Appl Geomat (2017) 9:1–12
DOI 10.1007/s12518-016-0179-2

ORIGINAL PAPER

# Evaluation of pan-sharpening methods for spatial and spectral quality

**Jagalingam Pushparaj**[1] **· Arkal Vittal Hegde**[1]

Received: 20 May 2016 / Accepted: 5 December 2016 / Published online: 13 December 2016
© Società Italiana di Fotogrammetria e Topografia (SIFET) 2016

**Abstract** Many pan-sharpening methods have been proposed to fuse the high spectral and low spatial resolution of multispectral (MS) image with the high spatial resolution of panchromatic (PAN) image to produce a multispectral image with improved spatial resolution. In this study, the effectiveness of pan-sharpening methods such as principal component analysis (PCA), brovey transform (BT), modified intensity hue saturation (M-IHS), multiplicative, wavelet-intensity-hue-saturation (W-IHS), wavelet principal component analysis (W-PCA), hyperspectral colour space (HCS), high-pass filter (HPF), gram-schmidt (GS), subtractive resolution merge (SRM), Fuze Go and Ehlers was assessed and compared by fusing the PAN and MS imagery of Quickbird-2. The qualities of the pan-sharpening methods were evaluated by both visual and quantitative analyses with respect to spatial and spectral fidelity. In quantitative analysis, the spectral indices such as spectral angle mapper (SAM), relative dimensionless global error in synthesis (ERGAS), structural similarity index method (SSIM), relative average spectral error (RASE), correlation coefficient (CC) and universal image quality index (Q) were used. The spatial indices such as spatial correlation coefficient (SCC), gradient and image entropy (*E*) were used. The result of both analyses revealed that the Ehlers and Fuze Go methods performed better than the other methods. The Ehlers method was superior by retaining the colour information, and Fuze Go best enhanced the spatial details in the fused image.

✉ Jagalingam Pushparaj
lingam.jai10@gmail.com

Arkal Vittal Hegde
arkalvittal@gmail.com

[1] Department of Applied Mechanics and Hydraulics, National Institute of Technology Karnataka, Surathkal, Mangaluru 575025, India

**Keywords** Pan-sharpening · Spectral and spatial quality · Quantitative analysis · Qualitative analysis

## Introduction

In remote sensing systems, the earth-observing satellites such as Quickbird, Worldview, Ikonos, Landsat and IRS series provide satellite image with increased number of spectral bands, and also, spatial resolution of the image is enhanced significantly. This satellite captures the images of earth with panchromatic (PAN) and multispectral (MS) sensors. The PAN sensors offer image with high spatial resolution. On the other hand, the MS sensors offer image with high spectral resolution but low spatial resolution when compared to the PAN image (Zhang and Mishra 2013). Generally, PAN image covers wider spectral wavelength whereas MS image covers the minute range of wavelength. Thus, there is a trade-off between the sensors in the form of spatial resolution, spectral resolution and swath width, etc., which are caused due to technical and budget limitations (Yun Zhang 2004a, b). PAN image with high spatial resolution is good for urban studies and feature extraction whereas the MS image with high spectral resolution is good for land use land cover (LULC) studies Ranchin and Wald (2000).

For many remote sensing applications, the satellite image with high spatial and the high spectral information is often required. It means that high spatial resolution and the spectrum information must be precisely offered by a single image. Till date, remote sensing sensor cannot offer a single image with both high spatial and high spectral resolutions. Therefore, to meet this goal, various pan-sharpening or image fusion methods have been proposed to improve the spatial resolution of MS image including principal component analysis (PCA) (Chavez and Kwarteng 1989), brovey transform (BT) (Hallada and Cox 1983), modified intensity hue saturation (M-IHS) (Siddiqui 2003), hyperspectral colour space (HCS) (Padwick et al. 2010), high-pass filter (HPF) (Chavez et al. 1991), gram-schmidt (GS) (Laben and Brower 2000), multiplicative (Crippen 1989), Ehlers (Ehlers et al. 1984) and subtractive resolution merge (SRM) (Ashraf et al. 2012). Some hybrid pan-sharpening methods such as wavelet principal component analysis (W-PCA) and wavelet-intensity-hue-saturation (W-IHS) are also used widely nowadays. These hybrid methods work on the principle of wavelet decomposition (Ranchin and Wald 1993; King and Wang 2001). More details of these hybrid methods can be found in González-Audícana et al. (2005).

Image fusion is the process of transferring the spatial resolution of PAN image to MS image to obtain a single (fused) image with both high spatial and spectral resolutions (Zhang 2010). During the process of image fusion, the two most key quality aspects of fused images are the enhancement of spatial resolution and preservation of spectral information. In other words, the effectiveness of image fusion algorithm should not distort the spectral information of an MS image while enhancing the spatial resolution.

In order to evaluate the performance of the pan-sharpening methods, researchers have proposed visual and quantitative analyses. The visual analysis evaluates the quality of fused image by visual interpretation (Fonseca et al. 2011), while the quantitative analysis is adopted by two approaches namely with reference image and without reference image. When the reference image is available, the following quality metrics such as root-mean-square error (RMSE) (Zoran 2009), spectral angular mapper (SAM) (Alparone et al. 2007), relative dimensionless global error in synthesis (ERGAS) (Du et al. 2007), mean bias (MB) (Yusuf et al. 2013), percentage fit error (PFE) (Naidu 2010), signal-to-noise ratio (SNR) (Alimuddin et al. 2012), peak signal-to-noise ratio (PSNR) (Naidu 2010; Harish Kumar and Singh 2010), correlation coefficient (CC) (Vander Meer 2006), universal quality index (UQI) (Alparone et al. 2008), relative average spectral error (RASE) (Wald 2000), structural similarity index measure (SSIM) (Wang et al. 2004), spatial correlation coefficient (SCC) (Zhou et al. 1998; Choi 2006), gradient (Wu et al. 2015) and image entropy ($E$) (Du et al. 2007) are used. When the reference image is not available, the quality of the fused image is evaluated by using the following quality metrics such as standard deviation ($\sigma$) (Wang and Chang 2011), spatial frequency (SF) (Yang et al. 2010) and quality with no reference image (Alparone et al. 2008). More details of quantitative analysis can be found in Shahdoosti and Ghassemian (2015), Vivone et al. (2014), Aiazzi et al. (2011) and Jagalingam and Hegde (2015).

Recently, many studies have evaluated and compared the efficiency of different pan-sharpening methods by using quality metrics. Table 1 summarizes some comparative study of pan-sharpening methods in very high-resolution image using a variety of quality metrics. It is evident that most of the pan-sharpening methods generate spatial and spectral distortions in the fused image. Therefore, the selection of best pan-sharpening methods for improving the spatial resolution and for retaining the spectral information of MS image is challenging. As the availability of new satellite images has improved, there is a need to reevaluate the existing pan-sharpening methods. In the present study, the Fuse Go method is adopted to fuse the PAN and MS imagery of Quickbird-2 and the effectiveness of this method is compared with the well-known pan-sharpening methods. All of these methods are evaluated and compared by using visual analysis and spatial and spectral metrics.

