Understanding Image Fusion

by Yun Zhang

Image fusion, also called pan-sharpening, is a technique used to integrate the geometric detail of a high-resolution panchromatic (Pan) image and the color information of a low-resolution multispectral (MS) image to produce a high-resolution MS image. This technique is particularly important for large-scale applications.

Importance of image fusion

Why is image fusion important? Most earth resource satellites, such as SPOT, IRS, Landsat 7, IKONOS, QuickBird and OrbView, plus some modern airborne sensors, such as Leica ADS40, provide both Pan images at a higher spatial resolution and MS images at a lower spatial resolution. An effective image fusion technique can virtually extend the application potential of such remotely sensed images, as many remote sensing applications require both high-spatial and high-spectral resolutions, especially for GIS based applications.

Why don't most satellites collect high-resolution MS images directly, to meet this requirement for high-spatial and high-spectral resolutions? There are two major technical limitations involved: (1) the incoming radiation energy to the sensor, and (2) the data volume collected by the sensor. In general, a Pan image covers a broader wavelength range, while a MS band covers a narrower spectral range. 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. In addition, the data volume of a high-resolution MS image is significantly greater than that of a bundled high-resolution Pan image and low-resolution MS image. This bundled solution can mitigate the problems of limited on-board storage capacity and limited data transmission rates from platform to ground.

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.

Existing image fusion techniques

In the mid-1980s, image fusion received significant attention from researchers in remote sensing and image processing, as SPOT 1 (launched in 1986) provided high-resolution (10m) Pan images and low-resolution (20m) MS images. Since that time, much research has been done to develop effective image fusion techniques. For example, a review paper on image fusion techniques, published in 1998 in the *International Journal of Remote Sensing*, referenced approximately 150 academic papers on image fusion. Since 1998, further scientific papers on image fusion have been published with the emphasis on improving fusion quality and reducing color distortion. Among the hundreds of variations of image fusion techniques, the most popular and effective are, for example, IHS (Intensity, Hue, Saturation), PCA (Principal Components Analysis), arithmetic combinations, and wavelet base fusion.

- The IHS fusion converts a color image from the RGB (Red, Green, Blue) space into the IHS color space. Because the intensity (I) band resembles a Pan image, it is replaced by a high-resolution Pan image in the fusion. A reverse IHS transform is then performed on the Pan together with the hue (H) and saturation (S) bands, resulting in an IHS fused image.
- 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.
- Different arithmetic combinations have been developed for image fusion. The Brovey Transform, SVR (Synthetic Variable Ratio), and RE (Ratio Enhancement) techniques are some successful examples. 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 SVR and RE techniques are similar, but involve more sophisticated calculations for the MS sum for better fusion quality.
- In wavelet fusion, a high-resolution Pan image is first decomposed into a set of low-resolution Pan images with corresponding wavelet coefficients (spatial details) for each level. Individual bands of the MS image then replace the low-resolution Pan at the resolution level of the original MS image. The high-resolution spatial detail is injected into each MS band by performing a reverse wavelet transform on each MS band together with the corresponding wavelet coefficients.

Limitations of existing fusion techniques

Many research papers have reported the limitations of existing 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. No automatic solution has been achieved to consistently produce high quality fusion for different data sets.

To reduce the color distortion and improve the fusion quality, a wide variety of strategies have been developed, each specific to a particular fusion technique or image set. For example:

- For IHS fusion, a common strategy is to match the Pan to the I band before the replacement, stretch the H and S bands before the reverse IHS transform, or stretch individual I, H or S bands with respect to individual data sets.
- In PCA fusion, suggested solutions have been, for example, stretching the principal components to give a spherical distribution, or discarding the first principal component.
- With arithmetic combination methods, color distortion varies depending upon the band combinations being fused. Preprocessing and operator's fusion experience are important to achieving a good fusion result.

continued on page 658

continued from page 657

- In wavelet fusion, many variants of wavelet fusion have been developed to deal with color distortion problems.

