Quality assessment of ten fusion techniques applied on Worldview-2

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Abstract
Fusion or merging or pansharpening is the digital processing that combines the high spatial and multispectral information to obtain a fused multispectral image that retains the spatial information from the high resolution panchromatic image, as well as the spectral characteristics of the lower resolution multispectral image. Many fusion algorithms were developed and tested on different commercial satellite data such as Ikonos and Quickbird, however, the efficacy of these algorithms is weakly assessed on the new satellite images of Worldview-2 with very high spatial resolution. In the present study ten well known fusion techniques namely Color Normalized (CN), Ehlers, Gram-Schmidt, High Pass Filter (HPF), Local Mean Matching (LMM), Local Mean and Variance Matching (LMVM), Modified IHS (Modihs), Pansharp, PCA and Wavelet are used for the fusion of Worldview-2 panchromatic and multispectral data. Fused images were evaluated for spectral and spatial fidelity using visual inspection and different quality indexes such as the correlation coefficient (CC), ERGAS, the Universal Image Quality Index (Q), the Expanded Quality Index (Q4expand) and the Entropy values. Under each quality metric the fusion algorithms were ranked and best performances were indentified. It has been proved that all fusion algorithms have a different performance with the new multispectral bands of Worldview-2 in comparison to the classical ones. It has also been proved that almost all quality indices present a very strong dependency to the spatial resolution of the input data. The Q4expand quality index is proposed as the main quality discriminator since it gave the most robust results independently of the spectral and spatial input resolution. Pansharpen algorithm took the lead in spatial enhancement while Ehlers and HPF are ranked in the first places for spectral preservation.

Keywords: Fusion, Worldview-2, quality, index.

Introduction
With only a few exceptions (eg. Worldview-1, EROS, Cartosat), the majority of the earth observing satellites launched in the last fifteen years such as SPOT-5, Landsat-7, Landsat-8, Ikonos, Quickbird, Kompasat, Formosat, Geoeye and more recently Worldview-2, collect at the same time a panchromatic image with a higher spatial resolution and many
multispectral bands with lower spatial resolution. The high spatial resolution is a necessity in order to detect and map with accuracy small features and structures. At the same time, the high spectral resolution is needed in order to discriminate and classify different land-use and land-cover types [Wald, 2000; Ranchin et al., 2003; Ehlers et al., 2010]. Most remote sensing applications require at the same time high spatial and spectral resolution images that the satellites cannot provide due to technical constraints such as limited storage capacity, small data transfer rate and limited energy autonomy. Under these limitations, it is considered that the most effective solution for providing high-spatial resolution and high-spectral-resolution remote sensing images is to develop effective image fusion techniques. Fusing panchromatic and multispectral images with complementary characteristics can improve the visualization of the study area and produce better results [Wald, 2000; Ranchin et al., 2003].

Image fusion can be applied both to data collected from different sensors (inter-sensor), or from the same sensor (intra-sensor), as well as to data collected at the same time under the same conditions (single-dated) or at different dates (multi-date). The goals of the fusion process could be used as described in Karathanassi et al. [2007] and Ehlers et al. [2008]: to sharpen images [Chavez et al., 1991]; to improve geometric corrections [Strobl et al., 1990]; to provide stereo-viewing capabilities for stereophotogrammetry [Bloom et al., 1988]; to enhance certain features not visible in either of the single data alone [Leckie 1990]; as supplement to datasets for improved classification [Schistad-Solberg et al., 1994]; to detect changes using multitemporal data [Duguay et al., 1987]; to substitute missing information (e.g. clouds – VIR, shadows – SAR) in one image with signals from another sensor image [Aschbacher and Lichtenegger 1990] and replace defective data [Suits et al., 1988].

Different merging methods have been proposed in the literature [Welch and Ehlers, 1987], using Principal Component Analysis [Chavez et al., 1991], Intensity Hue Saturation (IHS) transforms [Haydn et al., 1982; Carper et al., 1990], Brovey Transform [Gillespie et al., 1987], Multiplicative Transform [Crippen, 1989], Wavelet Transform [Li et al., 1995; Zhou et al., 1998; Fanelli et al., 2001], Pansharpen Transform [Zhang, 1999], Back Propagated Neural Networks [Del Carmen and Inamura, 2001], High Pass Filters [Schowengerdt, 1980; Erdas, 2008], or Smoothing filters [Liu, 2000]. At the same time many studies applying those algorithms to different data sets and results’ comparisons have been published [Chavez et al., 1991; Vaiopoulos et al., 2001; Hill et al., 1999; Aiazzi et al., 2002; Wang et al., 2005; Laporterie-Dejean et al., 2005; Nikolakopoulos, 2008], and consequently an international contest for image fusion algorithms has been carried out [Alparone et al., 2007].

Generally, image fusion methods can be differentiated between three levels: pixel level, feature level and decision level. Pixel level fusion requires the least amount of pre-processing. It uses the Digital Number (DN) or radiance values of each pixel from different sources in order to derive the useful information. At least a very accurate geometric registration has to be performed when the Panchromatic (Pan) and the Multispectral (MS) images are acquired from different sensors. All the fusion techniques involved in this study work at pixel level.

A successful fusion should lead to a fused image that preserves the spectral properties of the multispectral data and the spatial information of the panchromatic data. Many researchers
mentioned that there are problems and limitations linked to the fusion algorithms [Chavez et al., 1991; Wald and Ranchin, 1997; Wang, 2002; Ling et al., 2007; Nikolakopoulos 2008; Witharana et al., 2013]. The most significant problem is that the fused image usually has a notable deviation in visual appearance and in spectral values from the original image. These deviations, called color distortion, affect further interpretation, especially when the wavelength range of a panchromatic image does not correspond to that of the employed multispectral image [Kalpoma and Kudoh, 2007; Ling et al., 2007].

Thus, the quality assessment of the fusion is a very difficult task [Alparone et al., 2004], and there is a necessity to assess the quality of the fused images both qualitative and quantitative. The visual inspection of the fused and the original images is the simplest way of comparing fusion algorithms [Nikolakopoulos, 2008], but at the same time it is subjective and depends on the experience of the interpreter [Alparone et al., 2004; Klonus and Ehlers 2007; Ehlers et al., 2010].

Many quality indexes, such as Standard Deviation Difference, Bias Index, Mean Absolute Error, Root Mean Square Error, Information Entropy, Correlation Coefficient, Spectral Angle Mapper, Relative Dimensionless Global Error (ERGAS), Universal Image Quality Index (Q), Global Quality Measurement Q4 and the Expanded Quality Q4 have been proposed and used among others in image quality studies [Wald et al., 1997; Li, 2000; Piella and Heijmans, 2003; Wang et al., 2004; Alparone et al., 2004; Wang et al., 2005; Wang and Zhao 2008]. According to the Wald’s protocol [Wald et al., 1997], a reference MS image at the resolution of the Pan image should exist in order to be compared with the fused images. If there is no obvious reference MS image available at the Pan resolution, original Pan and MS images should be spatially degraded down to a lower resolution in order to compare the fused product with the only genuine references formed by the original MS set. Therefore, this is considered the most applicable way to check the synthesis properties [Wald et al., 1997; Thomas and Wald, 2006].

