High-resolution Image Fusion: Methods to Preserve Spectral and Spatial Resolution

Andreja Švab and Krisˇtof Oˇštir

Abstract

The main topic of this paper is high-resolution image fusion. The techniques used to merge high spatial resolution panchromatic images with high spectral resolution multispectral images are described. The most commonly used image fusion methods that work on the principle of component substitution (intensity-hue-saturation method (IHS), Brovey transform (BT), and multiplicative method (MULTI)) have been applied to Ikonos, QuickBird, Landsat, and aerial orthophoto images. Visual comparison, histogram analyses, correlation coefficients, and difference images were used in order to analyze the spectral and spatial qualities of the fused images. It was discovered that for preserving spectral characteristics, one needs a high level of similarity between the panchromatic image and the respective multispectral intensity. In order to achieve this, spectral sensitivity of multispectral and panchromatic data was performed, and digital values in individual bands have been modified before fusion. It has also been determined that spatial resolution is best preserved in the event of an unchanged input panchromatic image.

Introduction

Earth observation satellites provide an increasing amount of data at different spatial, temporal, and spectral resolutions. In order to be able to (effectively) solve real world problems, advanced methods of data fusion are being developed. These methods integrate different data in order to obtain additional information that merely the data that can be derived from each of the sensors. During the last decades, data fusion has been a rapidly developing area of research in remote sensing. Several authors have recently documented new or improved methods and their applications. Pohl and van Genderen (1998) published an extensive review on image fusion techniques, listing approximately 150 references.

Most of the newest remote sensing systems, such as Ikonos, QuickBird, IRS, SPOT, and Landsat 7, provide sensors with one high spatial resolution panchromatic (PAN) and several multispectral bands (MS). There are several reasons for not capturing the images merely in high resolution: the most important of them being the incoming radiation energy and the data volume collected by the sensor (Zhang, 2004). PAN images cover a broader wavelength range and in order to receive the same amount of incoming energy, the size of a PAN detector can be smaller than that of a MS detector. Therefore, on the same satellite or airplane platform, the resolution of the PAN sensor can be higher than that of the MS sensor. On the other hand, the data volume of a high-resolution MS image would be significantly larger and could mitigate the problems of limited on-board storage capacity and limited data transmission rates between the platform and ground (Zhang, 2004).

Since a number of applications need both high spectral and high spatial resolution, image fusion, or more precisely, band sharpening or resolution merge, is used. Image fusion is a method, which increases the spatial resolution of multispectral images (ideally without the loss of spectral information), through the combination of low spatial but high spectral resolution multispectral data and higher spatial but low spectral resolution panchromatic data.

A short overview of the image fusion methods is given in the paper. However, only the three most commonly used methods that work on the principle of component substitution, i.e., the intensity-hue-saturation method (IHS), Brovey transform (BT), and the multiplicative method (MULTI), are treated in greater detail. They are tested with different combinations of Ikonos, QuickBird, Landsat, and aerial orthophoto images. Special attention is paid to the quality analysis of the results regarding the preservation of spectral and spatial resolution.

Image Fusion Methods

Numerous methods have been implemented to fuse multitemporal, multisensor, and multisresolution data. For a comprehensive review of the development one should refer to the recent overview papers in remote sensing (Pohl and van Genderen, 1998; Zhang, 2004), and related fields, such as signal processing (Li et al., 1995), or medical imaging (Barillot et al., 1993; Townsend and Cherry, 2001).

In general, the image fusion techniques can be divided into two classes: color related techniques, and statistical or numerical methods. The first group comprises of the tristimulus color composition in the red, green, blue RGB color space as well as more sophisticated transformations (for example IHS). Statistical approaches use channel statistics including correlation (principal components analysis (PCA), regression), and filters (high pass), while numerical methods follow arithmetic operations such as image addition, division,
and subtraction. A sophisticated and very successful numerical approach uses wavelet transform in a multiresolution environment (Pohl and van Genderen, 1998). The newer geographical image processing software includes at least a basic set of image fusion methods. Among the hundreds of variations, the most popular and effective are IHS, PCA, arithmetic combinations, and wavelet base fusion (Zhang, 2004). In this paper three techniques functioning with component substitution will be evaluated in greater detail:

- the intensity-hue-saturation method (IHS),
- Brovey transform (IHT), and
- the multiplicative method (MULT).

