QUALITY ASSESSMENT FOR MULTI-SENSOR MULTI-DATE IMAGE FUSION

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WG IV/4

KEY WORDS: Image Processing, Sharpening, Image Understanding, Fusion, Environmental Monitoring, Colour, Multisensor

ABSTRACT:

Generally, image fusion methods are classified into three levels: pixel level (iconic), feature level (symbolic) and knowledge or decision level. In this paper we focus on iconic techniques for image fusion. Usually, image fusion techniques such as intensity-hue-saturation (IHS) or Brovey are used to fuse high spatial resolution panchromatic and lower spatial resolution multispectral images that are simultaneously recorded by one sensor. This is done to create high resolution multispectral image datasets (pansharpening). In most cases, these techniques provide very good results, i.e. they retain the high spatial resolution of the panchromatic image and the spectral information from the multispectral image. These techniques, when applied to multitemporal and/or multisensoral image data, still create spatially enhanced datasets but usually at the expense of the spectral consistency. In this study, a method for image fusion is presented that preserves the spectral characteristics of the multispectral image also for multi-date and multi-sensor data (Ehlers fusion). A series of eight multitemporal multispectral remote sensing images (seven SPOT scenes and one FORMOSAT scene) is fused with one panchromatic Ikonos image. The fused images are visually and quantitatively analyzed for spectral characteristics preservation. These results are then compared to those from a number of standard and advanced fusion techniques. It can not only be proven that the Ehlers fusion is superior to all other tested algorithms but also the only one that guarantees an excellent color preservation for all dates and sensors.

1. INTRODUCTION

Most of the earth observation satellites such as Landsat, Spot, Ikonos, Quickbird, Formosat or Kompsat and also some digital airborne sensors like DMC or UltraCam provide panchromatic images at a higher spatial resolution than at their multispectral mode and other satellites provide only panchromatic images, such as EROS-B or WorldView I. The difference in spatial resolution between the panchromatic and the multispectral mode can be measured by the ratio of their respective ground sampling distances (GSD) and may vary between 1:2 and 1:5. This ratio can get worse if data from different satellites are used. For example, the resolution ratio (RR) between Ikonos and SPOT 5 (multispectral mode) is 1:10, for SPOT 4 even 1:20. The objective of iconic image fusion is to combine the high spatial and the multispectral information to form a fused multispectral image that retains the spatial information from the high resolution panchromatic image and the spectral characteristics of the lower resolution multispectral image.

The goals of the fusion process are manyfold: to sharpen multispectral images, to improve geometric corrections, to provide stereo viewing capabilities for stereophotogrammetry, to enhance certain features not visible in either of the single datasets alone, to complement data sets for improved classification, to detect changes using multitemporal data and to replace defective data (Pohl and van Genderen, 1998). In this paper, we concentrate on the image sharpening process and the question of quality assessment.

Generally, image fusion methods can be differentiated into three levels: pixel level (iconic), feature level (symbolic) and knowledge or decision level. Of highest relevance for remote sensing are techniques for iconic image fusion, for which many different methods have been developed (see, for example, Welch and Ehlers, 1987; Pohl and van Genderen, 1998; Alparone et al., 2006).

Iconic image fusion techniques can be grouped into three classes: color related techniques, statistical methods and numerical methods (Ehlers, 2004). The first class includes color composition of three image bands in the RGB color space as well as more sophisticated color transformations such as intensity hue saturation (IHS) or the hue saturation value (HSV) transforms. On the basis of band statistics including correlation and filters, statistical approaches were developed, such as principal component (PC) transform. The numerical methods employ arithmetic operations such as image multiplication, summation and image rationing. More sophisticated numerical approaches use wavelets in a multi-resolution environment (Otazu et al., 2005).

Many publications have focused on how to fuse high resolution panchromatic images with lower resolution multispectral data to obtain high resolution multispectral imagery while retaining the spectral characteristics of the multispectral data. It has been proven that these methods seem to work well for many applications, especially for single-sensor single-date fusion. Most methods, however, exhibit significant color distortions for multitemporal and multisensoral case studies (Ehlers 2004; Klonus and Ehlers, 2007). The new fusion technique presented in this article has been designed to overcome these problems and has already proven its superiority over the standard pansharpening techniques such as IHS, PC, Brovey and multiplicative fusion methods (Ehlers, 2004; Ehlers and Klonus, 2004; Ling et al., 2007).