In this study, ten very commonly used fusion techniques, implemented in commercial software packages, are compared. These algorithms have been applied to Worldview-2 data. Worldview-2 is the first satellite that collects a panchromatic (Pan) band and 8 multispectral (MS) bands at the same time (Tab. 1). The Pan data provide a spatial resolution of 0.46 m while the MS data have a spatial resolution of 1.84 m. In contrary to the respective Pan band of Ikonos and Quickbird that range between 0.45 and 0.90 micrometers, the Worldview Pan band is narrower and ranges between 0.45 and 0.8 micrometers. The MS bands include four conventional visible and near-infrared bands common to multispectral satellites like Ikonos, Quickbird, Geoeye Landsat-7 etc., and four new bands. These new channels enable access to spectral regions where distinguishable differences exist between multiple classifications within the scene, which may be overlooked by traditional MS systems [Jawak and Luis, 2013]. Thus, it is quite interesting to investigate the assessment of the common used fusion algorithms with Worldview-2 data.

The assessment of the fusion results is based in a variety of quantitative quality indexes and visual inspection. The remainder of the current paper is structured as follows. In the next section the study area, data, fusion algorithms and evaluation criteria are described. In section 3 the results are reported. Section 4 contains a discussion on the results and the performance of the evaluators. Finally in section 5 the conclusions are presented.
Table 1 - The spectrum of the Worldview-2 bands.

| Band Name   | Center Wavelength (nm) | Minimum Lower Band Edge (nm) | Maximum Upper Band Edge (nm) |
|-------------|------------------------|------------------------------|-----------------------------|
| Panchromatic| 632                    | 464                          | 801                         |
| Coastal     | 427                    | 401                          | 453                         |
| Blue        | 478                    | 447                          | 508                         |
| Green       | 546                    | 511                          | 581                         |
| Yellow      | 608                    | 588                          | 627                         |
| Red         | 659                    | 629                          | 689                         |
| Red Edge    | 724                    | 704                          | 744                         |
| NIR 1       | 831                    | 772                          | 890                         |
| NIR 2       | 908                    | 862                          | 954                         |

Materials and methods

Study area and data

Many studies have been published during the last years focusing on single-date, intra-sensor data fusion. As presented in Table 2 the researchers evaluate the performance of fusion algorithms mainly on Ikonos and Quickbird data. Fewer studies were presented for Geoeye data, but Worldview-2 data have been only used in three papers (Tab. 2).

In the current study a Worldview-2 demo image freely distributed by Digital Globe has been used for the fusion quality assessment. The bundle image was collected on December 10th 2009 over the city of Rome.

Table 2 - Summary of satellite data used in similar studies.

| Data used in fusion Studies | Reference                                                                 |
|-----------------------------|---------------------------------------------------------------------------|
| Geoeye-1                    | Nikolakopoulos et al., 2010; Zhang and Mishra, 2012; Witharana et al., 2013; Zhang et al., 2015 |
| Ikonos                      | Zhang, 2002; Ranchin et al., 2003; Wang et al., 2005; Aiazzi et al., 2007; Kalpoma and Kudoh, 2007; Klonus and Ehlers, 2007; Ling et al., 2007; Nencini et al., 2007; Shah et al., 2008; Zhang, 2008; Wang et al., 2010; Yang et al., 2012; Zhang and Mishra, 2012; Sarp, 2014; Shahdoosti and Ghassemian, 2015 |
| Quickbird                   | Alparone et al., 2004; Aiazzi et al., 2007; Alparone et al., 2007; Karathanassi et al., 2007; Ling et al., 2007; Nencini et al., 2007; Klonus and Ehlers, 2007; Han et al., 2008; Nikolakopoulos, 2008; Shah et al., 2008; Zeng et al., 2010; Ashraf et al., 2012; Yang et al., 2012; Zhang and Mishra, 2012; Johnson et al., 2013; Sarp, 2014; Shahdoosti and Ghassemian, 2015 |
| Wordview-2                  | Zhang and Mishra, 2012; Yuhendra et al., 2012; Jawak and Luis, 2013       |
| Landsat 7 ETM+              | Vaiopoulos et al., 2001; Choi et al., 2002; Zhang, 2002; Lillo-Saavedra et al., 2005; Gangkofner et al., 2008; Shah et al., 2008; Zeng et al., 2010; Shahdoosti and Ghassemian, 2015 |
Methods

Two different procedures were followed for the fusion algorithms evaluation (Fig. 1). As the existence of a reference image with high spatial resolution is not always available, we made exactly the same experiments twice: firstly with the original MS image and in the second step with a spatial degraded MS image in order to evaluate both the performance of the fusion techniques, and the credibility of the quality indexes.

The original MS image was fused with the original Pan image using the fusion techniques. Ten new fused images with a spatial resolution of 0.5 m called “Fused-0.5m” were created. The original MS image was resampled to the Pan pixel size (0.5 m) and the new image “MS_0.5” was used as a reference in order to evaluate the fusion techniques (Fig. 2). Then the original Pan and MS images have been downsampled by 4 and a new image set called “Degraded” was created, using the image degradation tool in ERDAS IMAGINE software. As it is described in ERDAS imagine manual, “Degrade averages all of the original “small” pixels that make up the new “big” pixels. If the X and Y factors are large, this method takes more of the original pixels into account in the computation than a bilinear interpolation or cubic convolution resample would, since these resampling methods use only a small window for computation”. In this new data set the spatial resolution of the MS image is 8 m and the respective resolution of the Pan image is 2 m. Then the fusion algorithms were applied and the fused images with spatial resolution of 2 m were created. These images called “Fused-2m” were compared with the original MS image (Fig. 3).

In this study ten algorithms namely the Color Normalized (CN), Ehlers, Gram-Schmidt, High Pass Filter (HPF), Local Mean Matching (LMM), Local Mean and Variance Matching (LMVM), Modified IHS (Modihis), Pansharpen, Principal Component Analysis (PCA) and Wavelet were used for the fusion of Worldview-2 data. These algorithms are very commonly
encountered in the literature (Tab. 3) as they are implemented in popular commercial software like ERDAS Imagine, Envi and PCI Geomatica. Two of the algorithms, LMM and LMVM were programmed in Matlab (Tab. 3). Some of the algorithms used in this study allow various parameter settings. Consequently, many different tests were run. For every algorithm the best visual result was selected for the quality assessment.

