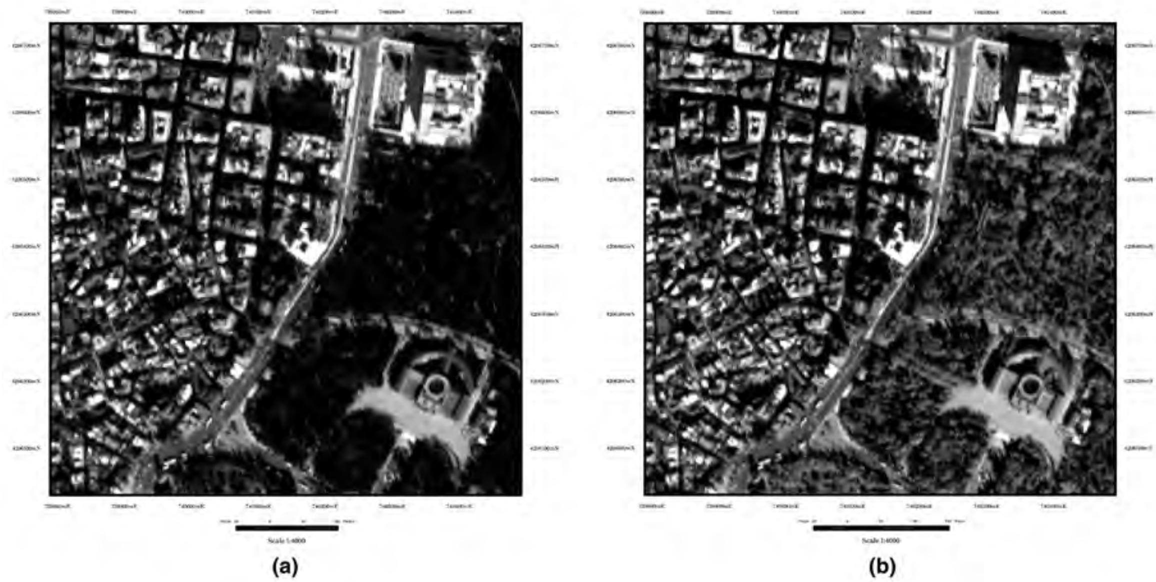

Figure 1. (a) A RGB 3,2,1 combination of the original multispectral image with 2.8 m resolution, and (b) A RGB 4,3,2 combination of the original multispectral image with 2.8 m resolution. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

A new statistics based fusion called Pansharp was presented by (Zhang, 2002). This statistics-based fusion technique solves the two major problems in image fusion: color distortion and operator (or dataset) dependency. It is different from existing image fusion techniques in two principle ways: (a) it utilizes the least squares technique to find the best fit between the grey values of the image bands being fused and to adjust the contribution of individual bands to the fusion result to reduce the color distortion, and (b) It employs a set of statistic approaches to estimate the grey value relationship between all the input bands to eliminate the problem of dataset dependency (i.e., reduce the influence of dataset variation) and to automate the fusion process.

As the Brovey transform and the IHS transform produce RGB images with only three bands, we have used different RGB combinations (3,2,1; 4,3,2; 4,2,1) of the original MS bands. The modified HIS algorithm has solved this problem. Since this transform relies on the RGB to IHS algorithm that can only process three bands at a time, we have to select in groups of three to get the bands processed that we need in the output image. So in order to merge a four-band QuickBird scene, we had to merge 3,2,1 and 4,3,2; thereby, covering all four bands in two iterations. The final fused image has four bands the same as the original MS image.

Results

Visual Comparison

As already mentioned in this study, quality was evaluated both qualitatively and quantitatively. Visual comparison of all the possible band combinations of the fused images was used for the qualitative assessment, since it is the most simple but effective tool for showing the major advantages and disadvantages of a method. Natural color and color-infrared RGB composites are presented for the original MS and all the fused images in order to facilitate the visual evaluation.

