Two improvement schemes of PAN modulation fusion methods for spectral distortion minimization

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Fusion of panchromatic (PAN) and multispectral (MS) images is one of the most promising issues in remote sensing. PAN modulation fusion methods are usually based on an assumption that a ratio of two different-resolution versions of an MS band is equal to a ratio of two different-resolution versions of a PAN image. In such fusion methods, image haze is rarely taken into account, and it may produce serious spectral distortion in synthetic images. In this paper, assuming that the previous ratio relationship only holds for haze-free images, two relevant improvement schemes are proposed to better express the ratio relationship of haze-included images. In a test on a spatially degraded IKONOS dataset, the first scheme synthesizes an image with minimum spectral distortion, and the second modifies several current PAN modulation fusion methods and generates high-quality synthetic products. The experiment results confirm that image haze can seriously impact the quality of fused images obtained by using PAN modulation fusion methods, and it should be taken into account in relevant image fusion.

1. Introduction

Image fusion is one of the most promising issues in remote sensing. Numerous fusion techniques were developed to merge high-spectral-resolution multispectral (MS) and high-spatial-resolution panchromatic (PAN) images in order to synthesize images with high spectral and spatial resolutions (Schowengerdt 1980, Burt and Adelson 1983, Chavez 1986, Moran 1990, Ranchin and Wald 1993, Garguet-Duport et al. 1996, Pohl and Genderen 1998, Nunez et al. 1999, Aiazzi et al. 2002, Ranchin et al. 2003, Teggi et al. 2003, González-Audicana et al. 2004, Lillo-Saavedra and Gonzalo 2007, Nencini et al. 2007). To perform spatiotemporal image fusion, wavelet and curvelet transforms are frequently employed. Very recently, instead of the wavelet and curvelet transforms, detrended fluctuation analysis has been employed. The latter has already proved its usefulness in several complex systems, like NDVI (Normalized Difference Vegetation Index) fields, surface air-pollutants (Varotsos et al. 2005), aerosol index (Varotsos et al. 2006), total ozone content (Varotsos 2005a, b), global tropospheric temperature (Varotsos and Kirk-Davidoff 2006), and carbon dioxide fluctuations (Varotsos et al. 2007).
Among present widely used fusion methods, one kind is based on PAN modulation, such as Brovey (Hallada and Cox 1983, Gillespie et al. 1987), Pradines’ (Pradines 1986), Synthetic Variable Ratio (SVR) (Munechika et al. 1993, Zhang 1999) and Smoothing Filter-based Intensity Modulation methods (Liu 2000). These PAN modulation fusion methods may be generalized as follows:

\[ M_{i,f} = M_i \cdot PAN / P_a, \]  

where \( M_{i,f} \) denotes the fused ith MS band, \( M_i \) the corresponding ith MS band, \( PAN \) the high-resolution PAN image and \( P_a \) an assumed low-resolution PAN image. Equation (1) can be rearranged as follows:

\[ \frac{M_{i,f}}{M_i} = \frac{PAN}{P_a}, \]  

which indicates that the ratio of a high-resolution MS band \( M_{i,f} \) to a low-resolution MS band \( M_i \) is equal to the ratio of a high-resolution PAN image to the assumed low-resolution PAN image \( P_a \).

Existing PAN modulation fusion methods are similar except assigning \( P_a \) differently. For instance, Pradines’ method employs a sum of the high-resolution PAN pixels superimposed by each low-resolution MS pixel, \( P_a = \sum_i PAN_i \), where \( q \) denotes the number of the superimposed PAN pixels; the Smoothing Filter-based Intensity Modulation method employs an average of the superimposed PAN pixels, \( P_a = \frac{1}{q} \sum_i PAN_i \); the Brovey method involves an average of a MS band triplet, \( P_a = \frac{1}{3} \sum_i M_i \); and the SVR method utilizes a weighted sum of multiple MS bands, \( P_a = \sum_i a_i M_i \), where the coefficients \( a_i \) are obtained through physical simulation or through a multiple regression of the PAN and MS images. With respect to the assumed low-resolution PAN image as the divisor of the PAN image, current PAN modulation fusion methods may be classified into two categories: one employing a spatially degraded PAN image as the divisor and another utilizing a MS component.

