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ASSESSMENT OF VERY HIGH RESOLUTION SATELLITE DATA FUSION TECHNIQUES FOR LANDSLIDE RECOGNITION

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ABSTRACT:

Pan-sharpening is gaining an increasing attention in the remote sensing community, and its usefulness have been demonstrated in several environmental applications. A variety of pan-sharpening techniques, aiming at improving the quality of the fused image have been proposed in literature, but the ranking of their efficiency is a difficult task since the quality of the pan-sharpened image depends on the considered applications. In the literature the IHS-based technique has been proposed as the most effective for landslide detection, but in a more generic framework, other methods such as the Gram-Schmidt Adaptive (GSA) and the General Laplacian Pyramid (GLP) have been found as most performing than the IHS, together with their improved Context Adaptive versions, the GSA-CA and GLP-CA, that relies on local statistics. In the context of the MORFEO project, funded by the Italian Spatial Agency (ASI), this work aims at verifying these conclusions by comparing the performances of IHS, GSG and GSA-CA methods together with those of the Principal Component (PC) and the widely used Gram Schmidt (GS) methods. The comparison have been performed on IKONOS multispectral data, by evaluating the results both in a quantitative and qualitative way. The qualitative assessment has been performed by means of a visual assessment in terms of landslide detection by photointerpretative techniques. Possible correlation and or differences found among the quantitative and the visual assessment have been analyzed.

1. INTRODUCTION

Data fusion techniques are widely applied in the scientific community to exploit the potentiality of complementary data (Pohl and Genderen, 1998), and in particular the Pan-sharpening that is a branch of data fusion devoted to the improvement of multispectral data quality by merging Multispectral (MS) and Pancromatic (Pan) data characterized by complementary spatial and spectral resolution (Chavez, 1991; Wang, 2005). This is due to the increasing quantity of multispectral data acquired by the new spaceborne sensors (SPOT, IKONOS QuickBird). The usefulness of pan-sharpened data have been demonstrated in several environmental applications, (Couloigner, et al., 1998; Fanelli et al., 2001; Gonzáles and Seco, 2002; Yang et al., 2000) and a variety of pan-sharpening techniques have been proposed in literature (Wang et al. 2005; Chavez et al. 1991; Zhang, 2002), aiming at improving the quality (from the qualitative and/or quantitative point of view) of the fused images. As a matter of fact, the resulting quality of a fused image is related to many factors, such as spatial, spectral, radiometric accuracy and feature distortion, and therefore different pan-sharpening methods have been developed aiming at different goals.
An important family of pan-sharpening techniques is that of the component substitution (CS) methods, such as those based on IHS (Carper et al., 1990; Edwards et al. 1994; Liu, 2000; Tu et al. 2001), on the Brovey transform (Gillespie, 1987) and on the Principal Component (PC) Analysis (Chavez and Kwarteng, 1989). These methods are fast, have good spatial performances and are useful for many visual interpretation tasks (Wang et al. 2005), but PC and IHS methods are highly sensitive to bands misalignment, as it happens for some VHR (Very High Resolution) imager such as IKONOS (Zhang, 2004); therefore the Gram-Schmidt (GS) technique has been developed to improve CS methods accuracy in such context. Concerning the spectral quality, these methods generally provide pan-sharpening images with a high visual quality, but having often a noticeable spectral distortion (colour changes) and differences in mean (Alparone, 2007); to partially overcome these drawbacks, a generalization of the CS methods has been proposed by considering a synthetic intensity generation that takes into account the different spectral responses of the multispectral bands and the Pan image.
In fact, a high spectral quality of the pan-sharpened images is important for some remote sensing application such as soil and vegetation analysis (Liu, 2000, Garguet-Duport et al. , 1996). Therefore other methods different from the CS one, such as the HPF filter (Chavez et al. 1991; de Béthune et al. 1998) and the SFIM (Liu, 2000) have been developed aiming at a better performance in terms of spectral fidelity. A statistic based fusion method named Pansharp has been also presented by Zhang (Zhang, 2002) to mitigate colour distortion and the dependency of the data fusion performances on operator skill and dataset characteristics. Finally, Multi-Resolution Analysis techniques (MRA) have been extensively studied, based on performing tools such as the à trous wavelet tansform (AWT), and Laplacian Pyramids (AWLP) (Aiazzi, et al., 2002; Ranchin et al., 2003). These methods show a potentiality in tuning the trade-off among spatial and spectral quality (Zhou et al., 1998), at the cost of a most time-consuming process, and critical requirement for co-registration accuracy (Liu, 2000). To overcome these drawbacks, Aiazzi et al (Aiazzi et al, 2002)