**Table 3 - Fusion algorithms used in this study, related literature and software.**

| Algorithm used                  | Implementation       | Reference                                                                 |
|---------------------------------|----------------------|---------------------------------------------------------------------------|
| Color Normalized CN             | ENVI                 | Vrabel, 1996; Vrabel et al., 2002; Klonus and Ehlers, 2007; Ehlers et al., 2008; Shah et al., 2008; Zhang and Mishra, 2012; Witharana et al., 2013 |
| Ehlers                          | ERDAS IMAGINE        | Klonus and Ehlers, 2007; Ehlers et al., 2008; Nikolakopoulos et al., 2010; Jawak and Luis, 2013; Yuhendra et al., 2012; Witharana et al., 2013 |
| Gram Schmidt                    | ENVI                 | Laben et al., 2000; Aiazzi et al., 2007; Karathanassi et al., 2007; Klonus and Ehlers, 2007; Nencini et al., 2007; Ehlers et al., 2008; Shah et al., 2008; Nikolakopoulos et al., 2010; Yuhendra et al., 2012; Zeng et al., 2010; Wang et al., 2010, 2012; Zhang and Mishra, 2012; Jawak and Luis, 2013; Witharana et al., 2013; Sarp, 2014 |
| High Pass Filter                | ERDAS IMAGINE        | Chavez et al., 1991; Vrabel, 1996; Aiazzi et al., 2002; Alparone et al., 2004; Wang et al., 2005; Nencini et al., 2007; Gangkofner et al., 2008; Nikolakopoulos et al., 2010; Yang et al., 2012; Yuhendra et al., 2012; Zhang and Mishra, 2012; Jawak and Luis, 2013; Witharana et al., 2013 |
| Local Mean Matching             | Programmed in Matlab | De Bethune et al., 1998; Karathanassi et al., 2007; Nikolakopoulos, 2008; Nikolakopoulos et al., 2010; Witharana et al., 2013 |
| Local Mean and Variance Matching| Programmed in Matlab | De Bethune et al., 1998; Karathanassi et al., 2007; Nikolakopoulos, 2008; Nikolakopoulos et al., 2010; Asraf et al., 2012; Witharana et al., 2013 |
| Modified IHS                    | ERDAS IMAGINE        | Siddiqui, 2003; Klonus and Ehlers, 2007; Ehlers et al., 2008; Nikolakopoulos, 2008; Nikolakopoulos et al., 2010; Yakhdani and Azizi, 2010; Yuhendra et al., 2012; Yang et al., 2012; Zhang and Mishra, 2012; Witharana et al., 2013 |
| Principal Component Analysis    | ERDAS IMAGINE        | Chavez et al., 1991; Vrabel, 1996; Wang et al., 2005; Ling et al., 2007; Karathanassi et al., 2007; Ehlers et al., 2008; Nikolakopoulos, 2008; Shah et al., 2008; Nikolakopoulos et al., 2010; Yakhdani and Azizi, 2010; Yang et al., 2012; Zhang and Mishra, 2012; Han et al., 2013; Jawak and Luis, 2013; Witharana et al., 2013; Sarp, 2014 |
| Pansharpen                      | PCI GEOMATICA        | Zhang, 2002; Alparone et al., 2007; Karathanassi et al., 2007; Nikolakopoulos, 2008; Nikolakopoulos et al., 2010; Wang et al., 2010; Zhang and Mishra, 2012; Han et al., 2013 |
| Wavelet                         | ERDAS IMAGINE        | Choi et al., 2002; Kalpoma and Kudoh, 2007; Karathanassi et al., 2007; Gangkofner et al., 2008; Nikolakopoulos, 2008; Nikolakopoulos et al., 2010; Yakhdani and Azizi, 2010; Zhang and Mishra, 2012; Jawak and Luis, 2013; Yang et al., 2012; Yuhendra et al., 2012; Witharana et al., 2013 |
Figure 2 - In the first line from a to c: The original Pan with 0.5 m pixel size, and two RGB combinations of the original MS images. In the lines 2-4 from d to k: different RGB combinations of the fused images with a spatial resolution of 0.5 m.
Figure 3 - In the first line from a to c: The degraded Pan with 2 m pixel size, and two RGB combinations of the degraded MS images with a pixel size of 8 m. In the lines 2-4 from d to k: different RGB combinations of the fused images with a spatial resolution of 2 m.
For each fused image true and false color composites were produced and visually inspected. The visual control of the fused images is always the first step in a fusion quality assessment study. The visual analysis includes the following controls: existence of color distortion locally or globally in the image, existence of color tonality differences, detection of linear distortion in roads, buildings, monuments etc., general appearance of the image (brightness, contrast etc). In order to facilitate the visual comparison, the original and the degraded Pan and MS images are presented in Figures 2 and 3 respectively. In Figure 2a the original Pan data with a spatial resolution of 0.5 m is presented. The degraded Pan data (2 m) is presented in Figure 3a. Two different RGB combinations are used. The first, associated to the adjective “classic”, corresponds to a classical 432 (NIR1, Red, Green) combination (Figs. 2b and 3b). Three new bands (NIR2, Red Edge, Yellow) are used for the second RGB combination and indicated with the adjective “inov” (Figs. 2c and 3c).

Then a series of quality metrics was used in order to evaluate the spatial and spectral fidelity of the fused images compared to the original MS data. Furthermore, in order to quantify the quality of the fused images the following quality indices, Correlation Coefficient (CC), ERGAS, the Universal Image Quality Index (Q), the Expanded Quality Index (Q4\textsubscript{expand}) and Entropy were calculated. These indexes are very often used in similar studies (Tab. 4). The mathematical expression, the ideal values and the references of the studies where each quality index was used are presented in Table 4. In general, the quality indexes used in this study are in accordance with the general quality assessment criteria that have been described in previous studies [Gonzalez et al., 2005; Lillo Saavedra et al., 2005; Vijayaraj et al., 2006; Pradhan et al., 2006; Kalpoma and Kudoh 2007; Karathanassi et al., 2007; Nikolakopoulos, 2008; Gangkofner et al., 2008; Borel and Spencer, 2009; Ehlers et al., 2010; Yang et al., 2012; Abdikan et al., 2014].

**Results**

**Visual evaluation**

Figures 2 and 3 depict the Colosseum and the broader area that was selected for the visual evaluation of the fusion algorithms. The specific subarea was selected for the color similarity assessment as it presents spectrally heterogeneous objects such as trees, rooftops, roads buildings and of course the Colosseum.

The first remark is that some algorithms gave different results when applied to the downsampled MS data than when applied to the original MS data. The CN, Gram-Schmidt, PCA and Wavelet fusion technique gave unacceptable results when they were applied to the degraded MS data producing the “Fused-2m” images. The major problem of these algorithms is the spatial degradation of the fused images. Two classical 432 combination of the fused image with the CN algorithm are presented in Figures. 2d and 3d. In the “Fused-0.5m” CN image (Figs. 2d and 2e), the fusion improves the detectability of the road network, and the buildings. The pavement around the Colosseum is more easily distinguished from the road. The colors are almost identical with those of the original image. In the “Fused-2m” CN image (Fig. 3d), the fusion gives contrary results. There is a spatial distortion of the image. At the left of the Colosseum there are blocks of red pixels. It is very difficult to recognize even the shape of the big building at the left of the Colosseum. In comparison with the original MS data (Figs 2b and 2c) the CN “Fused-2m” data have much less information. Three other
fusion techniques namely Gram-Schmidt (3e), PCA (3f) and Wavelet gave respectively good results when applied to the original data, and unacceptable results when applied to the degraded data.

In Figure 2f a classical combination of the Ehlers “Fused-0.5m” image is presented. The fusion improves the detectability of all the targets. Even the curves inside the Colosseum can be detected. The spectral preservation of the original colors is very high. In Figure 3g a RGB combination of new bands of the Ehlers “Fused-2m” image is presented. The image is almost identical to the original one (Fig. 2c). Thus, it can be pointed out that the Ehlers technique provides a fairly good spatial and spectral visual result, independently of the spatial resolution of the input data and independently of the spectral content. The fused images with the High Pass Filter algorithm present similar results.

The LMM and the LMVM algorithms improve the spatial resolution (Figs. 2g and 2h respectively). They cause a very small change to the color tonality that is more intense when the classical bands are presented. LMVM produces some very small color alternations when applied to the degraded data. As it can be observed in Figures 3h and 3i, in the “Fused-2m” images there are some sparse blue pixels between the Colosseum and the big building at the left.