Over the last few years, a number of improved algorithms have been developed with the promise to minimize color distortion while retaining the spatial improvement of the standard data fusion algorithms. Especially wavelet techniques led to a number of new fusion methods (Otazu et al., 2005; Lillo-Saavedra & Gonzalo, 2006; Yunhao et al., 2006). We selected four of these new fusion methods for comparison. These algorithms are the color normalization spectral sharpening (CN), the Gram Schmidt fusion, the modified IHS fusion and a wavelet based fusion method the proportional additive wavelet fusion (AWLP). The other fusion techniques for comparison were the 'standard methods' Brovey, PC and multiplicative.

2. DATA AND METHODOLOGY

2.1 Study Area and Datasets

The study area is located in the North of Spain, southwest of the town Vitoria Gasteiz. It represents the region around Santo Domingo de la Calzada. This area was used as a control site of the JRC (Joint Research Centre of the European Commission) in the project "Control with Remote Sensing of Area-Based Subsidies" (CwRS) (see the project website at: http://agrifish.jrc.it/marspac/DCM/).

Eight different multispectral SPOT and Formosat images were used for this investigation (see Table 1).

Satellite Sensor	Recording Date	Ground Sampling Distance
SPOT 4	3 November 2003	20 m
SPOT 4	24 April 2004	20 m
SPOT 4	15 May 2004	20 m
SPOT 5	24 July 2004	10 m (20 m SWIR)
SPOT 2	10 December 2004	20 m
SPOT 5	10 April 2005	10 m (20 m SWIR)
SPOT 4	20 July 2005	20 m
Formosat 2	12 August 2005	8 m

Table 1: Multispectral remote sensing datasets for the study site of Santo Domingo de la Calzada

These multispectral images cover a time frame of almost 2 years and virtually all seasons and thus pose an excellent challenge for a spectral characteristics preserving data fusion. All images were merged with a panchromatic Ikonos image from 30 May 2005 (1 m GSD) using eight different fusion algorithms.

2.2 Preprocessing

The first and extremely important part of the fusion process is the creation of coregistered datasets. For areas with terrain relief a differential registration procedure is necessary to ensure that the images are in perfect registration. Otherwise the quality of the fused image will decrease significantly. Even small misalignments can cause color artifacts in the fusion process. Consequently, the images were orthocorrected and their accuracy checked from different European Union (EU) data contractors as part of the standard CwRS routine. After the orthocorrection of the original multispectral images, they were resampled using a cubic convolution function to the ground resolution (1 m) of the panchromatic Ikonos image. All bands of the original images were used for the fusion process. For the output format we chose float single to avoid any loss of information and to ensure the conformity of all images. The image processing was performed using ERDAS Imagine and ENVI software packages.

2.3 Image Fusion

We employed eight different algorithms for fusion of the images. All eight images were fused with the panchromatic Ikonos image resulting in a dataset of 64 fused images. All images were evaluated visually and statistically for color preservation, we made use of standard techniques and a number of recently developed algorithms: The modified IHS fusion (Siddiqui 2003), the CN spectral sharpening (Vrabel et al., 2002), the Gram Schmidt spectral sharpening (Laben et al., 2000), the Brovey Transform (Hallada and Cox, 1983), the PCA (Chavez et al., 1991), the multiplicative (Crippen, 1989) the Ehlers Fusion (Klonus & Ehlers, 2007) and AWLP (Otazu et al., 2005).

2.4 Evaluation

For the visual analysis, we concentrated on the issue of color preservation although also the spatial improvement was analyzed. This analysis, however, has the disadvantage that it is very subjective and depends heavily on the interpreter. Therefore, we also subjected the fusion results to a thorough statistical analysis using a number of quality parameters. From the results, however, it was clearly visible that some fusion methods failed miserably for multisensor fusion or were inconsistent, a fact that did not warrant a quantitative analysis.

Statistical evaluation procedures have the advantage that they are objective, quantitative, and repeatable. We selected three different statistical evaluation methods. First, we employed the RMS error as proposed by Wald (2002, S. 160), which is computed as the difference of the standard deviation and the mean of the fused and the original image. As second evaluation method we calculated the correlation coefficients between the original multispectral bands and the equivalent fused bands. As third procedure, we selected the deviation per pixel, developed by Wald (2002, S.147-160). For this method it is necessary to degrade the fused image to the spatial resolution of the original image. This image is then subtracted from the original image on a per pixel basis. As final step, we calculated the average deviation per pixel measured as digital number (DN) which is based on an 8-bit or 16-bit range, depending on the radiometric resolution of the employed images.