The resolution of all the fused images is improved in comparison with the original MS data (Figure 1a and 1b), and it is comparable to the resolution of the original PAN data (Figure 2).

As we can observe at Figures 3 and 4, the Multiplicative algorithm improves the spatial resolution of the MS data. We can now distinguish the cars and locate the edges of the buildings. We can also distinguish the trees as they are characteristically observed in the middle of the image. The

Figure 2. The original panchromatic image with 0.7 m resolution.

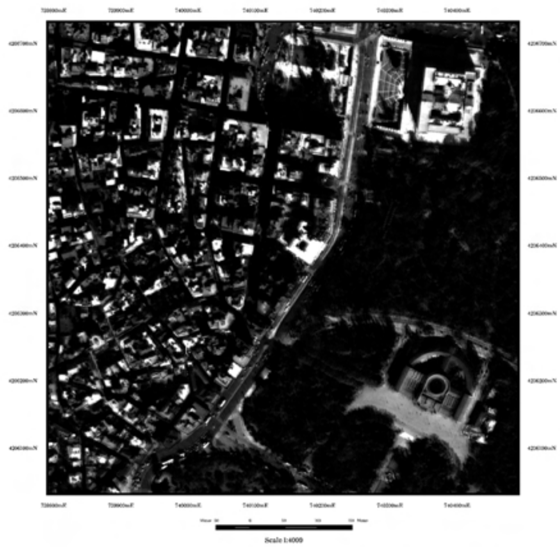

Figure 3. A natural color RGB (3,2,1) combination fused image with the Multiplicative transform. The resolution of the fused image is improved in comparison to the original multispectral data. There is a significant change at the colors. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

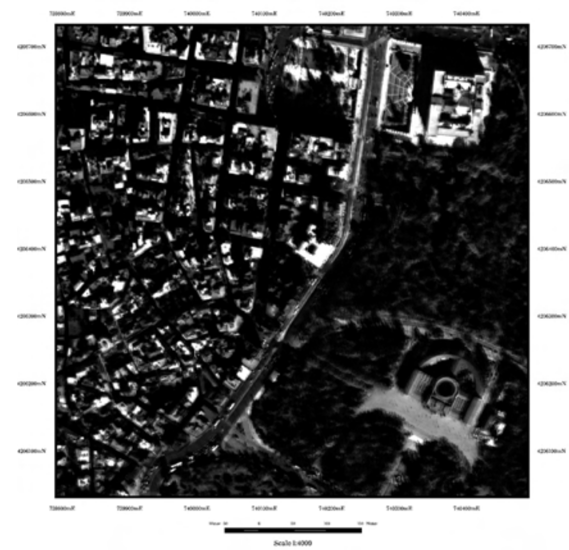

Figure 4. An infrared color RGB (4,3,2) combination fused image with the Multiplicative transform. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

algorithm changes the colors of the 3,2,1 RGB combination (Figure 3). The color of the trees has changed from green-brown to blue. In contrary it doesn't change the colors of the 4,3,2 RGB combination (Figure 4), but it makes the colors darker.

The Brovey transform (Figures 5 and 6) has similar results. It ameliorates the resolution but also changes the colors. It is remarkable that the red color of the trees has changed to blue in the 3,2,1 RGB combination (Figure 5). Similarly in the 4,3,2 RGB combination, the vegetation is represented with a red-violet color instead of red (Figure 6).

The classical IHS transform (Figures 7 and 8) improves the resolution of the fused image. It causes the same effects

Figure 5. Fused image with the Brovey transform (3,2,1 RGB combination). The algorithm ameliorates the resolution but causes some changes to the colors. It is remarkable that the red color of the trees has changed to blue. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 6. Fused image with the Brovey transform (4,3,2 RGB combination). The algorithm ameliorates the resolution but causes some changes to the colors. The vegetation is represented with a red-violet color instead of red. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 7. Fused image with the IHS transform (3,2,1 RGB combination). It is remarkable that the red color of the vegetation has changed to blue. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 8. Fused image with the IHS transform (4,3,2 RGB combination). The red color of the vegetation has reduced sharpness in comparison to the original MS image. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

at the image colors with the Brovey transform when the 3,2,1 RGB combination is used (Figure 7). It is also remarkable that the red color of the vegetation has reduced sharpness in the 4,3,2 RGB combination (Figure 8).