The colors of the fused image with the Modified IHS algorithm (Fig. 2i) are almost identical with the original image (Fig. 2b) when the algorithm is applied to the original data. However, there is a small color tonality difference when the algorithm is applied to the degraded data. The “Fused-2m” image (Fig. 3j) shows slightly darker colors compared to the original one (Fig. 2b).

The Pansharpen algorithm increases the possibility of visual interpretation as it ameliorates the spatial resolution of the original data. When applied to the classic bands it preserves the colors of the original image independently of the spatial resolution of the input data (Figs. 2j and 3k). When applied to the new bands (Fig. 2k) it produces darker color tonality.

The Wavelet algorithm preserves exactly the same colors with the original image when the new bands are used, and provokes a minor change to the color tonality when the classical bands are used. But, as it has been marked already, it gave unacceptable spatial results when applied to the degraded data, producing the “Fused-2m” images.

In general, six of ten fusion techniques produce images with a fairly better spatial resolution, and improve the target detectability independently of the spatial resolution of the input data. Four fusion techniques (CN, Gram-Schmidt, PCA and Wavelet) produced very bad results when applied to the degraded MS data. All algorithms present a quite good spectral preservation as they provoke minor changes to the color tonality and to the contrast of the image.

Quantitative assessment

The results of the visual evaluation were corroborated using five different spectral and one spatial metric. Tables 5-11 summarize the scores of the quality metrics and two grey colors (medium and light grey) were used to highlight the best scores.
Table 4 - Summary of quantitative quality metrics, mathematical expression and related literature.

| Quality index | Mathematical expression | Reference |
|---------------|--------------------------|-----------|
| Correlation Coefficient CC | 
\[ CC(B_k, B'_k) = \frac{\sum_{m=1}^{M} \sum_{n=1}^{N} (B_k(m,n) - B_k) \left( B'_k(m,n) - B'_k \right)}{\sqrt{\left( \sum_{m=1}^{M} \sum_{n=1}^{N} (B_k(m,n) - B_k)^2 \right) \left( \sum_{n=1}^{N} \sum_{m=1}^{M} (B'_k(m,n) - B'_k)^2 \right)}} \]  
\[ = \frac{\sum_{m=1}^{M} \sum_{n=1}^{N} (B_k(m,n) - B_k) \left( B'_k(m,n) - B'_k \right)}{\left( \sum_{n=1}^{N} \sum_{m=1}^{M} (B_k(m,n) - B_k)^2 \right)^{\frac{1}{2}} \left( \sum_{n=1}^{N} \sum_{m=1}^{M} (B'_k(m,n) - B'_k)^2 \right)^{\frac{1}{2}}} \]  
Ideal values: as close to 1 as possible. | Aiazzi et al., 2002; Choi et al., 2002; Wang et al., 2005; Gonzalez et al., 2005; Pradhan et al., 2006; Karathanassi et al., 2007; Kalpoma and Kudoh, 2007; Karathanassi et al., 2007; Ehlers et al., 2008; Han et al., 2008; Gangkofner et al., 2008; Nikolakopoulos, 2008; Gangkofner et al., 2008; Zhang, 2008; Ehlers et al., 2010; Nikolakopoulos et al., 2010; Yakhdani and Azizi, 2010; Zeng et al., 2010; Yang et al., 2012; Jawak and Luis, 2013; Witharana et al., 2013; Sarp, 2014; Shahdoosti and Ghassemian, 2015; Zhang et al., 2015 |
| Erreur relative globale adimensionnelle de synthèse ERGAS | 
\[ ERGAS = 100 \times \frac{h}{l} \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left( \frac{RMSE(k)}{M_k} \right)^2} \]  
where h is the spatial resolution of the Pan image, l is the respective resolution of the MS image, N is the number of the bands and M_k is the mean (average) of the k^{th} band.  
Ideal values: As small as possible. | Wald et al., 1997; Wald, 2002; Choi et al., 2002; Ranchin et al., 2003; Alparone et al., 2004; Gonzalez et al., 2005; Lillo-Saaavedra et al., 2005; Aiazzi et al., 2007; Alparone et al., 2007; Nencini et al., 2007; Kalpoma and Kudoh, 2007; Shah et al., 2008; Zhang Y., 2008; Nikolakopoulos et al., 2010; Jawak and Luis, 2013; Witharana et al., 2013; Shahdoosti and Ghassemian, 2015; Zhang et al., 2015 |
| Universal Image Quality Index (Q) | 
\[ Q = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \cdot \frac{2 \bar{X} \bar{Y}}{(\bar{X})^2 + (\bar{Y})^2} \cdot \frac{2 \sigma_x \sigma_y}{\sigma_x^2 + \sigma_y^2} \]  
Where x is the original image and y is the fused image.  
Ideal values: as close to 1 as possible. | Wang and Bovik, 2002; Alparone et al., 2004; Wang et al., 2005; Karathanassi et al., 2007; Shah et al., 2008; Nikolakopoulos et al., 2010; Jawak and Luis, 2013; Shahdoosti and Ghassemian, 2015 |
Table 4 (continued) - Summary of quantitative quality metrics, mathematical expression and related literature.

| Quality index                                      | Mathematical expression | Reference                                                                 |
|---------------------------------------------------|-------------------------|---------------------------------------------------------------------------|
| Expanded spectral quality index (Q4expand)        | $Q_{MS}^4 (M,F) = \frac{1}{|W|} \sum_{w \in W} Q_4(M,F)|_W$ | Wang and Zhao, 2008; Wang et al., 2010                                     |
| Where $Hp$ is the original Pan image, $M$ is the resampled MS image to the spatial resolution of $Hp$, $F$ is the fused image and $|W|$ is the total of sliding step. Ideal values: as close to 1 as possible. |
| Expanded spatial quality index (Q4expand)         | $Q_{PAN}^4 (Hp', F') = \frac{1}{|W|} \sum_{w \in W} Q_4\left(\frac{Std(F')} {Std(Hp')}\right)|_W$ | Wang and Zhao, 2008; Wang et al., 2010                                     |
| For a ratio $r$ between the Pan and the MS image, a High Pass Filter of a $(2r+1)\times(2r+1)$ kernel size window in which the center value is $(2r+1)\times(2r+1)-1$ and others are -1, is used in order to extract the spatial information from $Hp$ and $F$. $Hp'$ is the produced spatial information image of $Hp$ and $F'$ is the produced spatial information image of $F$. Ideal values: as close to 1 as possible. |
| Entropy                                           | $E = -\sum_{i=0}^{L} -p_i \cdot \log_2 (p_i)$ | Price, 1987; De Bethune et al., 1998; Choi et al., 2002; Lillo Saavedra et al., 2005; Vijayaraj et al., 2006; Karathanassi et al., 2007; Han et al., 2008; Skianis and Nikolakopoulos, 2009; Nikolakopoulos et al., 2010; Yakhdani and Azizi, 2010; Zeng et al., 2010; Witharana et al., 2013 |
| Where $p_i$ is the percentage of the pixels of the image with digital number $i$. $L$ is the quantization level (tonality range) of the image. Ideal values: The smallest possible Entropy difference between the original MS and the fused images. |

