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ORIGINAL PAPER

Quality assessment of pan-sharpening methods in high-resolution satellite images using radiometric and geometric index

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Abstract This paper focuses on quality assessment of fusion of multispectral (MS) images with high-resolution panchromatic (Pan) images. Since most existing quality assessments take the entire image into account simultaneously and generate some uncertainties, a novel and rather objective quality index has been proposed for image fusion. The index is comprised of geometric and radiometric parts. Both geometric and radiometric measurements are calculated using morphological algorithm applied on an edge image to create a mask which is used to separate high-frequency regions from low-frequency ones. The accuracy assessment is made using common existing criteria on geometric and radiometric segments, and then a weighted sum is calculated to generate radiometric and geometric index (RG index). Several commonly used fusion algorithms such as IHS, modified IHS, PCA, Gram-Schmidt, Brovey Transform, Ehlers, High-Pass Modulation, Schowengerdt and UNB were applied on a very high-resolution GeoEye-1 and WorldView-2 images. In order to perform quality assessment, methods of Spectral Angle Mapper, Structural SIMilarity, correlation coefficients and universal quality index for which the normalization were possible (for comparison purposes) were used. The utilized RG index showed that by separating spectral and spatial component quality measurement, the quality assessment is made on fused images in a more distinct, explicit, accurate and objective manner.

Keywords Image fusion · Multispectral imagery · Quality assessment · Geometric distortion · Radiometric quality · Geometric quality

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Introduction

The widespread and diverse range of image fusion methods require accurate quality assessment criteria for comparison of results obtained from different algorithms. Since human perception of fused image is of fundamental importance, subjective criteria have been widely used to evaluate performance of different image fusion methods (DadrasJavan and Samadzadegan 2014; Toet and Franken 2003). However, as the digital applications of fused images are being increased, objective assessment criteria are getting more attention. Objective performance assessment is a rather complicated issue due to the variety of different application requirements and the lack of a clearly defined ground-truth. Image fusion methods have often been evaluated by comparing ideal fused image to a reference image (Ghosh and Joshi 2013; Wang et al. 2005). The assessment of quality normally involves computation of a number of different image fusion quality indices such as correlation coefficient (CC) between each band of the fused and reference MS images (Zhang 2008). Structural SIMilarity (SSIM) (Wang et al. 2004). universal quality index (UQI) (Alparone et al. 2004a) and Spectral Angle Mapper (SAM) (Alparone et al. 2004b). These are amongst measures of the spectral distortion introduced by the fusion process.

Recently, several performance measures have been introduced by (Hazini and Hashim 2015; Helmy and El-Tawel

2015; Khan et al. 2009; Wang et al. 2005; Alparone et al. 2004a; Wald et al. 1997; Wang et al. 2004) for image fusion quality analysis. Since the methods did not take into account the knowledge of information content, they did not probably offer obvious advantages. However, incorporating indices to deal with information content should obviously increase the quality of the assessment. This may be achieved by explicit separation of information content into more objective components in fused image and compare them with corresponding components in reference image.

A variety of image fusion techniques have been studied by researcher for panchromatic (Pan) and multispectral (MS) pan-sharpening. For the purpose of quality assessment in this study, the successful ones such as IHS (Tu et al. 2001). modified IHS (IHS*) (Tu et al. 2004). PCA (Pohl and Van Genderen 1998). Gram-Schmidt (GS) (Laben and Brower 2000). Brovey Transform (BT) (Pohl and Van Genderen 1998). Ehlers (EHL) (Ehlers 1991). High-Pass Modulation (HPM) (Schowengerdt 2006). Schowengerdt (SWT) (Schowengerdt 2006) and UNB (Zhang 2002) have been implemented on a satellite image which contains both spatial and spectral details.

In this research, an image quality index, namely radiometric and geometric index (RG Index), for MS images with four spectral bands has been proposed and applied to assess the performance of different image fusion methods. The proposed quality index shows that by isolating image content to edge and background and computing each component's quality with corresponding component of reference image, measuring image fusion performance is done more accurately. The proposed quality index is evaluated by using very high-resolution satellites GeoEye-1 and WorldView-2 data with one 0.5-m Pan band and four 2.0-m MS bands for GeoEye-1 and eight 2.0-m MS bands for WorldView-2 of an urban area. Furthermore, classical quality parameters are also computed and visual comparisons reported, to assess the reliability and the completeness of the proposed method for performance evaluation of image fusion algorithms.

Fusion of MS images with corresponding Pan images

New mapping satellites, such as IKONOS, WorldView-2, WorldView-3, Quick Bird and GeoEye-1, provide both Pan images at a higher spatial resolution and MS images at a lower spatial resolution but rich spectral information. There are some tradeoffs due to several technological limitations to have a sensor with high spatial and spectral characteristics. So the remote sensing customers have switched to integrate MS and Pan images to exhibit complementary characteristics of spatial and spectral resolutions and this new product image is entitled as pan-sharpened images. Pan-sharpening has become integral part of many applications of remote sensing like land use/cover classification (Alipour Fard et al. 2014; Saeidi et al. 2014). image change detection (Du et al. 2013). map updating (Pohl and Hashim 2013). hazard monitoring (Nichol and Wong 2005) and many other geo-information usages.

In this regard, it is inevitable to investigate assessment of pan-sharpening methods to have reasonable output result for any application of remote sensing images. On the other hand, the existing quality assessment methods did not take into account the knowledge of information content and they did not probably offer obvious advantages. This issue may be achieved by explicit separation of information content into more objective components in fused image and compare them with corresponding components in reference image. In the next section, we focus on new assessment procedure to better evaluating performance of pan-sharpening methods.