In Figures 9 and 10, the LMM fused image (natural color and color infrared respectively) are presented. The colors of the LMM are a little lighter than the colors of the original MS image in the 3,2,1 RGB combination (Figure 9). Generally, the LMM algorithm doesn't change the original colors in all the possible RGB combinations.

The LMVM fusion algorithm has similar results in improving the resolution as the LMM algorithm. As we can observe in Figures 11 and 12, the trees and the cars can be distinguished. The colors of the original image remain invariable with all the RGB combinations when the LMVM algorithm is used for the fusion.

Figure 9. Fused image with the LMM transform (3,2,1 RGB combination). The colors of the LMM are somewhat lighter than the colors of the original MS image. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 10. Fused image with the LMM transform (4,3,2 RGB combination). No significant changes in comparison to the original MS image. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 11. Fused image with the LMVM transform (3,2,1 RGB combination). The trees and the cars can be easily distinguished. The colors of the original image remain invariable. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 12. Fused image with the LMVM transform (4,3,2 RGB combination). The trees and the cars can be easily distinguished. The colors of the original image remain invariable. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

The modified IHS transform (Figures 13 and 14) also improves the resolution of the fused image. It changes the image colors when the 3,2,1 RGB combination is used (Figure 13). The green color of the vegetation has changed to blue. In contrary, when the bands 4, 3, and 2 are used in an infrared combination the algorithm preserve the colors of the original image as is shown in Figure 14.

The PCA fusion algorithm (Figures 15 and 16) facilitates the target detection as it ameliorates the resolution. It also preserves the original colors in all the possible combinations. The colors seem to be a little lighter in comparison with the colors of the original MS image.

The Pansharp transform (Figures 17 and 18) also preserves the original colors in all the possible band combinations.

Figure 13. Fused image with the modified IHS transform (3,2,1 RGB combination). The green color of the vegetation has changed to blue. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 14. Fused image with the modified IHS transform (4,3,2 RGB combination). The algorithm preserves the colors of the original image. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 15. Fused image with the PCA transform (3,2,1 RGB combination). The PCA fusion algorithm facilitates the target detection as it ameliorates the resolution. The colors seem to be a somewhat lighter in comparison with the colors of the original MS image. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 16. Fused image with the PCA transform (4,3,2 RGB combination). The colors seem to be a somewhat lighter in comparison with the colors of the original MS image. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Generally, it gives very good visual results, but the colors are little lighter in comparison with the colors of the original MS image.

The Wavelet transform fusion technique (Figures 19 and 20) keeps exactly the same colors with the original MS image. But it seems to present some distortions problems (Figure 21). These distortion problems do not appear when we fused ETM PAN and MS data (Nikolakopoulos, 2004).

As mentioned earlier, we have used both the nearest neighborhood and the cubic convolution resampling methods during the fusion of the PAN with the MS data. During the first visual comparison we did not notice any

Figure 17. Fused image with the Pansharp transform (3,2,1 RGB combination). In this RGB combination, the colors are somewhat lighter in comparison with the colors of the original MS image. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 18. Fused image with the Pansharp transform (4,3,2 RGB combination). In this RGB combination the colors are somewhat lighter in comparison with the colors of the original MS image. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 19. Fused image with the Wavelet transform (3,2,1 RGB combination). The fusion algorithm preserves the original colors exactly, but seems to present some distortions problems. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 20. Fused image with the Wavelet transform (4,3,2 RGB combination). The fusion algorithm preserves the original colors exactly, but seems to present some distortions problems. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