3. RESULTS AND DISCUSSION

All eight images were visually and statistically analyzed for all eight fusion methods. Our comprehensive analysis is based on all 64 single results. For demonstration purposes, we selected the SPOT 5 image of July 2004 because it is very representative for the encountered fusion effects. Figure 3 shows the original multispectral SPOT 5 (bands 3 – near infrared, 2 – red, and 1 – green) as a standard false color infrared display and the panchromatic Ikonos image data as well as the eight different fusion results. It is clearly visible that only the Ehlers (Fig. 3b) and the AWLP fusion (Fig. 3f) retain almost all the colors from the original image. All other fusion methods such as Brovey (Fig. 3a), IHS (Fig. 3c), multiplicative (Fig. 3d), PC (Fig. 3e), CN (Fig. 3g), and Gram Schmidt (Fig. 3h) show significant color distortions and degradations. Especially the green field in the lower left edge appears darker than in the original image. For PC and Gram Schmidt it has even changed into another color (red instead of green in the false color display). A comparison with the panchromatic Ikonos image confirms that the darker color is due to the panchromatic information in this region.

While the AWLP fusion generates an image that preserves the original colors very well, it is also evident that it does not produce a spatially improved image. The fused image shows only sketchy spatial improvement in some parts of the image. The overall impression is that of a very blurred image (similar to the original resampled one) with some overlaid sketch lines on top (Fig. 3h).

Figure 1. Original multispectral Spot 5 image recorded on 24 July 2004 in the band combination 3 (near infrared), 2 (red), 1 (green)

Figure 2. Original panchromatic Ikonos image recorded on 3 May 2005

All images were evaluated using the previously described scheme. The Ehlers and the AWLP fusion show almost no color distortions and achieved the best results for all images as far as spectral characteristics preservation is concerned. The AWLP fusion, however, provides almost no spatial improvement and – as such - does not fulfill the basic requirement for pansharpening. Brovey and IHS fusion show sometimes acceptable results, but were never without serious color changes. The best results for these two fusion techniques was achieved for the SPOT image which was recorded in April 2005, i.e. the closest to the acquisition date of the panchromatic Ikonos image. Multiplicative fusion shows best results for the fall images, but never without significant color changes. PC and Gram Schmidt fusion have the most serious color deficiencies and should not be used for multitemporal and/or multisensoral image fusion.