The main objective of this study is to evaluate the quality of fused image. In particular, it assesses the spectral and spatial

**Table 1** Detailed survey of various comparison studies of pan-sharpening methods

| Pan-sharpening methods | Satellite image | Quality metrics used | References |
|---|---|---|---|
| PCA, AIHS, IAIHS, proposed GFIHS | Ikonos Quickbird | CC, ERGAS, Q, RASE, RMSE, SAM, SID, SC | Jameel et al. (2016) |
| HCS and Enhanced HCS | World view-2 Quickbird | Visual, UIQI, ERGAS, SSIM, SCC, entropy, gradient | Wu et al. (2015) |
| BT, GS, PCA, IHS | Ikonos Quickbird | CC, RMSE and SSIM | Sarp (2014) |
| Brovey, IHS, eFIHS, PCA, Mallat, Atrous, Atrous-IHS, Atrous-PCA | GeoEye, Worldview, Quickbird, Ikonos | Zhou, ERGAS, CC, Spectral ERGAS, Q | Marcello et al. (2013) |
| BT, multiplicative, ModIHS, HCS, PCA, GS, HPF, PANSHARP, PANSHARP-2, wavelet-PCA, wavelet-IHS, Ehlers | Worldview-2 | RMSE, MSE, PSNR, CC, NQM, IFC, MSSIM, UIQI | Ghosh and Joshi (2013) |
| GS, PCA, GIHS, WT, HPF | ALOS Quickbird | change detection analysis | Du et al. (2013) |
| GS, HPF, M-IHS, W-PCA and FFT-enhanced IHS (FFT-E) | GeoEye-1 Quickbird | visual inspection, histogram analysis, correlation analysis | Yusuf et al. (2013) |
| GS, Ehlers, ModIHS, HPF, wavelet-PCA | Quickbird Worldview-2 | MSE, RMSE, MAE, EME, SNR, PSNR, UIQI, SVM-based classification | Alimuddin et al. (2012) |

distortion of fused image produced by various pan-sharpening methods using visual and quantitative analyses. In this study, the pan-sharpening methods such as Ehlers, SRM, Fuze Go, HPF, GS, HCS, W-PCA, W-IHS, PCA, M-IHS, BT and multiplicative are selected for evaluation due to easy access to commercial software. The selection of quantitative analysis represents the image characteristics such as spectral, spatial and structural information content. Finally, the study recommends the best pan-sharpening methods for preserving the spectral content and for enhancing the spatial resolution.

## Data used

A high-resolution imaging satellite named Quickbird-2 was launched on October 18, 2001. Quickbird-2 acquires five bands covering panchromatic, blue, green, red and near-infrared (NIR). The spectral response of Quickbird-2 imagery is shown in Fig. 1. The specifications of Quickbird-2 imagery are shown in Table 2. The satellite senor captures the PAN image with a high spatial resolution of 0.60 m and MS image with high spectral resolution but a low spatial resolution of 2.4 m. The data location is the opera house in Sydney, Australia (33° 51′ 25″ S 151° 12′ 55″ E), provided by DigitalGlobe. The wavelength range of four bands such as blue, green, red and NIR matches with the PAN band; thus, all four bands are layer stacked to obtain the MS image. The imagery of Quickbird-2 covers the features such as commercial buildings, urban area, road, vehicles, water, roof, tree, grass and shadows. In the MS image, the shape of the vehicles and building roofs are not easily identifiable; on the other hand, these are easily recognizable in the PAN image. Therefore, enhancing the spatial resolution of MS image of Quickbird-2 will help in increasing the accuracy of classification mapping and extraction of features.

## Methodology

The overall methodology adopted in the paper for examining the spatial and spectral quality of fused image is as follows: step 1: pre-processing—co-registration of PAN and MS image; step 2: selection of band, the wavelength range of MS band should match the wavelength range of PAN band; step 3: up-sampling, the spatial resolution of MS image to the PAN image; step 4: pan-sharpening methods such as PCA, M-IHS, BT, W-PCA, W-IHS, HPF, GS, HCS, multiplicative, Ehlers, SRM and Fuze Go are processed to obtain the fused image; step 5: quality of fused image is evaluated using qualitative and quantitative analysis; and step 6: the selection of best fused image. The detailed explanations of each step are given in the following:

### Pre-processing

The accurate co-registration of PAN and MS images for a pan-sharpening method is very important. However, in the present study, both PAN and MS images of Quickbird-2 are acquired by the same sensor at the same time. Thus, the images are processed directly without co-registration (Padwick et al. 2010).

### Band selection

In general, the wavelength range of PAN image and MS image should be the same. The spectral range of blue, green, red and

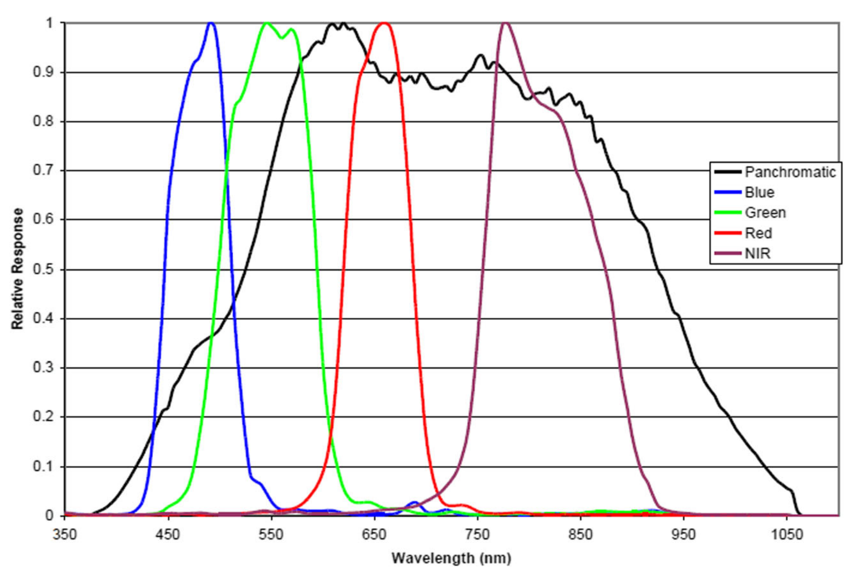



**Fig. 1** Spectral response of the Quickbird-2 sensor system (source: DigitalGlobe)

**Table 2** Specifications of Quickbird-2 imagery

| Satellite/sensor name | Bands | Resolution (in m) | Spectral range (in nm) |
|---|---|---|---|
| Quickbird-2/EarlyBird Panchromatic (EBP) | PAN | 0.61 | 405–1053 |
| Quickbird-2 EarlyBird Multispectral (EBM) | Blue | 2.4 | 430–545 |
| | Green | 2.4 | 466–620 |
| | Red | 2.4 | 590–710 |
| | NIR | 2.4 | 715–918 |

NIR matches the wavelength range of PAN. Hence, all these bands are selected for fusing with the PAN image.

## Resampling

The up-sampling of the original MS image to the spatial resolution of the PAN image is an important prerequisite for performing many pan-sharpening techniques. The most common resampling methods are nearest neighbour, bilinear interpolation and cubic convolution. The best suitable resampling methods for pan-sharpening technique were selected on the basis of the present literature, as well as recommendation in the software manuals.

