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Evaluation of the quality of Quickbird fused products

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ABSTRACT: Most of the satellite sensors, presently operating in the optical domain, are providing a data set comprising multispectral images at a low spatial resolution and images at a higher spatial resolution but with a lower spectral content. The trend of satellite sensors is similar to the present situation. The idea of fusing multispectral images with a highest spatial resolution enables the creation of useful products for a set of applications. This paper aims at evaluating a set of methods for construction of synthetic multispectral images having a highest spatial resolution available within the data set. These methods are evaluated through the construction of fused products from a set of Quickbird panchromatic and multispectral images. Of interest are the most used methods: the Intensity-Hue-Saturation method, the Brovey transform, the multiplicative methods and a set of methods derived from the ARSIS concept. The different methods are shortly presented. These methods are tested in a dataset from the area of Madrid. The dataset proposed a good diversity of landscape allowing the measure of the impact of fusion methods on different cases. The resulting images are evaluated through visual criteria from a set of photo-interpreters. They classified the fused products and pro-vided a ranking for the visual quality. Then the proposed protocol defined by Wald et al. (1997) is applied to all methods. A set of quantitative parameters is computed allowing an objective comparison of the results. Finally a new parameter allowing the quantification of the information brought by the fusion method is proposed. This parameter is based on the analysis of the difference of the real structures of a multispectral image and of the computed structures of the fused products. It is applied to the different methods and favors the evaluation of the impact of an algorithm on the resulting images. Some conclusions are drawn on the ranking of the different methods and on the appropriate parameters for the evaluation of the quality of fused products.

1 INTRODUCTION

The trend of building satellite sensors is for several years the combination of multispectral images at a low spatial resolution and images at a higher spatial resolution but with a lower spectral content. Several studies and publications have shown that merging broadband high spatial resolution images with low spatial resolution high spectral resolution images proves to be of great benefit in many applications. Many methods have been developed in that purpose and produce multispectral images having the highest spatial resolution available within the data set. With the launch of very high resolution sensor such as those on-board the SPOT 5, IKONOS or Quickbird satellites, the interest on merging of those type of data set is growing.

In this paper, a set of fusion methods is tested when applied to the Quickbird case and the quality of the products evaluated. Quickbird satellite delivers a set of images composed of a Panchromatic band (0.45-0.90 µm) at 0.61 m and a set of multispectral images in the Blue, Red Green and Near Infrared Red (NIR) bands (B0: 0.45-0.52 µm, B1: 0.52-.60 µm, B2: 63-0.69 µm and B3: 0.76-.90 µm) at 2.44 m. The next paragraph made a short presentation of the methods under comparison. Then, the protocol of evaluation of the quality is exposed. This protocol, defined by Wald *et al.* (1997) allows the comparison of fused products on an objective way. In order to improve the understanding of the behavior of the different methods proposed a new parameter is proposed. It allows analyzing of the difference of the real structures of a multispectral image and of the computed structures of the fused products. From the set of parameters a ranking of the methods is proposed both from visual and radiometric point of view.

2 THE FUSION METHODS EVALUATED

Eleven methods were selected. They are relevant to the three groups of techniques currently used:

- Projection of original data sets into another space, substitution of one vector by the high resolution image and inverse projection into the original space. We selected the IHS (Intensity, Hue, and Saturation) method and the PCA (Principal Component Analysis) method (Carper *et al.* 1990).
- Relative spectral contribution. We selected the Brovey transform (Pohl & van Genderen, 1998) and the additive multiplicative method available in the ERDAS© software. It should be noted that the Brovey transform does not well represent this group because of its poor principles in construction. Nevertheless, it is often used.
- Scale by scale description of the information content of both images and synthesis of the high-frequency information missing to transform the low spatial resolution images into high spatial resolution high spectral content images. The ARSIS concept (Ranchin & Wald, 2000, Ranchin *et al.*, 2003) has developed in several methods. We selected three models presented by Ranchin & Wald (2000), making use of wavelet transform: Model 1, Model 2 and Model 3.

Additionally, we used combinations of IHS with wavelet based decomposition as proposed by Nuñez *et al.* (1999) or Hong & Zhang (2003) and of PCA with wavelet based decomposition as proposed by Gonzalez-Audícana *et al.* (2003) with modeling of the wavelet coefficient as proposed in the ARSIS concept. Two models are used in these cases the M1 and M2 models.

