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Fusion of multispectral and panchromatic satellite sensor imagery based on tailored filtering in the Fourier domain

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A new methodology for fusing satellite sensor imagery, based on tailored filtering in the Fourier domain is proposed. Finite-duration Impulse Response (FIR) filters have been designed through an objective criterion, which depends on source image characteristics only. The designed filters allow a weighted fusion of the information contained in a fine spatial resolution image (PAN) and in a multispectral image (MULTI), respectively, establishing a trade-off between spatial and spectral quality of the resulting fused image. This new technique has been tested with Landsat Enhanced Thematic Mapper Plus (ETM+) imagery. Spatial and spectral quality of the fused images was compared with the results provided by Mallat's Wavelet algorithm. The images fused by the proposed method were characterized by a spatial resolution very close to the PAN image, and by the spectral resolution of the MULTI image.

1. Introduction

There is a wide variety of data fusion techniques described in the literature e.g. Intensity, Hue, Saturation (IHS), Principal Components Analysis (PCA) and one of the more widely used—Mallat's Wavelet algorithm (Pohl 1999, Mallat 1999). Another image fusion technique is based on the application of filters in the Fourier domain (Ghassemian 2001, Steinnocher 1999). This can be formally stated according to equation (1):

$$\mathrm{FUS} = \mathrm{FT}^{-1}\{\mathrm{LPF}\{\mathrm{FT}(\mathrm{MULTI})\} + \mathrm{HPF}\{\mathrm{FT}(\mathrm{PAN})\}\} \tag{1}$$

where FT represents the Fourier transform, LPF and HPF low pass and high pass filters, respectively; and FUS corresponds to the fused image. The basic idea is that information contained in the low frequency range of a MULTI image will provide the necessary information to generate the background of a final fused image, while information contained in the high frequency range of the PAN image will provide information about its details. In this way, it is possible to obtain a multispectral image that integrates the best features of the two source images. This technique presents two principal problems: false edges in the fused images and spectral

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degradation. Both are due to a subjective design of the filters. The main goal of this work is to avoid these disadvantages, proposing an objective criterion for determining the Finite-duration Impulse Response (FIR) filter parameters: the order (M) and the cut-off frequency (ω_c). They will be determined through the power and the entropy of the source images. Spatial and spectral indices of the fused images have been compared with those provided by Mallat's Wavelet algorithm.

2. Fusion method

Before the fusion process, source images should be pre-processed. The multispectral image must be resized to the panchromatic image size by an interpolation method, and also it should be co-registered with this last image. In this paper, data control points and a bicubic polynomial fit method have been used for co-registering the source images. On the other hand, usually, fusion methods require an image radiometric correction, as for example the matching histograms between the PAN image and each one of the spectral bands to be fused. In this work it will be shown that the proposed fusion method implicitly performs this matching.

The first step is to obtain the Fourier transforms of the source images and further to calculate the FIR filter's parameters (M, ω_c). Then, the PAN image and each one of the spectral bands are transformed to the Fourier domain and are high and low pass filtered, respectively. The fused image is obtained by inverse Fourier transforming the sum of the filtered images (MULTI_Low and PAN_High) (figure 1).