These techniques were selected since they are well studied, simple and widely available. More advanced methods, like high frequency addition and principal components analysis, have been also tested, but excluded in detailed analysis because of higher complexity, especially regarding the quality of the final result. Wavelet based methods, that are very promising because of the multiresolution approach have not been studied, since they are more computationally demanding and require special algorithms (wavelet transform), not yet available in off-the-shelf remote sensing software.

The IHS color transformation effectively separates spatial (intensity) and spectral (hue and saturation) information from an image (Chavez et al., 1991; Carper et al., 1990). The fusion method first converts a RGB image into intensity (I), hue (H) and saturation (S) components. In the next step, intensity is substituted with the high spatial resolution panchromatic image. The last step performs the inverse transformation, converting IHS components into RGB colors, the so-called synthetic multispectral bands.

The Brovey transformation (Hallada and Cox, 1983) normalizes multispectral bands used for RGB display; each multispectral band is divided with the panchromatic image, obtained from the original multispectral data. Next, the result is multiplied by the original panchromatic image to add data intensity or the brightness component to the image. The Brovey transformation was developed to visually increase the contrast in the low and high ends of an image’s histogram and thus change the original scene’s radiometry. It was created to produce RGB images, and therefore only these bands can be merged.

The Multiplicative method (MULT) can be performed with any number of input bands. The algorithm is derived from the four-component technique, as described by Crippen (1989). Of the four possible arithmetic methods that can be used to incorporate an intensity image into a chromatic image (addition, subtraction, division, and multiplication), only multiplication is unlikely to distort the color. The relatively simple multiplicative algorithm can be used to merge PAN and MS images, however special attention has to be paid to color preservation.

Many recent papers have demonstrated that the spectral content of an image changes as the spatial resolution changes; for example, an extensive discussion is given in Wald et al. (1997). Moreover, a number of authors have mentioned, that the input images need preprocessing, but usually no attention is given to the algorithms of changing the input data and its effects on the quality of the fused image, a topic discussed in greater detail below.

Spectral Sensitivity of Sensors
The main goal of all image fusion methods is to link a panchromatic and a multispectral image. From the high-resolution panchromatic data one wishes to extract information, which will improve the spatial resolution of the multispectral image, while at the same time hopefully not influence its spectral characteristics.

The panchromatic image is closely linked to the intensity component (for all applied methods), and therefore, the preservation of spectral characteristics is possible only in the event of a spectral equality of these two. However, since the panchromatic image has a higher spatial resolution, exact color preservation is even theoretically impossible. The investigation of the correlation between the intensity data acquired from multispectral images and the panchromatic data therefore suggests additional preprocessing in order to use panchromatic images as an intensity component of the fused product. That is why a comparison of the spectral sensitivity for panchromatic and multispectral sensors of different platforms should be studied. Spectral sensitivities of the sensors onboard of Ikonos, QuickBird, and Landsat 7 satellites are shown in Plate 1. The spectral response curves are similar for Ikonos and QuickBird: the panchromatic band covers most of the visible and a significant part of the near infrared wavelengths. Its sensitivity is slightly lower in green and very low in blue. The responses of individual bands, especially blue and green, partially overlap. The Landsat ETM+ panchromatic sensor does not detect the blue part of the spectrum; its spectral response sensitivity increases with wavelength, being relatively low in green, significant in red, and optimal in infrared.