The Brovey transform, the multiplicative and PCA methods were performed using the commercial software ERDAS. The authors have coded the other algorithms.

3 PROTOCOL OF EVALUATION

The protocol of evaluation proposed by Wald *et al.* (1997) is the basis of the comparison of the eleven methods proposed. In the Quickbird case, the four multispectral images B_{il} have an original resolution of 2.44 m. The high spatial resolution image A_h is the panchromatic band P with a spatial resolution of 0.61 m. The synthetic bands B^*_{ih} are the B1 to B4 bands synthesized at 0.61 m.

Following this protocol, the merging methods under concern aim at constructing synthetic images B^*_{ih} close to the reality. Wald *et al.* (1997) established the properties of such synthetic images:

- Any synthetic image B^*_{ih} once degraded to its original resolution l: $(B^*_{ih})_l$, should be as identical as possible to the original image B_{il}.
- Any synthetic image B^*_{ih} should be as identical as possible to the image B_{ih} that the corresponding sensor would observe with the highest spatial resolution h.

- The multispectral set of synthetic images B^*_{ih} should be as identical as possible to the multispectral set of images B_{ih} that the corresponding sensor would observe with the highest spatial resolution h.

Wald *et al.* also propose to check whether a fused product meets these properties. For each property, a visual inspection of the fused product is performed first and compared to the ideal product. It shows the major drawbacks of a method. These drawbacks can be quantified by a quantitative assessment of the discrepancies between the fused product and the ideal one.

To assess the first property, the synthetic image B^*_{ih} made at 0.61 m are filtered before resampling to degrade the resolution down to 2.44 m: $(B^*_{ih})_l$. They are then compared to the original images B_{ih}. The filtering function is a sine cardinal (sinc) kernel truncated by a Hanning apodisation function of size 13x13.

To test the second and third properties, the P and multispectral images are degraded to a resolution of 2.44 (A_{2h}) and 9.76 m ($(B_i)_{2l}$), respectively. Then, images B^*_{il} are synthesized at a 2.44 m resolution and compared to the original XS images B_{il} by a visual inspection on the one hand, and by performing a difference pixel per pixel. The discrepancies are analyzed and synthesized in five sets of criteria, which deal respectively with:

- each spectral band in a global way,
- the statistical distribution of errors at pixel level for each spectral band,
- information correlation between the different spectral images,
- the multispectral aspect, that is the errors in reconstructing spectral signatures,
- the reconstruction of the most frequent spectral signatures.

Wald *et al.* discussed the extrapolation of the quality assessments made at 20 m to 10 m. They underlined the unpredictability of such assessments when changing the resolution. That is, it cannot be said whether the error at 10 m is larger or lower than that at 20 m. By testing several methods on SPOT images degraded to 40 and 80 m, they found in several cases that the quality was best at 20 m than at 40 m. They suggested that one could assume that the quality of the synthetic images at 10 m may be considered as similar to that of the synthetic images at 20 m. Such a hypothesis will be considered as valid in the Quickbird case.

4 A NEW QUANTITATIVE PARAMETER

A difficult parameter to evaluate in the quality of fused products is their spatial behavior. Not only the radiometric values are of interest in the evaluation of the quality of the product, but also its geometric quality. In the framework of image fusion, the difference of information between the original image and the fused product consists only in the high resolution structures added to the original image, because the first property of the fused products should be respected. Hence according to this, one can find the way of evaluating the contribution or the so-called details added to original image.

If the problem is evaluated from the signal or image processing point of view, one should evaluate the high frequencies added to the original image. Hence time-frequency or space-scale tools seems to be adapted to evaluated such a contribution. Wavelet transform tools are good tools for such an analysis.

4.1 *The wavelet transform as analysis tool*

In order to facilitate the understanding, the wavelet transform will be presented in its continuous version and in the mono-dimensional case. The main property of the wavelet transform is to adapt the analysis window to the phenomena under study, providing local information. The wavelet transform leads to a time-frequency representation. In the case of images, the wavelet transform leads to a scale-space representation. Some examples will be provided in order to illustrate this main property.