## Pan-sharpening methods

### *Principal component analysis*

The principal component analysis method translates the original MS image into a new set of uncorrelated images called principal components. The first principal component (PC1) is a good indicator of PAN image (spatial information) and PC2,…, PCn collects the spectral data of MS image. Therefore, PC1 is replaced by the PAN, and finally, the inverse transformation is applied to obtain a fused image.

### *Brovey transform*

The Brovey transform is a simple image fusion method that injects the overall brightness of the PAN image into each pixel of the MS image according to an algebraic expression. The general mathematical formula of BT based fusion is

$$DN(i)_{\text{fused}} = \left[ DN(i) \Big/ \sum DN(i) \right] \times DN_{\text{PAN}} \quad (1)$$

### *Multiplicative*

The multiplicative method works by processing a simple multiplicative algorithm. The following equation is used to merge two rasters PAN and MS images.

$$(DN_{\text{PAN}}) \times (DN_{\text{MS}}) = DN_{\text{newMS}} \quad (2)$$

This method is simple and is one of the quickest methods for fusing two different datasets.

### *Modified intensity hue saturation and hyperspectral colour space*

Modified intensity hue saturation and hyperspectral colour space use the concept of replacing the intensity component with the PAN band. To derive the intensity component, the original spectral bands of the MS image are transferred to colour space. The IHS method has a limitation of merging only three bands whereas M-IHS and HCS merge more than three bands. The M-IHS method first estimates the overlap of the wavelength range between each MS band and PAN band. The method improves the quality of the fused image when the wavelength ranges of both PAN and MS images are overlapped. The HCS method replaces the intensity component of the MS image in the hyperspherical colour space with the intensity-matched form of the PAN band.

### *Wavelet-intensity-hue-saturation and wavelet principal component analysis*

Wavelet-intensity-hue-saturation and wavelet principal component analysis are hybrid methods that work on the principle of the wavelet decomposition of the image. The IHS or PCA transformation is performed prior to wavelet analysis. The working process of W-IHS and W-PCA is schematically represented in Fig. 2.

### *High-pass filter*

The high-pass filter method computes the ratio 'R' between the spatial size of the PAN and MS images. A small high-pass filter is placed on the PAN image, and the pixel size of the MS image is resampled to that of the high-pass PAN image. The filtered high-pass PAN image is added to the resampled MS image to obtain a merged image with both high spatial and rich spectral information.

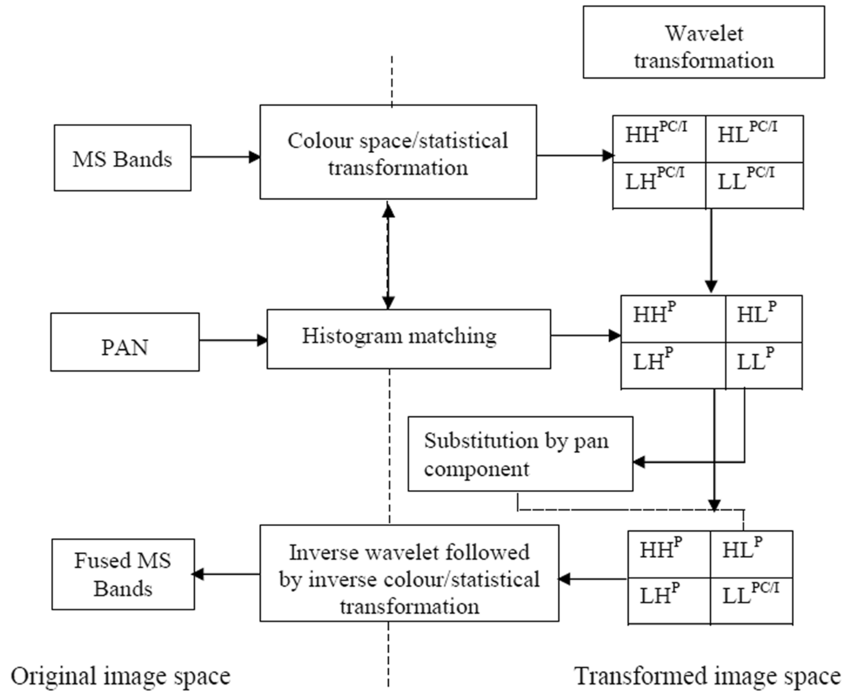



**Fig. 2** General flowchart for the wavelet-based method

*Gram-Schmidt*

The basic concept of the GS method is to simulate a high-resolution PAN band from the low spatial MS bands with appropriate weights. GS transformation is executed by using the simulated PAN band as the first band. Later, the first band of the GS transformation is replaced with the high resolution of PAN image; the inverse GS transformation is applied to generate a pan-sharpened MS image.

*Ehlers*

The Ehlers fusion involves an FFT-enhanced IHS transformation of the original MS image. The method is iteratively executed with a combination of all bands (Ehlers et al. 1984). The extensive details of this method can be found in Klonus and Ehlers (2007). The working process of Ehlers is schematically represented in Fig. 3.

*Subtractive resolution merge*

The SRM method generates a low-resolution panchromatic synthetic (LRPISYN) image from the weighted sum of the LRMI bands. This LRPISYN is then up-sampled to a high-resolution panchromatic synthetic (HRPISYN) image and then subtracted from HRPI (which is not synthetic), which provides the edge details. The SRM also uses a mix of HPF and LPF to control spatial details. Spectral detail is maintained through the use of a normalization function and panchromatic contribution weights.

*Fuze Go*

The Fuze Go method achieves a pan-sharped MS image by implementing the following process: The MS bands having a spectral range equal to that of the PAN band are selected. Standard deviation, mean and covariance are calculated for both the selected MS band and the PAN band. Then, histogram standardization is implemented on both bands. By implementing the mean and standard deviation, all of the selected sets of MS and PAN bands are standardized. The coefficient values are computed by applying the selected MS and PAN bands. Band weights calculated from the covariance matrix are applied for simulating a synthetic PAN band. Subsequently, a synthetic PAN band is created by applying the selected MS bands and set weights. The product-synthetic ratio is determined by applying the standardized PAN band, standardized MS bands and synthetic PAN image to obtain the fused image. Further details can be found in (Zhang (2004a, b). A flowchart for the Fuze Go method is shown in Fig. 4.

All of the pan-sharpening methods such as PCA, M-IHS, HCS, BT, multiplicative, W-IHS, W-PCA, HPF, Ehlers and SRM are processed using ERDAS imagine 2014. The GS method was processed using ENVI 5.1. The Fuze Go method was performed using the Fuze Go tool (http://www.fuze go.com). The processing of each pan-sharpening method was done based on the suggestions in the software manuals and also on the basis of the existing literature.