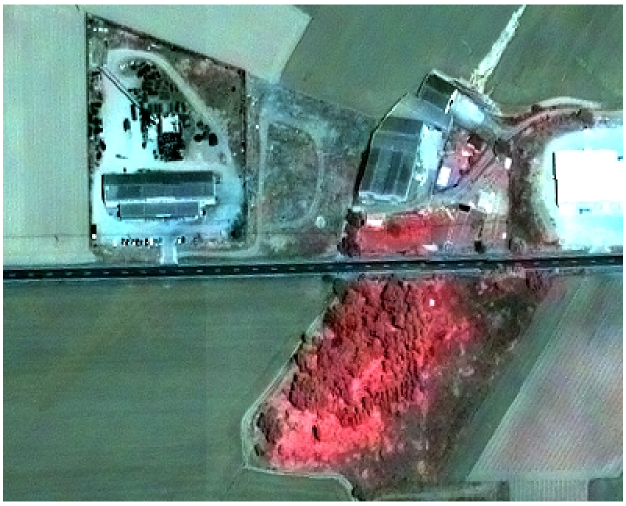

Figure 3a. Brovey fusion

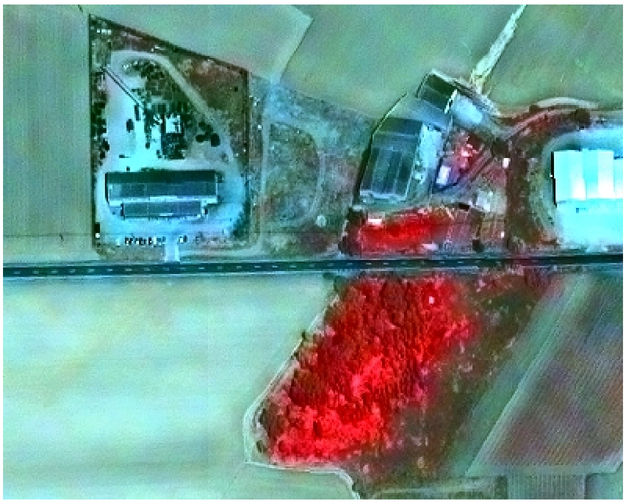

Figure 3b. Ehlers fusion

Figure 3c. IHS fusion

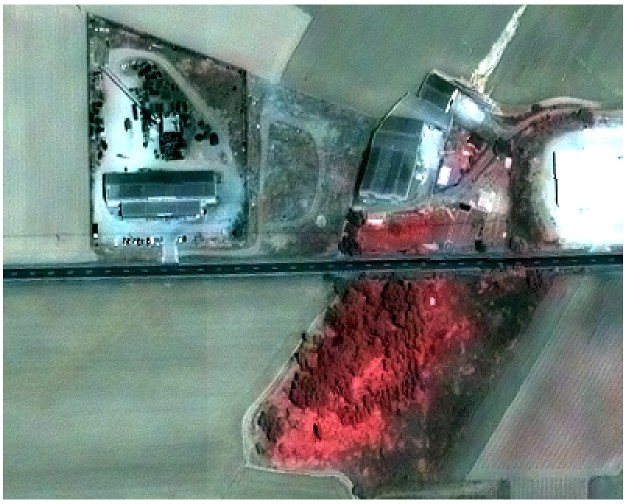

Figure 3d. Multiplicative fusion

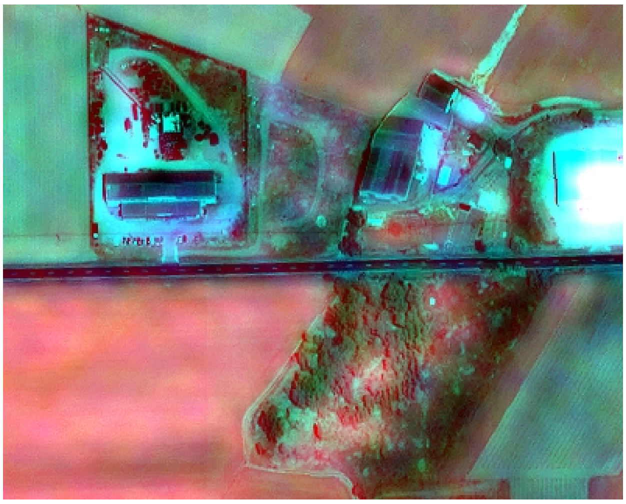

Figure 3e. PC fusion

Figure 3f. AWLP fusion

Considering the spatial enhancement in the fused images, all methods were sufficient with the exception of the AWLP function which did not pansharpen the images. Often only stripes instead of spatial enhancement were visible in the fused images. Particularly in homogeneous areas, no spatial improvement could be found at all. This was true for all multitemporal images.

