Comparison Between Four Methods for Data Fusion of ETM+ Multispectral and Pan Images

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ABSTRACT Four data fusion methods, principle component transform (PCT), brovey transform (BT), smoothing filter-based intensity modulation (SFIM), and hue, saturation, intensity (HSI), are used to merge Landsat-7 ETM+ multispectral bands with ETM+ panchromatic band. Each of them improves the spatial resolution effectively but distorts the original spectral signatures to some extent. SFIM model can produce optimal fusion data with respect to preservation of spectral integrity. However, it results the most blurred and noisy image if the coregistration between the multispectral and pan images is not accurate enough. The spectral integrity for all methods is preserved better if the original multispectral images are within the spectral range of ETM+ pan image.

KEYWORDS data fusion; ETM+; multispectral; PC transform; SFIM

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Introduction

The increasing availability of space-born sensors, imaging in a variety of ground scales and spectral bands, made multispectral fusion of multi-sensor data a significant operation in the field of digital remote sensing over the two past decades. Image fusion is the combination of two or more different images to form a new image by using a certain algorithm. Multispectral and panchromatic image merging, also known as data fusion or pan sharpening, is designed to enhance the spatial resolution of multispectral images by merging a higher spatial resolution panchromatic image of the same geographic area. This practice can increase photointerpretive potential as well as analytical capabilities and is useful in a variety of environmental, planning, and resource related studies.

Different methodological schemes of multi-resolution image fusion have been used by several researchers in recent years. Since the main intent of data fusion is enhancing the spatial resolution of a multispectral image, preservation of spectral integrity may be neglected to some extent. However, for a data fusion model to be effective, the merged image should retain the high spatial resolution information from the panchromatic data set while maintaining the spectral information of the original multispectral data.

The enhanced thematic mapper plus (ETM+) instrument borne on the Landsat 7 satellite is an improved version of the Thematic Mapper instruments that flew on Landsat 4 and 5. The ETM+ acquires data for six visible, near-infrared, and shortwave infrared spectral bands at a spatial resolution of 30 meters. The ETM+ instrument also incorporates a 15-meter resolution panchromatic band (0.52 μm-0.90 μm) as well as improved ground resolution for the thermal infrared band (60 m vs. 120 m).

This paper presents the results of a comparative study of ETM+ pan data fusion using four data fusion techniques, principle component transform (PCT), hue, saturation and intensity
(HSI), smoothing filter-based intensity modulation (SFIM) and brovey transform (BT), based on their performance with respect to spatial resolution and preservation of spectral integrity. Chadormalu mine area in Central Iran was selected as the test area for interpretation of spectral and textural features relating to geology. A subsene of ETM+ image taken on 14 August, 2000 has been used for the study.

1 Methods

The four techniques implemented in this study act upon the data sets within the spatial, algebraic and spectral domains. Each data fusion model will be analyzed.

The spatial domain model used here is based on smoothing filter-based intensity modulation\(^1\). The SFIM is defined as:

\[
SFIM = \frac{\langle X_{i,j,k} \cdot PN_{i,j} \rangle}{FP_{i,j}}
\]

where \( SFIM \) is the output image, \( i \) and \( j \) are pixels of band \( k \) of multispectral \( (X) \) image co-registered to pan image \( (PN) \), and \( FP \) is a simulated low-resolution image derived from pan image using an averaging filter for a neighborhood equivalent to the resolution of multispectral image. The ratio between \( PN \) and \( FP \) in Eq. (1) cancels the spectral and topographical contrasts of the higher resolution image, but retains the high-resolution textures\(^1\) and the result is independent of the contrast and spectral properties of the higher resolution image for modulation.

The spectral domain models used in this study are principle components and HSI transformations. In the principle component transform, first the multispectral data set is subjected to a principle component transformation using the following equation:

\[
PCI_{i,j} = Y_1X = y_{i1}BV_1 + y_{i2}BV_2 + \ldots + y_{in}BV_n
\]

where \( PCI_{i,j} \) are the brightness values for the first principle component vector, \( X \) is the vector representing the digital numbers of the spectral bands, and \( BV \) are the digital numbers of the image, which represent the brightness values. The PCI contains, theoretically, all the information that is common to all the bands input to the PCT and is mainly related to intensity or brightness\(^2\). By substituting the panchromatic data for the first principle component and applying an inverse PCT, an image with fine spatial resolution will be created, which will be reasonably correct with respect to brightness values whenever PCI and the pan images are highly correlated.