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proposed a context-based injection model that operates at a local level (GLP-CBD).
In a comparison work (Alparone et al. 2007) the GLP-CBD and the AWLP methods result as the most performing among a set of data fusion techniques such as FSRF, G-IHS-GA, GIHS-TP, GLP-CBD, UNB Pansharp, WiSpeR, WSiS; in particular the conclusion is that the MRA-based algorithms generally perform better than the CS based ones, even if MRA method may originate ringing and aliasing effect in the fused images, emphasized if a misregistration among MS and Pan images is present. Because of this drawback, the CS techniques are still investigated by the scientific community, and especially the method based on the Gram-Schmidt (GS) spectral sharpening, patented by Eastman Kodak (Laben and Brawer, 2000) and implemented in the Environment for Visualizing Image (ENVI) program package. The GS method and some of its improved versions has been considered in a recent work of Aiazzi et al. (Aiazzi et al. 2009). In this paper, two GS based methods, namely the Gram-Schmidt Global Adaptive (GSG) (Aiazzi et al. 2007) and the Gram-Schmidt Adaptive – Context Adaptive (GSA-CA) have been considered in comparison with the Generalized IHS method (GIHS), which is an improved version of the IHS algorithm, and reaches performances next to those of the most performing techniques of the MRA family, the Generalized Laplacian Pyramids (Aiazzi et al., 1999) and the Generalized Laplacian Pyramid (GLP) – Context Adaptive (GLP-CA). The PC method and the widely used GS method has been also taken into account.
As previously mentioned, because of the different quality characteristics required by the different utilization of the pan-sharpened images (Wald, 1999), an original gold reference is not available to globally evaluate the quality of the fused image, and the efficacy of the pan-sharpening techniques (Alparone et al., 2007); nevertheless some general score indexes have been developed, by considering some average metrics such as the Q4 (Alparone et al., 2004) that is an MS extension of the Q index (Wang and Bovik, 2002), the Spectral Angle Mapper (SAM) (Alparone et al., 2008), the Erreur Relative Globale Adimensionnelle de Synthèse (ERGAS) (Ranchin and Wald, 2000) and the Quality with No Reference (QNR), that is computed at full scale even if the reference is not available (Alparone et al., 2008).
Some works based on the aforementioned indexes and on statistical and visual considerations have been presented in literature to compare the performances of pan-sharpening techniques (Wang et al. 2005, Alparone et al., 2007, Nikolakopoulos, 2008). Te Ming To (Te-Ming To, 2004) showed that the IHS fusion technique is fast and computationally light, but may introduce spectral distortion in presence of spectral mismatch between Pan and MS bands, and Chavez (Chavez et al, 1991) established that PC techniques performances are better than those of the IHS; moreover Zhang (Zhang, 2004) found that if Panchromatic and Multispectral bands are not perfectly overlapped, as it happens in some advanced sensors such as IKONOS and QuickBird, the IHS- and PC- based methods may yield poor performances in terms of spectral accuracy.
Notwithstanding the great effort in assessing the performances of the various pan-sharpening techniques, the resulting ranking could not be suitable in certain contexts with particular quality requirements. In this case a devoted quality assessment could be necessary, such as in the landslide detection field.
As a matter of fact, in the context of landslide detection from remote sensing data, the work of Marcelino (Marcelino et al, 2009) compares six image fusion techniques (Brovey, HSV, PC, IHS, WTVE and WTYO) to select the most performing in landslide visualization on pan-sharpened image . The result was that the IHS method appears to be the best available technique for preserving and enhancing the spatial and spectral information useful to identify landslides. On the opposite side, Nichol (Nichol et al., 2005) found that Pan-sharp methods perform better than IHS, Brovey, SFIM for landslide detection. A first conclusion is that at the present the performances of some of the most performing methods have not yet clearly assessed in the landslide detection task.
This work has been carried out in the framework of MORFEO project, an ASI funded study devoted to the evaluation of the potentiality of EO optical data acquired by satellite platform in landslide detection. It aims at comparing the performances of the GSG and GSA methods together with those of the G-IHS, the PC, the GS fusion methods in the specific context of the landslide detection by considering an IKONOS data set. The quality of the resulting pan-sharpened MS images are then compared in a quantitative and qualitative way. From the quantitative point of view, some quality score indexes related to the characteristics useful in landslide detection have been selected and evaluated, whereas the qualitative assessment has been performed by considering a visual inspection of skilled photointerpretes.