When the relationship (2) holds for haze-free images, it will no longer be valid for haze-included images. Given two non-zero haze values, \( h_p \) and \( h_i \), related to atmospheric effects in PAN band and in the ith MS band, respectively, the equation (2) will no longer hold true:

\[ \frac{M_{i,f} + h_i}{M_i + h_i} \neq \frac{PAN + h_p}{P_a + h_p}, \]  

and consequently, the corresponding fused ith MS band \( (M_{i,f} + h_i) \) cannot be derived from relation (3). Therefore, the equation (2) must be modified to eliminate haze effect.

Haze is one important component in spectral bands, especially in short-wavelength bands. Its values can be determined for each of the bands using the minimum grey level values in the image, according to an image-based dark-object subtraction method (Chavez 1988, 1996, Moran et al. 1992). Rarely addressed in current PAN modulation fusion methods, haze effect can cause fusion to fail. Haze can be determined before fusion is conducted and be added back to the resultant synthetic image after fusion is done. Taking into account haze for the two categories of PAN modulation fusion methods will result in two relevant improvement schemes for haze-included images.
This paper is organized as follows: in §2, the two important schemes will be described; §3 introduces test data, fusion methods for comparison and evaluation criteria; §4 provides the comparison between the proposed fusion schemes and several current fusion methods. Discussions will be carried out in §5, and a conclusion will be drawn in the last section.

2. Methodologies

2.1 Haze-and-ratio-based fusion scheme

In the first category of PAN modulation fusion methods, the assumed low-resolution PAN image presented in equation (2) can be a spatially degraded PAN image $P_L$. The $P_L$ can be obtained by averaging the high-resolution PAN pixels superimposed by each low-resolution MS pixel to match the low spatial resolution of the MS image. Denoting the haze values in the $i$th MS band and in PAN band as $h_i$ and $h_p$, respectively, equation (2) can be modified as follows:

$$\frac{M_{i,f} - h_i}{M_i - h_i} = \frac{P_{AN} - h_p}{P_L - h_p}. \tag{4}$$

The fused $i$th MS band can be calculated directly from the following formula:

$$M_{i,f} = (M_i - h_i) \frac{P_{AN} - h_p}{P_L - h_p} + h_i. \tag{5}$$

In practice, the MS band and the spatially degraded PAN image in the above equation are upsampled to match the pixel size of PAN image using a bicubic resampling approach.

As demonstrated in equations (4) and (5), a haze-free spatially degraded PAN image is employed as the divisor of a haze-free high-resolution PAN image in this fusion scheme. For the purpose of brevity, this scheme is called the Haze-and-Ratio-based (HR) fusion method.

2.2 Component-specific haze-and-ratio-based fusion scheme

A relationship of the spatially degraded PAN image $P_L$ and all MS bands can be established through a multiple regression as follows:

$$P_L = \sum_{i=1}^{n} a_i M_i + b + e, \tag{6}$$

where the regression coefficients $a_i$ and $b$ can be determined by the least-squares method, and $e$ is residual. An $n \times 1$ regression coefficient vector $\{a_1, a_2, \ldots, a_n\}$ can be denoted as $a$ with length $|a|$, representing a direction on which the projection from the MS image is the closest to the degraded PAN image.

In the second category of PAN modulation fusion methods, the assumed low-resolution PAN image $P_a$, as the divisor of a high-resolution PAN image in equation (1), is an MS component $C$:

$$C = \sum_{i=1}^{n} w_i M_i + b_2, \tag{7}$$

where weights $w_i$ and constant $b_2$ are specific for each fusion method. For instance, the weights for the three MS bands in Brovey method are 1, 1, and 1, respectively.
Removing haze from the MS image yields the following expression:

$$C' = \sum_{i=1}^{n} w_i (M_i - h_i) + b_2. \quad (8)$$

Denoting an $n \times 1$ weight vector \{w_1, w_2, ..., w_n\} as $W$ with length $|W|$, the projection of $(C' - b_2)$ on vector $a$ is

$$C'_p = \frac{\langle a, W \rangle}{|a| |W|} \sum_{i=1}^{n} [w_i(M_i - h_i)] = \frac{1}{|W|^2} \sum_{i=1}^{n} (a_i \cdot w_i) \cdot \sum_{i=1}^{n} [w_i(M_i - h_i)], \quad (9)$$

where ‘$\langle , \rangle$’ denotes the inner-product of two vectors.