The HSI transform\(^3\) is the method most widely used for data fusion. The multispectral data set, i.e. RGB color composite, is first transformed into perceptual color space of HSI and then intensity component is replaced by a coregistered higher resolution pan image. Then, by transforming the image back to RGB, a color composite with improved spatial resolution will be produced\(^4\).

The algebraic models operate on data sets using pixel by pixel arithmetic functions, such as addition, subtraction, multiplication, and division. The brovey transform based on the chromaticity transform (Gilespie et. al, 1987) is a ratio method where the data values of each multispectral band are divided by the sum of the multispectral data set and then multiplied by the pan data set (Eq. 3):

\[
BT = \frac{XS_{i,j,k}}{\sum XS_{i,j,k}} \cdot PN_{i,j}
\]

where \( BT \) is the output image and \( i \) and \( j \) are pixels of band \( k \). The Brovey Transform maintains the spectral intensity of each band by incorporating the proportionate value of each band as related to the multispectral data set before merging it with pan data set.

2 Fusion method compared on spectral integrity and spatial resolution

Fig. 1 shows the fusion results of 30-m resolution ETM+ bands of 5, 3 and 1 RGB color composite with 15-m resolution ETM+ pan image of Chadormalu mine area in Central Iran. It is obvi-
ous that all the techniques used for fusion improve spatial resolution effectively. The SFIM image is almost as sharp as other images, even an NW trending fault in the lower-left part of the image is more apparent in this image, but it produces some blurred and noisy edges. Fig. 1 shows that all the images are similar to the original with respect to color but close observation reveals some subtle spectral distortion in BT, HSI, and PCT fusion images. The color change in BT is more obvious and shows a bluish tone. The SFIM is more faithful to the spectral properties of the original image. This is more apparent in small parks near the residential place of the mine, which are in dark brown and dark blue in the original image. These parts become brighter in PCT, BT, and HSI fusion images. The reason is that the spectral range of ETM+ pan (0.52 μm-0.90 μm) covers the vegetation reflection peaks in green and nearer infrared. The intensity replacement and modulation in the HSI, PCT, and BT with the pan data have increased the intensity level in these parts (Liu, 2000). The rock units of upper left part of the image also show subtle changes in these images.

![Image of fusion results](image)

Fig. 1  Fusion results of 30-m resolution ETM+ bands 531 with 15-m resolution ETM+ pan image of Chadormalu mine area, Central Iran

In order to evaluate the spectral integrity of four fused images, different quantifying methods were employed. Table 1 shows the correlation matrix for ETM+ bands 5, 3 and 1 RGB color composite and its fusion images. The correlation matrices show the ability of the data fusion models to maintain correlation among channels. All the fusion models used show a general trend similar to the original data. The HIS model maintains the best overall correlation among channels when compared with the XS correlation, followed by PCT, FSIM and BT, respectively. When the correlation between the data fusion models and the original data is compared, the correlation should optimally be one. Table 1 shows that the SFIM maintains the correlation for bands 3 and 5 at the 96 percent level, while PCT maintains correlation among all three bands at 95 percent level.

General image statistics of mean and standard deviation (Table 2) show the trends of each data fusion model for RGB color composite of bands 5, 3 and 1. The PCT model tends to decrease the mean for all bands, but retains it within one standard deviation of the original data. The BT model decreases brightness values significantly for all three bands with a difference much greater than one standard deviation.
and HSI models the statistics are significantly close to the original data. The relative deviation between the fused image and the original multispectral image is calculated by:

$$D_I = \frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[ \frac{R(i,j) - F(i,j)}{F(i,j)} \right]$$  \hspace{1cm} (4)