The measured energy in an individual channel is the sum (integral) of incoming radiation and relative spectral sensitivity. Theoretically, it is possible to obtain the values in the panchromatic band with the summation of respective spectral bands. In ideal conditions all spectral bands would be well separated and would cover exactly the same wavelengths as the panchromatic band (Plate 2). Since no sensor shows such a situation, adequate weights have to be defined. The panchromatic band can be obtained as the following:

\[ \text{PAN} = w_B \cdot B + w_G \cdot G + w_R \cdot R + w_NIR \cdot \text{NIR} + \text{other}. \] (1)

In the equation \( \text{PAN} \), \( B \), \( G \), \( R \), and \( \text{NIR} \) are individual spectral bands (panchromatic, blue, green, red, and near infrared, respectively). \( w_B, w_G, w_R \), and \( w_NIR \) are weights belonging to the corresponding spectral bands, and \( \text{other} \) is the influence of the spectral range covered with the panchromatic band, but missing from multispectral bands.

With Equation 1 and an appropriate combination of the respective spectral bands, it is possible to compute the panchromatic band digital values. Since this is acquired by the sensor, the relation enables matching (preprocessing) of individual bands prior to image fusion. The main reason for changing the panchromatic band is to obtain a strong resemblance to the intensity image, which will be replaced during the fusion process.

As can be seen from Figure 1 for the Ikonos data the intensity image obtained from different spectral bands can differ significantly. The intensity acquired from bands 4, 3, and 2 (i.e., near infrared, red, and green) will be closer to the panchromatic image than the intensity image acquired from spectral bands 3, 2, and 1 (red, green, blue), because the panchromatic band completely covers bands 4 and 3 and to a great extent band 2, while the spectral band 1 is poorly covered with the panchromatic band. The greatest difference between the Ikonos panchromatic image and the intensity image, acquired from bands 3, 2, and 1, is seen in vegetated areas, where the reflectance of the infrared radiation is the strongest.

If, during the fusion, the intensity from bands 3, 2, and 1 is replaced by the panchromatic image, spectral characteristics of the original multispectral image would change considerably.
The bands in image fusion have to be modified with appropriate weights to match the panchromatic image.

Spectral response curves are available from appropriate managing agencies for all used datasets, which is Ikonos, QuickBird, and Landsat ETM+ (Space Imaging, 2005; Padwick, 2004; Irish, 2000). Required weights were calculated by considering the in-band radiance at the sensor aperture (Space Imaging, 2005, Irish, 2000):

\[ L_k = \int L(\lambda) R_k(\lambda) d\lambda. \]  

(2)

In the equation, \( \lambda \) is the wavelength, \( k \) the band number, \( L_k \) the in-band radiance, \( L(\lambda) \) the spectral radiance at the sensor aperture, and \( R_k(\lambda) \) the peak-normalized spectral response. The weights are obtained by comparing the response of individual bands of the sensor and the response of the panchromatic band. Theoretical weights that should be used in Equation 1 are listed in Table 1 for Ikonos, QuickBird, and Landsat. For aerial orthophoto images, also used in the comparison, spectral response curves were not available, and therefore the weights were estimated from the image data.

If the respective components of the original multispectral images are combined according to Equation 1, images which closely resemble the corresponding panchromatic images are obtained. Turned around, the panchromatic image, which will replace the intensity image, will be spectrally similar to the intensity image if bands not included in the intensity are subtracted (adequately weighted) from it.

Unfortunately, the spectral band to be subtracted from the high-resolution panchromatic image has a lower spatial resolution than the original panchromatic image, leading to a deterioration in spatial resolution. If the spectral characteristics are well preserved, the spatial quality is lost. Considering the spectral sensitivity and width of individual bands with all methods tested, the following modified panchromatic images were used:

\[
\begin{align*}
\text{PAN}_{\text{IKO}}_{\text{321}} &= \text{PAN}_{\text{IKO}} - 1.2 \text{NIR}_{\text{IKO}} \\
\text{PAN}_{\text{IKO}}_{\text{432}} &= \text{PAN}_{\text{IKO}} - 0.2 \text{B}_{\text{IKO}} \\
\text{PAN}_{\text{TM7}}_{\text{321}} &= \text{PAN}_{\text{TM7}} - 0.5 \text{NIR}_{\text{TM7}} \\
\text{PAN}_{\text{TM7}}_{\text{432}} &= \text{PAN}_{\text{TM7}} \\
\text{PAN}_{\text{TM7}}_{\text{765}} &= \text{PAN}_{\text{TM7}} 
\end{align*}
\]  