## Quality assessment of pan-sharpened images

Assessing the quality of fused image is very important in remote sensing applications. The main theme of a pan-sharpening

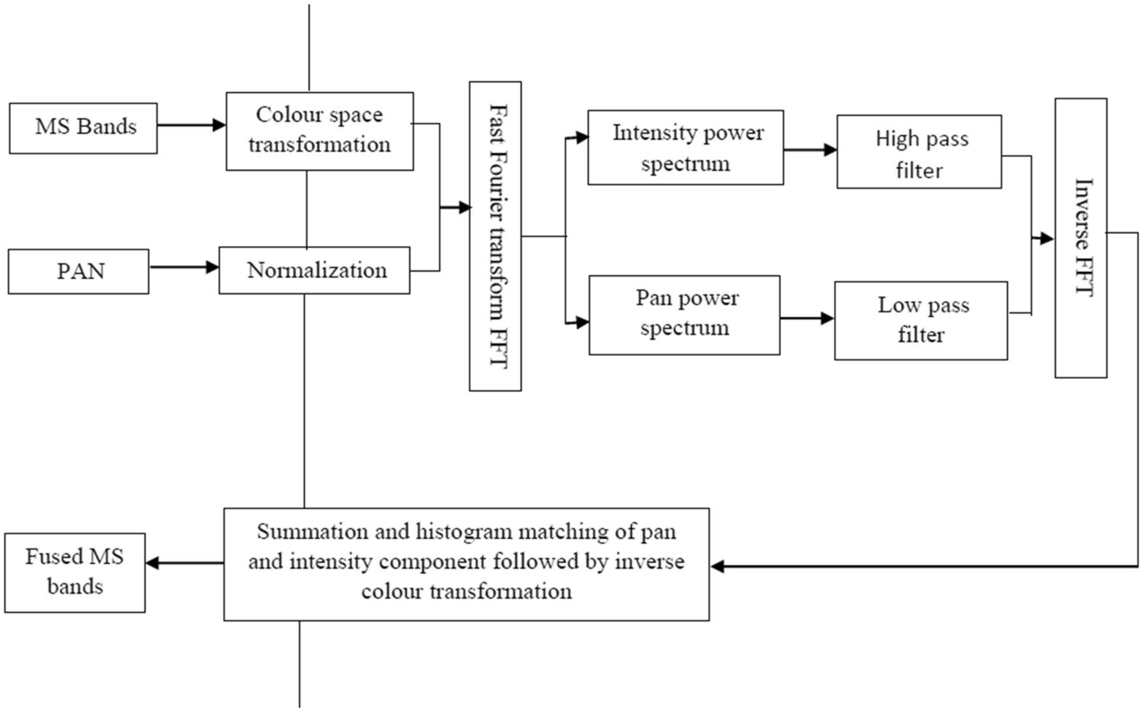



**Fig. 3** General flowchart for the Ehlers method

method are to preserve the relevant information that presents in the input images and to reduce the spatial and spectral distortion of fused image. Hence, the performance of different pan-sharpening methods is evaluated using visual and quantitative analyses.

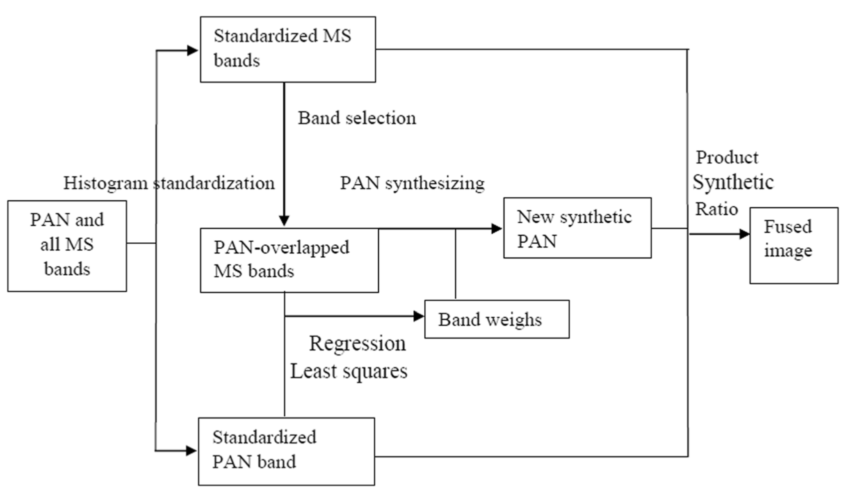
*Visual analysis*

Visual analysis is a well-known qualitative analysis. In this analysis, the viewer compares the fused image with original MS and PAN images by considering the visual quality parameters such as spatial details, spectral characteristic and size of objects. In particular, we compared the fused image visually with original MS and PAN images to find out which fused image has higher spatial and spectral distortion.

*Quantitative analysis*

Quantitative analysis is based on the mathematical model, and it is also known as an objective analysis. It compares the spectral and spatial quality of fused image with a reference image and without the reference image. In this study, spectral indices such as SAM, CC, SSIM, RASE,

**Fig. 4** General flowchart for the Fuze Go method



ERGAS and Q are used to assess the spectral quality of fused image in comparison with the reference MS image. In order to process these indices, reference MS image with the same size as that of PAN image is required. In reality, obtaining a reference image with this requirement is challenging. Nevertheless, a reference image can be obtained by resampling of the original MS image to the size of the PAN image (Gangkofner et al. 2008). The spatial indices such as SCC, gradient and $E$ are used to evaluate the spatial quality of fused image with original PAN as a reference image.

### Quantitative indices for assessing spectral distortion

*Spectral angle mapper*

Spectral angle mapper indicates the value of a spectral angle between two vectors produced from each pixel of reference and fused images. To obtain a value of SAM between the fused and the reference images, each consists $L$ and $B$ bands and two spectral vectors $v$ and $w$ are constructed and both having L components. The ideal value zero indicates the best spectral quality of the fused image. The following equation is used to compute the value of SAM:

$$\cos^{-1}\left(\frac{\sum_{i=1}^{L} v_i w_i}{\sqrt{\sum_{i=1}^{L} v_i^2}\sqrt{\sum_{i=1}^{L} w_i^2}}\right) \tag{3}$$

where $v = \{v_1, v_2, \ldots.., v_L\}$ with $v_k = B(k)(i,j)$ corresponding to pixel $(i,j)$. In the $k^{th}$ original band, $w = \{w_1, w_2, \ldots., w_L\}$ with $w_k = \text{Fused } B(k)(i,j)$ corresponding to pixel $(i,j)$ in the $k^{\text{th}}$fused band

*Correlation coefficient*

Correlation coefficient represents the similarity of the spectral features between the reference and fused images. The ideal value one is the best spectral performance of the fused image. The general mathematical form of CC is

$$\frac{\sigma_{xy}}{\sigma_x \sigma_y} \tag{4}$$

*Relative dimensionless global error in synthesis and relative average spectral error*

Relative dimensionless global error in synthesis and relative average spectral error compute the quality of fused image in terms of normalized average error of each band of processed image. The increase in the value of ERGAS and RASE indicates distortion in the fused image. The ideal value is zero. It is calculated using the following formula:

$$100\frac{h}{l}\sqrt{\frac{1}{N}\sum_{k=1}^{N}\frac{\text{RMSE}(B_k)^2}{\overline{x}_k^{\,2}}} \tag{5}$$

$$\frac{100}{\overline{x}}\sqrt{\frac{1}{N}\sum_{k=1}^{N}\text{RMSE}(B_k)^2} \tag{6}$$

*Universal image quality index (Q)*

Universal image quality index represents contrast and brightness distortions and correlation difference between the fused and reference images. The ideal value 1 is the best spectral performance of the fused image. The mathematical form of Q is

$$\frac{4\sigma_{xy}\overline{x}\,\overline{y}}{\left(\sigma_x^2+\sigma_y^2\right)\left[\overline{x}^2+\overline{y}^2\right]} \tag{7}$$

Note that for CC to Q, $x$ is the reference image, $y$ is the fused image, $\sigma$is the standard deviation, and $\frac{h}{l}$ represents the high to low spatial resolution ratio. $N$is the number of spectral bands, $B_k$is the spectral band $k$ and $\overline{x}_k$ is the mean value of band $(B_k)$of the original image, and $\overline{x}$ and $\overline{y}$ are the means of $x$and$y$, respectively.