2. STUDY AREA

This study has been performed on a test site located in the Umbria region (Italy); the test area has an extension of about 80 Km^2 and corresponds to a part of the catchment basin on the left of Tevere river. Elevation range from 145 to 634 m without high slope gradients. The soil is characterized by sedimentary rocks, such as limestone, sandstone and unconsolidated sediment, and the vegetation coverage is varied and mainly consists in agricultural area and woodlands. The climate is of Mediterranean type; the annual precipitation average is lower than 900 mm and the rain is usually concentrated in the period from September to December. Because of its geological nature, this area is affected each year by a high number of landslides, the most part of which are soil slides of small to medium dimensions, caused mainly by rainfall or in some cases by the snow melting.

3. DATA SET

The assessment of data fusion techniques have been performed on IKONOS data, composed by a Panchromatic (PAN) band with a nominal Ground Sampling Distance (GSD) of 1m, and by four multispectral (XS) bands (near-infrared, red, green, blue) with a nominal GSD of 4m. The PAN and the XS bands are simultaneously acquired during the summer season and image the same area with a radiometric resolution of 11 bits. Table 1 reports the main characteristics of the IKONOS data set.

	IKONOS	
Date of acquisition	Summer 2005	
Spectral band	PAN	R, G, B, NIR
Spatial Resolution	1 m	4 m
Radiometric resolution	11 bit	

Table 1. Main characteristics of the IKONOS image.

To evaluate the potentiality of the IKONOS pan-sharpened images in terms of the landslide study, an inventory of the landslide to be considered as "ground truth" was needed. To this purpose, a thematic map reporting soil slide phenomena occurred on the test area during autumn-winter 2004-2005 has been produced by IRPI-CNR with the usual "state of art" stereoscopic photointerpretation techniques.

4. METHODOLOGY

The IKONOS multispectral images have been aligned with the related panchromatic image by a suitable pre-processing. Then the multispectral bands have been pan-sharpened with the panchromatic image by means of the fusion techniques under analysis, that is the GIHS, the PC, the GS, the GSG and the GSA-CA. The PC and the GS pan-sharpening have been performed by means of the related tools of ENVI, whereas the GIHS, the GSG and the GSA-CA fusion techniques have been carried out with a devoted software developed by IFAC-CNR. The radiometric correction, usually performed before the fusion procedure to achieve a conformity with a mean and variance equalization of the bands (Gaurguet-Duport et al., 1996, Schowengerdt, 1997; Mather, 1999) have not been performed in our study because not necessary, since a physical significance of the pixel value is not required in the proposed procedure of quality evaluation. As a matter of fact, the study is based on a qualitative visual inspection and on a quantitative evaluation of suitable score indexes: the visual inspection is focused only on the analysis of the features of the images, and since no threshold with physical given value is applied, it is not a-priori necessary to have pixel value with a physical significance. The quantitative assessment is made by performing a comparison with the original images by considering the Wald's protocol, and can be carried out in terms of the digital number all the same. Moreover, the GSG and GSA-CA methods perform an injection of details that is weighted by some statistical functions of the images, and the generation of the synthetic intensity band from the multispectral bands is carried out in order to obtain the desired conformity with the original Panchromatic image. In the application of the GIHS-based pan-sharpening method, an histogram matching is instead necessary. The pan-sharpened data are then orthonormalized with the related tools of ENVI by considering a DEM at 10m of spatial resolution and the Rational Polinomial Coefficient (RPC) provided together with the IKONOS data, and finally the quality assessment is performed.

5. QUALITY EVALUATION

Quality evaluation of the pan-sharpened images can be performed, as a general rule, in two ways, that based on quantitative assessment, spatial and/or spectral, and that based on a qualitative visual inspection. It is important to point out that either the quantitative and the qualitative assessment can be performed globally or by considering local characteristics of the images. This procedure is of particular interest in some given task, such as the landslide detection considered in this paper. Therefore, the quality ranking produced with a general visual inspection could differ from the quality ranking obtained when the specific task of landslide detection is considered; similarly, the quantitative result obtained with a general-purpose score index could be not suitable to assess the quality of the fused products for this particular task. The correlation among the quality measured by some quantitative score indexes proposed in literature and the quality in term of landslide detection assessed with a visual inspection is therefore an interesting question to be analysed.

