COMPARISON OF PANSHARPENING ALGORITHMS FOR COMBINING RADAR AND MULTISPECTRAL DATA

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ABSTRACT:

Iconic image fusion is a technique that is used to combine the spatial structure of a high resolution panchromatic image with the spectral information of a lower resolution multispectral image to produce a high resolution multispectral image. This process is often referred to as pansharpening. In this study, image data of the new RADAR satellite TerraSAR-X are used to sharpen optical multispectral data. To produce these images, use is made of the Ehlers fusion, a fusion technique that is developed for preserving maximum spectral information. The Ehlers Fusion is modified to integrate radar data with optical data. The results of the modified Ehlers fusion are compared with those of other standard fusion techniques such as Brovey, Principal Component, and with recently developed fusion techniques such as Gram-Schmidt, UNB, wavelet based fusion and CN-Spectral Sharpening. The evaluation is based on the verification of the preservation of spectral characteristics and the improvement of the spatial resolution. The results show that most of the fusion methods are not capable to integrate TerraSAR-X data into multispectral data without color distortions. The result is confirmed by statistical analysis.

KURZFASSUNG:

Ikonische Bildfusion ist eine Technik, um die räumliche Struktur von hochaufgelösten panchromatischen Bilddaten mit den spektralen Informationen eines niedriger aufgelösten Multispektralbildes zu kombinieren, um ein hochaufgelöstes multispektrales Bild zu erhalten. Dieser Prozess wird auch „Pansharpening“ genannt. In dieser Untersuchung werden Bilddaten des neuen RADAR Satelliten TerraSAR-X verwendet, um die geometrische Auflösung der optischen multispektralen Daten zu verbessern. Um diese Bilder zu erstellen, wird die Ehlers Fusion verwendet. Dieses Fusionsverfahren wurde speziell zur bestmöglichen Erhaltung der spektralen Informationen entwickelt. Die Ehlers Fusion wurde modifiziert, um RADAR Daten in optische Daten zu integrieren. Die Resultate der modifizierten Ehlers Fusion wurden mit Standard-Fusionstechniken wie der Brovey Transformation oder dem Principal Component Verfahren und auch mit aktuelleren weiter entwickelten Fusionsverfahren, wie Gram-Schmidt, UNB, Wavelet basierter Fusion und Color-Normalized Spectral Sharping verglichen. Die Evaluierung der Ergebnisse basiert auf der Untersuchung der Erhaltung der spektralen Charakteristiken und der Verbesserung der geometrischen Auflösung. Die Ergebnisse zeigen, dass die Fusionsverfahren überwiegend daran scheitern, die TerraSAR-X Daten in die multispektralen Daten ohne Farbveränderungen zu integrieren. Die quantitativ-statistischen Ergebnisse bestätigen diese Aussage.

1. INTRODUCTION

Image fusion is a technique that is used to combine the spatial structure of a high resolution panchromatic image with the spectral information of a lower resolution multispectral image to produce a high resolution multispectral image. This process is often referred to as pansharpening.

In this study, image data of the new RADAR satellite TerraSAR-X are used to sharpen optical multispectral data. TerraSAR-X is the first non-military RADAR satellite which provides data with a ground resolution of 1 m. The opportunity to acquire images independent of any illumination by the sun and independent of weather conditions such as, for example, cloud coverage allows measurements at any time of day or night. Fusion with multispectral image data from other dates can make it possible to produce higher resolution color images, even under clouded skies or adverse weather conditions. These enhanced images can be submitted to rescue staff in conflict areas caused by disaster such as earthquakes, tsunamis or flooding. With this information, for example, it will be easier for rescue forces to identify the most affected areas, the extent and degree of damage and site accessibility.