*Structural similarity index method*

The structural similarity index method compares the local patterns of pixel intensities between the reference and fused images. The value 1 denotes the best fused image. The mathematical form of SSIM is

$$\frac{\left(2\mu_{I_r}\mu_{I_f}+C_1\right)\left(2\sigma_{I_r}\sigma_{I_f}+C_2\right)}{\left(\mu^2 I_r+\mu^2 I_f+C_1\right)\left(\sigma^2 I_r+\sigma^2 I_f+C_2\right)} \tag{8}$$

where $\mu_{I_r}$ is the mean value of the reference image, $\mu_{I_f}$ is the mean value of the fused images, and $\sigma_{I_r}$ and $\sigma_{I_f}$ are standard deviations of reference and fused images, respectively, while $C_1$ and $C_2$ are constants.

### Quantitative indices for assessing spatial distortion

*Gradient*

The larger value of $G$ denotes high gradation of the image and high spatial detail. The value of $G$ is computed using the following formula:

$$G = \frac{1}{(M-1)(N-1)} \sum_{i=1}^{m} \sum_{j=1}^{n} \sqrt{\frac{1}{2}\left[\Delta \mathrm{xf}(i,j)^2 + \Delta \mathrm{yf}(i,j)^2\right]} \tag{9}$$

where $\Delta \mathrm{xf}(i,j)$ and $\Delta \mathrm{yf}(i,j)$ are the first-order differences of pixel $(i,j)$along $x$ and $y$ directions.

*Spatial correlation coefficient*

Spatial correlation coefficient represents the similarity of the spatial features between the PAN and fused images. The value of SCC differs from −1 to 1. The higher value of SCC represents the best fused image with high spatial detail. The mathematical form of SCC is expressed as

$$\mathrm{SCC}(F,G) = \frac{\sum\sum (F_i-\mu_F)^2 (G_i-\mu_G)^2}{\sqrt{\sum (F_i-\mu_F)^2 \sum (G_i-\mu_G)^2}} \tag{10}$$

where $G$ is the fused image and $F$is the pan image, $\mu_F$is the mean of the pan image, and $\mu_G$is the mean of the fused image.

*Image entropy (E)*

Image entropy measures the information content of the fused image. The higher value of $E$ denotes the fused image with more spatial information. The equation of $E$ is expressed as

$$E = -\sum_{i=0}^{N-1} P(i)\ln[P(i)] \tag{11}$$

where $P(i)$ indicates the pixel occurrence frequency of greyscale value $i$ in the image and $N$ is the greyscale level of the pixel.

## Results and discussions

The true MS, PAN and resampled MS images of Quickbird-2 are shown in Fig. 5a–c. The fused images of Quickbird-2 generated by 12 pan-sharpening methods are shown in Figs. 6a–f and Fig. 7a–f. The image size of Quickbird-2 is 16.5 km × 16.5 km. Since the size of an image is large, it was not promising to compare every individual feature visually; therefore, subset images are presented to highlight the effect of different pan-sharpening methods.

### Visual analysis

To conduct a concrete estimation and to compare the spatial and spectral quality of fused images, all of the fused and original PAN and MS images of Quickbird-2 are exhibited at the same zoom level. The MS and fused images of Quickbird-2 are presented in the RGB colour approach, as bands 4, 3 and 2 are assigned to each corresponding colour.

The fused image of PCA (Fig. 6a) exhibits improvement in the spatial resolution, while the spectral information was unchanged. The BT-fused image (Fig. 6b) enhancement of spatial information was noted but not as identical to the original PAN image, and minor colour variation (spectral distortion) was also observed. The BT method generates the fused image by increasing the colour intensity, which is not identical to the original MS image. The fused image of M-IHS (Fig. 6c) increases the spatial resolution, which is equal to the PAN image, but minor spectral variation was observed. The multiplicative fused image (Fig. 6d) exhibits high spatial and spectral distortion, which is not equal to the original MS and PAN images. The red colour of vegetation in the original MS image has changed to rose colour; therefore, it was visualized that the method produced fused image with high colour variation and exposed less spatial improvement; thus, the multiplicative method delivered an unacceptable fused image.

The fused image of W-IHS (Fig. 6e) improved the spatial resolution, but minor spectral distortion was observed when compared to the original MS image. The fused image of W-PCA (Fig. 6f) exhibits improvement in the spatial resolution, and minor colour distortion was identified. It can be noted that fused images from W-IHS and W-PCA are identical to each other. The HCS-fused image (Fig. 7a) retains the spectral information of the original MS image, but minor spatial distortion was identified. The fused image of HPF (Fig. 7b) increment in the spatial detail was noticed, and minor colour variation appears in the fused image compared to the original MS image. The fused image of GS (Fig. 7c) improvement in the spatial detail was noted, but edges of the building are less sharpened and also changes in the spectral information were notable. The red colour of vegetation in the original MS image has changed to a dark colour; hence, changes in the spectral information were visualized.

The fused image of SRM (Fig. 7d) improved the spatial information and also colour information was retained, which is nearly equal to the original MS and PAN images. The fused image of Fuse Go (Fig. 7e) retains the spectral information of the original MS image; correspondingly, spatial detail is identical to the original PAN image. The fused images of Ehlers


**Fig. 5** Quickbird-2 original MS (**a**), PAN (**b**) and resampled MS (**c**)

(Fig. 7f) edges are not sharpened enough, and colour information is nearly identical to the original MS image.

In general, all the pan-sharpening methods improved the spatial resolution of fused image. By comparing the fused image of PCA, M-IHS, multiplicative and BT, the multiplicative method generates the fused image with high spatial and spectral distortion. The M-IHS and BT produced fused image with minor colour variation. The M-IHS best improved the spatial details than the BT image. The PCA method performed better than the M-IHS, multiplicative and BT by better preserving the spectral information and also improved the spatial detail, which closely matched the original PAN and MS images. In comparison, with the fused image of W-IHS, W-PCA and HCS, the minor spectral distortion was noted in both W-IHS- and W-PCA-fused images. The HCS method best preserved the spectral information of the original MS image compared to the fused image of W-IHS and W-PCA. However, the spatial information was better improved in the W-IHS and W-PCA when compared to the HCS method.