By selecting a proper fusion technique and applying an appropriate adjustment strategy, successful results can be achieved for the fusion of SPOT Pan or IRS Pan images with other low-resolution MS images, such as Landsat TM, SPOT MS, or IRS MS. But, the operator's experience plays an important role for the success.

However, quality results are rarely obtained for the fusion of Pan and MS images obtained from many satellites launched post-1999 (e.g. IKONOS, QuickBird, OrbView, Landsat 7). This is true regardless of fusion technique or color adjustment strategy employed. When traditional fusion and adjustment techniques are used with this newer imagery, significant color distortion becomes a significant problem.

Reasons for the color distortion

For the new satellite images, a major reason for the significant color distortion in fusion is the wavelength extension of the new satellite Pan images. Unlike the Pan image of the SPOT and IRS sensors, the wavelength range of the new satellites is extended from the visible into the near infrared (Table 1). This difference significantly changes the grey values of the new Pan images. Therefore, traditional image fusion techniques – useful for fusing SPOT Pan with other MS images – cannot achieve quality fusion results for the new satellite images.

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
OrbView	0.45 - 0.90

The significant grey value difference between the SPOT Pan and the IKONOS Pan can be clearly seen in Figure 1a and 1b. For example, vegetation areas in the SPOT Pan image (Figure 1a) appear darker than pavement areas. However, they appear brighter than pavement areas in the IKONOS Pan image (Figure 1b) because of the influence of near infrared content.

Figure 1c shows the I band from the IHS transform of the IKONOS MS bands 1, 2 and 3. The grey value difference between the I band and the IKONOS Pan is significantly greater than that between the I band (the I band of Landsat TM is similar) and the SPOT Pan. The grey value of the I band (Figure 1c) is even close to the reverse of the IKONOS Pan (Figure 1b). When the I band is replaced by the IKONOS Pan for the IHS fusion, it will, of course, lead to significant color distortion.

However, if the I band (Figure 1c) was replaced by a high-resolution Pan image with the grey value like the SPOT Pan (Figure 1a), the color distortion would be significantly reduced. Therefore, it is no wonder that the IHS algorithms, successful for the fusion of SPOT Pan with other MS images, cannot achieve quality fusion results with the new satellite images.

Figure 2 shows the first and second principal components (PC1 and PC2) from the IKONOS MS bands 1, 2 and 3, compared to the original IKONOS Pan. The PC1 (similar to the I band) is significantly different from the IKONOS Pan. The difference between the PC2 and IKONOS Pan is more significant. The PCA fusion – replacing PC1 or PC2 with the IKONOS Pan – will certainly cause significant color distortion.

Figure 3 illustrates original IKONOS Pan and MS bands and the wavelet decomposition of the original Pan image. It can be clearly seen that the original Pan is significantly different from all three original MS bands. If a set of high-resolution MS bands were available, the spatial details extracted from the three high-resolution MS bands would certainly be different than those from the high-resolution Pan image. Therefore, by injecting spatial details from a Pan image (Figure 3e upper right, lower left, and lower right) into each of the three low-resolution MS bands, the wavelet fusion technique will introduce color distortion into the fusion result.

Other fusion techniques, such as the Brovey, SVR and RE techniques, also produce unsatisfactory fusion results for new satellite images due to the spectral range extension of the Pan images.

To address the significant color distortion problem in the fusion of the new satellite images, recent industry advances have sought to

(a) (b) (c)

Figure 1. Grey value difference between SPOT Pan (a), IKONOS Pan (b), and the I band of the IHS transform from IKONOS MS bands 1, 2 and 3 (c), images showing the Fredericton campus of the University of New Brunswick.

further improve the wavelet fusion, or to find more effective strategies to stretch, match and/or adjust individual components (or bands) in the IHS or PCA fusion. Some new wavelet-based fusion techniques have demonstrated a reduction in color distortion. Some IHS based or PCA based fusion techniques have also achieved better fusion results by integrating more effective adjustment strategies. However, the color distortion is still obvious in many cases, and the fusion quality varies upon the data sets being fused.