The proposed RG index

The output of any fusion method is an RGB image that should be compared to original MS image to measure image fusion performance. To do this, in existing quality assessment methods, each complete band of fused image is used to estimate image quality performance. These methods have some uncertainty because they coarsely take into account the image content by using global quality indices which include both spatial and spectral information of each fused bands simultaneously.

To overcome this incompatibility, the proposed method segments fused image into two components of edge information and background information. The edge component that contains high-frequency and geometric signals is compared to the edge information of the Pan image. Similarly, background component that contains radiometric and spectral information is compared to the radiometric information of the MS image. As it is known, the goal of fusion methods is to fuse the Pan image containing geometric properties with MS image containing radiometric properties. This concept has simply led us to propose this more accurate quality index to measure fusion performance. Figure 1 shows the fusion process and the subsection of quality assessment which is done in two geometric and radiometric components separately leading to the RG Index.

Geometric component of fused image

The procedure is initiated by extracting edge of the Pan image by canny algorithm (Canny 1986). The edges are then

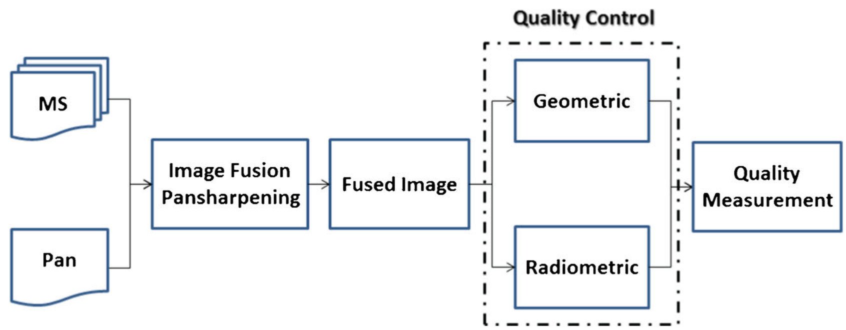


Fig. 1 Fusion process and the subsection of quality assessment in two geometric and radiometric components

widened by applying morphological operator of dilation to include radiometric edge information in the image. In this study, due to the certain amount of detail which is related to the ground features and resolution, the dilation has been done two times. The binary dilation of A by B, denoted $A \oplus B$, is defined as the set operation (Eq. 1):

$$A \oplus B = \left\{ z \middle| \left(\hat{B} \right)_z \cap A \neq \varnothing \right\} \tag{1}$$

where $\hat{B}$ is the reflection of the structuring element B. In other words, it is the set of pixel locations z, where the reflected structuring element overlaps with foreground pixels in A when translated to z (Gonzalez et al. 2010). Then, using edge map of the Pan image, a mask is created to extract the edge information from both the Pan and the fused image which will be used to evaluate the geometric component of the fused image.

Radiometric component of fused image

In order to extract radiometric component, geometric component is used. By subtracting geometric component from fused image, radiometric component is obtained (Fig. 2). The mask is actually being used to segment the fused image into geometric and radiometric components.

RG index

Computation of RG index is performed in two parts of geometric component (Eq. 2) and radiometric component

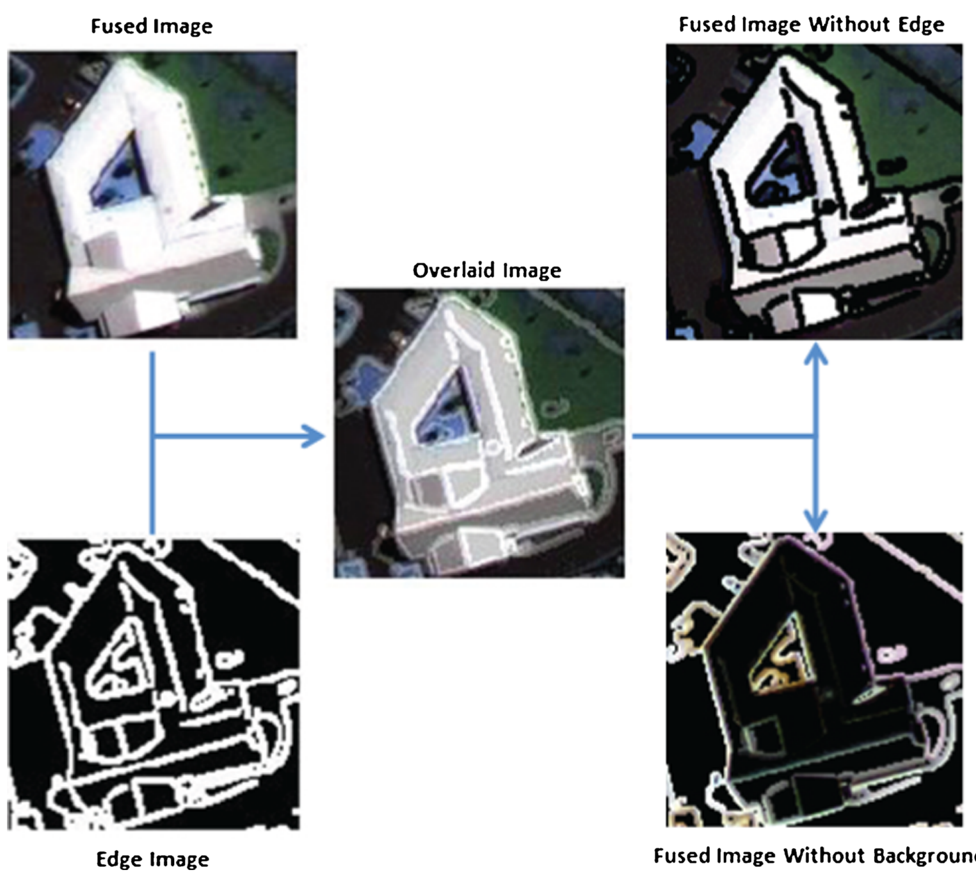
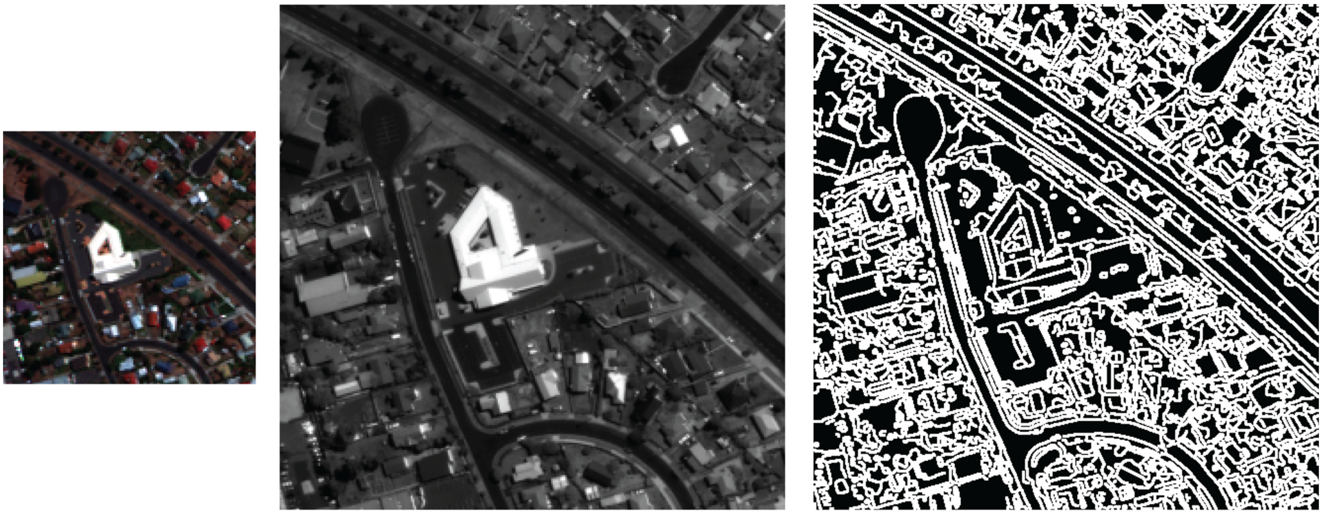