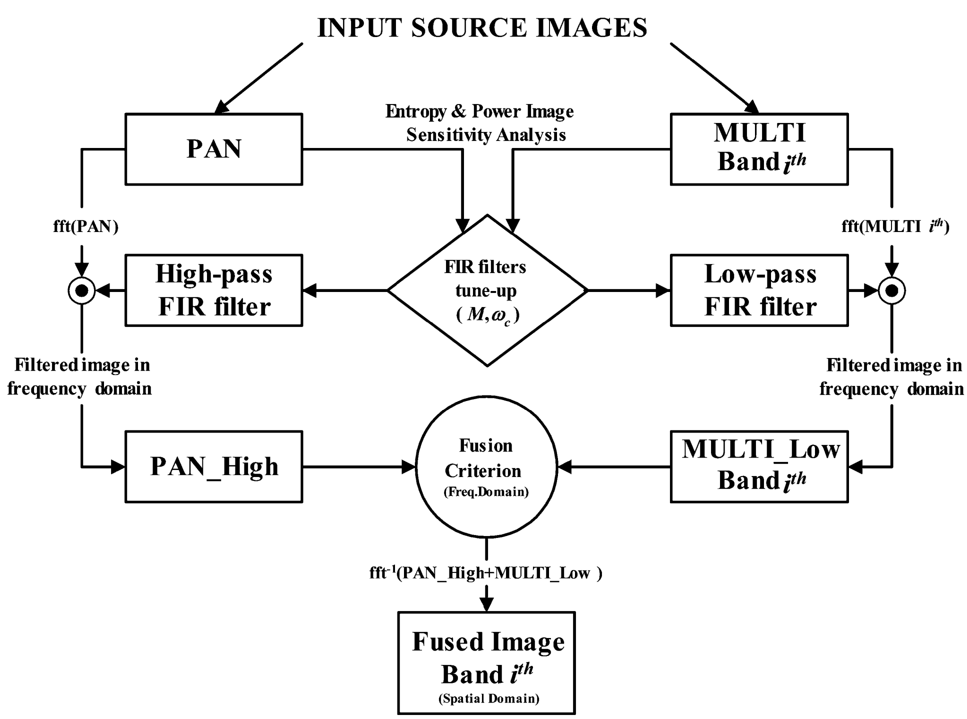


Figure 1. Flow chart of the adaptive fusion methodology defined in the Fourier domain.

3. Determination of M and ω_c

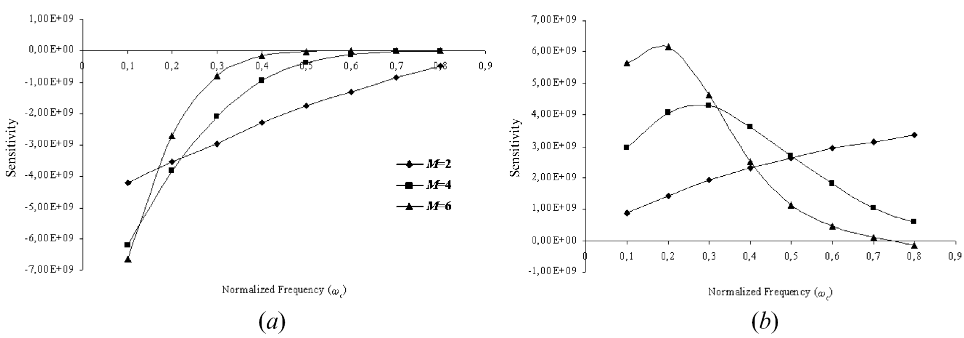
An analysis of the power sensitivity of source images, with respect to the variation of ω_c, has been performed to determine the M parameter value. For that, a different filtered image has been obtained for each pair of values (M, ω_c). M has ranged from 2 to 50 and ω_c from 0 to 1. Different low pass filters are applied to each spectral band of MULTI and high pass filters to PAN. The Image Power (IP) was calculated for each filtered image. From the results, it has been observed that a saturation effect is produced by high values of M. That means the sensitivity of IP decreases as M increases, or in other words, a better IP control can be achieved through the variation of ω_c for low M values. It is not advisable to use values of M higher than 6. To refine the sensitivity analysis, the variation of the IP first derivate with respect to ω_c, for $M=2$, 4 and 6, has been studied (figure 2(*a*) and (*b*)). Independent of the type of filter, the curve corresponding to $M=6$ presents a saturation behaviour in the extremes of the frequency range. Since the curve profiles for $M=2$ and 4 are similar, different experiments for these two values will be presented and discussed in the next section.

The ω_c values determine the amount of information that every source image will bring to the fused image, which can be evaluated by determining the corresponding entropies, according to equation (2) (Price 1987):

$$H = -\sum_{j=0}^{\mathrm{DN}_{\max}} p_j \log_2 p_j \tag{2}$$

where p_j represents the probability of the digital numbers (DN) in the image.