significant difference in the fused images according to the resampling method. In Figure 22, the fused images with the LMVM and the Brovey algorithm are presented at a scale 1:1 000 instead of the suggested scale for mapping with QuickBird orthorectified images that ranges between 1:2 500 and 1:3 000. As it can be observed, the resampling method does not provoke any change at all to the fused images. Only with the use of the IHS algorithm and with a 4,2,1 RGB combination, the resampling method seems to affect the result image. As we can see in Figure 23a, the cubic convolution resampling method gives a very poor result in comparison with the nearest neighbor resampling method that gives quite good results (Figure 23b). It should be mentioned here that it is difficult to explain this phenomenon;

Figure 21. Distortions problems provoked by the Wavelet transform fusion technique. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

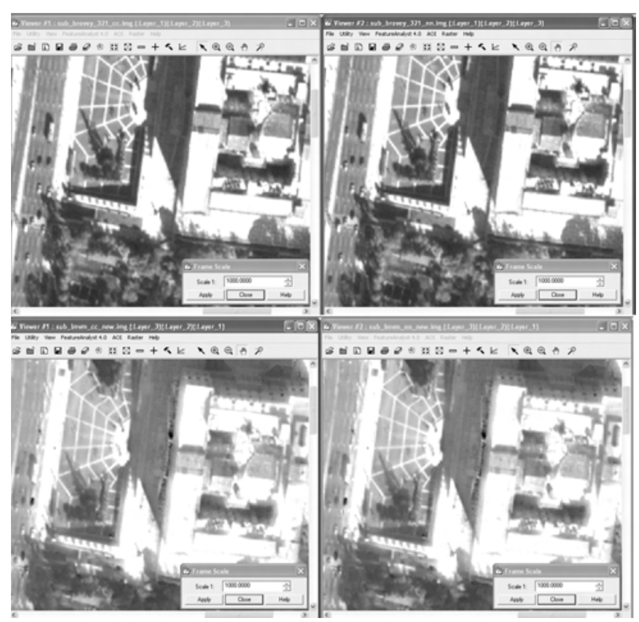

Figure 22. The fused images with the LMVM and the Brovey algorithm at a scale 1:1 000 instead of the suggested scale for mapping with QuickBird orthorectified images that ranges between 1:2 500 and 1:3 000. As can be observed, the resampling method does not provoke any change at all to the fused images. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

Figure 23. Fused image with the IHS transform (4,2,1 RGB combination): (a) the cubic convolution resampling method gives a very poor result in comparison with (b) the nearest neighbor resampling method that gives quite good results. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

the same procedure (of fusion with the IHS algorithm using the 4,2,1 RGB combination) was repeated three times using three different software (ERDAS Imagine® 8.7, ERDAS Imagine® 9.0, and ENVI 4.0).

Statistical Control

Correlation Coefficient

The closeness between two images can be quantified in terms of the correlation function. The correlation coefficient ranges from −1 to +1. A correlation coefficient value of +1 indicates that the two images are highly correlated, i.e., very close to one another. A correlation coefficient of −1 indicates that the two images are exactly opposite to each other.

Each band of the original MS image has been correlated with the respective nine fused bands. Correlation coefficients were computed with the results shown in Figure 24. Also, the correlation between each band of the MS image before and after the application of the fusion techniques was computed (Figure 25). The best spectral information is available in the MS image, and hence, the fused image bands should have a correlation closer to that between the MS image bands. The spectral quality of the fused image is good if the correlation values are closer to each other.

The LMVM and the LMM fusion techniques create bands with a very high correlation of approximately 0.90. It is remarkable that the second and the third bands present almost equal correlation coefficients. The first and the fourth bands present reverse results. The first LMVM band has a very high correlation (0.90) with the first original MS band and the fourth LMVM band having a little lower correlation (0.85) with the fourth original MS band. The respective coefficients for the LMM bands are 0.85 and 0.91.

The IHS and the Brovey techniques create bands with the lowest correlation. The bands created with the Pansharp and the PCA algorithms present a medium correlation that ranges between 0.77 and 0.79.