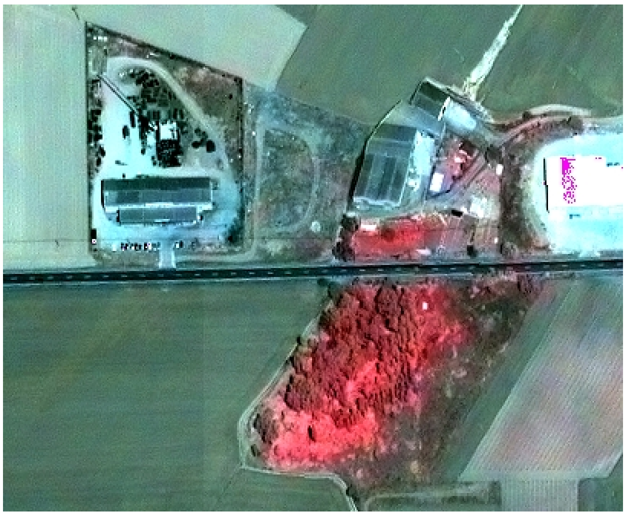

Figure 3g. CN Spectral Sharpening

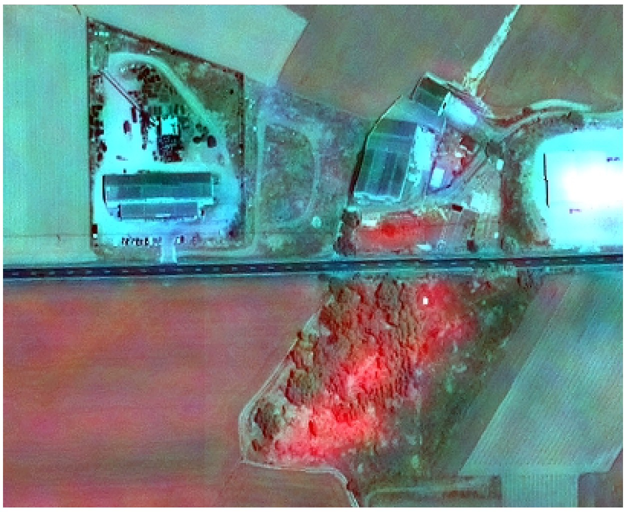

Figure 3h. Gram Schmidt fusion

Brovey, Ehlers, IHS, CN spectral sharpening and multiplicative fusion showed good to very good spatial sharpening results in all images. PCA and Gram Schmidt showed some improvement in spatial resolution but never as good as the other methods. In some cases, the fused images looked still blurred. As we focused on the issue of color preservation, we did not subject the fusion techniques to a quantitative analysis with respect to the spatial improvement. But even from the visual inspection it is clear that Gram Schmidt, CN, wavelet and PC fusion techniques should not be used for multitemporal image merging.

The quantitative analyses for color constancy confirmed the visual inspection findings. Ehlers and wavelet fusion were always the best for all employed quality measurements. For the RSME, the AWLP function showed best results. Again, it is evident that the spectral fidelity of the AWLP fusion comes at the expense of the spatial improvement. The AWLP fusion fails here badly. The calculated and ranked RMSE values are presented in Table 2. The lower the point score (P) in the last column, the better the result.

	03/11/ 2003	**24/04/ 2004**	**15/05/ 2004**	**24/07/ 2004**
Ehlers	0.3860	0.4291	0.4521	0.2470
Gram	0.7245	1.3416	1.8439	0.2408
AWLP	1.1275	1.3332	0.8805	0.4630
IHS	3.7869	3.2602	8.3122	3.5600
PC	7.6334	12.6179	20.9599	4.4556
CN	9.9045	10.5073	26.3343	4.9273
Brovey	59.6848	68.3178	101.2562	65.7872
Multi	7088.21	7811.94	10641.60	7574.49

Table 2a. RMSE values (PART A).

	10/12/ 2004	**10/04/ 2005**	**20/07/ 2005**	**12/08/ 2005**	**P**
Ehlers	0.1689	0.3211	0.3219	0.4645	**9**
Gram	0.3058	1.8871	3.6719	1.6455	**19**
AWLP	1.4481	2.3318	1.2195	0.6638	**20**
IHS	3.4574	2.3602	6.3045	2.1385	**32**
PC	7.9674	14.7177	45.7655	16.1171	**43**
CN	67.1670	8.4565	40.6541	20.7049	**46**
Brovey	8.3085	77.8213	134.4051	85.5477	**55**
Multi	1851.18	9022.38	13342.90	9302.98	**64**

Table 2b. RMSE values (PART A).

	03/11/ 2003	**24/04/ 2004**	**15/05/ 2004**	**24/07/ 2004**
AWLP	0.23	0.32	0.20	0.01
Ehlers	1.30	0.62	0.55	0.72
IHS	11.60	10.22	18.20	6.68
Gram	9.99	20.75	29.23	6.58
CN	11.51	12.08	24.62	7.27
PC	11.74	46.70	26.26	7.09
Brovey	58.26	64.65	95.98	65.31
Multi	6771.82	7296.31	33076.53	7369.47

Table 3a. Per-pixel deviation between the fused and the original images (Part A)

	10/12/ 2004	**10/04/ 2005**	**20/07/ 2005**	**12/08/ 2005**	**P**
AWLP	0.09	0.12	0.07	0.03	**8**
Ehlers	0.35	0.68	0.62	1.02	**16**
IHS	5.55	7.19	23.76	12.96	**28**
Gram	4.15	12.86	32.02	13.72	**33**
CN	64.95	8.34	38.92	21.82	**40**
PC	8.10	18.30	46.70	19.71	**44**
Brovey	8.19	74.02	130.43	84.45	**55**
Multi	1740.32	8269.13	12803.17	8987.29	**64**

Table 3b. Per-pixel deviation between the fused and the original images (Part B)

The lowest (and best) values are associated with the Ehlers fusion, but this was to be expected because the fused images almost look like the originals. In constrast to the visual inspection the Gram-Schmidt fusion shows the second best results with small RMSE values, the AWLP fusion shows slightly higher values. With the exception of the multiplicative fusion which consists of a simple multiplication without rescaling and was not scaled to the original image and has therefore the highest RMSE values, the worst results were produced by the PC, CN and Brovey methods. This result is confirmed by the average per-pixel deviation with Ehlers and wavelet very closely first followed by IHS and Gram Schmidt. Again, PC, CN and multiplicative show unacceptable results (Table 3).