(3)

In the equations, 321, 432, and 765 are panchromatic images used for sharpening multispectral images composed from bands 3, 2, and 1 or 4, 3, and 2 or 7, 6, and 5, respectively, while \text{IKO} and \text{TM7} denote Ikonos and Landsat data. Plate 3 compares the results of image fusion with original and modified (according to spectral sensitivity analysis) panchromatic image.

### Quality Analysis of Fused Images

Several authors describe different spatial and spectral quality analysis techniques of the fused images. Some of them enable subjective, the others objective, numerical definition of spatial or spectral quality of the fused data.

#### Table 1. Weights Used to Determine the Panchromatic Band from the Multispectral Data

<table>
<thead>
<tr>
<th>Sensor</th>
<th>( w_B )</th>
<th>( w_G )</th>
<th>( w_R )</th>
<th>( w_{NIR} )</th>
<th>Other</th>
</tr>
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<tbody>
<tr>
<td>Ikonos</td>
<td>0.4</td>
<td>0.8</td>
<td>1.2</td>
<td>1.4</td>
<td>70</td>
</tr>
<tr>
<td>QuickBird</td>
<td>0.4</td>
<td>0.8</td>
<td>1.2</td>
<td>1.2</td>
<td>53</td>
</tr>
<tr>
<td>Landsat ETM+</td>
<td>0.0</td>
<td>0.7</td>
<td>0.9</td>
<td>1.0</td>
<td>69</td>
</tr>
</tbody>
</table>

Figure 1. Comparison of (a) the panchromatic band and intensity images obtained from bands (b) 4, 3, and 2; and (c) 3, 2, and 1 of the same Ikonos image.
The most commonly used spectral quality analysis techniques are (Chavez et al., 1991):

• visual comparison,
• histogram analysis,
• statistical comparison, and
• difference images.

In visual comparison differences on the fused images can be spotted. Eventual changes in color indicate that the spectral characteristics of the observed object were deformed or changed because of the fusing method that was used. The histogram analysis deals with gray value histograms of all components of the original multispectral image and the fused image. A greater difference of the shape of the corresponding histograms represents a greater spectral change. Spectral characteristics of the fused data can also statistically be compared regarding the spectral characteristics of the original multispectral data. Mostly, the correlation coefficients between multispectral components of the resampled original image and the fused image are calculated and analyzed. Difference images (normalized absolute differences) obtained by the subtraction of the fused image’s components from the corresponding original resampled multispectral components are also an effective method of analyzing the spectral quality. The average absolute differences of images provide a global conception of the spectral deformations of the fused image.

The theoretical spatial resolution of the fused images is supposed to be equal to the resolution of the high spatial resolution panchromatic image; however, in reality it is reduced. We estimated the spatial quality of all fused images with visual examination and the computation of correlation coefficients. With the visual examination, the quality of the preservation of spatial characteristics can be defined by the observation of the original and enhanced (for example, highpass or edge filtered) panchromatic and fused images. Analogous to the spectral quality, the calculation of correlation coefficients can also be used. In order to evaluate the spatial properties of the fused images, a panchromatic image and intensity image of the fused image have to be compared (Tu et al., 2001).