Denoting $\frac{1}{|W|^2} \sum_{i=1}^{n} (a_i \cdot w_i)$ as $k$, replacing the divisor $(P_L - h_p)$ in equation (5) with $(C'_p + b)$ results in a fused $i$th MS band as follows:

$$M_{i,f} = (M_i - h_i) \frac{PAN - h_p}{k [C - b_2 - \sum_{i=1}^{n} (w_i \cdot h_i)]} + h_i. \quad (10)$$

In practice, the MS component $C$ here is bicubically upsampled to have the same pixel size as PAN image.

Unlike the first improvement scheme employing a haze-free spatially degraded PAN image as the divisor of a haze-free high-resolution PAN image, this Component-specific Haze-and-Ratio-based (CHR) fusion scheme utilizes an expectation of the haze-free spatially degraded PAN image. The expectation is derived from a MS component utilized in the second category of PAN modulation fusion methods. In this scheme, the MS component is removed of haze and scaled with reference to the spatially degraded PAN image employed in the first improvement scheme previously proposed. This is done in order to reduce the difference between the MS component and the spatially degraded PAN image and thus to lessen the spectral distortion in synthetic products.

3. Test data, fusion methods for comparison, and evaluation criteria

A subset of IKONOS Beijing scene of May 2000 was employed to test the two fusion methods proposed in this paper and to compare them with several current fusion methods. This dataset is composed of MS bands 1–4, which are blue (0.45–0.53 μm), green (0.52–0.61 μm), red (0.64–0.72 μm), and near-infrared (NIR) (0.77–0.88 μm) bands, respectively, of size 512 × 512 and a corresponding PAN band (0.45–0.90 μm) of size 2048 × 2048. The MS and PAN images have 4-m and 1-m spatial resolutions, respectively. Figures 1(a) and 2(c) demonstrate small fragments of size 128 × 128 of the MS and PAN images, respectively.

One HR fusion experiment taking into account haze and another HR fusion experiment ignoring haze were respectively applied to the test dataset in order to evaluate haze impact on image fusion. For comparative purposes, two popular fusion methods besides HR were applied to the test data, including PANSHARP (Zhang 2002a, b) and Gram–Schmidt (GS) spectral sharpening methods (Laben et al. 1998).

In addition, in order to evaluate the CHR improvement scheme, the SVR method of Zhang (1999) and Brovey’s method as well as their CHR-modified versions were applied to the dataset, including:
In Brovey fusion, a triplet of MS bands 1, 3, and 4 was employed to produce the first fused band, and another triplet of MS bands 2–4 was utilized to offer fused bands 2–4. Each resultant fused image had a 1-m spatial resolution, and it should be compared with a 1-m MS image in order to assess its quality. Since the latter image did not exist, spatially degraded images were utilized. The original PAN and MS images were spatially degraded by 4, respectively, to simulate the fusion of PAN and MS images with a spatial resolution ratio of 1 : 4. Then, all fusion experiments were carried out on the degraded data. The resultant synthetic products were visually compared with the true 4-m reference MS data and statistically compared with the

![Figure 1](image1.png)

Figure 1. 128 × 128 details of original and 4-m synthetic images shown in true-colour composition. (a) True 4-m MS. (b) 16-m MS bicubically upsampled to 4 m. (c) Degraded PAN at 4 m. (d) HR fusion. (e) Modified SVR fusion. (f) SVR fusion. (g) Modified Brovey fusion. (h) Brovey fusion. (i) PANSHARP fusion. (j) GS fusion.

- SVR$_m$: CHR-modified SVR method with $W = a$, $b = 0$ and $b_2 = 0$;
- Brovey$_m$: CHR-modified Brovey method with $W = \{0, 1, 1\}$, $b \neq 0$ and $b_2 = 0$.

![Figure 2](image2.png)

Figure 2. 128 × 128 details of original and 1-m synthetic images shown in true-colour composition. (a) True 4-m MS. (b) 4-m MS bicubically upsampled to 1 m. (c) 1-m PAN. (d) HR fusion. (e) Modified SVR fusion. (f) SVR fusion. (g) Modified Brovey fusion. (h) Brovey fusion. (i) PANSHARP fusion. (j) GS fusion.
latter with respect to three protocols (Wald et al. 1997): mean bias, correlation, and standard deviation of error. In addition, in order to score the global spectral quality of each synthetic product, four comprehensive indices were utilized, including Relative Average Spectral Error (RASE) (Ranchin and Wald 2000), Relative Global Dimensional Synthesis Error (ERGAS) (Wald 2000), Spectral Angle Mapper (SAM) (Yuhas et al. 1992, Kruse et al. 1993) and quality index $Q_4$ (Alparone et al. 2004).