Table 1: Correlation matrix for the RGB color composite bands 5, 3, 1 and its data fusion images (row labels are the transpose of column labels)

|       | B1-XS | B3-XS | B5-XS | B1-PC | B3-PC | B5-PC | B1-BT | B3-BT | B5-BT | B1-SFIM | B3-SFIM | B5-SFIM | B1-HSI | B3-HSI | B5-HSI |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|---------|---------|--------|--------|--------|
|       | 1.000 | 0.929 | 0.797 | 0.958 | 0.880 | 0.783 | 0.903 | 0.880 | 0.797 | 0.910   | 0.895   | 0.771   | 0.858  | 0.870  | 0.748  |
|       | 0.929 | 1.000 | 0.901 | 0.884 | 0.952 | 0.894 | 0.884 | 0.962 | 0.910 | 0.853   | 0.963   | 0.869   | 0.850  | 0.950  | 0.871  |
|       | 0.797 | 0.901 | 1.000 | 0.709 | 0.807 | 0.954 | 0.729 | 0.842 | 0.958 | 0.754   | 0.968   | 0.711   | 0.857  | 0.954  |        |
|       | 0.958 | 0.884 | 0.709 | 1.000 | 0.923 | 0.780 | 0.973 | 0.909 | 0.786 | 0.945   | 0.900   | 0.732   | 0.896  | 0.727  |        |
|       | 0.880 | 0.952 | 0.807 | 0.923 | 1.000 | 0.821 | 0.957 | 0.965 | 0.900 | 0.887   | 0.968   | 0.829   | 0.931  | 0.895  | 0.850  |
|       | 0.783 | 0.894 | 0.954 | 0.780 | 0.891 | 1.000 | 0.836 | 0.914 | 0.955 | 0.923   | 0.975   | 0.826   | 0.926  | 0.991  |        |
|       | 0.903 | 0.884 | 0.729 | 0.973 | 0.957 | 0.838 | 1.000 | 0.945 | 0.838 | 0.935   | 0.924   | 0.773   | 0.938  | 0.784  |        |
|       | 0.880 | 0.962 | 0.842 | 0.995 | 0.914 | 0.945 | 1.000 | 0.922 | 0.882 | 0.974   | 0.858   | 0.918   | 0.992  | 0.878  |        |
|       | 0.797 | 0.910 | 0.958 | 0.786 | 0.900 | 0.995 | 0.838 | 0.922 | 1.000 | 0.823   | 0.941   | 0.972   | 0.842  | 0.934  | 0.988  |
|       | 0.910 | 0.853 | 0.754 | 0.945 | 0.887 | 0.823 | 0.935 | 0.882 | 0.823 | 1.000   | 0.913   | 0.831   | 0.935  | 0.877  | 0.833  |
|       | 0.895 | 0.963 | 0.880 | 0.900 | 0.968 | 0.925 | 0.924 | 0.974 | 0.924 | 0.933   | 1.000   | 0.915   | 0.901  | 0.974  | 0.897  |
|       | 0.771 | 0.869 | 0.968 | 0.732 | 0.829 | 0.975 | 0.773 | 0.858 | 0.972 | 0.831   | 0.915   | 1.000   | 0.765  | 0.874  | 0.978  |
|       | 0.885 | 0.850 | 0.711 | 0.963 | 0.931 | 0.826 | 0.977 | 0.918 | 0.824 | 0.935   | 0.901   | 0.765   | 1.000  | 0.924  | 0.788  |
|       | 0.870 | 0.950 | 0.857 | 0.896 | 0.989 | 0.926 | 0.936 | 0.992 | 0.934 | 0.877   | 0.974   | 0.874   | 0.924  | 1.000  | 0.901  |
|       | 0.748 | 0.871 | 0.954 | 0.727 | 0.850 | 0.991 | 0.784 | 0.878 | 0.988 | 0.783   | 0.897   | 0.978   | 0.888  | 0.901  | 1.000  |