Many other publications have already 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 (see, for example, Welch and Ehlers 1987 or González-Audícana et al. 2006). Fewer publications focus on the use of SAR data for Fusion. Ehlers (1991) showed that fused SIR-B and Landsat TM data improved the quality for vegetation mapping. Ricciettti (2001) used SAR data as a panchromatic input for image fusion with optical data. He used the SAR image to fuse it with Landsat TM data. Chibani (2006) used Spot panchromatic and SAR data to integrate this information into multispectral Spot data.

2. STUDY AREA AND DATASETS

The study area is located in Egypt and shows the area around the pyramids of Gizeh. A TerraSAR-X image (Fig. 1) of this area was provided by the DLR (German Aerospace Centre). The image is despeckled with a 7x7 median filter. For the same area a multispectral Quickbird image (Fig. 2) with a ground resolution of 2.40 m is also available. To demonstrate the effects of spatial improvement in the fused image, the Quickbird image is spatially degraded by a factor of 3. Before the fusion is performed, the degraded Quickbird image is resampled using cubic convolution to the spatial resolution of the TerraSAR-X image.

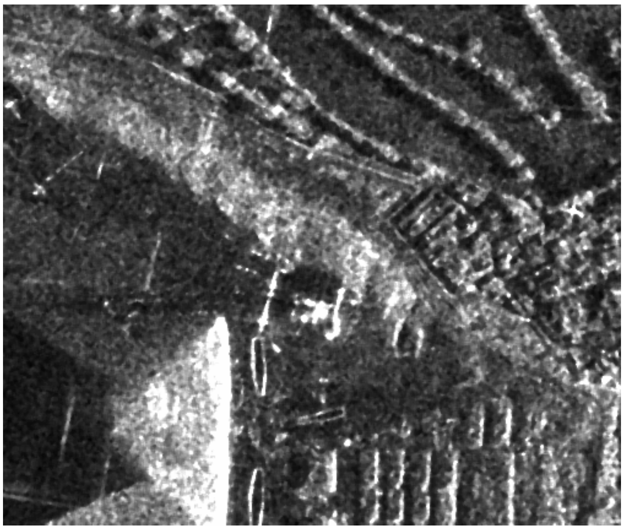

Figure 1: TerraSAR-X image of Gizeh recorded in high resolution spot mode. Recording date: 29th November 2007 ©DLR (2007)

Figure 2: Multispectral Quickbird image recorded on the 2nd February 2002, degraded to 7.20 m displayed in the band combination 4 (nir), 3 (red), 2 (green).

3. METHODS

3.1 Fusion Methods

Eight different fusion methods are used in this investigation:

To fuse the images with the IHS fusion, three bands of a multispectral image are transformed from the RGB domain into the IHS color space. The panchromatic component is matched to the intensity of the IHS image and replaces the intensity component. We make use of the **modified IHS fusion** from Siddiqui (2003) which was developed for a better fit of the fused multispectral bands to the original data. After the matching, the panchromatic image replaces the intensity in the original IHS image and the fused image is transformed back into the RGB color space.

The AWL method (Núnez et al. 1999) is one of the existing multiresolution wavelet-based image fusion techniques. It was originally defined for a three-band red-green-blue (RGB) multispectral image. In this method, the spectral signature is preserved since the high resolution panchromatic structure is integrated into the luminance L-band of the original low resolution multispectral image. Hence this method is only defined for three bands. It was extended to n bands by Otazu et al. (2005). It maintains the spectral signature of an n-band image in the same way as AWL does with RGB images. This generalized method is called proportional AWL (**AWLP**).

The **color normalization** (CN) spectral sharpening is an extension of the Brovey algorithm and groups the input image bands into spectral segments defined by the spectral range of the panchromatic image. The corresponding band segments are processed together in the following manner: Each input band is multiplied by the sharpening band and then normalized by dividing it by the sum of the input bands in the segment (Vrabel et al. 2002).

The **Gram Schmidt** fusion simulates a panchromatic band from the lower spatial resolution spectral bands. In general, this is achieved by averaging the multispectral bands. As the next step, a Gram Schmidt transformation is performed for the simulated panchromatic band and the multispectral bands with the simulated panchromatic band employed as the first band. Then the high spatial resolution panchromatic band replaces the first Gram Schmidt band. Finally, an inverse Gram Schmidt transform is applied to create the pansharpened multispectral bands (Laben et al. 2000).