4. Results

4.1 Visual comparison

Figures 1(b) and (c) present two subsets of the 16-m MS image and the 4-m PAN image, respectively. Figures 1(d)–(j) demonstrate all 4-m synthetic products except the HR fused image ignoring haze due to space limits, applied with an identical histogram stretching scheme for comparative purposes. In these products, objects free of vegetation cover, such as bare land, roads, and buildings, have similar tonalities to the corresponding ones in the reference image of figure 1(a). Vegetation pixels may have colours different from the reference. Most vegetation pixels in the fused images generated by HR, CHR, and PANSHARP methods have almost identical colours to their corresponding reference pixels. In contrast, the tonal variation of vegetation pixels within the SVR and Brovey fused images is noticeable. The vegetation pixels within the GS fused image are tinged with grey.

Figures 2(a) and (b) illustrate two subsets of the 4-m MS image and its upsampled version, respectively. Figures 2(d)–(j) exhibit subsets of size 128 × 128 of all 1-m synthetic products except the HR fused image ignoring haze, applied with an identical histogram stretching scheme. These products have similar tonalities to the low-resolution MS image in figure 2(b). In the SVR and Brovey fused images, some sunlit tree crowns are bright cyan spots, whereas some shaded crowns look like shadow. Conversely, in the CHR fused images, most crowns have similar tonalities of the reference. In the GS fused image, some sunlit crowns are similar to bright bare land, whereas some shaded crowns seem shadowed. The PANSHARP fused image is almost tied with the HR and CHR fused images.

4.2 Statistical comparison

Each 4-m fused band has a trivial mean bias which is not demonstrated here. Tables 1–3 report the correlation, standard deviation of error and comprehensive quality index statistics calculated for all the 4-m synthetic products, respectively. In each table, ‘HR_no_H’ row denotes the fused image obtained using HR method ignoring haze and ‘Exp’ row refers to the 16-m MS image bicubically upsampled to 4-m pixel size. The latter row reflects the errors in the 16-m MS image with reference to the 4-m original.

The correlation values in table 1 provide a global view of the similarities of the spectral bands for the fused and reference images. It can be seen that the HR method provides the highest correlation for each spectral band. However, when haze is ignored in fusion, the HR method yields considerably lower values for bands 1 and 2. The PANSHARP method offers correlation values nearly identical to the HR method as well as GS supplies lower values than PANSHARP.

SVR method offers low correlation values for bands 1 and 2, whereas the CHR-modified SVR method significantly improves the correlation values for the two
bands. Similarly, the Brovey method yields low correlation values for bands 1, 2, and 4, whereas the CHR-modified Brovey method significantly improves the correlation values for the three bands.

Table 2 illustrates the discrepancies of the spectral bands for the fused and reference images in terms of standard deviation of error. The HR method provides the lowest error for each spectral band. When image haze is ignored in HR fusion, the resultant fused bands 1 and 2 contain noticeably high errors. The PANSHARP method yields evidently higher errors than the HR approach, yet lower errors than GS. It can be observed that the CHR-modified SVR method drastically reduces the