Fig. 2 Geometric and radiometric components of fused image



a b c

Fig. 3 GeoEye-1 image. **a** MS image. **b** Pan image. **c** Edge extracted from Pan image

(Eq. 3). By utilizing existing quality indices (e.g. SAM, SSIM, CC and UQI), separate computations are made for the two components.

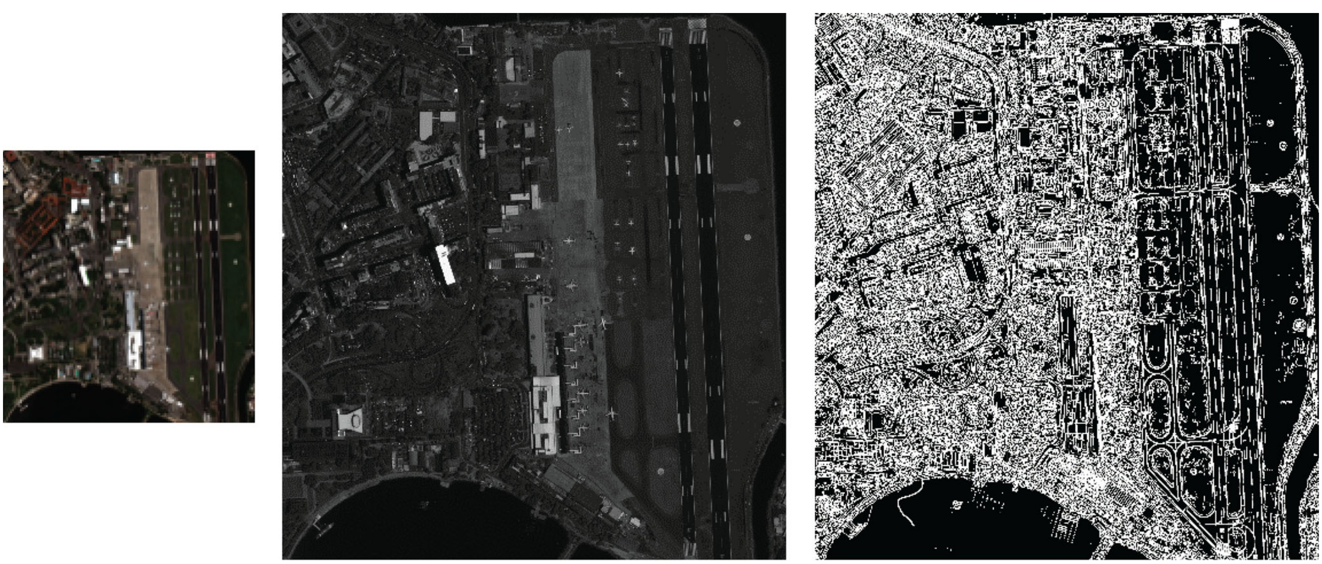
$$\mathrm{SAM}_{\mathrm{Geometric}} = \cos^{-1}\left(\frac{\langle I_e \,.\, \mathrm{PAN}\rangle}{\|I_e\|.\|\mathrm{PAN}\|}\right) \tag{2}$$

$$\mathrm{SAM}_{\mathrm{Radiometric}} = \cos^{-1}\left(\frac{\langle I_b \,.\, \mathrm{MS}\rangle}{\|I_b\|.\|\mathrm{MS}\|}\right) \tag{3}$$

where I_e and I_b are edge and background components of fused image, respectively. In this manner, edge component (I_e) compares with Pan image and background component (I_b) compares with MS image. Similarly, SSMI, CC and UQI indices have been divided to two components (radiometric and geometric) (Eqs. 4–9).