The **Ehlers fusion** (Ehlers 2004) is based on an IHS transform coupled with a Fourier domain filtering. This technique is extended to include more than 3 bands by using multiple IHS transforms until the number of bands is exhausted. A subsequent Fourier transform of the intensity component and the panchromatic image allows an adaptive filter design in the frequency domain. Using fast Fourier transform (FFT) techniques, the spatial components to be enhanced or suppressed can be directly accessed. The intensity spectrum is filtered with a low pass filter (LP) whereas the panchromatic spectrum is filtered with an inverse high pass filter (HP). After filtering, the images are transformed back into the spatial domain with an inverse FFT and added together to form a fused intensity component with the low-frequency information from the low resolution multispectral image and the high-frequency information from the TerraSAR-X image. This new intensity component and the original hue and saturation components of the multispectral image form a new IHS image. As the last step, an inverse IHS transformation produces a fused RGB image. These steps can be repeated with successive 3-band selections until all bands are fused with the panchromatic image (for a complete description of the method see Klonus & Ehlers 2007).

To apply the **UNB** (University of New Brunswick) fusion algorithm (Zhang 2004) a histogram standardization is calculated on the input images (multispectral and panchromatic). The multispectral bands in the spectral range of the panchromatic image are selected and a regression analysis is calculated using the least square algorithm. The results are used as weights for the multispectral bands. Via multiplication with the corresponding bands and a following addition, a new synthesized image is produced. To create the fused image each standardized multispectral image is multiplied with the standardized panchromatic image and divided by the synthesized image.

Two additional standard techniques were also applied, the **Brovey** Transform (Hallada and Cox 1983) and the **Principal component (PC)** fusion (Chavez et al. 1991)

3.2 Evaluation Methods

The evaluation is based on the verification of the preservation of spectral characteristics and the improvement of the spatial resolution. First the fused images are visually compared. The visual appearance, however, is very subjective and depends on the human interpreter. Therefore, we use a number of statistical evaluation methods to measure the color preservation which are objective, reproducible, and of quantitative nature. These methods are:

Correlation coefficients between the original multispectral bands and the equivalent fused bands. This value ranges from -1 to 1. The best correspondence between fused and original image data show the highest correlation values.

A **root-mean-square error** is computed from the standard deviation and the mean of the fused and the original image as proposed by Wald (2002, S. 160). The smaller the value, the better the correspondence between the images.

For a per-pixel deviation (see Wald 2002, pp. 147-160) 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 calculate the average deviation per pixel measured as digital number (DN) which is based on an 8-bit or 16-bit range. Again zero is the best value.

The **Structure Similarity Index** (**SSIM**) was proposed by Wang et al. (2004). The SSIM is a method that combines a comparison of luminance, contrast and structure and is applied locally in an 8 x 8 square window. This window is moved pixel-by-pixel over the entire image. At each step, the local statistics and the SSIM index are calculated within the window. The value vary between 0 and 1. Values close to 1 show the highest correspondence with the original images.

In most analyses, emphasis has been placed on the spectral evaluation. It is, however, also mandatory to investigate the performance of the pansharpening algorithms as far as the spatial improvement is concerned. Otherwise, the original image with no spatial improvement would produce the best results. The objective is to find the fused image with the optimal combination of spectral characteristics preservation and spatial improvement. To quantitatively measure the quality of the spatial improvement, two different quantitative methods are chosen:

High pass correlation: Correlation between the original panchromatic band and the fused bands after high pass filtering. This algorithm was proposed by Zhou et al. (1998). The high pass filter is applied to the panchromatic image and each band of the fused image. Then the correlation coefficients between the high pass filtered bands and the high pass filtered panchromatic image are calculated.