<table>
<thead>
<tr>
<th>Fused band</th>
<th>Blue</th>
<th>Green</th>
<th>Red</th>
<th>NIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>0.918</td>
<td>0.933</td>
<td>0.932</td>
<td>0.914</td>
</tr>
<tr>
<td>HR_no_H</td>
<td>0.804</td>
<td>0.901</td>
<td>0.930</td>
<td>0.909</td>
</tr>
<tr>
<td>PANSHARP</td>
<td>0.911</td>
<td>0.927</td>
<td>0.926</td>
<td>0.909</td>
</tr>
<tr>
<td>GS</td>
<td>0.867</td>
<td>0.893</td>
<td>0.891</td>
<td>0.857</td>
</tr>
<tr>
<td>SVR_m</td>
<td>0.916</td>
<td>0.931</td>
<td>0.930</td>
<td>0.913</td>
</tr>
<tr>
<td>SVR</td>
<td>0.799</td>
<td>0.897</td>
<td>0.928</td>
<td>0.908</td>
</tr>
<tr>
<td>Brovey_m</td>
<td>0.914</td>
<td>0.929</td>
<td>0.927</td>
<td>0.911</td>
</tr>
<tr>
<td>Brovey</td>
<td>0.774</td>
<td>0.887</td>
<td>0.929</td>
<td>0.887</td>
</tr>
<tr>
<td>Exp</td>
<td>0.802</td>
<td>0.786</td>
<td>0.786</td>
<td>0.731</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fused band</th>
<th>Blue</th>
<th>Green</th>
<th>Red</th>
<th>NIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>14.41</td>
<td>21.23</td>
<td>26.90</td>
<td>36.70</td>
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<tr>
<td>HR_no_H</td>
<td>32.75</td>
<td>29.20</td>
<td>27.14</td>
<td>38.07</td>
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<td>PANSHARP</td>
<td>15.68</td>
<td>24.46</td>
<td>30.94</td>
<td>42.08</td>
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<tr>
<td>GS</td>
<td>18.62</td>
<td>28.36</td>
<td>35.72</td>
<td>48.16</td>
</tr>
<tr>
<td>SVR_m</td>
<td>14.62</td>
<td>21.57</td>
<td>27.31</td>
<td>36.86</td>
</tr>
<tr>
<td>SVR</td>
<td>33.33</td>
<td>29.87</td>
<td>27.57</td>
<td>38.15</td>
</tr>
<tr>
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<td>21.81</td>
<td>27.63</td>
<td>37.60</td>
</tr>
<tr>
<td>Brovey</td>
<td>23.42</td>
<td>27.92</td>
<td>32.00</td>
<td>44.35</td>
</tr>
<tr>
<td>Exp</td>
<td>21.29</td>
<td>36.19</td>
<td>45.56</td>
<td>62.03</td>
</tr>
</tbody>
</table>

bands. Similarly, the Brovey method yields low correlation values for bands 1, 2, and 4, whereas the CHR-modified Brovey method significantly improves the correlation values for the three bands.

Table 2 illustrates the discrepancies of the spectral bands for the fused and reference images in terms of standard deviation of error. The HR method provides the lowest error for each spectral band. When image haze is ignored in HR fusion, the resultant fused bands 1 and 2 contain noticeably high errors. The PANSHARP method yields evidently higher errors than the HR approach, yet lower errors than GS. It can be observed that the CHR-modified SVR method drastically reduces the

<table>
<thead>
<tr>
<th>Index</th>
<th>RASE (%)</th>
<th>ERGAS</th>
<th>SAM (°)</th>
<th>Q4</th>
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<tbody>
<tr>
<td>HR</td>
<td>9.25</td>
<td>2.67</td>
<td>1.830</td>
<td>0.881</td>
</tr>
<tr>
<td>HR_no_H</td>
<td>10.99</td>
<td>2.98</td>
<td>2.43</td>
<td>0.857</td>
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<tr>
<td>PANSHARP</td>
<td>10.58</td>
<td>3.06</td>
<td>2.08</td>
<td>0.833</td>
</tr>
<tr>
<td>GS</td>
<td>12.19</td>
<td>3.53</td>
<td>2.45</td>
<td>0.802</td>
</tr>
<tr>
<td>SVR_m</td>
<td>9.34</td>
<td>2.70</td>
<td>1.834</td>
<td>0.879</td>
</tr>
<tr>
<td>SVR</td>
<td>11.12</td>
<td>3.01</td>
<td>2.43</td>
<td>0.854</td>
</tr>
<tr>
<td>Brovey_m</td>
<td>9.49</td>
<td>2.74</td>
<td>1.84</td>
<td>0.877</td>
</tr>
<tr>
<td>Brovey</td>
<td>11.52</td>
<td>3.27</td>
<td>2.37</td>
<td>0.807</td>
</tr>
<tr>
<td>Exp</td>
<td>15.48</td>
<td>4.48</td>
<td>2.45</td>
<td>0.682</td>
</tr>
</tbody>
</table>
errors in the first two SVR fused spectral bands. Similarly, the CHR-modified Brovey method significantly lessens the error in each Brovey fused band.