$$\mathrm{SSIM}_{\mathrm{Radiometric}} = \frac{\left(2\overline{I_b} \times \overline{\mathrm{MS}} + C_1\right)\left(2\sigma_{I_b\mathrm{MS}} + C_2\right)}{\left(\overline{I_b}^2 + \overline{\mathrm{MS}}^2 + C_1\right)\left(\sigma_{I_b} + \sigma_{\mathrm{MS}} + C_2\right)} \tag{4}$$

$$\mathrm{SSIM}_{\mathrm{Geometric}} = \frac{\left(2\overline{I_e} \times \overline{\mathrm{PAN}} + C_1\right)\left(2\sigma_{I_e\mathrm{PAN}} + C_2\right)}{\left(\overline{I_e}^2 + \overline{\mathrm{PAN}}^2 + C_1\right)\left(\sigma_{I_e} + \sigma_{\mathrm{PAN}} + C_2\right)} \tag{5}$$



a b c

Fig. 4 WorldView-2 image. **a** MS image. **b** Pan image. **c** Edge extracted from Pan image

$$\mathrm{CC}_{\mathrm{Radiometric}} = \frac{\sum_{ij}\left(I_b - \overline{I_b}\right)\left(\mathrm{MS} - \overline{\mathrm{MS}}\right)}{\sqrt{\sum_{ij}\left(I_b - \overline{I_b}\right)^2 \sum_{ij}\left(\mathrm{MS} - \overline{\mathrm{MS}}\right)^2}} \tag{6}$$

$$\mathrm{CC}_{\mathrm{Geometric}} = \frac{\sum_{ij}\left(I_e - \overline{I_e}\right)\left(\mathrm{PAN} - \overline{\mathrm{PAN}}\right)}{\sqrt{\sum_{ij}\left(I_e - \overline{I_e}\right)^2 \sum_{ij}\left(\mathrm{PAN} - \overline{\mathrm{PAN}}\right)^2}} \tag{7}$$

$$\mathrm{UQI}_{\mathrm{Radiometric}} = \frac{4 \times \sigma_{I_b\mathrm{MS}} \times \overline{I_b} \times \overline{\mathrm{MS}}}{\left(\overline{I_b}^2 + \overline{\mathrm{MS}}^2\right)\left(\sigma_{I_b} + \sigma_{\mathrm{MS}}\right)} \tag{8}$$

$$\mathrm{UQI}_{\mathrm{Geometric}} = \frac{4 \times \sigma_{I_e\mathrm{PAN}} \times \overline{I_e} \times \overline{\mathrm{PAN}}}{\left(\overline{I_e}^2 + \overline{\mathrm{PAN}}^2\right)\left(\sigma_{I_e} + \sigma_{\mathrm{PAN}}\right)} \tag{9}$$

In order to compare these indices with existing indices, it is necessary to have the RG index in the form of a unique value. The RG index should include both estimated geometric and radiometric components which requires a weighting procedure to be applied (Eq. 10).

$$\mathrm{SAM}_{\mathrm{RG\ index}} = \mathrm{SAM}_{\mathrm{Geometric}} \times W_{\mathrm{Geometric}} + \mathrm{SAM}_{\mathrm{Radiometric}} \times W_{\mathrm{Radiometric}} \tag{10}$$