The correlation of Modified IHS bands present high fluctuation. The first band has the second lower value of 0.65, and the second band presents a medium value of 0.79. The values of the third and the fourth band are high 0.86 and 0.83, respectively. In contrary, the correlation of all the Multiplicative bands is high and quite stable around 0.88.

Additional correlation between each band of the MS image before and after the application of the fusion techniques was computed and the results are interesting:

- The Multiplicative algorithm increases the correlation between the MS bands (Figure 25). It is remarkable that the correlation between the first and the fourth band passes from 0.78 (original MS bands) to 0.96 (fused MS bands).
- The Brovey and the IHS algorithms notably decrease the correlation between the first and the third band. The correlation value passes from 0.96 (original MS bands) to 093 and 0.94 (fused MS bands), respectively.

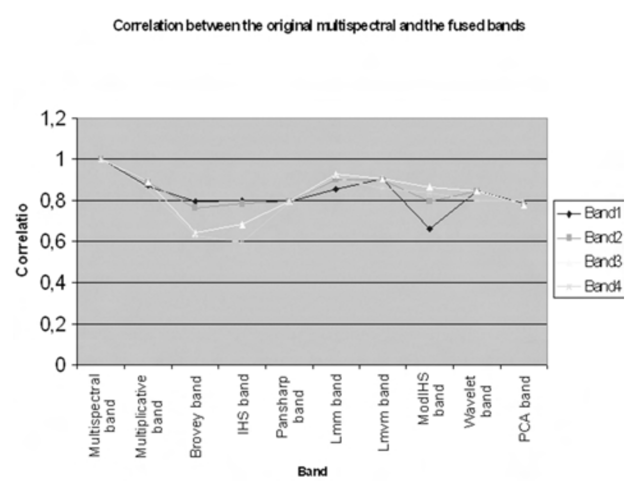

Figure 24. Each band of the original MS image has been correlated with the respective nine fused bands. Correlation coefficients were computed and presented in this diagram. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

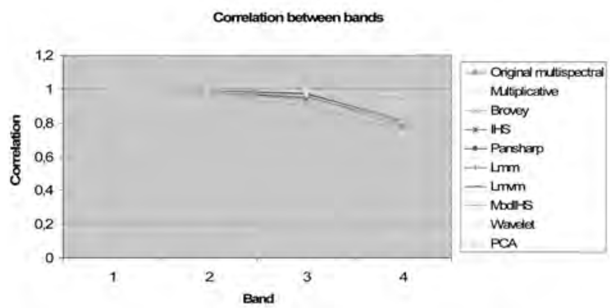

Figure 25. The correlation between each band of the MS image before and after the application of the fusion techniques was computed. Those correlation coefficients are presented in this diagram. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

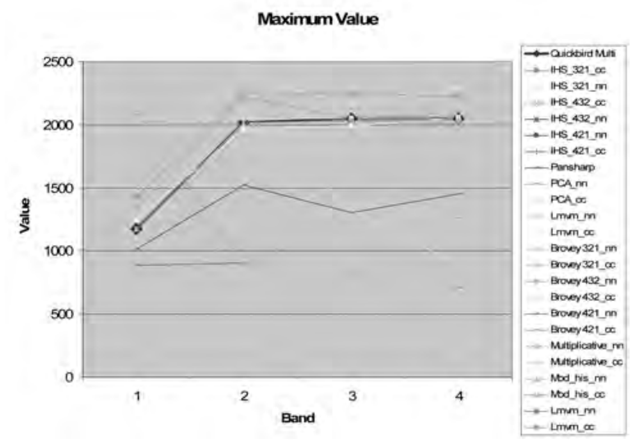

Figure 27. The maximum value of all the bands of the original MS and the fused images. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

- The Pansharp, the LMM, the LMVM, and the Wavelet algorithm increase the correlation value between the first and the fourth band. The correlation value between the first and the third band presents small fluctuation of 0.010.
- The Modified IHS results in important decreases to the correlation values of all the bands after the fusion. In contrary, the PCA algorithm results in increases to all the correlation values.