The previous findings were again confirmed by the third statistical analysis, the calculation of the correlation coefficient between the fused and original image bands. Best results were obtained by the Ehlers and AWLP methods. The AWLP function showed a higher coefficient only for one date (10 December 2004). Brovey, IHS, multiplicative and PC fusion present their best results in the image of the 10 April 2005 which is the closest in time to the panchromatic Ikonos image. Here, the multiplicative function showed better results than the other functions with the exception of Ehlers and wavelet. CN, IHS, Brovey, PC, and Gram Schmidt had very low correlation coefficients (with the exception for the April 2005 image). Table 4 presents the correlation results. The correlation coefficient represents the average value for all bands.

	03/11/ 2003	**24/04/ 2004**	**15/05/ 2004**	**24/07/ 2004**
Ehlers	0.9644	0.9825	0.9860	0.9501
AWLP	0.9403	0.9548	0.9527	0.9099
Multi	0.7990	0.8494	0.8415	0.6729
CN	0.6918	0.8559	0.7273	0.6412
IHS	0.5593	0.7762	0.7029	0.7064
Brovey	0.5938	0.6471	0.5720	0.4970
PC	0.6316	0.2982	0.3191	0.5129
Gram	0.6273	0.5694	0.2908	0.5694

Table 4a. Correlation Coefficients between fused and original multispectral bands (Part A)

	10/12/ 2004	**10/04/ 2005**	**20/07/ 2005**	**12/08/ 2005**	**P**
Ehlers	0.9282	0.9866	0.9908	0.9486	**9**
AWLP	0.9591	0.9403	0.9542	0.9444	**15**
Multi	0.7908	0.8960	0.8095	0.7268	**27**
CN	0.3009	0.9315	0.6486	0.4483	**36**
IHS	0.2381	0.8937	0.5320	0.4805	**43**
Brovey	0.3227	0.8890	0.4329	0.4500	**49**
PC	0.3377	0.6858	0.2632	0.3022	**54**
Gram	0.3122	0.7476	0.2021	0.4031	**55**

Table 4b. Correlation Coefficients between fused and original multispectral bands (Part B)

4. CONCLUSIONS

The results of this research confirm previous findings that the standard and even most of the advanced fusion methods that are implemented in commercial image processing systems cannot cope with the demands that are placed on them by multisensor/multitemporal fusion. Serious color distortions ranging from brightness reversion to a complete change of spectral characteristics are the results of many operational and often used fusion techniques. Principal component, color normalization or Gram Schmidt fusion should only be used for singles-sensor, single-date images. Wavelet based fusion retains most of the spectral characteristics at the expense of spatial improvement. The only technique of those that were employed in our comparative study that delivers pansharpened images with almost no spectral change is the Ehlers fusion of which a first version has recently been implemented in the ERDAS Imagine Software.

There exists a number of recently developed fusion algorithm that we have not yet tested. Future research will compare the Ehlers fusion with the algorithms for instance promoted by Zhang (2002), Alparone et al. (2005), or Gungor & Shan (2006). First tests with the Zhang fusion implemented in PCI‘s Geomatica software revealed spectral distortions when applied to multi-date and multi-sensor images (Klonus 2006). In a related issue, a predecessor of the Ehlers fusion with less flexibility proved to be superior to a combined IHS/wavelet fusion (Ling et al. 2007).

What is also needed is a combined method for a quantitative assessment of spatial improvement and spectral preservation because otherwise the best color preservation is observed if no pansharpening is performed. This would, however, defeat the purpose of the fusion process. Only a combined assessment of spatial improvement and spectral characteristics preservation can be used as a quality measure for image fusion. Nevertheless, it seems to be possible to fuse multitemporal and multisensoral image data with sufficient spatial enhancement and spectral fidelity.

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