PROBLEMS IN THE FUSION OF COMMERCIAL HIGH-RESOLUTION SATELLITE AS WELL AS LANDSAT 7 IMAGES AND INITIAL SOLUTIONS

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ABSTRACT:
Currently available image fusion techniques are not efficient for fusing the new satellite images such as IKONOS and Landsat 7. Significant colour distortion is one of the major problems. Reasons for this distortion are analyzed in this paper. A new initial automatic solution for fusing the new images is introduced. The new solution has reached an optimum fusion result – with minimized colour distortion and maximized spatial detail.

1. INTRODUCTION

The fusion of low-resolution multispectral and high-resolution panchromatic satellite images is a very important issue for many remote sensing and mapping applications. Usually, a panchromatic band covers a broad wavelength range of the visible and near infrared spectrum, while a multispectral band just covers a narrow spectral range. For receiving a same amount of incoming energy, the size of a panchromatic detector can be smaller than that of a multispectral detector. Therefore, most sensors of earth recourse satellites, such as SPOT, IRS, Landsat 7, IKONOS and QuickBird, provide panchromatic and multispectral images at different spatial resolutions. To effectively utilize such images, techniques that can effectively combine high-resolution panchromatic and low-resolution multispectral images into one colour image are demanded. Such techniques can largely extend the application potential of the raw remote sensing images.
Many image fusion algorithms and software tools have been developed (Pohl and Van Genderen 1998). The well-known techniques are, for example, the IHS (Intensity, Hue, Saturation), PCA (Principal Components Analysis), arithmetic combination based fusion, and wavelet based fusion (Cliche et al.1985, Welch and Ehlers 1987, Albertz *et al.* 1988, Chavez *et al.* 1991, Ehlers 1991, Shettigara 1992, Munechika et al.1993, Garguet-Duport et al. 1996, Yocky 1996, Wald et al. 1997, Zhou et al. 1998, Zhang and Albertz 1998, Zhang 1999, Ranchin and Wald 2000). Most techniques have been developed based on the fusion of the SPOT pan with other multispectral images, such as Landsat TM and SPOT HRV XS. Among the fusion techniques the IHS and PCA techniques have become the very popular.

However, a common problem associated with the available techniques is the colour distortion of the fused images. To date, well-fused satellite images with SPOT or IRS panchromatic band as a high-resolution input have been presented in some publications; however, publications on well-fused IKONOS and Landsat 7 images have been rarely seen. Another common problem associated with the existing algorithms is that the fusion quality is operator and data dependent. Different operators or data sets may lead to different fusion qualities.

In this study, the principles of different fusion techniques are reviewed. The spectral characteristics of the available earth recourse satellite images are analyzed. Available software tools (IHS, PCA etc.) are applied to fusing different images. Based on the analyses of the spectral relationships and different fusion results, a new technique has been developed. This technique can effectively fuse the new satellite images, e.g., IKONOS and Landsat 7, and reduce the manual interactions during the process. The spectral distortion of the fused images is significantly reduced and the fusion quality becomes operator and data set independent.

2. CHARACTERISTICS OF AVAILABLE TECHNIQUES

Pohl and Van Genderen (1998) provided a comprehensive review of image fusion techniques. Among the numerous techniques the following four types of fusion techniques have demonstrated most promising results for effectively fusing SPOT pan with other images, e.g., IHS (Intensity, Hue, Saturation), PCA (Principal Components Analysis), arithmetic combination based fusion, and wavelet based fusion. The general concepts and characteristics of these techniques are reviewed here to provide a background for analyzing their limitation for IKONOS as well as Landsat 7 fusions.

2.1. HIS technique

The IHS colour transform can effectively separate a standard RGB (Red, Green, Blue) image into spatial (I) and spectral (H, S) information. The basic concept of IHS fusion is shown in Figure 1. The most important steps are: (1) transform a colour image composite from the RGB space into the IHS space, (2) replace the I (intensity) component by a panchromatic image with a higher resolution, (3) reversely transform the replaced components from IHS space back to the original RGB space to obtain a fused image. The IHS technique has become a standard procedure in image fusion (Albertz *et al.* 1988, Chavez *et al.* 1991, Ehlers 1991, Shettigara 1992, Zhang and Albertz 1998, Zhang 1999).