As indicated by the comprehensive quality index statistics in table 3, HR method performs the best in this test. The HR fused image has the lowest RASE, ERGAS and SAM values of 9.25%, 2.67, and 1.830, respectively, as well as the highest $Q_4$ of 0.881. However, when image haze is ignored in HR fusion, the resultant fused image has considerably poorer indices of 10.99%, 2.98, 2.43, and 0.857, respectively. The consideration of haze is justified by the relatively better-quality indices of the fused image obtained using the HR method with haze involved. The indices for the PANSHARP and GS methods are poorer than those for the HR method with haze taken into account, indicating that the two former methods perform relatively worse than the latter.

It can be noticed that the second best method is the CHR-modified SVR which obtains the second lowest RASE, ERGAS and SAM values of 9.34%, 2.70, and 1.834, respectively, as well as the second highest $Q_4$ of 0.879. This modified method performs almost the same as the HR method and outperforms the SVR method. Similarly, the modified Brovey method offers a notably better synthetic product than the Brovey method. The high quality of the fused images generated by the two CHR-modified methods confirms that the CHR improvement scheme works well in improving the PAN modulation fusion methods of the second category, each of which utilizes a MS component as the assumed low-resolution PAN image in equation (1).

5. Discussions

Equation (1) can be written for MS pixel $M$ and the corresponding fused pixel $M_f$ in the form of a vector as follows:

$$M_f = M \cdot PAN / P_a, \quad (11)$$

which indicates that in PAN modulation image fusion, each MS pixel previously upsampled to match the pixel size of PAN image will develop spectrally along the pixel vector to a fused pixel in space. It is easy to find from equations (5) and (10) that each MS pixel in HR and CHR image fusion will develop spectrally along the pixel vector minus a haze vector, composed of the haze values in all MS bands, to a fused pixel. The haze in the MS image influences the spectral change direction of each MS pixel in image fusion and thus the resultant fused pixel. Such an impact upon the fusion of vegetation MS pixels is significant. For a sunlit vegetation MS pixel $M$ with low visible band values and a significant NIR band value, it may develop spectrally along a pixel vector to a fused pixel $M_f$ in PAN modulation image fusion, as demonstrated in figure 3. A resultant SVR or Brovey fused version of the vegetation MS pixel will have higher visible band values than the vegetation pixel. In contrast, the sunlit vegetation pixel will develop spectrally along the pixel vector $H$ minus a haze vector to a fused pixel $M'_f$ in HR and CHR image fusion. The resultant fused pixel will have similar low visible band values for the original vegetation MS pixel. Therefore, as described in the visual comparison of fused vegetation pixels obtained using different fusion methods in the preceding section, the SVR and Brovey fused vegetation pixels have more discrepancies from the reference image than the HR and CHR fused vegetation pixels. In GS fusion, a sunlit vegetation pixel will develop spectrally along vector $\alpha$ previously described to a fused pixel $M''_f$. In the previous test, the vector $\alpha$ is significantly different from the
pixel vector minus a haze vector, and each resultant GS fused sunlit vegetation pixel has considerably higher visible band values than the reference.

The spectral quality of CHR fused images is dependent upon the angle between the vectors $\mathbf{a}$ and $\mathbf{W}$ within equation (9). Such an angle in the CHR-modified SVR method is zero, and the resultant fused image will be nearly tied with the HR fused image; the angle in the CHR-modified Brovey method is larger, and the resultant fused image will have a poorer quality than the HR fused image, as verified by the previous test. If different MS band triplets are employed in CHR-modified Brovey fusion, as the angle increases, the quality of the resultant fused images will decrease.

As demonstrated in Table 4, when triplets of MS bands 2–4, of bands 1, 2, and 4, of bands 1, 2, and 4, and of bands 1–3 are employed in CHR-modified Brovey fusion with $b_2$ equal to 0, the angles between vectors $\mathbf{a}$ and $\mathbf{W}$ are 12.0°, 47.7°, 48.0°, and 58.1°, respectively. As expected, the quality of the four resultant fused images reduces gradually. The triplet of bands 2–4 with the least angle offers the best fused image; the triplet of bands 1–3 with the largest angle supplies the worst product. When all MS bands are employed in CHR fusion with $\mathbf{W} = \{1, 1, 1, 1\}$ and $b_2 = 0$, the angle is significant, and the resultant fused image is of a low quality.