Results and Discussion
We have produced several combinations of fused images for the applied methods, i.e., the intensity-hue-saturation method (IHS), Brovey transform (BT), and the multiplicative
Plate 3. Spectral sensitivity analysis can significantly improve the spectral properties of fused images. Original (a) panchromatic and multispectral Ikonos images were fused with (b) intensity-hue-saturation method, (c) Brovey transform, and (d) multiplicative method. Images on the left were obtained from original panchromatic band and images of the right with preprocessing according to spectral sensitivity analysis.
method (MULTI). Different spatial and spectral quality analysis techniques have been used for all methods and all image combinations. Before further analyses, the results were examined and since all quality analysis techniques produced the same conclusions, only the results with correlation coefficients are referred in detail below. In order to classify the results according to spatial and spectral quality and to simultaneously find out the reasons for their quality, charts of data interdependence were produced. To simplify the comparison of the results, the average values of correlation coefficients for every fused image were calculated.

Spectral Quality
The similarity between the original panchromatic image and intensity images has already been discussed. It has been found that the correlation between them is essential for the preservation of the spectral characteristics of the original multispectral image. Figure 2 shows the relation of the spectral quality of the fused image to similarity between intensity and the panchromatic image. As can be seen from Figure 2, BT, IHS, and MULTI fusion methods follow a similar shape. For all three methods, the spectral quality of the fused image depends on the similarity between the panchromatic and intensity images. Greater resemblance offers a better result. Particularly strong resemblance is needed for the IHS and BT methods, while the MULTI method is more flexible and gives relatively good results in all cases. Even if Ikonos panchromatic images are fused with spectral bands 3, 2, and 1 of the same satellite and the panchromatic image is not changed, the results are better for MULTI than for IHS and BT methods.

The average correlation coefficients were also computed in order to verify the preservation of spectral characteristics regarding the similarity between the intensity image and the panchromatic aerial orthophotos. Figure 3 shows the correlation coefficients for spectral bands 3, 2, and 1 of the Ikonos multispectral image when merged with black-and-white aerial panchromatic photography. As shown in Figure 3, the panchromatic spectral sensibility of the Ikonos sensor entirely covers the red band (3), approximately half of the green band (2), and only a small amount of the blue band (1). Aerial panchromatic photographs used in the study cover (almost uniformly) all the wavelengths. The obtained correlation coefficients clearly confirm this dependence, and again the MULTI method is less sensitive to discrepancy of spectral bands than the BT and IHS methods.

The hypothesis that the spectral band not covered by the panchromatic band would have greater spectral deformations on the fused image has been confirmed for the cases of fusing spectral bands 1, 2, 3, and 4 of the Ikonos or Landsat sensors. For Landsat, we were also able to test the fusion of bands not at all covered with the panchromatic image (7, 6, and 5). None of these lays in the panchromatic band, yet the correlation between the panchromatic and intensity images is substantial, especially for bands 7 and 5 (Figure 4). In Figure 4 it can be observed that only band 6 is extensively modified. The reason for this is lower spatial resolution (60 m comparing to 30 m) and a completely different part of the spectrum (0.5 to 0.9 μm in panchromatic and 10.4 to 12.5 μm in the thermal band). The results confirm that Landsat bands 7 and 5 can be used in PAN sharpening, while the use of band 6 should be omitted.
Spatial Quality

It can be clearly observed on the fused images that all used methods sharpen the respective multispectral bands. As shown in Figure 5, the improvement factor of spatial resolution was defined with the correlation coefficients between the original panchromatic image and the intensity image of the fused image. The correlation has also been used to estimate the resolution of the obtained sharpened multispectral images (listed in Table 2 for several image combinations).

Regarding the preservation of spatial resolution, all discussed methods behave very similarly. However, a greater resemblance between the panchromatic and the intensity image does not mean better preservation of spatial resolution. It has already been mentioned that every change in the original panchromatic image means a deterioration in the spatial characteristics. That is why spatial resolution of the original panchromatic image is better preserved in the case of a minimal change of the input panchromatic image, producing best results when the input panchromatic image is not changed at all. The largest deformation of spatial resolution can be seen on the image obtained from the Ikonos panchromatic and multispectral bands 3, 2, and 1, where in order to preserve the spectral characteristics the entire near infrared band has been cut off. This meant the elimination of approximately one-third of the panchromatic band and with that, a considerable part of spatial information. From the analyzed methods the multiplicative method was the worst in preserving spatial resolution.