2.2. PCA technique

The PCA is a statistical technique that transforms a multivariate inter-correlated data set into a new un-correlated data set. The basic concept of PCA fusion is shown in Figure 2.

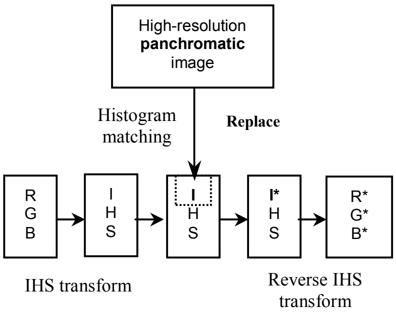

Figure 1. Schematic flowchart of IHS image fusion

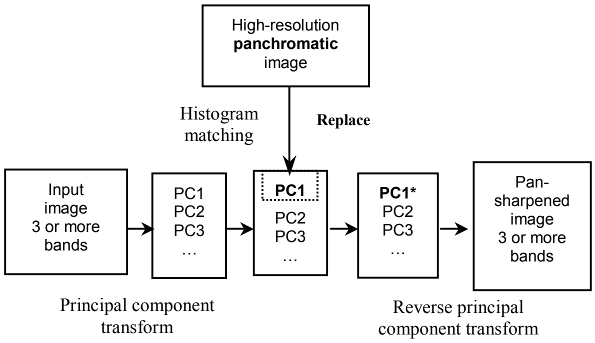

Figure 2. Schematic flowchart of PCA image fusion

Its most important steps are: (1) perform a principal component transformation to convert a set of multispectral bands (three or more bands) into a set of principal components, (2) replace one principal component, usually the first component, by a high resolution panchromatic image, (3) perform a reverse principal component transformation to convert the replaced components back to the original image space. A set of fused multispectral bands is produced after the reverse transform (Chavez *et al.* 1991, Shettigara 1992, Zhang and Albertz 1998, Zhang 1999).

2.3. Arithmetic Combination technique

Different arithmetic combinations have been employed for fusing multispectral and panchromatic images. The arithmetic operations of multiplication, division, addition and subtraction have been combined in different ways to achieve a better fusion effect. Brovey Transform, SVR (Synthetic Variable Ratio), and RE (Ratio Enhancement) techniques are some successful examples for SPOT pan fusion. Brovey Transform uses addition, division and multiplication for the fusion of three multispectral bands (ERDAS 1999). Its concept can be described with equation 1. Its basic processing steps are: (1) add three multispectral bands together for a sum image, (2) divide each multispectral band by the sum image, (3) multiply each quotient by a high resolution pan. The SVR and RE techniques are similar, but involved more sophisticated calculations for the sum image (Cliche et al.1985, Welch and Ehlers 1987, Chavez *et al.* 1991, Munechika et al.1993, Zhang and Albertz 1998, Zhang 1999).

$$Fusion_i = \frac{Multi_i}{Multi_{Sum}} \times Pan \qquad (1)$$

with i = 1, 2 and 3, and $Multi_{Sum} = Multi1 + Multi\ 2 + Multi\ 3$.

2.4. Wavelet technique

Wavelet transform is a mathematical tool developed in the field of signal processing. It can decompose a digital image into a set of multi-resolution images accompanied with wavelet coefficients for each resolution level. The wavelet coefficients for each level contain the spatial (detail) differences between two successive resolution levels. The wavelet based fusion is performed in the following way (Figure 3): (1) decompose a high resolution panchromatic image into a set of low resolution panchromatic images with wavelet coefficients for each level, (2) replace a low resolution panchromatic with a multispectral band at the same resolution level, (3) perform a reverse wavelet transform to convert the decomposed and replaced panchromatic set back to the original panchromatic resolution level. The replacement and reverse transform is done three times, each for one multispectral band (Garguet-Duport et al. 1996, Yocky 1996, Wald et al. 1997, Zhou et al. 1998, Ranchin and Wald 2000).