Edge detection in the panchromatic image and the fused multispectral bands: For this, we selected a Sobel filter (Jensen 2005) and performed a visual analysis of the correspondence of edges detected in the panchromatic and the fused multispectral images. This was done independently for each band. The value is given in percent and varies between 0 and 100. 100 % means all of the edges in the panchromatic image were detected in the fused image.

4. RESULTS

The results of the fusion process are shown in Fig. 3 – Fig. 10. For the visual analysis, each band of the fused image was compared to the appropriate original multispectral band for preservation of the spectral characteristics. Then, the identical band combinations of the fused and original images were compared, such as true color or false color infrared combination. In this paper, the false color infrared combination was chosen because it is very representative for the fusion effects.
In comparison with the orginal multispectral image (Fig. 2) it is clearly visible, that only the AWLP (Fig. 3) and the Ehlers fusion (Fig. 6) preserve almost all the colors of the original image. All other methods like Brovey (Fig. 4), CN spectral sharpening (Fig. 5), Gram-Schmidt (Fig. 7), modified IHS (Fig. 8), PC (Fig. 9) and UNB (Fig.10) show massive color distortions. They retain more information of the SAR image which contaminates the information in the multispectral image. Some demonstrate a slightly better spatial resolution in the images than the Ehlers Fusion. It is may be possible to reach the same spatial improvement with the Ehlers Fusion, using a different filter design, this would, however, change the spectral characteristics and therefore we used this compromise between color and resolution enhancement. The AWLP, on the other hand, improves the spatial resolution of the original image only slightly.