The fused images generated by the HPF and GS methods were compared together, the method HPF improved the spatial details, but the GS method lacks sharpening the spatial information in the fused image. The GS and HPF methods generated colour variation. However, the HPF best retained the spectral information in the fused image than the GS method. In comparing the fused images of Ehlers, Fuse Go and SRM, the fused image of Ehlers was noticed with minor spatial distortion. The fused image of SRM enhanced the spatial information but not as equal to that of the Fuse Go method. However, better improvement of spatial detail was observed in the Fuse Go method over the Ehlers and SRM. The methods Ehlers, SRM and Fuse Go retained the spectral information, which is nearly identical to each other; however, the Ehlers method best retained the spectral information in the fused image.

From the visual analysis, it was found that all the pan-sharpening methods improved the spatial detail, but the multiplicative method generated the fused image with high spatial and spectral distortion. The spectral information was best retained by the Ehlers, Fuse Go, SRM and PCA methods. The better improvement in the spatial detail was observed by the Fuse Go, HPF and SRM methods. Overall, the Fuse Go method performed best by improving the spatial information in the fused image followed by the HPF and SRM methods. The spectral information was best retained in the fused image of Ehlers followed by the Fuse Go and HCS methods.

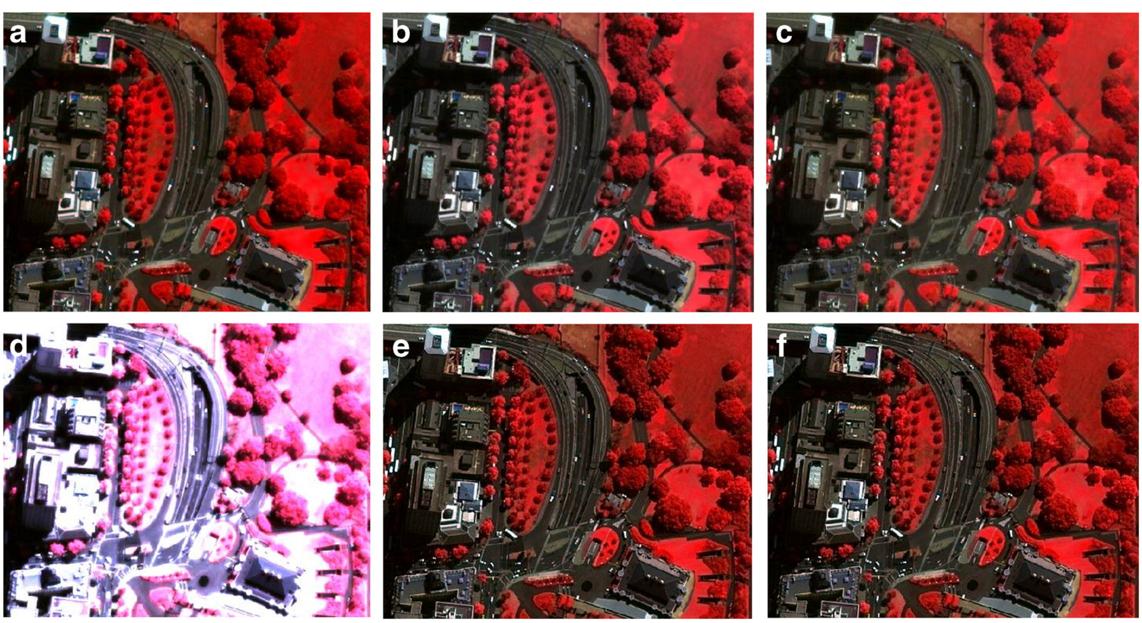



**Fig. 6** Fused image of PCA (**a**), BT (**b**), M-IHS (**c**), multiplicative (**d**), W-IHS (**e**) and W-PCA (**f**)

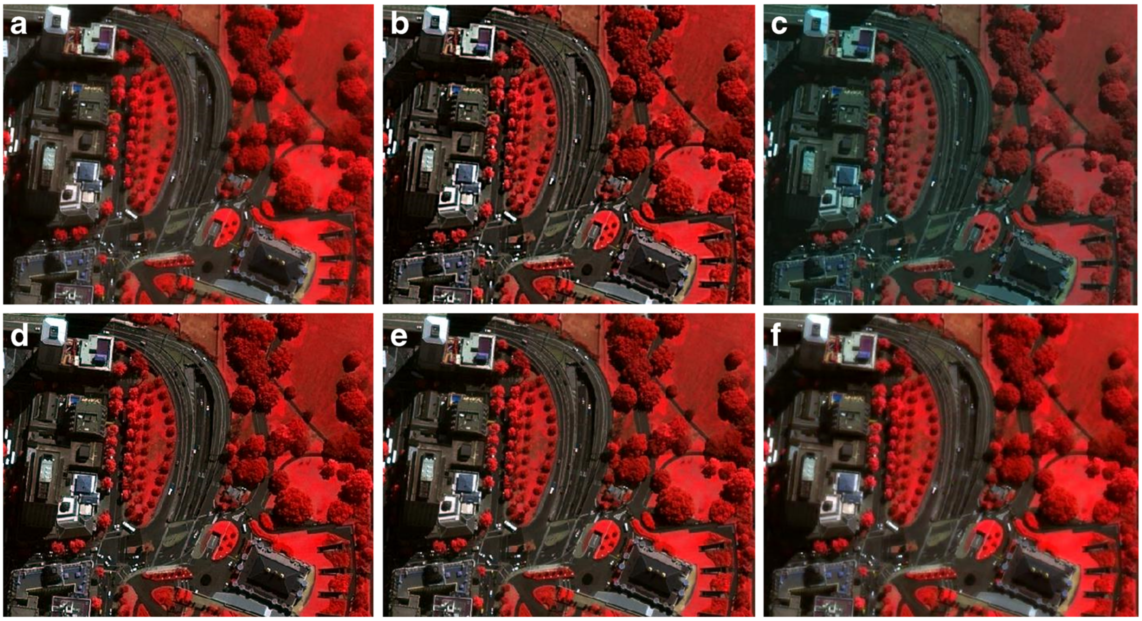



**Fig. 7** Fused image of HCS (**a**), HPF (**b**), GS (**c**), SRM (**d**), Fuse Go (**e**) and Ehlers (**f**)

## Quantitative analysis

To validate the results of the qualitative analysis, the aforementioned nine statistical indices were performed to assess the quality of Quickbird-2 fused images. These indices require the following conditions to be satisfied for selecting the best fused image with high spatial details and spectral information: (i) SCC, CC, Q and SSIM should be close to one; (iii) SAM, ERGAS and RASE should be close to zero; and (iv) gradient and *E* should have a higher value. The results obtained from the nine statistical indices are shown in Tables 3 and 4 in which the best fused images for each statistical index are labelled in italics.

Table 3 represents the results of six spectral indices; the results of SAM indicate that the value of the Ehlers method is closest to the original values of SAM followed by the Fuse Go and W-PCA methods; therefore, the Ehlers method retained the maximum spectral information in the fused image similar to the original image. The CC value indicates that the Fuze Go method generated a pan-sharpened image with the highest spectral information followed by Ehlers and HPF methods.