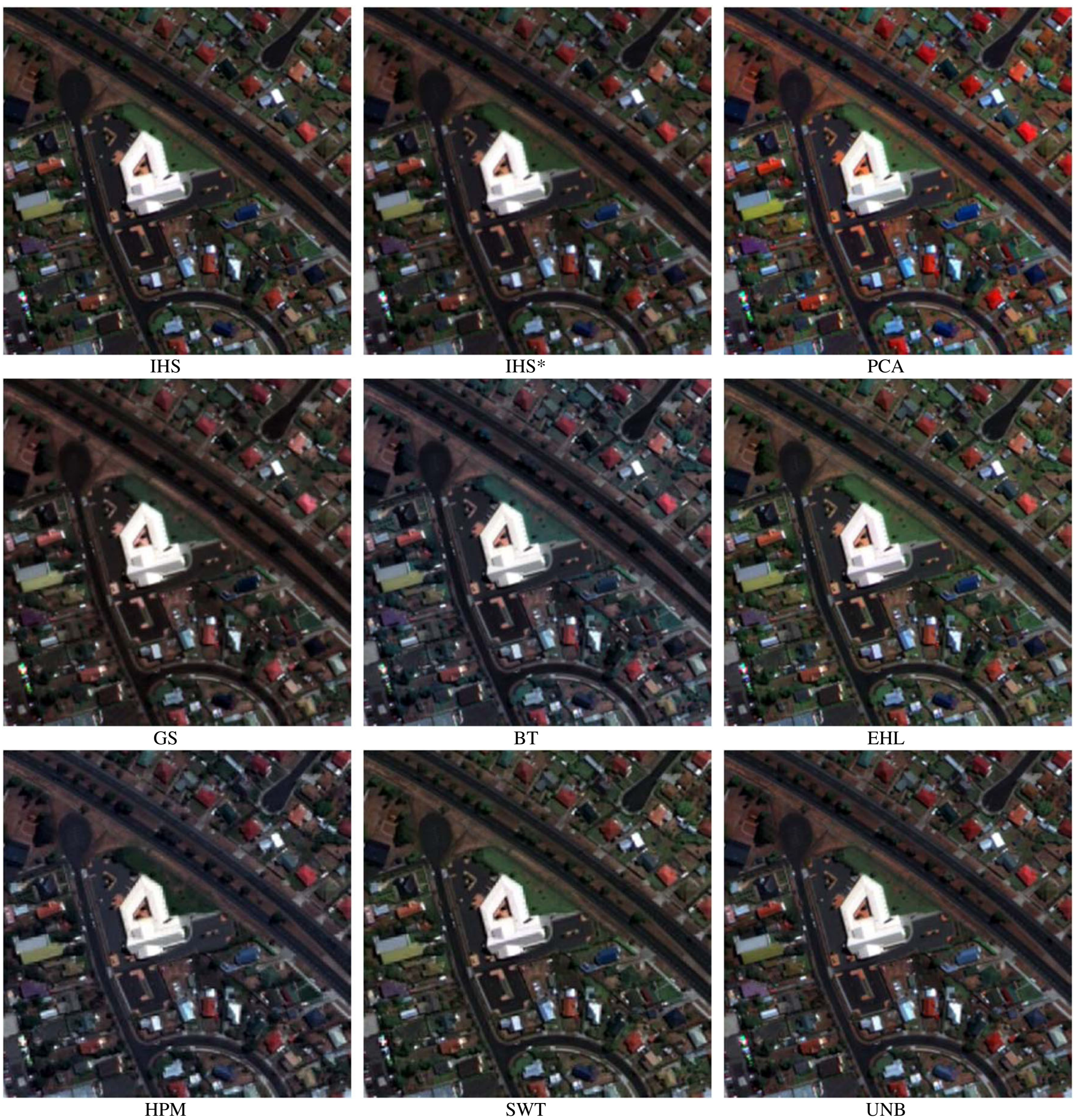


Fig. 5 Output of different fusion methods for GeoEye-1 data

where

$$W_{\text{Geometric}} = \frac{\text{Number of pixel in Edge section}}{\text{Number of pixel in Fused image}}$$

$$W_{\text{Radiometric}} = \frac{\text{Number of pixel in Background section}}{\text{Number of pixel in Fused image}}$$

Obviously, if the sum of the both weights is equal to one, then the RG index carries a normalization characteristic with itself. Therefore, $\text{SAM}_{\text{RG index}}$, $\text{SSIM}_{\text{RG index}}$, $\text{CC}_{\text{RG index}}$ and $\text{UQI}_{\text{RG index}}$ indices can be calculated by using weighting factors of both components in each type of quality measurements similar to Eq. 10. The proposed index can be used in every fusion technique by separating the result of fusion to radiometric and geometric component. In this manner, we can estimate and compute performance of each fusion technique in two different aspects. For investigating geometric properties of output result, geometric component of RG index is used. Also, for investigating radiometric properties of output result, radiometric component of RG index is used. Therefore, RG index can assess every individual fusion technique. In this regard, the user can see and use these three values (radiometric component, geometric component and RG Index),