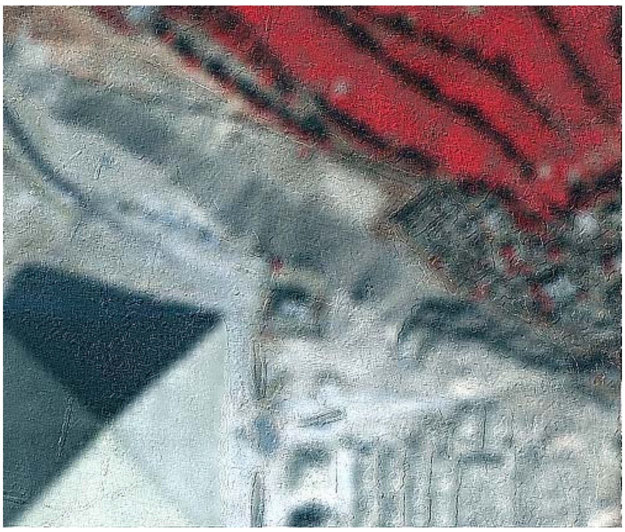

Figure 3: TerraSAR-X fused with Quickbird using AWLP

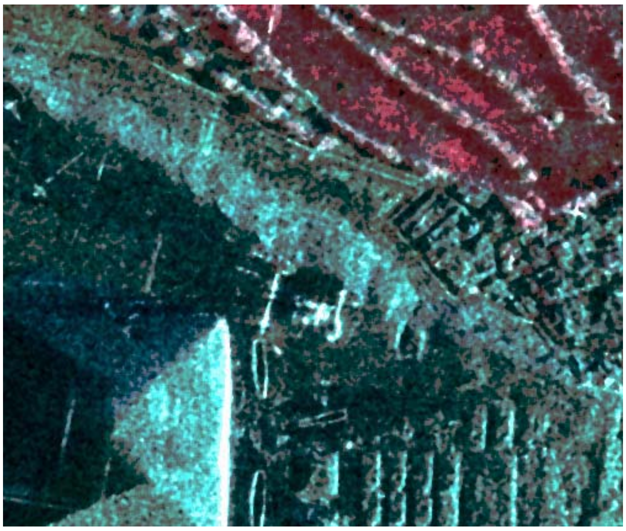

Figure 4: TerraSAR-X fused with Quickbird using Brovey

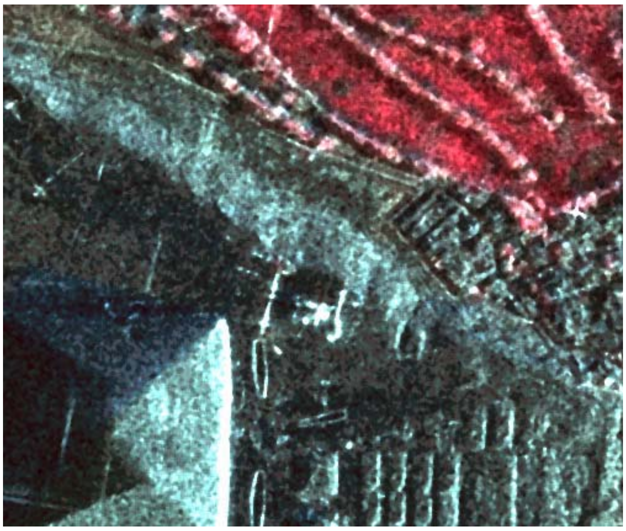

Figure 5: TerraSAR-X fused with Quickbird using CN spectral sharpening

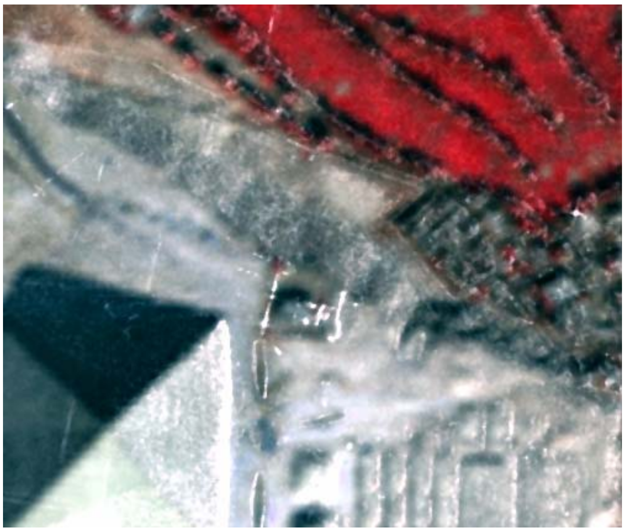

Figure 6: TerraSAR-X fused with Quickbird using Ehlers

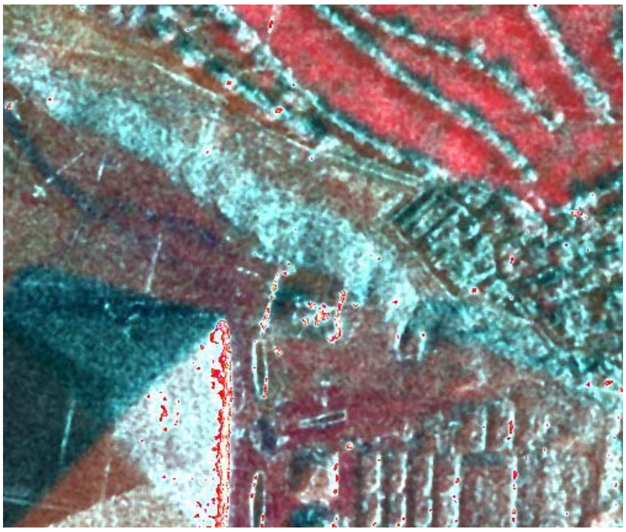

Figure 7: TerraSAR-X fused with Quickbird using Gram-Schmidt

Figure 8: TerraSAR-X fused with Quickbird using the modified IHS

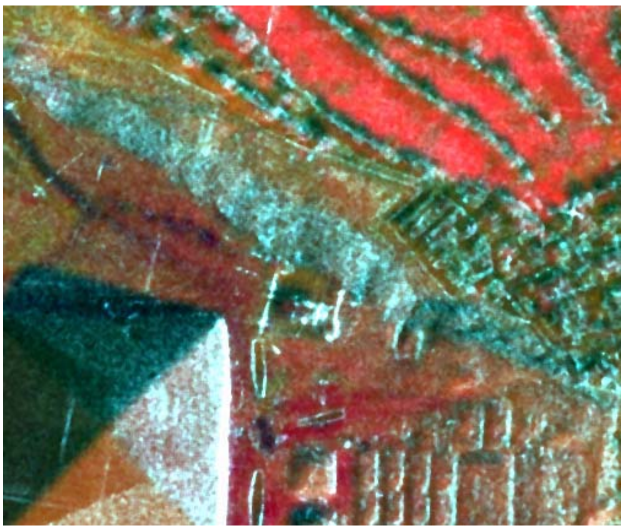

Figure 9: TerraSAR-X fused with Quickbird using PC

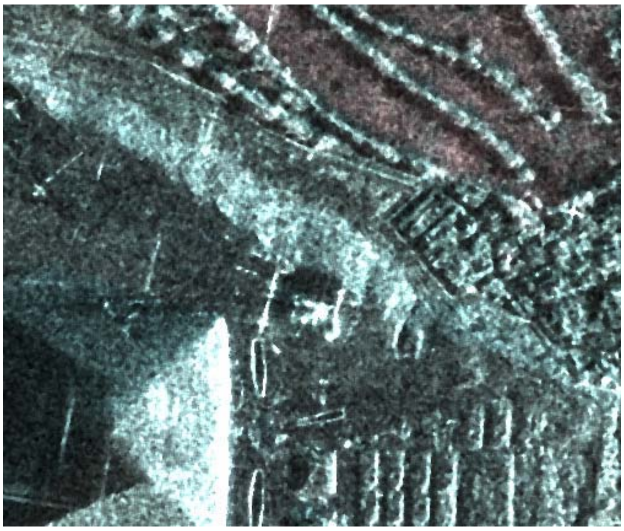

Figure 10: TerraSAR-X fused with Quickbird using UNB

As the visual analysis is very subjective and depends on the interpreter, a number of statistical analyses were performed, as described above. The best values in the tables are marked in bold letters. The correlation coefficients (Tab. 1) confirm the visual inspection findings. The Ehlers fusion shows the best results and the AWLP presents acceptable results. All other methods have a very low correlation values.

Band	1	2	3	4
AWLP	0,8702	0,8871	0,8972	0,7650
Brovey	0,2605	0,1332	0,1821	0,0065
CN	0,2629	0,1365	0,1851	0,0237
Ehlers	**0,9770**	**0,9760**	**0,9792**	**0,9600**
Gram	0,1620	0,1458	0,1602	0,5528