5.1 Quantitative evaluation

The quality assessment has been performed by evaluating the *synthesis property* proposed by Wald (Wald et al. 1997). As depicted in Figure 1, the original Panchromatic (Pan) and Multispectral (MS) images are spatially reduced by the same factor, so that the new spatial resolution of the Pan image is equal to the original resolution of the MS images.

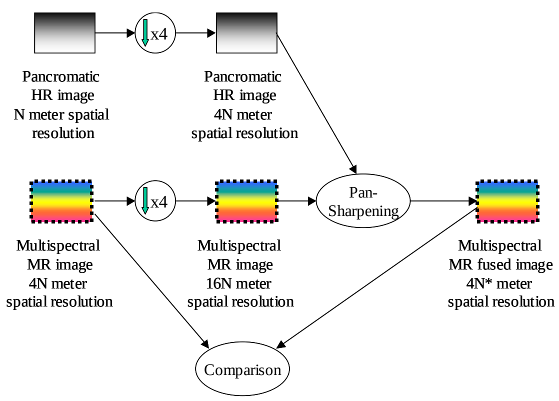

Figure 1. The adopted quality assessment procedure.

The degraded MS image is then pan-sharpened with the degraded Pan image, thus originating a fused MS image at the same spatial resolution of the original MS image; in such a way the original MS image can be adopted as reference. Trivially, the fused image has to be as similar as possible to the reference, to fulfill the so-called *synthesis property*. The synthesis properties have been evaluated by means of some quality indexes. The definition of quality index suitable for such task is still an open question (Li , 2000; Thomas and Wald, 2005), and the fidelity comparison is often performed by more than one index, each of them defined to take into account different characteristic of the image, such as spectral or spatial matching. In this work, five score indexes have been considered. The overall assessment on the entire data set has been performed by considering the ERGAS (relative dimensionless global error in synthesis) index, defined as:

$$\mathrm{ERGAS} \triangleq 100\frac{h}{l}\sqrt{\frac{1}{K}\sum_{k=1}^{K}\left(\frac{RMSE(k)}{\mu(k)}\right)^2} \qquad (1)$$

where h/l is the ratio between the pixel size of PAN and MS image respectively, K is the number of bands labelled with the k index and $\mu(k)$ is the mean of the k-th band. The fidelity from spectral point of view has been assessed by using the Spectral Angle Mapper (SAM) index, a point-wise score defined for each pixel (i,j) as:

$$SAM(\mathrm{v},\hat{\mathrm{v}}) = \cos^{-1}\left(\frac{\langle \mathrm{v},\hat{\mathrm{v}}\rangle}{\|\mathrm{v}\|_2\,\|\hat{\mathrm{v}}\|_2}\right) \qquad (2)$$

where **v** is the n-dimensional vector for each pixel position (*i*,*j*) composed by the multispectral values of the n pan-sharpened bands, while $\hat{\mathrm{v}}$ is the correspondent one for the reference bands. High values of SAM are related to high spectral distortion, but the radiometric distortion is not taken into account by the SAM index. A global evaluation of the image can be obtained by averaging the SAM values of all the pixels. Together with the ERGAS and SAM indexes, the usual RMSE, PSNR and Correlation score indexes have been also evaluated. The overall quality of a pan-sharpened image can be assessed by using a quality budget composed by a combination of more indexes, such as that proposed by Thomas and Wald (Thomas and Wald, 2007), but in the context of this paper the score indexes have been considered separately, in order to analyse the possible correspondence between the related ranking and the visual evaluation .

5.2 Qualitative evaluation

The qualitative evaluation has been performed on the full resolution pan-sharpened images by means of a visual inspection carried out by skilled photointerpreters, relying on a landslide inventory obtained by usual photointerpretation techniques on aereophotos of the study area. A suitable subset of the landslides present in the landslide inventory has been chosen, in order to consider the most significant ones. The analysis has been performed by considering the characteristics that allow the photointerpreter to map the landslide, such as quality of the linear features and textures, contrast and colour; the evaluation results have been averaged on the adopted subset and a related global quality evaluation has been finally produced.