In Table 5 the correlation values between the “MS_0.5” and the “Fused-0.5m” bands are presented. As it can be observed, all the fusion algorithms produce seven bands highly correlated to the original, with only one exception that of the coastal band. The fused bands, with the LMM, the LMVM and the Wavelet algorithm, present the higher correlation to the respective bands of the original image. The fused images with the HPF algorithm present the lower correlation values. The Gram-Schmidt and the PCA algorithms show the smaller fluctuation to the correlation values. The correlation values of the Gram-Schmidt fused bands range between 0.87 and 0.90. The correlation values of the PCA fused bands range between 0.77 and 0.83. There is no significant diversification between the correlation values of the new and the classic bands. The biggest difference is 0.05 (0.83 for the classic bands and 0.78 for the new bands when the ModIHS algorithm is used). The new and classic bands present exactly the same average correlation values when the LMVM and the Gram Schmidt algorithms are used.
Table 5 - The correlation values of the “Fused-0.5m” bands. With symbol * the best score is marked while with symbol ** the second best score is marked. The ideal value is 1.

| Fused-0.5m | Coastal | Blue | Green | Yellow | Red | Red Edge | NIR1 | NIR2 | Average New Bands | Average Classic Bands |
|------------|---------|------|-------|--------|-----|----------|------|------|------------------|-----------------------|
| Worldview MS | 1.00    | 1.00 | 1.00  | 1.00   | 1.00| 1.00     | 1.00 | 1.00 | 1.00             | 1.00                   |
| CN         | 0.54    | 0.72 | 0.85  | 0.90   | 0.92| 0.91     | 0.93 | 0.94 | 0.82             | 0.86                   |
| Ehlers     | 0.68    | 0.80 | 0.85  | 0.86   | 0.87| 0.87     | 0.91 | 0.91 | 0.83             | 0.86                   |
| Gram Schmidt | 0.88   | 0.88 | 0.87  | 0.87   | 0.88| 0.87     | 0.90 | 0.90 | 0.88             | 0.88                   |
| HPF        | 0.65    | 0.74 | 0.78  | 0.79   | 0.81| 0.81     | 0.84 | 0.83 | 0.77             | 0.79                   |
| LMM        | 0.76    | 0.88 | 0.93  | 0.94   | 0.95| 0.95     | 0.96 | 0.96 | 0.90**           | 0.93*                  |
| LMVM       | 0.91    | 0.91 | 0.92  | 0.92   | 0.93| 0.92     | 0.93 | 0.93 | 0.92*            | 0.92**                 |
| ModIHS     | 0.54    | 0.74 | 0.83  | 0.83   | 0.86| 0.85     | 0.88 | 0.88 | 0.78             | 0.83                   |
| Pansharl  | 0.80    | 0.86 | 0.88  | 0.88   | 0.89| 0.89     | 0.91 | 0.91 | 0.87             | 0.89                   |
| PCA        | 0.77    | 0.8  | 0.8   | 0.82   | 0.83| 0.79     | 0.83 | 0.83 | 0.80             | 0.82                   |
| Wavelet    | 0.85    | 0.91 | 0.93  | 0.92   | 0.93| 0.91     | 0.94 | 0.93 | 0.90**           | 0.93*                  |

In Table 6 the correlation values between the original MS bands (at 2 m) and the “Fused-2m” bands are presented. In comparison to the previous, the images fused with the wavelet fusion techniques show fairly lower correlation values. It is significant that when the specific algorithm is used, the correlation values decrease is more intense to the classic bands. The average correlation value of the classic bands for the Wavelet algorithm decreased from 0.93 to 0.68. Contrary to the Wavelet algorithm, the HPF algorithm provoked an increase to the correlation value of the classic bands (“Fused-2m” in the Tab. 6) in comparison to the classic bands (“Fused-0.5m” in the Tab. 5). PCA fusion technique produced more correlated bands than the original MS bands when it was applied to the degraded MS bands (Tab. 6). All the other fusion techniques produce similar results independently of the data set (degraded or not) to which they were applied.

The ERGAS value for all the fused images was calculated and the results are presented below in Table 7. In the first column the ERGAS values of the classical bands of the “Fused-0.5m” image are presented, and similarly the values of the classical bands of the “Fused-2m” image are shown in the second column. In the third and the fourth columns the respective ERGAS values of the new bands are presented.

As it can be observed, the majority of the values range between 4.15 and 8.7. Only the degraded bands that were fused with the Wavelet technique “Fused-2m” present extremely high values (worst results). The degraded bands that were fused with the CN technique “Fused-2m” present slightly higher values. This is in accordance with the visual comparison results, which proved that the CN and the Wavelet algorithm gave very bad results when applied to the degraded MS data. Contrary to the visual control results the PCA fusion technique produced lower ERGAS values (better results) when applied to the degraded MS data, resulting to the “Fused-2m” images.

With the exception of the CN algorithm the ERGAS values of the new bands are higher than the ERGAS values of the classical bands. This phenomenon is observed for both the “Fused-0.5m” and “Fused-2m”. This means that all ten algorithms cause greater distortion
to the new bands than to the classical.

ERGAS results are diversified depending on the data set used and also depending on the spectral content of the bands (classic or new bands). When the classic bands of the degraded Pan and MS data are fused resulting to the “Fused-2m” data set, the Ehlers and the HPF algorithms present the lower ERGAS values (best results), while the CN and the Wavelet algorithm present the higher ERGAS values (worst results). Regarding the new bands, the HPF and the Modihs algorithms present the lower ERGAS values (best results), while the CN and the Wavelet algorithms present the higher ERGAS values (worst results).

When the original Pan and MS data are fused resulting to the “Fused-0.5m” data set, independently of the use of classic or new bands, the LMM, the LMVM and the Wavelet algorithms present the lower ERGAS values (best results), while the HPF and the PCA algorithms present the higher ERGAS values (worst results).

Table 6 - The correlation values of the “Fused-2m” bands. With symbol * the best score is marked while with symbol ** the second best score is marked. The ideal value is 1.

| Fused-2m       | Coastal | Blue  | Green | Yellow | Red    | Red Edge | NIR1  | NIR2  | Average New Bands | Average Classic Bands |
|----------------|---------|-------|-------|--------|--------|----------|-------|-------|-------------------|-----------------------|
| Worldview MS   | 1.00    | 1.00  | 1.00  | 1.00   | 1.00   | 1.00     | 1.00  | 1.00  | 1.00              | 1.00                  |
| CN             | 0.55    | 0.75  | 0.86  | 0.90   | 0.90   | 0.92     | 0.90  | 0.95  | 0.83              | 0.85                  |
| Ehlers         | 0.69    | 0.78  | 0.90  | 0.86   | 0.96   | 0.88     | 0.96  | 0.91  | 0.83              | 0.90                  |
| Gram Schmidt   | 0.89    | 0.87  | 0.88  | 0.88   | 0.89   | 0.88     | 0.88  | 0.91  | 0.89              | 0.88                  |
| HPF            | 0.65    | 0.91  | 0.92  | 0.80   | 0.92   | 0.81     | 0.91  | 0.84  | 0.78              | 0.91*                 |
| LMM            | 0.77    | 0.76  | 0.86  | 0.95   | 0.90   | 0.95     | 0.91  | 0.96  | 0.91**             | 0.86                  |
| LMVM           | 0.92    | 0.88  | 0.89  | 0.92   | 0.89   | 0.92     | 0.89  | 0.93  | 0.92*             | 0.89**                |
| Modihs         | 0.81    | 0.78  | 0.89  | 0.89   | 0.92   | 0.90     | 0.91  | 0.91  | 0.88              | 0.89**                |
| Pansharpe      | 0.77    | 0.88  | 0.89  | 0.82   | 0.89   | 0.80     | 0.90  | 0.83  | 0.81              | 0.89**                |
| PCA            | 0.86    | 0.89  | 0.88  | 0.92   | 0.89   | 0.92     | 0.82  | 0.94  | 0.91**            | 0.87                  |
| Wavelet        | 0.55    | 0.64  | 0.63  | 0.84   | 0.64   | 0.86     | 0.64  | 0.88  | 0.78              | 0.64                  |

The mean Q value of the fused images bands was calculated and the results are presented in Table 8. In the first column the Q values of the classical bands of the “Fused-0.5m” image are presented. In the second column the values of the classical bands of the “Fused-2m” image are offered. In the third and in the fourth columns the respective Q values of the new bands are presented.