(a) (b) (c)

Figure 2. Grey value difference between PC2 (a), IKONOS Pan (b), and PC1 (c).

New approach to image fusion

A new method of image fusion – a statistics-based fusion, currently implemented in the PCI® Geomatica® software as special module, PANSHARP – shows significant promise as an automated technique. The fusion is a one-step process. If the original MS and Pan images are geo-referenced, the resampling process can also be accomplished together with the fusion within one step. All the MS bands can be fused at one time. The fusion can also be performed solely on user-specified MS bands. The fusion of a geo-referenced QuickBird scene with 16 bits, 4 MS bands and 12,000×12,000 Pan pixels took a total of 31 minutes, using a PC Pentium 4 desktop with 1.8 GHz CPU and 1 GB RAM. From the 31 minutes of processing time, 26 minutes were used for resampling and only 5 minutes for the fusion.

The 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:

(1) 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

(2) 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.

The front cover of this issue of *PE&RS* shows a mosaic of an original QuickBird MS 2.4m natural color image (left), a 0.6m Pan image (top), the result of the statistics-based fusion (center right), and the result of a color-enhanced fusion (bottom). The image covers the Opera House area of Sydney, Australia, with a part of downtown Sydney as well. No manual intervention was employed in the entire fusion process. For image display the same histogram stretching was applied to all the images including the original MS (left), the original Pan (top), the fused image (center right), and the color-enhanced fusion (bottom).

Compared to the color of the original MS image, the color of the fused image stays almost unchanged for all the objects in the image (front cover, compare left and center right). In terms of spatial detail, all spatial features of the Pan image are also perfectly integrated into the fused image (compare top and center right). Due to the effective combination of color and spatial detail, the details under shadows of high-rise buildings, such as cars, trees and windows, appear even clearer in the fused image than in the original Pan image.