6. RESULTS

The quantitative assessment of the GSA_CA, the GSG, the GS, the GIHS, and the PC fusion techniques have been performed by evaluating the ERGAS, the PSNR, the SAM, the RMSE and the Correlation Coefficient (CC) score indexes between the fused images and the reference ones. The adopted study area has not a rectangular shape, but the evaluation of the aforementioned quality indexes has been performed on a square subimage, in which the pixels outside the study area have been masked and set to the zero value. As a consequence, the high number of corresponding zero values between fused and reference image introduce a bias in the score indexes. In order to overcome this drawback and to obtain values that are easily comparable among the different fusion methods, the resulting score indexes have been normalized in percentage of the best achieved value. A value of 100 is therefore assigned to the better method among the tested ones, and consequently the higher is the number the worst is the performance for the ERGAS, the SAM, and the RMSE, whereas for the PSNR and the Correlation value the worst methods are characterized by the lower values. The normalized score indexes achieved by the tested fusion methods are listed in Table 2, together with the performance achieved by the "expanded" image, that is a simply resampled image obtained by interpolating the MS bands to be used as a reference to evaluate the improvement introduced by the pan-sharpening procedures.

	ERGAS %	SAM %	RMSE %	PSNR %	CORR %
GSA -CA	100.0000	104.1346	100.0000	100.0000	100.0000
GSG	104.0293	115.8417	195.1536	98.6895	99.9305
GS	112.2316	121.4751	114.3788	96.9539	99.7860
IHS	135.1306	130.9472	138.5633	92.4371	99.3656
PC	124.1912	128.3047	125.1895	94.9071	99.5846
EXP	134.9381	100.000	139.3647	91.8082	99.3706

Table 2. Results of the quantitative evaluation.

As expected, the GSA-CA and the GSG achieve the best performances for the most part of the adopted score indexes, even if GSG shows some problems in terms of RMSE, whereas the GS is found to be the best among the fusion methods implemented by ENVI.
From the visual point of view, the results have been summarized in the table 3, in which for each studied fusion technique the resulting quality in terms of the characteristics used by the photointerpreter to map the landslide are assessed together with a global judgment of the fused image; the evaluation is provided by means of a detectability rating scale, based on a five levels ranking, namely: 5 (insufficient), 4 (poor), 3 (medium), 2 (good), 1 (excellent).

	Features	Texture	Contrast	Colour	Overall
GSA	2	3	2	2	2
GSG	1	1	2	2	2
GS	1	1	2	2	1
IHS	3	3	2	3	3
PC	1	1	1	2	1

Table 3. Qualitative evaluation

By considering the scores of Table 3, the PC and the GS pan-sharpening techniques result as the best in the context of landslide detection among the tested ones. Also the GSG does not change linear features and texture, but is less satisfactory in term of colour quality, whereas GSA slightly suffers for some changes in linear features and texture useful in landslide detection.

7. CONCLUSIONS

Five pan-sharpening techniques, the Gram-Schmidt Global Adaptive (GSG), the Gram-Schmidt Adaptive – Context Adaptive GSA-CA, the Gram-Schmidt method (GS), the Principal Component method (PC) and the generalized-IHS (GIHS) method have been tested on a IKONOS multispectral data set acquired over Umbria region in Italy, and the quality of the resulting pan-sharpened images have been compared quantitatively and qualitatively in the specific context of landslide detection task. From the quantitative point of view, the synthesis property introduced by Wald et al. (Wald et al.

1997) have been evaluated by using five score indexes, namely the ERGAS, the SAM, the RMSE, the PSNR and the correlation value, usually adopted for such task, whereas the qualitative assessment have been performed by a visual inspection of skilled photointerpreters. This analysis has been focused on the characteristics of the image useful for landslide detection, such as linear features, textures, contrast and colour. Quantitative assessment confirms the result of some previous comparative works: the GSG and GSA-CA pan-sharpening techniques have been found as the most performing, and the performances of the GS method is however higher than those of the PC and the GIHS ones, because of a residual misalignment among panchromatic and multispectral IKONOS bands. On the opposite side, the visual analysis does not agree with the quantitative conclusions; as a matter of fact the GS method has been found as the most performing for the landslide detection tasks together with the PC. The GSG shows a similar high quality but presents some problems concerning the quality of the colour useful for landslide recognition, whereas the GSA-CA slightly suffers for some changes in linear features and textures useful in landslide detection task. As a consequence of the comparison among the quantitative and the qualitative assessment, it has been found that the procedures and the score indexes often proposed for the assessment of pan-sharpened images quality are not fully suitable for the ranking of the fusion techniques when landslide detection with photointerpretative techniques task is considered.

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