As the Fourier transform, the wavelet transform is equivalent to a decomposition of the signal in a base of elementary functions: the wavelets. The base is generated by dilatation and translation of a single function called the mother wavelet:

$$\psi_{a,b} = |a|^{\frac{-1}{2}} \psi\left(\frac{x-b}{a}\right) \tag{1}$$

where $a, b \in \Re$ and $a \neq 0$. a is called the dilation step and b the translation step.

Many mother wavelets exist. They are all oscillating functions, that are well localised both in time and frequency. All the wavelets have common properties such as regularity, oscillation and localisation, and satisfy an admissibility condition. For more details about the properties of the wavelets, one may refer to Meyer (1990) or to the book of Daubechies (1992). Even if they have common properties, each of them brings to a single decomposition of the signal related to the used mother wavelet. In the one dimension case, the continuous wavelet transform of a function f(x) is:

$$WT_f(a,b) = \rangle f, \psi_{a,b} \langle = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} f(x) \overline{\psi(\frac{x-b}{a})} dx \tag{2}$$

where $\psi_{a,b}$ is defined as in Eq. 1 and $\overline{\psi(\frac{x-b}{a})}$ is the complex conjugated of ψ. $WT_f(a,b)$ represents the information content of *f(x)* at scale *a* and location *b*. For fixed *a* and *b*, $WT_f(a,b)$ is called the wavelet coefficient. The computation of the wavelet transform for each scale and each location of a signal provides a local representation of this signal. The process can be reversed and the original signal reconstructed exactly (without any loss) from the wavelet coefficients by:

$$f(x) = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} WT_f(a,b)\, \psi_{a,b}(x) \frac{da db}{a^2} \tag{3}$$

where C_ψ is the admissibility condition of the mother wavelet. This last equation can be interpreted in two ways:

- *f(x)* can be reconstructed exactly if one knows its wavelet transform,
- *f(x)* is a superimposition of wavelets

These two points of view lead to different applications of the wavelet transform. In the first case, the processing of the signals and in the second their analysis. More details on the use of such a tool for analysis of remotely sensed data can be found in Ranchin (1997).

4.2 *Spatial quality parameter*

The wavelet transform allows representing the structures or details existing between different scales of an image. In the case of the fusion of Quickbird data, the ratio between multispectral and panchromatic data is 4. Hence, using a dyadic wavelet transform for representing the details between the original image and the fused products, two wavelet coefficients images should be evaluated. As proposed in the protocol of Wald *et al.* (1997), the P and multispectral images are degraded to a resolution of 2.44 (A_{2h}) and 9.76 m ($(B_i)_{2l}$), respectively. Then, images B^*_{il} are synthesized at a 2.44 m resolution and compared to the original XS images B_{il}. The new parameter proposed is based on the comparison of the wavelet coefficients images computed from the original image B_{il} and from the fused products B^*_{il} obtained at 2.44 m. First, a scale-by-scale comparison can be achieved. But in order to consider a generic parameter for evaluating the spatial content, it is proposed to evaluate all the scales together between 2.44 m and 9.76 m. To achieve this comparison, a linear relation (4) is computed using a least square fitting between each image:

$$\sum(\mathrm{WT}(B^*_{il})) = a * \sum(\mathrm{WT}(B_{il}))+b \qquad (4)$$

If the details are very well modeled by the fusion algorithm, one can obtain a = 1 and b = 0. Additionally, the representation of the statistical cloud representing the data should be concentrated along the axis. An example of this new parameter is proposed in the next paragraph.

5 QUICKBIRD PAN AND MULTISPECTRAL FUSION: RESULTS

The example provided in this paragraph is based on the fusion of an image acquired over the area of Madrid the 29th of January 2002.

5.1 *Statistical analysis*

Table 1 presents a set of statistical results for the different methods selected in paragraph 2 for the NIR band of Quickbird.

Table 1. Some statistics on the differences between the original and synthesized images, for NIR band.