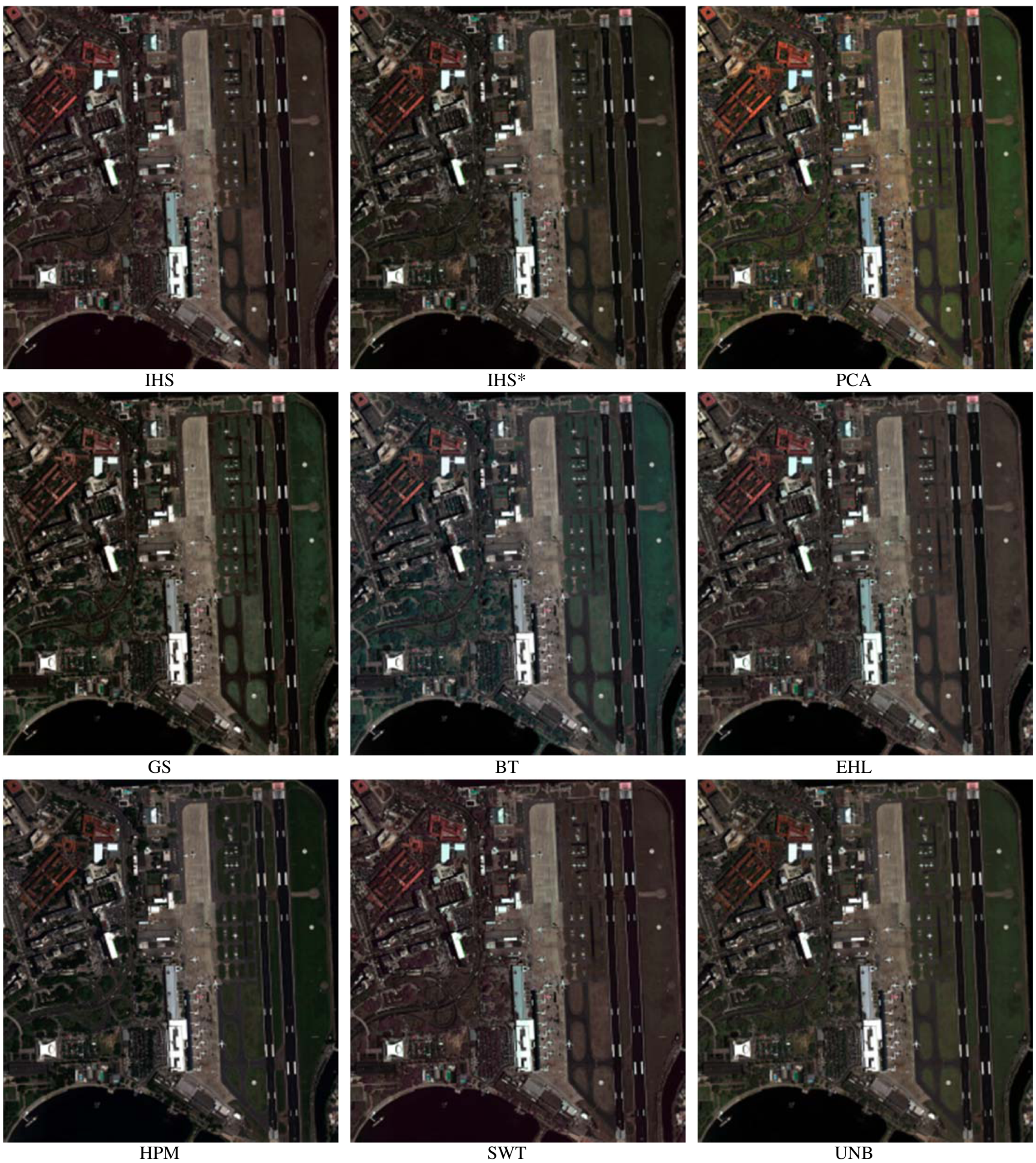


Fig. 6 Output of different fusion methods for WorldView-2 data

Table 1 Performance of different fusion methods in GeoEye-1 data

Fusion methods		IHS	IHS*	PCA	GS	BT	EHL	HPM	SWT	UNB
SAM	Geometric	2.66	4.87	2.96	5.38	1.66	3.74	9.36	5.84	3.55
	Radiometric	8.44	6.35	9.74	7.40	9.06	11.1	5.02	7.99	7.76
	RG index	5.50	5.60	6.29	6.37	5.29	7.36	7.23	6.89	5.62
	Old index	11.4	8.60	12.64	9.77	12.40	14.6	9.09	10.6	11.5
UQI	Geometric	0.98	0.96	0.72	0.94	0.98	0.96	0.96	0.96	0.96
	Radiometric	0.90	0.92	0.54	0.92	0.84	0.80	0.94	0.92	0.92
	RG index	0.94	0.94	0.64	0.92	0.92	0.88	0.94	0.94	0.94
	Old index	0.44	0.66	0.28	0.26	0.42	0.36	0.80	0.76	0.50
CC	Geometric	0.98	0.98	0.98	0.98	0.98	0.98	0.92	0.96	0.98
	Radiometric	0.92	0.94	0.90	0.94	0.92	0.90	0.96	0.94	0.92
	RG index	0.96	0.96	0.94	0.96	0.96	0.94	0.94	0.94	0.96
	Old index	0.86	0.92	0.84	0.88	0.86	0.82	0.92	0.88	0.86
SSIM	Geometric	0.98	0.98	0.88	0.96	0.98	0.98	0.98	0.98	0.98
	Radiometric	0.98	0.98	0.82	0.98	0.94	0.92	0.98	0.98	0.98
	RG index	0.98	0.98	0.84	0.96	0.96	0.96	0.98	0.98	0.98
	Old index	0.92	0.96	0.78	0.94	0.90	0.88	0.96	0.94	0.92

depending on the user's application; if the goal of application is something like map updating, then quality assessment of geometric component is more important than radiometric component.

Experiments and results

In order to show efficiency of RG index, commonly used pixel-level fusion algorithms such as IHS, IHS*, PCA, GS, BT, EHL, HPM, SWT and UNB have been implemented and the quality of fusions output have been measured by RG index.

Implementation of fusion algorithms

The image fusion techniques have been applied on two recent high-resolution satellite images, GeoEye-1 and WorldView-2. GeoEye-1 MS image has four 2.0-m resolution spectral bands (blue, green, red and near IR) and resolution of PAN image is 0.5 m (Fig. 3a, b).

Same as GeoEye-1 image, WorldView-2 image has eight 2.0-m resolution spectral bands (coastal blue, blue, green, yellow, red, red-edge, near IR1 and near IR2) and resolution of PAN image is 0.5 m (Fig. 4a, b).

The study areas for both datasets are chosen to cover different urban areas. To present performance of the quality RG

Table 2 Performance of different fusion methods in WorldView-2 data

Fusion methods		IHS	IHS*	PCA	GS	BT	EHL	HPM	SWT	UNB
SAM	Geometric	2.91	4.44	1.16	3.61	1.13	1.67	7.88	5.87	2.77
	Radiometric	7.58	5.71	9.83	8.97	9.66	8.76	4.69	7.82	8.16
	RG index	5.74	5.21	6.41	6.86	6.29	5.97	5.95	7.05	6.03
	Old index	8.94	6.73	10.72	9.71	10.57	9.55	6.50	8.74	9.83
UQI	Geometric	0.98	0.98	0.86	0.98	0.99	0.99	0.97	0.98	0.98
	Radiometric	0.77	0.81	0.57	0.80	0.78	0.80	0.88	0.83	0.77
	RG index	0.85	0.88	0.69	0.87	0.86	0.88	0.91	0.89	0.85
	Old index	0.91	0.88	0.40	0.86	0.84	0.86	0.92	0.85	0.85
CC	Geometric	0.99	0.98	1.00	0.99	1.00	1.00	0.95	0.97	0.99
	Radiometric	0.96	0.98	0.94	0.95	0.95	0.96	0.99	0.96	0.96
	RG index	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.97	0.97
	Old index	0.94	0.97	0.92	0.93	0.93	0.94	0.97	0.95	0.93
SSIM	Geometric	0.99	0.99	0.90	0.97	0.99	0.99	0.98	0.98	0.99
	Radiometric	0.98	0.99	0.79	0.97	0.97	0.97	0.99	0.98	0.98
	RG index	0.98	0.99	0.84	0.97	0.98	0.98	0.99	0.98	0.98
	Old index	0.91	0.95	0.78	0.90	0.89	0.91	0.95	0.93	0.90