The results of the SSIM index show that the value obtained by the Ehlers method was very close to the original value of SSIM; thus, this method is superior followed by Fuze Go and HPF. The statistical value obtained by the RASE index indicates that the index value of the Ehlers method is superior, followed by the HCS and Fuze Go methods. The statistical results of the ERGAS index show that the value of the HCS method was identical to the original value of ERGAS followed by the Ehlers and Fuze Go methods. The Q index indicates that the value of the SRM method was very close to the original value of Q followed by the Ehlers and Fuze Go methods.

Table 4 represents the results of three spatial quality indices; the results of the SCC index show that the value obtained by the Fuze Go method was very close to the original value of SCC; thus, this method is superior followed by HPF and SRM. The highest value of gradient was obtained by the

**Table 3** Spectral performance comparison of different pan-sharpening methods

| Fusion methods<br>Spectral indices | PCA | BT | M-IHS | Multiplicative | W-IHS | W-PCA | HCS | HPF | GS | SRM | Fuse Go | Ehlers |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAM | 5.6934 | 6.7291 | 5.8652 | 7.2374 | 4.2459 | 4.1984 | 5.2987 | 4.9415 | 4.5645 | 4.4564 | 3.4279 | *3.1374* |
| CC | 0.5876 | 0.6216 | 0.6680 | 0.4619 | 0.6874 | 0.6453 | 0.6106 | 0.7260 | 0.6829 | 0.7124 | *0.8359* | 0.8126 |
| SSIM | 0.6126 | 0.5126 | 0.5821 | 0.1825 | 0.6248 | 0.6531 | 0.5525 | 0.8354 | 0.6939 | 0.7156 | 0.8975 | *0.9124* |
| RASE | 6.3181 | 7.4788 | 8.2015 | 14.0123 | 7.1438 | 6.9374 | 6.0376 | 7.7102 | 7.7238 | 6.9814 | 6.1277 | *5.5004* |
| ERGAS | 5.7194 | 5.2851 | 6.3439 | 12.0914 | 4.9972 | 4.1247 | *1.4916* | 3.9537 | 4.0728 | 4.8435 | 3.5494 | 2.4517 |
| Q | 0.5825 | 0.5294 | 0.5939 | 0.2167 | 0.6689 | 0.6907 | 0.6868 | 0.6746 | 0.6973 | *0.8940* | 0.7915 | 0.8124 |

Best fused images for each statistical index are labelled in italics

**Table 4** Spatial performance comparison of different pan-sharpening methods

| Fusion methods<br>Spatial indices | PCA | BT | M-IHS | Multiplicative | W-IHS | W-PCA | HCS | HPF | GS | SRM | Fuse Go | Ehlers |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SCC | 0.6591 | 0.6076 | 0.7483 | 0.5367 | 0.7241 | 0.7129 | 0.7029 | 0.8895 | 0.7353 | 0.8123 | *0.9113* | 0.7131 |
| Gradient | 3.5317 | 3.8177 | 3.9222 | 1.0489 | 4.1741 | 4.0269 | 3.9271 | 5.0191 | 3.8807 | 4.7647 | *5.5737* | 3.8124 |
| *E* | 5.7177 | 5.5449 | 5.3031 | 1.2348 | 6.0189 | 6.5949 | 4.9769 | 6.8436 | 5.8037 | *7.5436* | 7.1288 | 5.4389 |

Best fused images for each statistical index are labelled in italics

Fuze Go method followed by the HPF and SRM methods; therefore, the Fuze Go method generated the fused image with high spatial information. The results of the *E* index indicate that the highest value was obtained by SRM followed by the Fuze Go and HPF methods.

Overall, to obtain detailed information in spectral domain, the majority of spectral indices indicate that the Ehlers method is best for retaining the spectral information. Similarly, in the spatial domain, the Fuse Go method was found to be best for enhancing the spatial detail.

## Conclusions

In this study, the effectiveness of the Fuse Go method is examined with the well-known pan-sharpening methods such as PCA, M-IHS, BT, W-PCA, W-IHS, HPF, GS, HCS, multiplicative, Ehlers and SRM by fusing the PAN and MS imagery of Quickbird-2 imagery. All of the fused images were assessed and compared by both visual and quantitative analyses. In general, the result of both the analyses revealed that all of the pan-sharpening methods improved the spatial resolution of the fused image.

The result of visual analysis revealed that the fused image of Ehlers, Fuse Go, SRM, HCS and PCA methods best retained the colour information of the original MS image. However, better improvement of spatial detail was observed by the fused image of the Fuse Go, HPF and SRM methods. The fused image of Ehlers and Fuse Go looked to be identical, but the Ehlers method performed best for retaining the spectral information while better spatial improvement was observed by the Fuse Go method.

The result of spectral indices revealed that the Ehlers method performed better for retaining the spectral information of the original MS image. The result of spatial indices revealed that the Fuse Go method best enhanced the spatial information. The result of both visual and quantitative analyses shows that the fused image of multiplicative contains high spatial and spectral distortion; therefore, the method generates an unsatisfactory fused image.

After the assessment of different pan-sharpening methods, it is revealed that the pan-sharpening methods cannot simultaneously improve the spatial details without degrading the spectral information. Therefore, it is very important to have a knowledge about the advantage of pan-sharpening methods in the specific application considered.

The remote sensing applications such as (change detection, extraction of features, spectral analysis, etc.) require a single image with both high spatial and high spectral information. Therefore, the qualities of 12 pan-sharpening methods are assessed and found that the Ehlers method can be used for certain applications, which demands high spectral fidelity with sufficient spatial quality. On the other hand, the Fuse Go method can be used when the maximum spatial detail is necessary.

Due to the financial and technical constrains, it is difficult for the satellite sensors to obtain an image with spectral resolution of MS image and spatial resolution of PAN image; therefore, the economic alternate solution for the sensors problems is the pan-sharpening method, to have an image with spectral resolution of MS image and spatial resolution of PAN image.

## References

Aiazzi, B, Alparone L, Baronti S, Garzelli A, Selva M (2011) Twenty-five years of pan sharpening, 2nd edition: 533–548. doi: 10.1201/b11656-30

Alimuddin I, Sumantyo JTS, Kuze H (2012) Assessment of pan-sharpening methods applied to image fusion of remotely sensed multi-band data. Int J Appl Earth Obs Geoinf 18:165–175. doi:10.1016/j.jag.2012.01.013

Alparone L, Aiazzi B, Baronti S, Garzelli A, Nencini F, Selva M (2008) Multispectral and panchromatic data fusion assessment without reference. Photogramm Eng Remote Sens 74:193–200

Alparone L, Wald L, Chanussot J, Thomas C, Gamba P, Bruce L (2007) Comparison of Pansharpening algorithms: outcome of the 2006 GRS-S data-fusion contest. IEEE Trans Geosci Remote SENSINGI 45:3012–3021

Ashraf S, Brabyn L, Hicks BJ (2012) Image data fusion for the remote sensing of freshwater environments. Appl Geogr 32:619–628. doi:10.1016/j.apgeog.2011.07.010