	IHS	PCA	Brovey	Multiplicative model	ARSIS Model 1	ARSIS Model 2	ARSIS Model 3	IHS+Model 1	PCA+Model 1	IHS+Model 2	PCA+Model 2
Bias (ideal value: 0) relative to the mean original value	-92 -37%	48 19%	126 50%	-90159 -35992 %	0.5 0.20%	0.5 0.20%	0.5 0.20%	0.2 0.08%	0.5 0.20%	0.69 0.28%	0.5 0.20 %
Actual variance-estimate (ideal value: 0) relative to the actual variance	-6856 -93%	-341 -4.6%	4862 66 %	$-2.0\ 10^{+9}$ $-2.8\ 10^{+7}$	-469 -6.3%	2067 28 %	2208 30%	-301 -4%	1845 25%	2670 36 %	2279 31 %
Correlation coeff. between original and estimate (ideal value: 1)	0.924	0.924	0.902	0.887	0.921	0.928	0.926	0.924	0.930	0.917	0.925
Standard-deviation of the differences (ideal value: 0) rel. to the mean of original value	52 21 %	34 14 %	46 18 %	45199 18044%	35 14 %	33 13%	33 13 %	34 14 %	32 13 %	36 14 %	34 13 %

Table 1 allows the test of the second property and reports some statistics on the relative discrepancies between the original image in the NIR band and the image synthesized for the eleven methods selected. The differences are computed on a pixel basis and one image of differences. From each image of differences, the mean value (bias) and the standard deviation are computed. The bias represents the difference between the means and the original and the synthesized image; the standard deviation globally represents the level of error for any pixel. These quantities are expressed in percent relative to the mean radiance value of the original image. The ideal value for these parameters is 0. In addition, the difference between the variance of the original image and that of synthesized is computed. It is expressed in percent relative to the variance of the original image. It expresses the quantity of information added or lost during the enhancement of the spatial resolution. Ideally, this value should be zero. The correlation coefficient between the original image Bkl and B*kl is also computed. The ideal value is 1.

These parameters were computed for the 4 bands of Quickbird with similar results. Two other synthetic parameters proposed by Wald (2002) are used to give a general ranking of the different methods. The relative average spectral error (RASE) is expressed in percent and characterizes the average performance of a method in the considered spectral bands. The lower the value, the better the method. The ERGAS parameter (from its French name "erreur relative globale adimensionnelle de synthèse" that means relative adimensional global error in synthesis) is expressed in percent and characterizes the global note of quality of the method. With a ratio between the high and the low resolution of 4, a good method should have a threshold less than 3. Table 2 presents these two parameters for the eleven methods.

Table 2. RASE and ERGAS parameters for the eleven methods.

	IHS	PCA	Brovey	Multiplicative model	ARSIS Model 1	ARSIS Model 2	ARSIS Model 3	IHS+Model 1	PCA+Model 1	IHS+Model 2	PCA+Model 2
RASE	49.5	20.9	54.3	160792	14.9	10.8	11.0	14.8	10.5	11.5	10.9
ERGAS	12.3	5.2	13.5	447477	3.8	2.7	2.7	3.7	2.6	2.8	2.7

From Table 2, the RASE clearly disqualifies the Multiplicative model, the Brovey, the IHS and the PCA methods. The ARSIS-M1 and IHS –M1 methods are of better quality, but the best achievable results are obtained by the PCA-M1, ARSIS-M2, PCA-M2, ARSIS-M3 and IHS-M2 methods.

The ERGAS gives the PCA-M1, ARSIS-M2, PCA-M2, ARSIS-M3 and IHS-M2 methods as good methods.

5.2 *New statistical parameter*

Figure 2 presents an example of the new parameter for the NIR band of the ARSIS-M1 method as proposed in part 4.2. This figure presents the cloud of corresponding points between the first component of the PCA of the wavelet coefficients images existing between 2.44 m and 9.76 m for the fused and the original products. Y-axis represents the wavelet coefficients images for the fused image and X-axis represents the wavelet coefficients images for the original image. With a perfect reproduction of the structures between the two resolutions, the cloud should have been located along the green line.

The dispersion of the cloud reflects the increasing of variance that is reported in Table 1. The more concentrated and close to the identity line the cloud, the better the spatial quality. Table 3 presents the a parameter of equation 4 computed for the eleven methods. The closer a to 1, the better the spatial quality. The b parameter is always close to zero except for the multiplicative model.

This table will be compared with the results obtains from the visual analysis.

Table 3. *a* parameter from equation 4.