Histogram Statistics

For all the images, the statistical parameters of the histogram and especially the minimum value (Figure 26), the maximum value (Figure 27), and the standard deviation (Figure 28) were studied. The statistical control is necessary in order to examine spectral information preservation. Thus, the minimum, mean, and maximum values are usually examined. As the value of the standard deviation is correlated with the possibility to recognize different unities, it is necessary to examine closely any significant decreases that may be the result of the fusion. In general, the preservation of the spectral fidelity of the original MS data is extremely important when the researcher wants to proceed to further processing of the data. The use of band ratios (e.g., vegetation indexes) or the classification using spectral libraries presuppose the spectral and consequently statistical integrity of the fused data.

The LMM, the LMVM, the Pansharp, and the Wavelet merging technique do not induce major changes to the statistical parameters of the original images. The Modified IHS results in minor changes to the statistical parameters more than the classical IHS or than the PCA. The Brovey and the Multiplicative algorithms result in the major changes to the statistical parameters.

All the possible combination of the Brovey transform algorithm eliminated the minimum values of all the MS bands, and the maximum values of all the MS bands are also

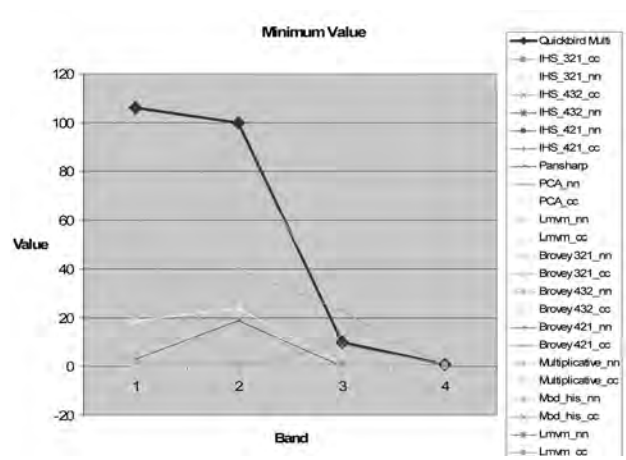

Figure 26. The minimum value of all the bands of the original MS and the fused images. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

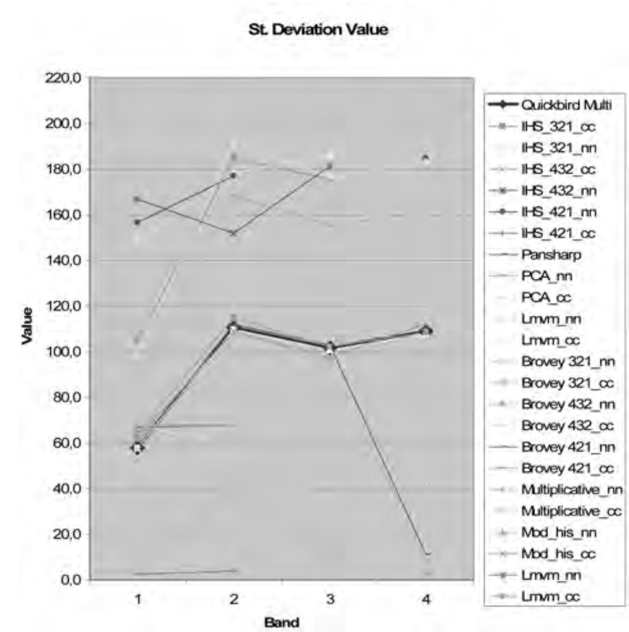

Figure 28. The standard deviation value of all the bands of the original MS and the fused images. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

decreased. There is also an important decrease to the values of the mean value and of the standard deviation with all the RGB band combinations. The resampling method does not appear to affect the statistics when we use the Brovey algorithm.