ModIHS	0,1991	0,3459	0,4219	0,0429
PC	0,2015	0,1898	0,1999	0,6853
UNB	0,1431	0,1442	0,1462	0,1488

Table 1: Correlation coefficients for the fused images in comparison with the multispectral Quickbird image

The RMSE shows again the best results for the Ehlers Fusion, with the exception of the near infrared band where the UNB fusion scores best. It should be mentioned that the result for the near infrared band is the lowest (e.g. the best) for all methods. A reason for this is probably that the near infrared band has the lowest grey value range in the original multispectral image with values between 0 and 928. In contrast the visible bands range from 0 to nearly 65000.

Band	1	2	3	4
AWLP	1669,70	1513,00	1406,60	43,57
Brovey	26774,00	29834,00	29894,00	496,90
CN	26654,00	29695,00	29756,00	494,24
Ehlers	**51,85**	**60,67**	**53,74**	1,03
Gram	4292,80	4356,80	4429,60	3,68
ModIHS	490,24	767,93	1089,40	17,56
PC	17722,00	17621,00	18271,00	140,61
UNB	3556,10	3645,30	3841,30	**0,07**

Table 2: RMSE for the fused images in comparison with the multispectral Quickbird image

The AWLP and the Ehlers fusion present the best results for the per-pixel deviation (Tab. 3). Although these values seem high for a per-pixel deviation, the percentage deviation is under 0.5 %. It needs to be investigated, however, if these values would influence a classification of the images.