<table>
<thead>
<tr>
<th>MS bands</th>
<th>$\mathbf{W}$</th>
<th>Angle (°) between $\mathbf{a}$ and $\mathbf{W}$</th>
<th>RASE (%)</th>
<th>ERGAS</th>
<th>SAM (°)</th>
<th>$Q_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brovey$_m$</td>
<td>2, 3, 4</td>
<td>${0, 1, 1, 1}$</td>
<td>12.0</td>
<td>9.49</td>
<td>2.74</td>
<td>1.84</td>
</tr>
<tr>
<td></td>
<td>1, 3, 4</td>
<td>${1, 0, 1, 1}$</td>
<td>47.7</td>
<td>19.60</td>
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</tr>
<tr>
<td></td>
<td>1, 2, 4</td>
<td>${1, 1, 0, 1}$</td>
<td>48.0</td>
<td>21.99</td>
<td>4.86</td>
<td>3.57</td>
</tr>
<tr>
<td></td>
<td>1, 2, 3</td>
<td>${1, 1, 1, 0}$</td>
<td>58.1</td>
<td>27.83</td>
<td>5.91</td>
<td>4.46</td>
</tr>
<tr>
<td></td>
<td>1, 2, 3, 4</td>
<td>${1, 1, 1, 1}$</td>
<td>34.7</td>
<td>12.18</td>
<td>3.22</td>
<td>2.26</td>
</tr>
</tbody>
</table>
Due to serious air pollution, the haze values in the 16-m MS bands 1–4 and in the 4-m PAN image in the previous test are 427, 422, 296, 274, and 288, respectively. These values are too significant to be ignored in fusion. As haze decreases with respect to wavelength, as indicated in tables 1–3, taking haze into account in HR and CHR fusion improves blue spectral band significantly, improves green band less significantly, and improves red and NIR bands the least. Such variable haze values in spectral bands account for the poor performance upon short-wavelength bands as well as the good performance upon long-wavelength bands of the SVR and Brovey methods in the test.

Different haze estimates result in different HR fused images. As haze values rise from 0 to 120% of the haze values employed in the previous test, three series of synthetic products can be obtained using HR, CHR-modified SVR, and CHR-modified Brovey methods with identical parameters as in the previous test. Figures 4(a)–(d) present the variations of the four comprehensive quality indices, RASE, ERGAS, SAM, and $Q_4$, calculated for the three series, respectively. As illustrated, each index curve has a clear tendency with the increase in haze. As the percentage value increases from zero, the first three indices decrease synchronously, reach minimum values at about 105% percent, and then rise dramatically; index $Q_4$ increases steadily, reaches a maximum value at about 105% and then drops down rapidly. It is worth pointing out that the three series continue to be of high quality within a wide range of haze estimates around 100%. Even though there are no completely dark objects in scene, and haze estimates contain some errors, a small

![Figure 4](image-url)

**Figure 4.** Variations of the four comprehensive quality indices of the series of HR (–), CHR-modified SVR (⋯) and CHR-modified Brovey (---) synthetic products with the change of haze in percent. (a) RASE. (b) ERGAS. (c) SAM. (d) $Q_4$. 
error within a haze estimate will not impact the spectral quality of HR and CHR synthetic products significantly.

6. Conclusion

Current PAN modulation fusion methods can be classified into two categories with respect to an assumed low-resolution PAN image as the divisor of the high-resolution PAN image input: one employing a spatially degraded PAN image, another utilizing a MS component. In this paper, image haze is taken into account in the two categories, and two improvement schemes of the latter are proposed. In the first scheme, the assumed low-resolution PAN image is set to a haze-free spatially degraded PAN image; in the second scheme, it is derived from a haze-free MS component. In a test on spatially degraded IKONOS MS and PAN images, the first scheme yields a synthetic product with minimum spectral distortion, and the second scheme allows the PAN modulation fusion methods of the second category to be modified to synthesize high-quality products. Both schemes are easy to understand and complement image processing.

References


ZHANG, Y., 2002a, Problems in the fusion of commercial high-resolution satellite as well as Landsat 7 images and initial solutions. In ISPRS Commission IV Symposium on Geospatial Theory, Processing and Applications, 9–12 July 2002, Ottawa, Canada.