Chavez P, Sides SC, Anderson JA (1991) Comparison of three different methods to merge multi resolution and multispectral data: Landsat TM and SPOT panchromatic. Photogramm Eng Remote Sens 57(03):295–303

Chavez PST, Kwarteng AY (1989) Extracting spectral contrast in Landsat Thematic Mapper image data using selective principal component analysis. Photogramm Eng Remote Sensing 55:339–348

Choi M (2006) A new intensity-hue-saturation fusion approach to image fusion with a tradeoff parameter. IEEE Trans Geosci Remote Sens 44(6):1672–1682

Crippen RE (1989) A simple spatial filtering routine for the cosmetic removal of scan-line noise from Landsat TM P-tape imagery. Photogramm Eng Remote Sensing 55:327–331

Du P, Liu S, Xia J, Zhao Y (2013) Information fusion techniques for change detection from multi-temporal remote sensing images. Information Fusion 14(1):19–27. doi:10.1016/j.inffus.2012.05.003

Du Q, Younan NH, King R, Shah VP (2007) On the performance evaluation of pan-sharpening techniques. IEEE Geosci Remote Sens Lett 4:518–522. doi:10.1109/LGRS.2007.896328

Ehlers MED-M, Kolouch D, Lohman P, Dennert-Möller E (1984) Nonrecursive filter techniques in digital processing of remote sensing imagery. In: Pres. Paper Xvth Int: 163–175

Fonseca L, Namikawa L, Castejon E (2011) Image fusion for remote sensing applications. InTech

Gangkofner UG, Pradhan PS, Holcomb DW (2008) Optimizing the high-pass filter addition technique for image fusion. Photogramm Eng Remote Sens 74:1107–1118. doi:10.14358/PERS.74.9.1107

Ghosh A, Joshi P (2013) Assessment of pan-sharpened very high-resolution WorldView-2 images. Int J Remote Sens 34(23):8336–8359. doi:10.1080/01431161.2013.838706

González-Audícana M, Otazu X, Fors O, Seco A (2005) Comparison between Mallat's and the "à trous" discrete wavelet transform based algorithms for the fusion of multispectral and panchromatic images. International Journal Remote Sens 26:595–614. doi:10.1080/01431160512331314056

Hallada W, Cox S (1983) Image sharpening for mixed spatial and spectral resolution satellite systems. International Symposium on Remote Sensing of the Environment 17:9–13

Harish K, Singh D (2010) Quality assessment of fused image of MODIS and PALSAR. Prog Electromagn Res 24:191–221

Jagalingam P, Hegde AV (2015) A review of quality metrics for fused image. Aquatic Procedia 4(Icwrcoe):133–142. doi:10.1016/j.aqpro.2015.02.019

Jameel A, Riaz MM, Ghafoor A (2016) Guided filter and IHS-based pan-sharpening. IEEE Sensors J 16(1):192–194

King RL, Wang JWJ (2001) A wavelet based algorithm for pan sharpening Landsat 7 imagery. In: Proceedings of the International of Geoscience and Remote Sensing Symposium (IGARSS 2001) 849–851

Klonus S, Ehlers M (2007) Image fusion using the Ehlers spectral characteristics preservation algorithm. GIScience & Remote Sensing 44(2):93–116. doi:10.2747/1548-1603.44.2.93

Laben C, Brower B (2000) Process for enhancing the spatial resolution of multispectral imagery using pan-sharpening. US Patent 6,011,875 1–8

Marcello J, Medina A, Eugenio F (2013) Evaluation of spatial and spectral effectiveness of pixel-level fusion techniques. IEEE Geosci Remote Sens Lett 10(3):432–436

Naidu VPS (2010) Discrete cosine transform-based image fusion. Def Sci J 60:48–54

Padwick C, Scientist P, Deskevich M et al (2010) WorldView-2 pan-sharpening. Asprs 2010(48):26–30

Ranchin T, Wald L (2000) Fusion of high spatial and spectral resolution images: the ARSIS concept and its implementation. Photogramm Eng Remote Sensing 66:49–61

Ranchin T, Wald L (1993) The wavelet transform for the analysis of remotely sensed images. Int J Remote Sens 14:615–619. doi:10.1080/01431169308904362

Sarp G (2014) Spectral and spatial quality analysis of pan-sharpening algorithms: a case study in Istanbul. European Journal of Remote Sensing 47:19–28

Shahdoosti HR, Ghassemian H (2015) Fusion of MS and PAN images preserving spectral quality. IEEE Geosci Remote Sens Lett 12(3):611–615. doi:10.1109/LGRS.2014.2353135

Siddiqui Y (2003) The modified IHS method for fusing satellite imagery. In Proceedings of the ASPRS 2003 Annual Conference: 153–158

Van der Meer F (2006) The effectiveness of spectral similarity measures for the analysis of hyperspectral imagery. Int J Appl Earth Obs Geoinf 8(1):3–17. doi:10.1016/j.jag.2005.06.001

Vivone G, Alparone L, Chanussot J, Mura MD, Garzelli A, Licciardi GA, Restaino R, Wald L (2014) Pansharpening algorithms. IEEE Trans Geosci Remote Sens 53(5):2565–2586

Wald L (2000) Quality of high resolution synthesised images: is there a simple criterion? In: International Conference of Fusion Earth Data, 99–103

Wang W, Chang F (2011) A multi-focus image fusion method based on Laplacian pyramid. J Comput 6:2559–2566. doi:10.4304/jcp.6.12.2559-2566

Wang Z, Bovik AC, Sheikh HR, Simoncelli EP (2004) Image quality assessment: from error visibility to structural similarity. IEEE Trans Image Process 13:1–14

Wu B, Fu Q, Sun L, Wang X (2015) Enhanced hyperspherical color space fusion technique preserving spectral and spatial content. J Appl Remote Sens 9:97291–97218. doi:10.1117/1.JRS.9.097291

Yang B, Jing Z, Zhao H (2010) Review of pixel-level image fusion. J Shanghai Jiaotong Univ 15:6–12. doi:10.1007/s12204-010-7186-y

Yun Zhang (2004a) Understanding image fusion. Photogramm Eng Remote Sens 657–661

Yusuf Y, Sri Sumantyo JT, Kuze H (2013) Spectral information analysis of image fusion data for remote sensing applications. Geocarto Int 28:291–310. doi:10.1080/10106049.2012.692396

Zhang J (2010) Multi-source remote sensing data fusion: status and trends. Int J Image Data Fusion 1:5–24. doi:10.1080/19479830903561035

Zhang Y (2004b) System and method for image fusion. 1:1–8

Zhang Y, Mishra RK (2013) From UNB PanSharp to Fuze go—the success behind the pan-sharpening algorithm. Int J Image Data Fusion 5:39–53. doi:10.1080/19479832.2013.848475

Zhou J, Civco DL, Silander JA (1998) A wavelet transform method to merge Landsat TM and SPOT panchromatic data. Int J Remote Sens 19:743–757. doi:10.1080/014311698215973

Zoran LF (2009) Quality evaluation of multiresolution remote sensing image fusion. UPB Sci Bull, Ser C 71:38–52