The Multiplicative algorithm stretches the histogram of all the MS bands, i.e., the minimum values became 0 and the maximum 2,047. All the other statistics values and especially the mean and the standard deviation decrease significantly. The choice of the resampling method does not have any important effect to the statistics.

The LMM technique results an increase to the maximum values of all the MS bands and decreases the minimum values to 1 or 2. The mean values of all the MS bands present very small changes that range between 1 and 3 units. The standard deviation values of the first three bands increase a little, and the value of the fourth band decrease by 0.7.

The LMVM algorithm technique increases the maximum value of the first band and decreases the maximum values of the other three MS bands. It also decreases the minimum values of the third and the fourth band to 1. The minimum value of the first band is decreased from 106 to 19, and the minimum value of the second band is decreased from 100 to 24. The mean values of all the MS bands present very small changes lower than 1 unit. The standard deviation values stay almost invariable. We discovered that the LMM and LMVM algorithms present exactly the same statistics irrespective of the resampling method that we used.

The Wavelet technique provokes a small decrease to the maximum values of the second, the third and the fourth MS bands. The image produced by the wavelet method presents exactly the same minimum values with the original MS image for all the bands. The standard deviation values do not appear to change. For example, the standard deviation of the second band decreases from 110.5 (original MS image) to 110.3 (fused image).

The Pansharp algorithm decreases both the minimum and the maximum values of all the MS bands. The decrease of the maximum value of the first band is small, while the decrease of the rest three bands is quite large. The values of the standard deviation present very small changes that range between 0.8 and 2.1 units.

All the possible combinations of the IHS algorithm stretch the histogram of all the MS bands. The values of all the spectral bands range from 1 to 2,047. There is also an increase to the values of the standard deviation when we use the 3,2,1 RGB band combination. The use of the cubic convolution resampling method with the 4,3,2 and the 4,2,1 RGB combinations provokes a very important decrease to the resulting values of the standard deviation. In contrary, the use of the nearest neighborhood resampling method with the 4,3,2 and the 4,2,1 RGB combinations provokes an increase to the values of the standard deviation.

We note that different RGB combinations of the initial MS bands provoke different results to the statistics of the fused bands. For example, the mean value of the second MS band changes from 254.2 (original image) to 292.7 (3,2,1 RGB combination) or to 266.2 (4,3,2 RGB combination) or to 280 (4,2,1 RGB combination) using the nearest neighbor resampling method.

The Modified IHS also provokes a small increase to the values of the standard deviation of the first and the fourth MS bands. In contrary, there is small decrease to the standard deviation of the second and the third MS bands. The Modified IHS algorithm decreases the minimum values of the first two bands independently of the resampling method used, and there is also a small decrease to all the mean values.

The PCA algorithm stretches the histogram of all the MS bands. It decreases the minimum values, and increases the maximum values. It also increases all of the mean and the standard deviation values of all the MS bands independently of the resampling method used.

Unsupervised Classification Control

After the visual and the statistical comparison, the nine fusion techniques were evaluated by classifying the fused image bands using an unsupervised clustering algorithm. The fused images were classified in the following three basic categories: buildings, roads, and vegetation; these three are the dominant categories of the image. Further, as in the original multispectral image, the vehicles cannot be recognized; it was decided not to discriminate them from the road.

The Iterative Self-Organizing Data Analysis Technique (ISODATA) (Tou and Gonzalez, 1974) clustering method has been used (ERDAS, 2003). It is iterative in that it repeatedly performs an entire classification (outputting a thematic raster layer) and re-calculates statistics. "Self-Organizing" refers to the way in which it locates the clusters that are inherent in the data. The ISODATA clustering method uses the minimum spectral distance formula to form clusters. It begins with either arbitrary cluster means or the means of an existing signature set, and each time the clustering repeats, the means of these clusters are shifted. The new cluster means are used for the next iteration. The ISODATA utility repeats the clustering of the image until either (a) a maximum number of iterations have been performed, or (b) a maximum percentage of unchanged pixels have been reached between two iterations.