Similarly to the ERGAS results, the degraded bands that were fused with the Wavelet technique “Fused-2m” present extremely low Q values (worst results). On the contrary, the “Fused-0.5m” bands that were fused with the Wavelet technique “Fused-2m” show very high Q values (quite good results).

Q results are strongly influenced by the input data set (degraded or not). When the degraded Pan and MS data are fused, resulting to the “Fused-2m” data set, the HPF and the Pansharpe algorithms present the higher Q values (best results), while the CN and the Wavelet algorithm present the lower Q values (worst results). When the original Pan and MS data are fused, resulting to the “Fused-0.5m” data set, the LMM, the LMVM and the Wavelet algorithms
present the higher Q values (best results), while the HPF and the PCA algorithms present
the lower Q values (worst results).

Table 7 - The ERGAS values. With symbol * the best score is marked while with symbol **
the second best score is marked. The ERGAS values should be as small as possible.

|                | Fused-0.5m Classic bands | Fused-2m Classic bands | Fused-0.5m New bands | Fused-2m New bands |
|----------------|--------------------------|------------------------|----------------------|-------------------|
| CN             | 6.736                    | 11.239                 | 6.560                | 9.895             |
| Ehlers         | 6.244                    | 5.211*                 | 6.716                | 6.832             |
| Gram Schmidt   | 6.237                    | 6.354                  | 6.527                | 7.310             |
| HPF            | 7.970                    | 5.584**                | 8.411                | 5.660*            |
| LMM            | 4.154*                   | 6.277                  | 4.293*               | 6.747             |
| LMVM           | 4.954                    | 6.169                  | 5.395**              | 6.683             |
| ModIHS         | 6.971                    | 6.147                  | 7.468                | 6.325**           |
| Pansharpe      | 6.029                    | 6.049                  | 6.323                | 6.762             |
| PCA            | 8.293                    | 7.017                  | 8.701                | 6.969             |
| Wavelet        | 4.783**                  | 32.540                 | 5.500                | 32.070            |

Table 8 - The Q values. With symbol * the best score is marked while with symbol **
the second best score is marked. The ideal Q value is 1.

|                | Fused-0.5m Classic bands | Fused-2m Classic bands | Fused-0.5m New bands | Fused-2m New bands |
|----------------|--------------------------|------------------------|----------------------|-------------------|
| CN             | 0.844                    | 0.798                  | 0.809                | 0.682             |
| Ehlers         | 0.861                    | 0.882                  | 0.828                | 0.835             |
| Gram Schmidt   | 0.874                    | 0.869                  | 0.871                | 0.850             |
| HPF            | 0.785                    | 0.900*                 | 0.762                | 0.906*            |
| LMM            | 0.933*                   | 0.845                  | 0.907                | 0.786             |
| LMVM           | 0.928                    | 0.875                  | 0.924*               | 0.869             |
| ModIHS         | 0.807                    | 0.844                  | 0.759                | 0.794             |
| Pansharpe      | 0.887                    | 0.877**                | 0.874                | 0.873**           |
| PCA            | 0.796                    | 0.863                  | 0.778                | 0.871             |
| Wavelet        | 0.928**                  | 0.002                  | 0.906**              | 0.0005            |

Q results are not significantly influenced from the discrimination of the spectral content
of the bands. The majority of the fusion techniques present very small differences of the
Q values between the classic and the new bands. With the exception of the CN values
of the “Fused-2m” bands all other differences are lower than 0.06. Nevertheless, all the
algorithms produce better results (higher Q values) with the classical bands than with the
new bands (lower Q values).
Also, it has to be pointed out that the images fused with the Pansharpe and the Gram Schmidt
algorithm present very stable Q values independently of the input data set and of the spectral
content.
In Table 9, the spectral, spatial and the total Q4 values are presented. The first remark is
that LMVM and Panshar algorithms present the higher values for the spatial information preserving quality, and for the total $Q_{\text{expand}}^{4}$ in all the fused image categories. That means that independently of the downsampling of the spatial resolution of the MS images and independently of the spectral content (new or classic bands) the specific algorithms infused more spatial information to the MS images during the fusion procedure. Thus, the total $Q_{\text{expand}}^{4}$ of the specific algorithms in all the fused images present the higher values. The spectral information preserving quality results are quite different. For the new bands independently of the spatial resolution of the input MS data the Ehlers algorithm presents the higher values. The same algorithm presents the second higher value for the classic “Fused-2m” bands. The Wavelet algorithm has a very bad performance (extremely low values) when applied to the “Fused-2m” bands.

Table 9 - The $Q_{\text{expand}}^{4}$ values. For each fused image the spectral and spatial quality values are calculated separately and then the total $Q_{\text{expand}}^{4}$ quality value is summed. With symbol * the best score is marked while with symbol ** the second best score is marked. The ideal $Q_{\text{expand}}^{4}$ value is 1.

| Fused-2m new bands | CN   | Ehlers | Gram Schmidt | HPF  | LMM  | LMVM  | Panshar | ModIHS | PCA  | Wavelet |
|-------------------|------|--------|--------------|------|------|-------|---------|--------|------|---------|
| Q_Spectral        | 0.490| 0.705* | 0.578        | 0.692** | 0.516| 0.580 | 0.610  | 0.601  | 0.647| 0.000    |
| Q_Spatial         | 0.165| 0.073  | 0.224        | 0.018 | 0.111| 0.271* | 0.225** | 0.018  | 0.017| 0.003    |
| Total Q           | 0.656| 0.778  | 0.802        | 0.710 | 0.627| 0.851* | 0.835** | 0.619  | 0.664| 0.003    |

| Fused-0.5m new bands | CN   | Ehlers | Gram Schmidt | HPF  | LMM  | LMVM  | Panshar | ModIHS | PCA  | Wavelet |
|----------------------|------|--------|--------------|------|------|-------|---------|--------|------|---------|
| Q_Spectral           | 0.224| 0.301* | 0.223        | 0.084| 0.267** | 0.202 | 0.206  | 0.108  | 0.122| 0.202    |
| Q_Spatial            | 0.086| 0.042  | 0.140        | 0.041| 0.071| 0.231* | 0.178** | 0.035  | 0.034| 0.017    |
| Total Q              | 0.310| 0.342  | 0.362        | 0.125| 0.338| 0.433* | 0.385** | 0.143  | 0.157| 0.219    |