continued on page 660

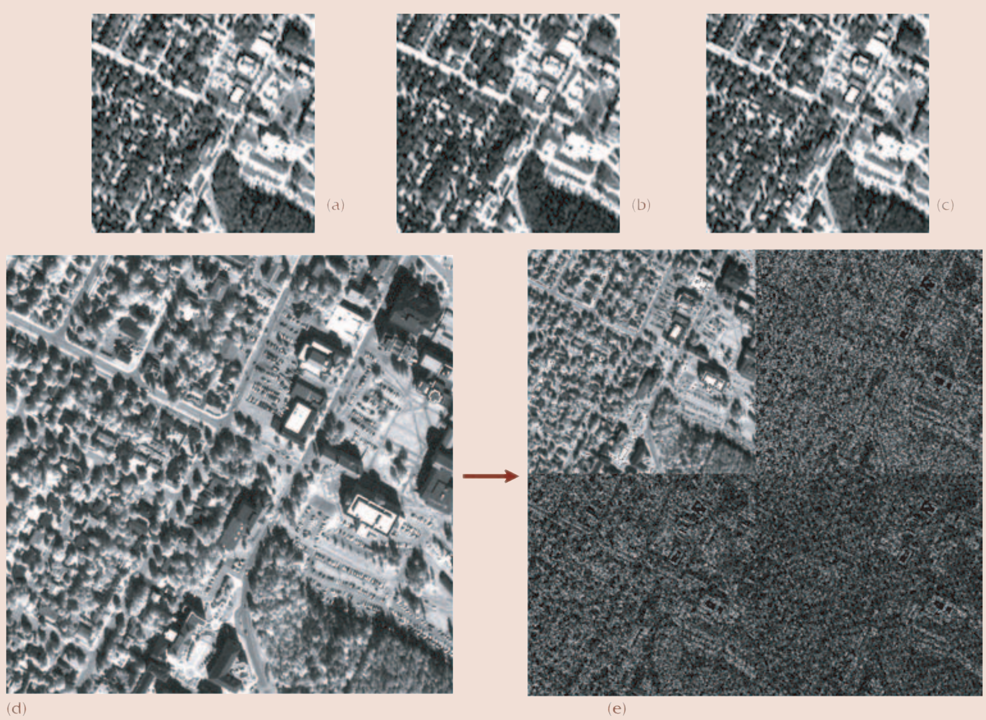

Figure 3. Original IKONOS MS band 1 (a), band 2 (b), band 3 (c), Pan (d), and the wavelet decomposition of the original Pan (e) with a low-resolution Pan (upper left) and wavelet coefficients (spatial details) in horizontal, vertical and diagonal directions (upper right, lower left, and lower right).