Band	1	2	3	4
AWLP	**282,79**	**295,87**	**301,34**	5,11
Brovey	22819,00	26230,00	26043,00	461,14
CN	22725,00	26118,00	25933,00	458,88
Ehlers	318,00	320,34	303,21	**4,94**
Gram	5767,50	5778,80	6002,10	48,32
ModIHS	5866,50	4972,20	4814,30	79,10
PC	15425,00	15313,00	15918,00	132,14
UNB	5793,00	5726,20	5993,50	66,12

Table 3: Per-pixel deviation for the fused images in comparison with the multispectral Quickbird image

The SSIM (Tab. 4) shows the similarity with the original image. All methods except of AWLP and Ehlers are near zero, which confirms the fact that there is only slight similarity with the original image.

Band	1	2	3	4
AWLP	**0,9721**	**0,9874**	**0,9885**	**0,9904**
Brovey	0,0000	0,0000	0,0000	0,0001
CN	-0,0001	-0,0001	0,0000	0,0003
Ehlers	0,9635	0,9659	0,9700	0,9794
Gram	-0,0960	-0,0917	-0,0543	0,5577
ModIHS	-0,0661	-0,1031	-0,0405	-0,0854
PC	-0,1153	-0,0694	-0,0094	0,7072
UNB	-0,0672	-0,0950	-0,0940	-0,0436

Table 4: SSIM for the fused images in comparison with the multispectral Quickbird image

Whereas the above tables (Tab. 1 – Tab. 4) showed values for the spectral preservation, the next two tables (Tab. 5 & Tab. 6) will present results of the evaluation of the spatial improvement.

The high pass filtering presents a good to very good spatial improvement for most of the methods such as Brovey, PC, CN and Ehlers. Acceptable results are obtained from UNB and the modified IHS. Only Gram-Schmidt and especially AWLP demonstrate a poor improvement.

Band	1	2	3	4
AWLP	-0,1464	-0,1463	-0,1456	-0,1405
Brovey	0,9898	**0,9932**	**0,9933**	0,2918
CN	0,9971	0,9989	0,9991	0,5971
Ehlers	0,8885	0,8619	0,8512	0,8319
Gram	0,2597	0,2386	0,2420	0,8735
ModIHS	0,6189	0,6488	0,6443	0,6016
PC	**0,9964**	0,9739	0,9819	0,6671
UNB	0,7805	0,7755	0,7707	**0,9677**

Table 5: High pass-filtering for the fused images in comparison with the panchromatic TerraSAR-X image

The values for the edge detection evaluation (Tab. 6) demonstrate good to excellent results for all methods except the AWLP.

Band	1	2	3	4
AWLP	74,74	73,16	73,59	74,18
Brovey	**98,51**	98,73	98,81	89,56
CN	98,75	99,14	**99,12**	90,64
Ehlers	91,02	90,37	90,46	90,51
Gram	97,45	97,92	97,09	95,53
ModIHS	88,07	89,34	89,18	87,38
PC	97,84	**98,87**	98,17	92,38
UNB	95,99	95,67	95,48	**97,13**

Table 6: Edge detection results for the fused images in comparison with the TerraSAR-X image

5. CONCLUSIONS

The results demonstrate that only the Ehlers fusion and the AWLP could fuse TerraSAR-X data with multispectral Quickbird data without color distortions. But only the Ehlers fusion is also capable of improving the spatial resolution. Despite the relative success, iconic image fusion of SAR and optical data has to be investigated further. The sensors are very different from each other and the results are not yet satisfactory. Future work will consider the impact of fusion on a classification of the fused images in comparison with the original image, especially the impact of the differences in the per-pixel deviation has to be investigated. Also to be considered in future work 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, which makes the fusion obsolete.

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