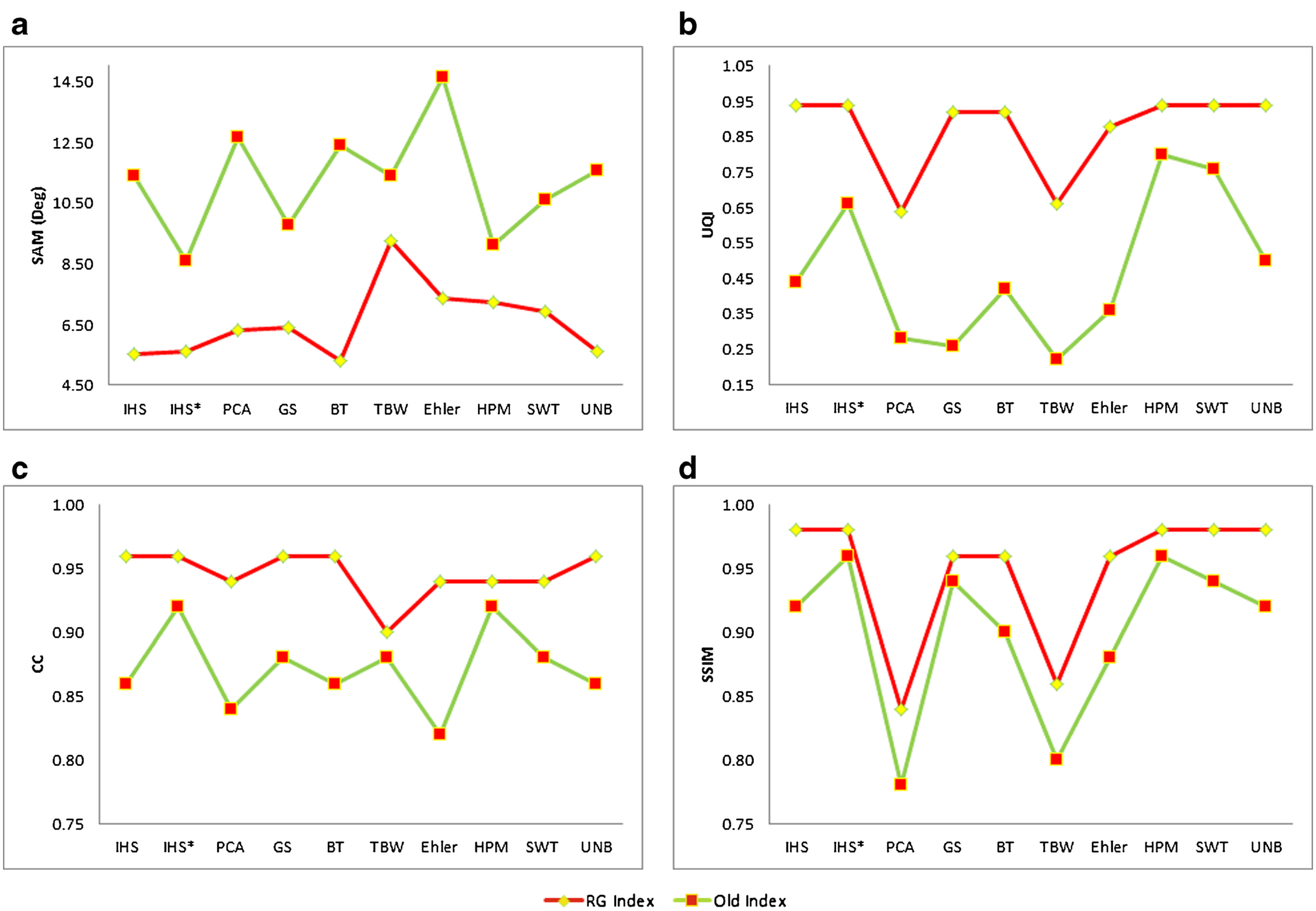


Fig. 7 Comparison between RG index and old index in GeoEye-1 data set. **a** SAM, **b** UQI, **c** CC and **d** SSIM

index, more popular MS+Pan merge algorithms (i.e. IHS, IHS*, PCA, GS, BT, EHL, HPM, SWT and UNB) have been implemented. GeoEye-1 and WorldView-2 fusions output for each algorithm are illustrated in Figs. 5 and 6, respectively.

Quality assessment

Quality assessment of fused images is a critical task in fusion process. In this study, four quality indices (i.e. SAM, SSIM, CC and UQI) have been calculated. These methods have been selected because they intrinsically have normalization parameter inside. For each type of quality measurements, four estimations of geometric, radiometric, RG index and the index itself (old index) have been made. Tables 1 and 2 illustrate the performance estimations for comparison purposes for two datasets (GeoEye-1 and WorldView-2). Obviously, the higher performance of SAM index tends to zero degree (angle between two vectors, 0° for high compatibility and 90° for opposite direction); also, the higher qualities of CC, SSIM and UQI indices tend to one, which implies the closeness of the fused image to both Pan and MS reference images objectively.

By comparing the RG quality indices with other four quality indices in Tables 1 and 2, it is clear that $SAM_{RG\ index}$, $SSIM_{RG\ index}$, $CC_{RG\ index}$ and $UQI_{RG\ index}$ which act objectively show higher sensitivity on reflecting the quality of the fusion when compared to the approach of taking the whole image into SAM, SSIM, CC and UQI index analysis. Also, by looking more closely to Figs. 7 and 8, it is clear that RG Index has the same trend of computation to evaluate and assess the performance of the existing pan-sharpening methods using two different high-resolution satellite images (GeoEye-1 and WorldView-2) and has higher sensitivity to compute this assessment. Therefore, the proposed RG index in this study is contributing in enhancement of each index. This is due to the fact that the quality assessment has been separated into two geometric and radiometric components to make it rather objective.