continued from page 659

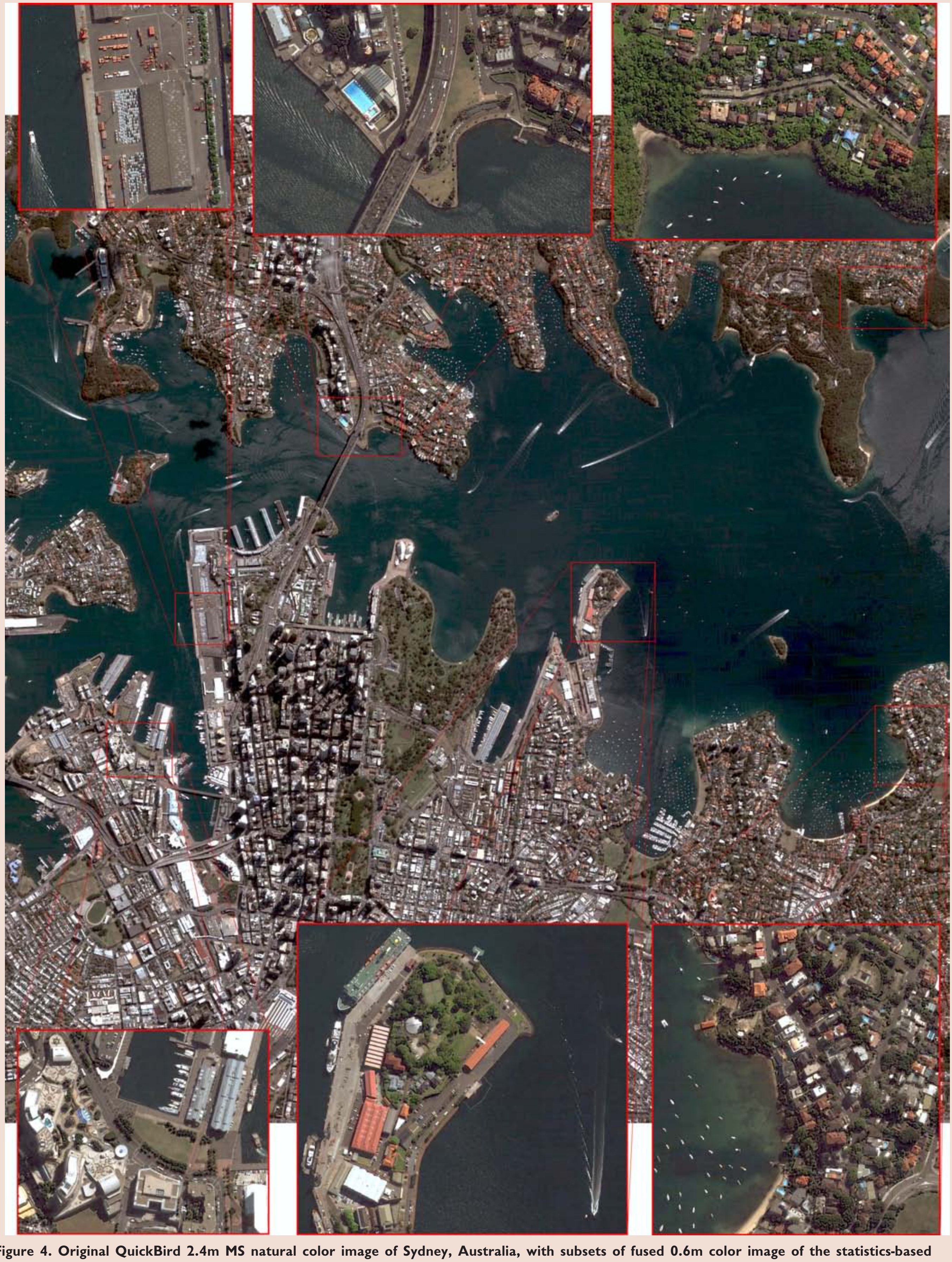

Figure 4. Original QuickBird 2.4m MS natural color image of Sydney, Australia, with subsets of fused 0.6m color image of the statistics-based fusion (top middle; bottom left and right) and subsets of 0.6m color enhanced fusion image (top left and right; bottom middle).

Figure 4 shows a sub-scene of an original QuickBird MS natural color image of Sydney, Australia, with a 2.4m resolution and 6km × 6km coverage. The full scene of a QuickBird image is 16.5km × 16.5km. The enlarged sub-scenes on the top and bottom of Figure 4 are subsets of a fused 0.6m natural color image of the statistics-based fusion (top middle; bottom left and right), and subsets of a color enhanced fusion image (top left and right; bottom middle). By comparing the sub-scenes of the statistics-based fusion with the original MS image, it can be seen that the color of the fused image (top middle; bottom left and right) is almost identical with that of the original MS image. The spatial detail in the fused sub-scenes is, however, significantly increased. Even the lanes in a swimming pool (top middle) and the bowsprit, masts and yardarms of a sailing vessel (bottom left) can be clearly recognized.

Conclusion and outlook

High-resolution and multispectral remote sensing images are an important data source for acquiring large-scale and detailed geospatial information for a variety of applications. Visual interpretation, digital classification, and color image visualization are three approaches often used to acquire or display detailed geospatial information.

Depending upon the purpose of a given application, (1) some users may desire a fusion result that shows more detail in color, for better image interpretation or mapping; (2) some may desire a fusion result that improves the accuracy of digital classification; and (3) some others may desire a visually beautiful fused color image, solely for visualization purposes. Therefore, distinct techniques for mapping-oriented fusion, classification-oriented fusion, and visualization-oriented image are in demand.

Currently, image fusion (or pan-sharpening) techniques have proven to be effective tools for providing better image information for visual interpretation, image mapping, and image-based GIS applications. The statistics-based fusion technique can fuse Pan and MS images of the new satellites, as well as images of SPOT and IRS, resulting in minimized color distortion, maximized detail, and natural color and feature integration (see front cover and Figure 4).

However, there is still a lack of effective techniques for classification-oriented fusion and visualization-oriented fusion. An initial automatic technique for visualization-oriented fusion, called color-enhanced fusion, has been developed in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick (see front cover, bottom; Figure 4, top left and right, and bottom middle). Trees and lawns appear more natural and stand out clearly from buildings, especially in densely built-up areas (front cover, compare trees in bottom and in center left). A simple straw poll among students and faculty members at the University of New Brunswick demonstrated that the color enhanced fusion image was most attractive to all surveyed.

Acknowledgments

It is with great appreciation that I thank Matthew Wood and Mary Bolton of DigitalGlobe for providing the raw QuickBird MS and Pan images, and David Stanley of PCI Geomatics for providing the PCIâ PANSHARP module.

About the Author

Dr. Yun Zhang is an assistant professor in the Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada. He received his PhD degree from the Free University of Berlin, Germany (1997). He has more than 10 years of first-hand research experience in remote sensing image processing, including image fusion and feature extraction. He has worked with a variety of universities and national research institutes worldwide, such as German Aerospace Center (DLR), Technical University of Berlin, and Wuhan University. He is a holder of many international and national scholarships and awards.