	IHS	PCA	Brovey	Multiplicative model	ARSIS Model 1	ARSIS Model 2	ARSIS Model 3	IHS+Model 1	PCA+Model 1	IHS+Model 2	PCA+Model 2
Blue band	1.06	0.46	0.36	305.73	1.18	0.27	0.23	1.02	0.32	0.38	0.26
Green band	0.85	0.52	0.28	239.62	0.65	0.30	0.28	0.81	0.36	0.30	0.30
Red band	0.73	0.59	0.24	203.76	0.76	0.34	0.32	0.69	0.41	0.26	0.34
NIR band	0.60	0.49	0.21	168.88	0.58	0.31	0.29	0.57	0.34	0.22	0.28

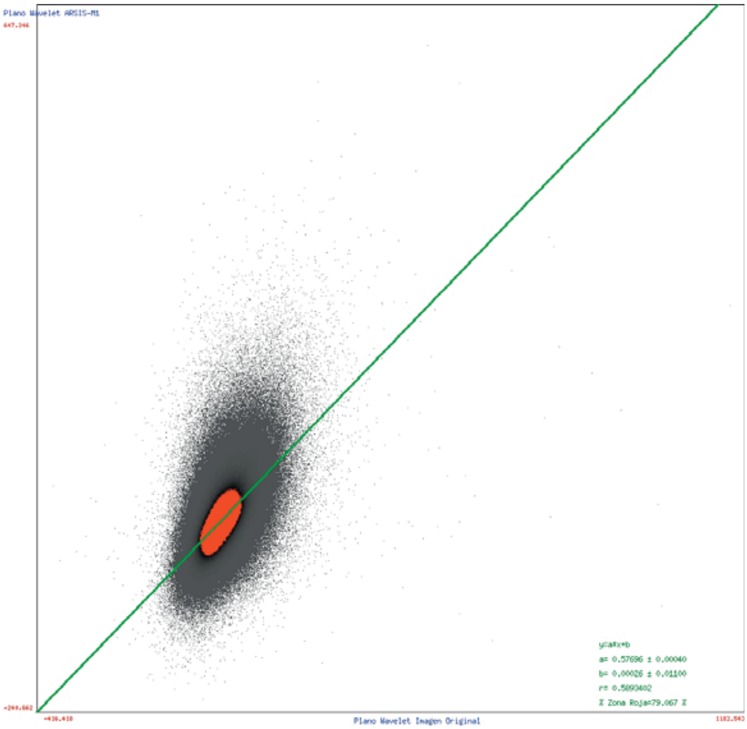

Figure 2. A new parameter for spatial quality of images based on the comparison of wavelet coefficients computed for the original and the fused products.

5.3 *Visual analysis*

The visual assessment of the products was achieved by a set of experienced interpreters. They firstly evaluate the fused products compared to the original one at the spatial resolution of 2.44 m and secondly the fused products at the resolution of the panchromatic image (0.61 m). In each case, the image analysts focus firstly on the quality of the details produced by the fused methods, i.e., how much objects can be detected and identified by their shapes and their sizes and how much these shapes and sizes are similar to the actual shapes and sizes. Then, they analyse the quality of the perception of the radiometry achievable through the fused products, i.e., how much the actual grey levels and colours are reproduced and how much objects can be detected and identified by their colours.

The methods were then ranked by the analysts using these two points of view: details and radiometry (table 4).

Table 4. Ranking of the eleven methods.

Ranking	Best					--->				Worst
Details	ARSIS-M1	IHS-M1	IHS	Brovey	PCA	PCA-M1	IHS-M2	PCA-M2	ARSIS-M2	ARSIS-M3	Multiplicative model
Radiometry	ARSIS-M2	ARSIS-M3	PCA-M2	IHS-M2	PCA	PCA-M1	IHS-M1	ARSIS-M1	IHS	Brovey	Multiplicative model

6 CONCLUSION

The results of the comparison between the different methods enhance the difficulty to answer to users needs with a single method. The different parameters proposed to evaluate the quality of the fused products for the eleven methods proposed allows helping the users to express their needs and to evaluate methods that try to answer them.

From the statistical evaluation, the PCA-M1, ARSIS-M2, PCA-M2, ARSIS-M3 and IHS-M2 methods can be considered as methods given good results. This is confirmed by the ranking on radiometric quality from the interpreters.

According to the new statistical parameter proposed for evaluating the spatial quality of the products, ARSIS-M1, IHS-M1 and IHS can be considered as good methods. This is also confirmed by the ranking delivered by the interpreters from the details point of view.

The set of quantitative parameters can be considered as giving a good trend of the ranking given by the users.

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