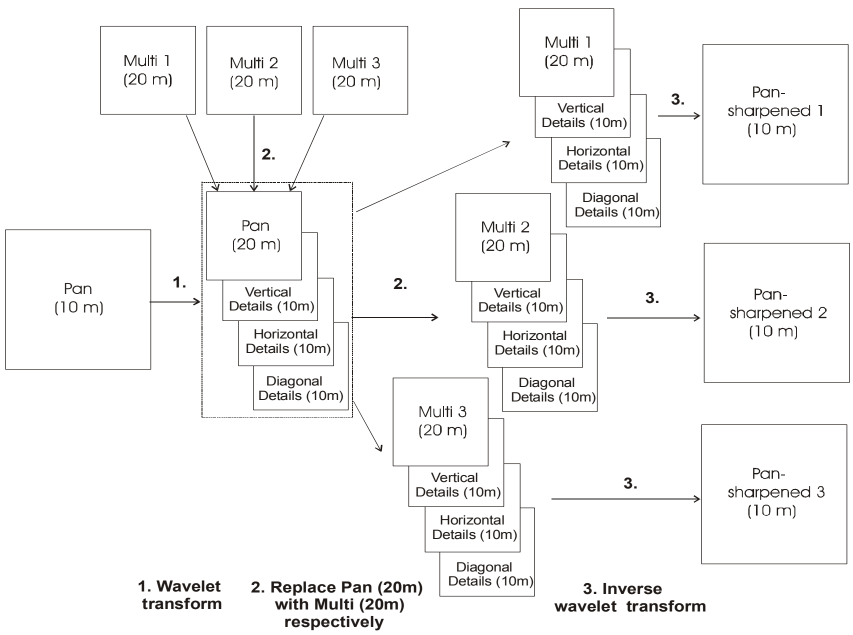

Figure 3. Schematic flowchart of wavelet based image fusion

3. PROBLEMS OF AVAILABLE TECHNIQUES

Problems and limitations associated with the available fusion techniques have been reported by many studies (Chavez et al. 1991, Pellemans et al. 1993, Wald et al. 1997, Van Der Meer 1997). The most significant problem is the colour distortion of fused images. Another most common problem is the operator and data dependency of the fusion quality. To reduce the colour distortion, different strategies have been developed for different techniques; nevertheless operator's experience still spays an important role for a good fusion result.

- The colour distortion of IHS technique is often significant. To reduce the distortion, the suggested strategies are, for example, matching the panchromatic to the intensity before the replacement, stretching the hue and saturation components before the reverse transform, or stretching individual I, H or S components with respect to individual data sets.
- In PCA image fusion, dominant spatial information and weak colour information is an often problem. The reason is that the first principal component being replaced usually contains a maximum variance. Such replacement maximizes the effect of panchromatic image in the fused image. Suggested solutions have been, for example, stretching the principal components to give a spherical distribution, or discarding the first principal component. The PCA approach is sensitive to the choice of area to be fused.
- With Brovey Transform, it is necessary to select only three bands. In general, the pixel grey values are smaller than those of other fusion techniques. The colour distortion is obvious and varies depending on the band combinations being fused. With the SVR and RE techniques, the colour effect of the fused image is generally better than Brovey Transform, but a suitable preprocessing is necessary before the fusion. Operator's experience plays an important role for all the three techniques.
- Wavelet based fusion is a computationally intensive process. It extracts spatial details from a high-resolution panchromatic image, and then adds them into the multispectral bands. In this manner, the colour distortion can be reduced to a certain extent, but the fused image appears like a result of a high-pass filtering fusion, e.g., the colour seems not being smoothly integrated into the spatial features. Other disadvantages have also been reported, for example, the loss of spectral content of small objects.

To date, successful results of fusing Landsat TM, SPOT HRV, or IRS LISS with SPOT panchromatic or IRS panchromatic images have been shown in many publications. Different strategies for reducing colour distortions and operator's fusion experiences have played an important role for such successes. However, colour distortions still remain. Figure 4 shows an example of the fused Landsat TM and SPOT pan images using HIS, PCA and SVR techniques. Different colour distortions can still be recgonized.