It is important to note that this control does not indicate classification accuracy, as the classification is not compared with any ground truth. This control is used to indicate the classification changes in the fused image bands compared to the corresponding MS bands.

In all the images, the result was not as good as expected because parts of the original image are in the shadow (Figure 1). As expected, the classification of the fused image with the Multiplicative algorithm gave the worst results (Figure 29). The Pansharp (Figure 30) and the Modified IHS images gave the best results in classification. The 4,3,2 RGB combination of the IHS (Figure 31) and the Brovey gave quite good results; all the other images gave similar quite good results.

Figure 29. The unsupervised classification result of the fused image with the Multiplicative algorithm which provided the worst results.

Figure 30. The unsupervised classification result of the fused image with the Pansharp algorithm which provided the best results.

Figure 31. The unsupervised classification result of the fused image with the IHS algorithm.

Conclusions

In this paper, nine different fusion algorithms, IHS, Modified IHS, PCA, Pansharp, Wavelet, LMM (Local Mean Matching), LMVM (Local Mean and Variance Matching), Brovey, and Multiplicative, were compared for the fusion of QuickBird PAN and MS data.

All the fusion techniques improve the resolution and the visual result. Even the Multiplicative that is the simplest fusion technique ameliorate the detection of small targets like cars and trees, and facilitate the mapping of the buildings.

The LMVM, the LMM, the Pansharp, the Wavelet, and the PCA fusion techniques preserve, in general, the original colors in all the possible RGB band combinations. Small differences are detected in the tonality and the sharpness of the colors. In contrast the IHS, the Brovey, and the Multiplicative fusion techniques cause changes in the colors of the original images and make the photo-interpretation more difficult. Thus, the color of the vegetation changes from green to blue when the blue band is used in natural color combinations. The influence of the modified IHS of the original colors depends on the different RGB band combinations. The wavelet algorithm causes small distortion problems. In general, with the use of the 4,3,2 RGB combination, all the fusion algorithms resulted in minor changes to the colors of the original MS image.

For the eight of the nine compared algorithms, there was not any significant difference in the fused images according to the resampling method. Only with the use of the IHS algorithm and with a 4,2,1 RGB combination, the resampling method seems to affect the result image. In that case, the cubic convolution resampling method gives the least desirable result.

The correlation coefficient was computed for different band combinations of the fused images. First, each band of the original MS image has been correlated with the respective nine fused bands. The correlation of the fused bands should be close to that of the original MS image to ensure good spectral quality. The values in Figure 24 indicate that the LMVM and the LMM methods produce the best correlation result. The Brovey and the IHS methods gave the worst results. The correlation of the IHS bands presents a high fluctuation.

Also, the correlation between each band of the MS image before and after the application of the fusion techniques was computed. Using the Pansharp, the LMM, the LMVM, the PCA, and the Wavelet algorithm, the correlation value between the first and the fourth band was increased proving the good spectral quality of the fused image.

The LMVM, the LMM, the Pansharp, and the Wavelet, more or less, do not change the statistical parameters of the original MS bands. The Modified IHS provokes minor changes to the statistical parameters than the classical IHS or the PCA. The Multiplicative algorithm stretches the histogram of all the MS bands and decreases the standard deviation values. The Brovey algorithm causes an important decrease to the values of the mean value and of the standard deviation with all the RGB band combination. It is remarkable that the LMM and LMVM algorithms present exactly the same statistics irrespective of the resampling method used.

During the unsupervised classification, the eight of the nine algorithms give quite good results. Only the multiplicative algorithm gave unacceptable results.

After all the controls, the LMVM, the Pansharp, and the LMM algorithms seem to gather the more advantages in fusion panchromatic and multispectral data. These algorithms are proposed if the researcher want to proceed to further processing using for example vegetation indexes or to perform classification using the spectral signatures.

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