The relation between the preservation of the spectral information and the preservation of spatial quality is shown in Figure 5. It can be seen that the spectral and spatial qualities are dependent. The improvement of the spatial quality of one image means the deterioration of the spectral quality and vice versa; nevertheless, the change is considerably smaller than expected. Because in most cases the fused images should preserve the spectral and spatial information, bands, which are equally covered with the panchromatic image and have equal spatial resolution should be used. Additionally the input panchromatic images should be altered to a minimum degree. For Ikonos, QuickBird, and Landsat this means using spectral bands 4, 3 and 2, which offer good results in all of the used methods.

Conclusions

The results presented in this paper confirmed that all applied methods, the intensity-hue-saturation method (IHS), Brovey transform (BT), and the multiplicative method (MULTI) could be successfully used to fuse panchromatic and multispectral images. The sharpened data contains a substantial part of spatial characteristics of the original high spatial resolution panchromatic images and the majority of spectral characteristics of the original high spectral resolution multispectral images. However, the study demonstrated that there is no single method or processing chain for image fusion. A good understanding of the principles of fusing operations, and

<table>
<thead>
<tr>
<th>Panchromatic Image</th>
<th>Multispectral Image</th>
<th>Correlation</th>
<th>Panchromatic Resolution (m)</th>
<th>Multispectral Resolution (m)</th>
<th>Sharpened Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerial orthophoto</td>
<td>Ikonos 321</td>
<td>0.53</td>
<td>0.5</td>
<td>4</td>
<td>2.1</td>
</tr>
<tr>
<td>Aerial orthophoto</td>
<td>Ikonos 432</td>
<td>0.80</td>
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<td>4</td>
<td>1.2</td>
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<td>1</td>
<td>4</td>
<td>1.5</td>
</tr>
<tr>
<td>Ikonos</td>
<td>Ikonos 432</td>
<td>0.92</td>
<td>1</td>
<td>4</td>
<td>1.3</td>
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<td>30</td>
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<td>Landsat</td>
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<td>0.66</td>
<td>15</td>
<td>30</td>
<td>20.1</td>
</tr>
</tbody>
</table>
especially good knowledge of the data characteristics, are compulsory in order to obtain the best results.

All discussed methods are based on a direct or indirect exchange of the panchromatic image and intensity image, but conditions for obtaining good quality of the fused image differ. An analysis of the results supported the hypothesis that the preservation level of spectral characteristics strongly depends on the resemblance between the original panchromatic image and the respective intensity image. These two are most similar when the multispectral bands are completely included in the panchromatic band. In other words, spectral bands used in fusion should cover the same wavelengths as the panchromatic band, and should follow a similar sensitivity of the sensor. Additionally, there should be no overlap between the respective spectral bands. Since such a situation is rarely possible, spectral sensitivity analysis of the sensor has to be performed before fusion, and a greater resemblance between the panchromatic image and respective intensity image should be produced with the weighted subtraction of bands not contained in the intensity component. Unfortunately, the change of the original panchromatic image not only improves the spectral characteristics, but also contributes to the decline in the spatial resolution of the original panchromatic image. Spatial resolution is best preserved in the event when the input panchromatic image has been minimally changed or not at all.

The study showed that BT and IRS transformation methods have very similar properties; both are strongly dependent on the resemblance between the panchromatic image and intensity and both are very good at preserving the spatial characteristics. The multiplicative method is less dependent on the resemblance of panchromatic images and gives good spectral results, but is not good at preserving the spatial characteristics.

The selection of an appropriate image fusion method depends on the application. Each user must use methods which will provide suitable results for a defined purpose; this might be a visually beautiful fused color image [better visualization], greater detail in color (easier image interpretation or more accurate mapping), or an improvement in classification accuracy.

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References