When the same fusion techniques are applied to the fusion of IKONOS or Landsat 7 images, the colour distortions are much more significant, even if great operator efforts have been employed. Figure 5 shows IKONOS multispectral, panchromatic and IHS fused images in two different areas – Fredericton, Canada and San Diego, USA. The same IHS algorithm and fusion parameters were applied to the two image sets. It can be clearly seen in the fused results that (1) the colour is totally distorted from their original colour, and (2) the colour distortions tend in different ways for different sets. Other techniques, such as PCA and SVR, produce similar results with significant colour distortions.

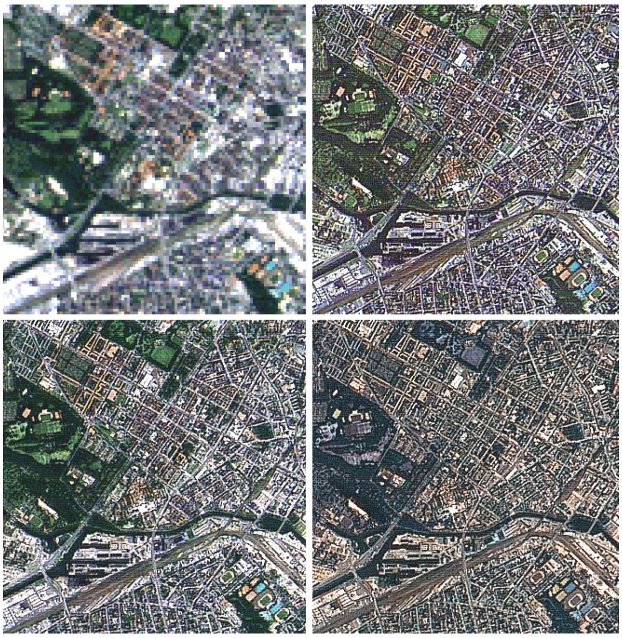

Figure 4: Landsat TM and SPOT pan fusion. (a) Original TM colour image, (b) PCA fusion result, (c) SVR fusion result, (d) IHS fusion result. (with a: upper left, b: upper right, c: lower left, d: lower right)

With wavelet base fusion technique, the colour distortion may be reduced to some extent. But, the integration of colour and spatial feature usually does not appear smooth. The spectral content of small objects is lost for many cases (Yocky 1996, Ranchin and Wald 2000). Therefore, this technique has not been tested in this study.

4. REASONS FOR THE COLOUR DISTORTION

A major reason for the insufficiency of available techniques for IKONOS fusion as well as Landsat 7 fusion is the change of the panchromatic spectral range. Different from SPOT panchromatic and IRS panchromatic images, the wavelength of IKONOS and Landsat 7 panchromatic images (same to QuickBird pan) was extended from visible to near infrared range (Table 1). This change makes the grey value relationship of an IKONOS or Landsat 7 panchromatic image significant different from that of a SPOT panchromatic or IRS panchromatic image (Figure 6a and 6b). For example, vegetation areas in the SPOT panchromatic image (Figure 6a) appear darker than pavement areas. However, they appear brighter than pavement areas in the IKONOS pan image because of the influence of near infrared content. Therefore, it is not a wonder that conventional fusion algorithms, which have been successful for the fusion of SPOT panchromatic and other multispectral images, cannot effectively fulfill the fusion of the new images.

Figure 6c shows the intensity (I) image transformed from IKONOS multispectral bands 1, 2 and 3. The grey value difference between the IKONOS pan and the I image is much more significant than that between the SPOT pan and the I image. When the I image is replaced by a significantly different image – IKONOS pan, the IHS fusion will, of course, lead to a significant colour distortion. In the opposite, if the I image was replaced by a pan image like the SPOT pan, the colour distortion of the IHS fusion would be much smaller. This comparison clearly illustrated the reason of the colour distortion of the IHS technique. The first component of the PCA technique (PC1) is also significantly different from the original IKONOS pan image. If the grey values of an IKONOS pan could be adjusted to the grey values similar to an I or PC1 image before the replacement, the colour distortion would be significantly reduced.