| Fused-2m classic bands | CN   | Ehlers | Gram Schmidt | HPF  | LMM  | LMVM  | Panshar | ModIHS | PCA  | Wavelet |
|------------------------|------|--------|--------------|------|------|-------|---------|--------|------|---------|
| Q_Spectral             | 0.550| 0.687** | 0.602        | 0.691* | 0.566| 0.604 | 0.640  | 0.639  | 0.618| 0.001    |
| Q_Spatial              | 0.151| 0.109  | 0.164        | 0.019| 0.120| 0.274* | 0.228** | 0.019  | 0.016| 0.003    |
| Total Q                | 0.701| 0.796  | 0.767        | 0.710| 0.686| 0.877* | 0.868** | 0.658  | 0.634| 0.003    |

| Fused-0.5m classic bands | CN   | Ehlers | Gram Schmidt | HPF  | LMM  | LMVM  | Panshar | ModIHS | PCA  | Wavelet |
|--------------------------|------|--------|--------------|------|------|-------|---------|--------|------|---------|
| Q_Spectral               | 0.200| 0.195  | 0.206        | 0.091| 0.262* | 0.217 | 0.203  | 0.121  | 0.118| 0.261**  |
| Q_Spatial                | 0.151| 0.052  | 0.171        | 0.040| 0.088| 0.245* | 0.215** | 0.037  | 0.032| 0.020    |
| Total Q                  | 0.351| 0.247  | 0.378        | 0.131| 0.350| 0.462* | 0.418** | 0.158  | 0.150| 0.281    |

It has to be marked that with the exception of the Wavelet all the others fusion techniques produced higher $Q_{\text{expand}}^{4}$ spectral and spatial values when applied to the degraded data which produced the “Fused-2m” images. This fact is suboptimal to the visual control results as the CN, Gram-Schmidt and PCA algorithms provided very bad visual results.
Additionally to the above mentioned measures, ERGAS, Q, and Q4 expand and in order to estimate the amount of information incorporated in the MS images another measure was used based on the entropy information. The specific index measures the additional information that was enhanced in the fused images compared to the original MS data. The ideal fusion algorithm should normally provoke no changes to the Entropy values.

The entropy difference between the original and all the fused bands was calculated and the results are presented in Table 10 and Table 11. The Entropy values of all the MS bands before and after the spatial resolution degradation are exactly the same. That means that the down sampling by 4 of the original MS data did not affect at all the information content and the histogram shape.

In Table 10 the Entropy values of the “Fused-0.5m” images are presented. A first remark is that all the fusion techniques cause very small changes to the Entropy values of the original image. Also, it has to be pointed out that there is a small increase to the Entropy values of the first five bands and a small decrease to the Entropy values of the last three bands (Red Edge, NIR1 and NIR2). CN and PCA fused images present the higher Entropy difference compared to the original bands for both the classic and the new bands. HPF and LMVM algorithms present the best scores in Entropy values preservation.

Table 10 - The Entropy values of the “Fused-0.5m” bands. With symbol * the smaller entropy difference between the original and the fused image is marked while with symbol ** the second smaller difference is marked.

| Fused-0.5m | Coastal | Blue | Green | Yellow | Red | Red Edge | NIR1 | NIR2 | Average New Bands | Average Classic Bands |
|------------|---------|------|-------|--------|-----|----------|------|------|------------------|----------------------|
| Worldview MS |        |      |       |        |     |          |      |      |                  |                      |
| CN         | -1,08  | -0,59| -0,16 | -0,05  | -0,02| 0,04     | 0,07 | 0,00 | -0,27            | -0,18                |
| Ehlers     | -0,36  | -0,40| 0,35  | 0,08   | 0,17 | 0,14     | 0,15 | 0,26 | 0,03             | 0,07                 |
| Gram Smchidt | -0,23 | -0,22| -0,06 | -0,15  | -0,20| 0,09     | 0,09 | 0,08 | -0,05           | -0,10                |
| HPF        | -0,33  | -0,11| 0,07  | 0,06   | 0,04 | 0,13     | 0,12 | 0,13 | 0,00*            | 0,03**               |
| LMM        | -0,42  | -0,15| 0,00* | 0,01*  | 0,01**| 0,00*    | 0,00*| 0,01**| -0,10           | -0,04                |
| LMVM       | 0,02*  | 0,01**| 0,01**| 0,01** | -0,01**| -0,01**  | 0,00*| 0,01**| 0,01*            |                      |
| ModIHS     | -0,31  | -0,04**| 0,07 | -0,03  | 0,01**| 0,02     | 0,34 | 0,09 | -0,05           | 0,10                 |
| Pansharpe | -0,16**| -0,04**| 0,03 | 0,02** | 0,00* | 0,02     | 0,02 | 0,54 | 0,11             | 0,01*                |
| PCA        | -0,52  | -0,41| -0,15 | -0,26  | -0,28| 0,14     | 0,16 | 0,15 | -0,12           | -0,17                |
| Wavelet    | -0,19  | -0,05| 0,06  | -0,03  | -0,03| -0,01    | 0,45 | 0,02 | -0,05           | 0,11                 |

In Table 11 the Entropy values of the “Fused-2m” images are presented. A first remark is that the Wavelet fusion technique causes a serious decrease to the Entropy values of all the “Degraded” bands. This is not observed in the “Fused-0.5m” bands (Tab. 10). All the other fusion techniques provoke very small changes to the Entropy values of the original image.
The PCA algorithm scores the best result for the new bands while Ehlers and LMVM keep the second place. It has to be mentioned that for the classic bands CN and Gram Schmidt score the best Entropy values, while ModIHS gets the second place.

Table 11 - The Entropy values of the “Fused-2m” bands. With symbol * the smaller entropy difference between the original and the fused image is marked while with symbol ** the second smaller difference is marked.

| Fused-2m | Coastal | Blue | Green | Yellow | Red | Red Edge | NIR1 | NIR2 | Average New Bands | Average Classic Bands |
|----------|---------|------|-------|--------|-----|----------|------|------|------------------|-----------------------|
| Worldview MS | 4.09 | 5.00 | 5.70 | 5.38 | 5.92 | 5.85 | 6.80 | 5.86 | 5.30 | 5.86 |
| CN | -1.56 | -0.44 | 0.03** | -0.45 | 0.17 | -0.29 | 0.29 | -0.08 | -0.60 | 0.01* |
| Ehlers | -0.45 | -0.50 | 0.00* | -0.17 | 0.04 | 0.03* | 0.10 | 0.42 | -0.04** | -0.09 |
| Gram Schmidt | -0.13 | -0.09 | 0.03** | -0.10 | -0.12 | 0.23 | 0.14 | 0.17 | 0.05 | -0.01* |
| HPF | 0.04* | 0.02* | 0.08 | 0.04 | -0.01* | 0.09 | 0.05 | 0.05 | 0.05 | 0.03 |
| LMM | -0.97 | -0.49 | -0.08 | -0.01* | -0.01* | 0.04** | 0.04** | 0.04** | -0.23 | -0.14 |
| LMVM | 0.07 | 0.05 | 0.06 | 0.03** | 0.01* | 0.03* | 0.02* | 0.02* | 0.04** | 0.03 |
| ModIHS | -0.55 | -0.19 | 0.10 | 0.15 | 0.07 | 0.11 | 0.09 | 0.10 | -0.05 | 0.02** |
| Pansharpend | 0.06** | 0.05** | 0.12 | 0.08 | 0.02** | 0.14 | 0.10 | 0.10 | 0.10 | 0.07 |
| PCA | -0.18 | -0.24 | -0.13 | -0.17 | -0.28 | 0.23 | 0.24 | 0.22 | 0.02* | -0.10 |
| Wavelet | 0.32 | 1.15 | 1.74 | 1.40 | 1.93 | 1.89 | 2.71 | 1.77 | 1.35 | 1.88 |

Discussion
The aim of this study was to enrich the knowledge on the effectiveness of commonly used fusion algorithms when applied to Worldview-2 data. Two separate visual and quantitative evaluations on the performance of ten fusion techniques were performed. All the fusion techniques were applied on both the original data and on spatial degraded data.