From Tables 1 and 2, it is clear that SAM index have good result in geometric component of the RG index for all the nine Pan-sharpening methods except for HPM. This means that the fused image performed better in the spatial component than the spectral component. Similarly for UQI index, fused image have high performance in spatial component than spectral component. Also, in CC index, fused image have high performance in spatial component than spectral component except HPM method. Finally for SSIM index, most of the fused

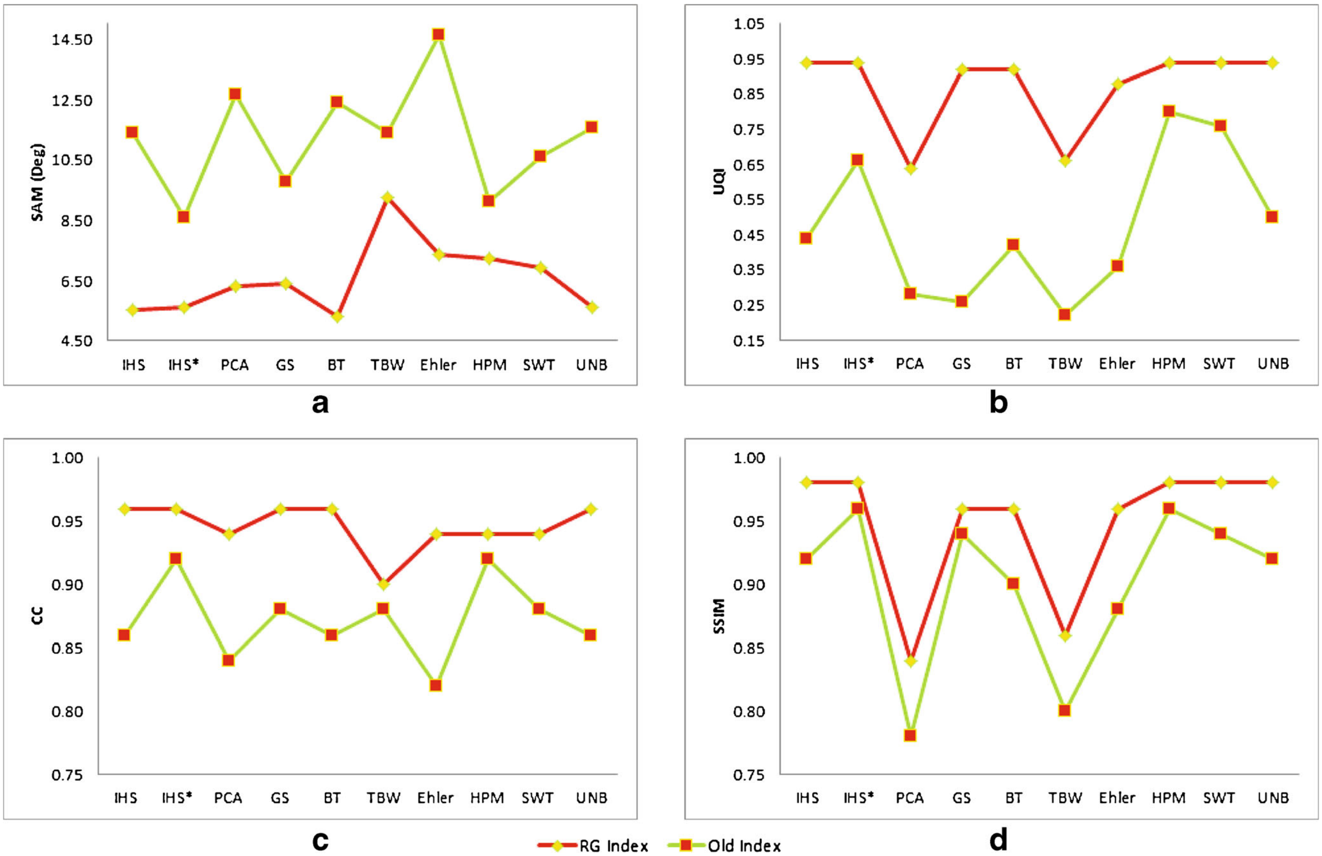


Fig. 8 Comparison between RG index and old index in WorldView-2 data set. **a** SAM, **b** UQI, **c** CC and **d** SSIM

images have high performance in spatial component rather than spectral component.

To sum up from the extracted result and proposed RG index, it is clear that most fusion and pan-sharpening methods focus on geometric information than the radiometric information. More importantly, most of the quality assessment indices and criteria cannot separate assessment between geometric and radiometric component, which RG index solved. Also, another advantage of proposed method is that the users can select the best method of pan-sharpening depending on their objective and application (e.g. map updating, change detection and so on).

Conclusion

Fusion aims to enhance the apparent information in images as well as to increase the reliability of the digital interpretation. Therefore, an objective index has been proposed in this study to meet the required quality of fused images when digital applications are involved. In this regard, the RG index method leads to more accurate pan-sharpening image assessment and increased incorporation in applications such as image segmentation and classification. The RG index has been designed under the assumption of the separate and direct impact of spectral component and spatial component on the quality of fused image.

The assessment of SAM, SSIM, CC and UQI quality indices on IHS, IHS*, PCA, GS, BT, EHL, HPM, SWT and UNB fusion algorithms have been implemented in this study. Results show that the proposed index exhibits a subtle and much higher discrimination capability by taking the spectral and spatial components separately into account as opposed to the previous approaches which took the whole image into SAM, SSIM, CC and UQI index analyses.

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