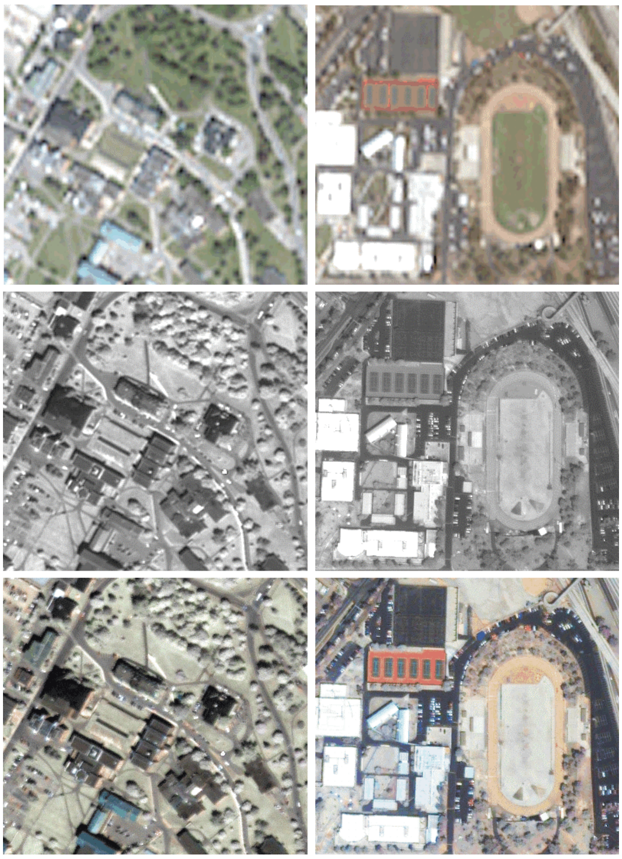

Figure 5. Significant colour distortions of the IHS technique for IKONOS fusion. From top to bottom: original IKONOS natural colour images with 4 m resolution, original IKONOS panchromatic images with 1 m resolution, and IHS fusion results. Left: Fredericton, Canada. Right: San Diego, USA.

Table 1. Spectral ranges of different panchromatic images

Satellite sensor	**Spectral range (μm)**
SPOT 1, 2, 3 (HRV)	0.51 – 0.73
SPOT 5 (HRG)	0.51 – 0.73
IRS 1C, 1D (PAN)	0.50 – 0.75
Landsat 7 (ETM+)	0.52 – 0.90
IKONOS	0.45 – 0.90
QuickBird	0.45 – 0.90

5. INITIAL SOLUTIONS AND RESULTS

Based on thorough studies and analyses of existing fusion algorithms and their fusion effects, an initial new automatic fusion approach has been developed by the author. This new technique solved the two major problems in image fusion – colour distortion and operator dependency. A technique based on least squares was employed for a best approximation of the grey value relationship between the original multi, panchromatic and the fused images for a best colour representation. Statistic approaches were applied to the fusion for standardizing and automating the fusion process.

Figure 7 shows two results of the new automatic fusion technique. No colour adjustment and manual interaction were employed during the fusion. In other words, the operator just needs to input the registered original multispectral and panchromatic images, and then receive the fusion result. Compared to the original colour image, the colour of the fused image of the new technique stays almost the same as the original one. The spatial details of the panchromatic image are also perfectly integrated into the fused image. An enormous improvement of the new fusion technique over the IHS fusion can clearly seen by comparing Figure 7 and Figure 5.

Another fusion result of the new technique is shown in Figure 8. The image covers a part of the main campus of the University of New Brunswick, Canada. The original 4m multispectral and 1m panchromatic images were taken in October 2001 when the maple trees began turning red. Compared to the original colour image, the colour of the fused image stays almost the same as the original image for all objects. In comparison with the original panchromatic image, the detail of spatial features in the fused image is as clear as in the pan image. Further, the colour and spatial detail of the original images have been perfectly integrated. No artificial effects between colour and spatial features can be recognized. Even spatial details under shadows can be seen in the fused image.