The first step of the quality assessment was the visual analysis of the fused images. It gave quite interesting results. Four of the fusion algorithms used the CN, the Gram-Schmidt, the PCA and the Wavelet. These algorithms seem to be affected by the spatial degradation of the original data by 4. Thus, the specific algorithms produced blurring and spatial degradation when applied to the downsampled Pan and MS data creating the “Fused-2m” images. The same algorithms gave quite good results when applied to the original data creating the “Fused-0.5m” images. LMVM produces some very small color alternations (sparse blue pixels) when applied to the degraded data. This artifact was also reported in previous study [Laporterie et al., 2004]. The specific study has negatively evaluated the LMM and the LMVM fusion techniques when applied on simulated PLEIADES HR images. Contrary to that, those two algorithms produced quite good results with the Worldview-2 data. Modified IHS algorithm presented a small color tonality difference (darker colors) when applied to the degraded data. Pansharpend
presented also a small color tonality difference (darker colors) only when applied to the new bands of the degraded data. All the other algorithms present the same results independently of the spatial resolution of the input data set. The Ehlers and the HPF algorithms caused minor changes to the color tonality and to the contrast of the image, improved the target detectability and thus they lead in the standing of the visual evaluation. As the validity of the visual assessment is often challenged by the investigators because of subjectivity and dependency to the interpreter issues, the results were confirmed using objective spectral and spatial quality indices.

Between the quality index, the correlation coefficient provided the least help in the discrimination of the best fusion algorithm. A general remark is that all the fusion algorithms produced images highly correlated to their references. It has to be pointed out that there is no significant diversification between the correlation values of the new and the classic bands. The only exception is the coastal band. All the fusion algorithms produced the lower correlation values with the coastal band. HPF, LMM and LMVM present the higher correlation values independently from the input data. The Wavelet technique produced high correlated fused images only when applied to the original data (“Fused-0.5m”).

In contrary to the correlation results, ERGAS values are diversified depending on the data set used and also depending on the spectral content of the bands (classic or new bands). With the exception of the CN algorithm, the ERGAS values of the new bands are higher than the ERGAS values of the classical bands. That means that nine out of ten algorithms cause bigger distortion to the new bands than to the classical ones. As described earlier in the results section, strong variation was also observed to the results depending on the input spatial and spectral resolution. Different algorithms present the best scores when applied to the degraded or to the original MS data and nine out of the ten algorithms performed better with the classical bands than with the new ones. It is worth mentioning that the Pansharpen algorithm presents the higher stability (small fluctuation) of the ERGAS values independently of the input data set and of the spectral content.

It is the same algorithm (Pansharpen) and Gram Schmidt that present very stable Q values. Q results are quite stable and seem not to be significantly influenced by the spectral content of the bands. All the algorithms produce imperceptibly (differences are lower than 0.06) better results with the classical bands than with the new ones. On the other hand, the spatial resolution of the input data strongly influences the algorithm’s performance. Different algorithms present the best results when applied to the degraded and to the original data as well.

Contrary to the Q, the Q4\_expand quality index gave more robust results. Two algorithms (LMVM and Pansharpen) took the lead (best scores) in all the fused image categories, both in spatial and in total quality (Q4\_expand) preservation. Another algorithm, Ehlers, presents a very good performance in spectral information preserving quality. This is in full accordance with the visual analysis as the specific algorithm caused minor color distortion to all the fused images. It has to be pointed out that all the fusion techniques present higher Q4\_expand values when applied to the degraded data resulting to the “Fused-2m” than when applied to the original data resulting to the “Fused-0.5m”. Sometimes the Q4\_expand of the former images are 2 or 3 times higher than that of the later. This can be explained: as the size of the pixel decrease (more lines and columns) the differences between the original image and the fused can more easily be detected, and thus the image quality index Q4\_expand deteriorates.

Finally, the Entropy index didn’t change the rating of the fusion techniques. It only certified
that the Wavelet algorithm produced really bad results when applied to the degraded data set. The performance of different quality indexes widely used in similar studies [Li, 2000; Wang et al., 2004; Alparone et al., 2004; Wang et al., 2005; Nenciny et al., 2006], didn’t allow emphatical conclusions of which fusion technique is the best for the fusion of Worldview-2 data. CC, Entropy and ERGAS gave the more confusing results. ERGAS presents discrepancies depending on the data set used (degraded or not) and depending on the spectral content of the bands. This is in accordance with other studies [Alparone et al., 2004; Nenciny et al., 2007; Zhang, 2008]. Q is also presenting a strong dependency to the spatial resolution of the input data (degraded or not). Q_{exp} seems to have a more robust performance as it gives the same results for the spatial information preserving quality, and for the total Q_{exp} in all the fused image categories. This is very important and it has to be examined more carefully in the future. In most cases there are no reference data to be compared with the fused ones, therefore the existence of a reliable quality index is very important.

**Conclusions**

Ten well known fusion techniques have been tested for the fusion of Worldview-2 Pan and MS data and different quality metrics have been used for the quality assessment of the produced fused images. It has been proved that all the fusion algorithms have a different performance with the new MS bands of Worlview-2 in comparison to the classical ones. According to the quality controls, all the algorithms produce better results (higher Q values, lower ERGAS values, higher Q_{exp} values and lower Entropy difference values) with the classical bands than with the new ones.

Also, it has been proved that most of the fusion algorithms are less or more influenced from the spatial resolution of the input data. Three algorithms the CN, Gram-Schmidt, PCA and Wavelet gave unacceptable results with the downsampled Pan and MS data sets and quite good results when applied to the original data set. In general it has been proved that both the visual (qualitative) and the quantitative analysis are necessary in similar studies, as they often give conflicting results. None of the quality indexes used in this study proved reliable enough in order to be used independently. None of the indexes impresses the bad performance of the CN, Gram-Schmidt and PCA algorithm when applied to the degraded data set resulting to the “Fused-2m” images. The visual control proved that the fused images are not acceptable, but the quality indexes didn’t register the bad results. The indexes registered only the bad performance of the Wavelet fusion technique. The Q_{exp} quality index is proposed as the main quality discriminator. The Pansharpen algorithm was proved to be the most effective as it gave quite stable and high quality values in most of the indexes. Ehlers and HPF algorithms are ranked first in spectral preservation. LMM, LMVM and Modihs fusion techniques are ranked in the next places and could be also used in photo-interpretation studies where the spectral characteristics are not a priority.

Future work should focus on the fusion algorithm evaluation on multi-sensor and multi-date images and on the investigation of the stability of quality indicators. This study provides a basis for further investigation as it has proved that the commonly used data fusion algorithms are scene dependent and the quality indexes may lead to confusing results. In any case both the visual inspection and the quantitative assessment are necessary.
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