The following first-order entropy was used to measure the amount of image information in each fused image:

$$- \sum_{i=1}^{N} P(i) \log_2 P(i)$$  \hspace{1cm} (5)

where $p(i)$ is the probability of occurrence of each grey level. Table 2 presents the entropy of ETM bands 1, 3 and 5 for different fused images. The average entropy values of the original multispectral image, PCA, HSI, SFIM and BT are 5.164, 5.223, 5.184, 5.343 and 3.767, respectively. According to the computation results, the increased entropy indicates the enhancement of information content through the HSI, PC and SFIM images. The SFIM provides the greatest improvement while BT shows a decrease in entropy. Another evaluating index which reflects the clarity of an image is average gradient which can be used to measure the spatial resolution of the fused image. Average gradient for the image $f$ can be calculated by use of the following equation:

$$g = \frac{1}{(M-1)(N-1)} \sum_{i=1}^{M-1} \sum_{j=1}^{N-1} \sqrt{\left( \frac{\partial f(i,j)}{\partial i} \right)^2 + \left( \frac{\partial f(i,j)}{\partial j} \right)^2}$$  \hspace{1cm} (6)

A larger average gradient means a better spatial resolution. As indicated in Table 2 the average gra-
dient values in all fused images show improvement compared to the original multispectral image. The best improvement is provided by SFIM, followed by HSI, BT and PCA respectively.

In order to further evaluate the performance of each fusion method, the signal to noise ratio (SNR) has also been calculated (Table 2). The following equation was used to calculate the SNR:

\[
\text{SNR} = 10 \cdot \log \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} [R(i,j) - F(i,j)]^2}{\sum_{i=1}^{M} \sum_{j=1}^{N} [F(i,j)]^2}
\]

(7)

where \( R \) and \( F \) are the fused and original images, respectively. The average value of SNR for PCT, BT, SFIM and HSI fused images are 20.423, 3.218, 28.718 and 28.665, respectively, showing the better performance of SFIM and HSI over PCT and BT models. The statistics of fusion images bands 432 (not shown) compared to those of bands 531 fusion products follow the same trend but are closer to the original data, showing a better preservation of spectral properties because the spectral range of ETM+ Pan is exactly the same as the total spectral range of the three VNIR bands.

In order to examine the sensitivity of fusion models to the accuracy of coregistration of multispectral and pan images, a less accurately coregistered image of the same area (with RMS nearly equal to 1 pixel) has been subjected to the same fusion operations. Fig. 2 presents the RGB color composite of ETM+ bands 5, 3 and 1 and its fusion products. The less accuracy of coregistration has caused significant textural and edge blurring in the SFIM fusion image which is especially noticeable in three circular bunkers of the mine, upper right of the center of image, although the spectral integrity is still more preserved in this image.

![Fig. 2 Fusion results of less accurately coregistered 30-m resolution ETM+ bands 531 with 15-m resolution ETM+ pan image of Chadormalu mine area, Central Iran](image)

### 3 Conclusions

All the data fusion models used in this study improves apparent spatial resolution effectively. Each of the models distorted the original spectral signatures to some extent. The fusion results of color composite of ETM+ bands 5, 3 and 1 with ETM+ pan show that all the images are similar to the original with respect to color, but subtle distortions can be seen in BT, HSI and PCT fusion images. The SFIM model shows a better performance upon the spectral integrity and looks to be independent of the spectral proper-
ties of the ETM+ pan used for fusion. This is confirmed by quantitative assessment of the fused images using different evaluating measures. However, the SFIM produces the most blurred and noisy image if the accuracy of coregistration between ETM+ multispectral and pan images is not high enough. The spectral distortion is less severe when the ETM+ color composite bands are within the spectral range of ETM+ pan (0.52 μm-0.90 μm).

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+10.2 m, and its average value is +5.9 m. The orientation change for the north map sheet corner in respect to the south one (along the south-north map border line of 1:1 M scale map in Chinese territory) will not be visible basically in most Chinese maps.

4) Due to the replacement between the two coordinate systems, the length of east-west and south-north map border lines will change in respect to their original one. The ranges of the length changes are −5.0 m to +1.0 m and −6.6 m to +1.6 m, respectively, their average values are −4.20 m and −2.20 m, respectively.

5) In general, if Xi‘an 80 coordinate system is replaced by GRS geocentric three-dimension coordinate system, the length change and orientation change of map border lines in different kinds of maps at various scales in Chinese territory are within mapping accuracy, hence, they can be neglected. This conclusion is also valid for length change and orientation change of lines connected by any two points in a map sheet.

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