Figure 6. Comparison of grey value differences between SPOT panchromatic (left), IKONOS panchromatic (middle), and IKONOS Intensity (right) images (with a: left, b: middle, c: right)

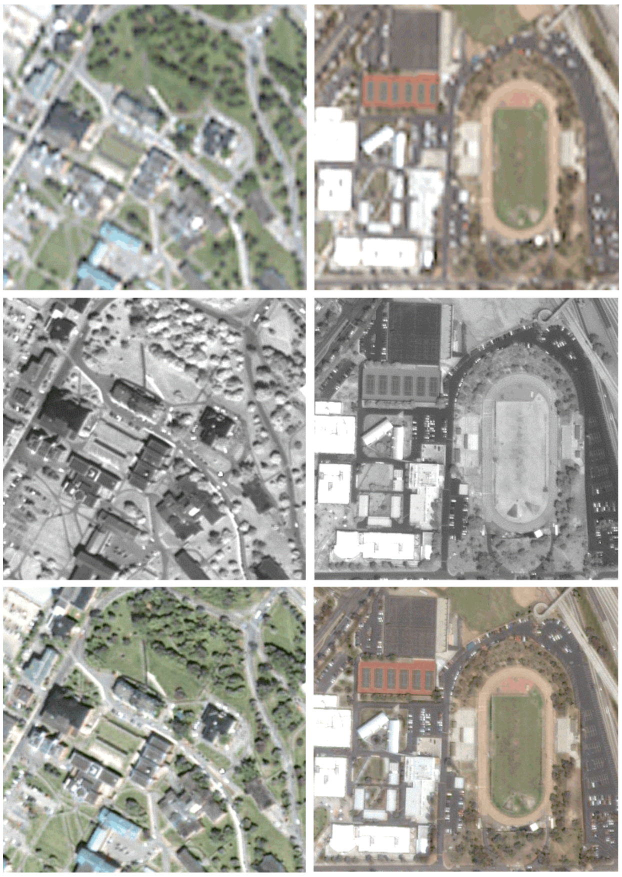

Figure 7. Minimized colour distortions of the new fusion technique. From top to bottom: original IKONOS natural colour images with 4 m resolution, original IKONOS panchromatic images with 1 m resolution, and IHS fusion results. Left: Fredericton, Canada. Right: San Diego, USA.

For different application purposes, three different fusion models – spectral information preserving model, spatial information preserving model, and colour enhancing model – have also been developed.

- The spectral information preserving model is developed mostly for digital classification purposes (Figure 9b). In this model, the colour of the fused image is kept as same to the original image as possible. The grey value variances within individual objects are kept smooth. These properties are important to conventional spectral based classifications for higher classification accuracy.
- The spatial information preserving model is developed for visual interpretation, image mapping, and photogrammetric purposes (Figure 9c). Spatial details and colour fidelity are both important in this model. The colour fidelity of the spatial model is not as high as the spectral model for some parts of objects; however, details of an object are significantly increased and the clarity of the image is improved.
- The colour enhancing model is developed for visualization and GIS integration purposes. In many cases, the colour of an IKONOS natural colour composite does not appear fresh. For example, vegetation areas are often darker and with less green intensity than we usually see on the ground. With this model, the colour of vegetation areas can be enhanced appearing fresher than in the original image, but the colour of other objects are keeping unchanged (Figure 9d).

6. CONCLUSIONS

The initial fusion technique has been tested with many IKONOS and Landsat 7 data sets covering different areas. The sizes of some data sets were more than 10,000 by 10,000 pixels. All the fusions have shown a perfect result – maximum detail increasing and minimum colour distortion.

Figure 8. IKONOS images covering the University of New Brunswick, Canada before and after the fusion. Left: Original 4m natural colour image, Middle: Original 1m panchromatic image, Right: Automatically fused natural colour image of the new technique.

Figure 9. Effects of three fusion models of the new fusion technique. (a) Original IKONOS 4 m natural colour image, (b) Fusion result of the spectra preserving model. (c) Fusion result of the spatial detail preserving model. (d) Fusion result of the colour enhancing model. (with a: upper left, b: upper right, c: lower left, d: lower right)

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