Hypothetically, a fused image that contains the same amount of information from the PAN and MULTI images will result in a new image with optimum features. Based on this idea, the values of ω_c have been calculated imposing this equality criterion. The application of this criterion can be understood as a kind of matching between the PAN image and each one of the spectral bands. The value of ω_c for the high pass filter will determine the amount of information from the PAN image that will contain each spectral band of the fused image, but this amount will always be conditioned to the amount of information provided by the corresponding band. That means a previous matching between the histogram of the PAN image and each of the spectral bands, can modify the values of ω_c, but it does not change the relative amount of information that each source image contributes to the fused image. To



(*a*) (*b*)

Figure 2. Sensitivity analysis for determining (*a*) the high and (*b*) the low pass filter order.

evaluate this, a study about the influence of the image radiometric correction in the determination of ω_c has been carried out.

4. Data and results

The data used for the evaluation of the proposed method correspond to a 4.5 km × 4.5 km scene located around the city of Madrid, Spain. The original images, MULTI and PAN, were collected by the Landsat Enhanced Thematic Mapper Plus sensor (ETM+) on 20 August 1999. The ETM1, ETM2, ETM3, ETM4, ETM5 and ETM7 bands of the ETM+ sensor, with a common 30 m spatial resolution, were fused with the Panchromatic (ETM8) image, with a 15 m spatial resolution, obtaining new multispectral images distinguished by a spatial resolution of 15 m and a spectral resolution of 6 bands. Figure 3(*a*) represents the PAN image and figure 3(*b*) and (*c*) the colour compositions (R=(ETM7+ETM5)/2, G=(ETM4+ETM3)/2 and B=(ETM1+ETM2)/2) of the MULTI and fused image.

Table 1 summarizes the values of ωc determined for each spectral band, for the four different cases established above.

When radiometric correction is applied, the values of ω_c are very similar for all spectral bands. This is due to the fact that the radiometric differences between the PAN and each spectral band have been minimized by the matching process. Without radiometric correction, ω_c takes different values for different bands. The spatial and spectral quality of the fused images, obtained through the filters designed with the parameters of table 1, has been evaluated and compared with one of Mallat's Wavelet algorithm.

The standard ERGAS index (*Erreur Relative Globale Adimensionalle de Synthèse*) has been calculated to quantify the spectral quality of the different fused images (Wald 2000). This index is defined by:

$$\mathrm{ERGAS} = 100\frac{h}{l}\sqrt{\frac{1}{\mathrm{NP}}\sum_{i=1}^{\mathrm{NP}}\left(\frac{\mathrm{RMSE}^2(\mathrm{band}_i)}{\mathrm{MULTI}_i^2}\right)} \tag{3}$$

where h and l represent the spatial resolutions of the source images, PAN and MULTI, respectively; NP is the total number of pixels in the fused image; MULTI_i is the radiance value of the MULTI image for the ith band; and RMSE

(*a*) (*b*) (*c*)

Figure 3. (*a*) PAN image, (*b*) and (*c*) colour compositions ((R=(ETM7+ETM5)/2, G=(ETM4+ETM3)/2 and B=(ETM1+ETM2)/2)) of the MULTI and fused image by the proposed methodology without radiometric correction, for M=2.

Table 1. Values of M and ω_c for designing the FIR filters.

Radiometric correction	M	ETM1	ETM2	ETM3	ETM4	ETM5	ETM7
Yes	4	0.2603	0.2431	0.2675	0.3051	0.2736	0.2601
	2	0.4540	0.4265	0.4565	0.5083	0.4714	0.4469
No	4	02867	0.2410	0.1790	0.2106	0.1383	0.1603
	2	0.4874	0.4204	0.3150	0.3720	0.2443	0.2829

is defined as:

$$\mathrm{RMSE}(\mathrm{band}_i) = \frac{1}{\mathrm{NP}} \sqrt{\sum_{i=1}^{\mathrm{NP}} (\mathrm{MULTI}_i - \mathrm{FUS}_i)^2} \tag{4}$$

Since the ERGAS index only considered the spectral characteristics of the image, a new spatial index, denoted as the spatial ERGAS index, has been defined, introducing a spatial RMSE defined by equation (5):

$$\mathrm{RMSE}(\mathrm{band}_i) = \frac{1}{\mathrm{NP}} \sqrt{\sum_{i=1}^{\mathrm{NP}} (\mathrm{PAN}_i - \mathrm{FUS}_i)^2} \tag{5}$$

where PAN_i represents a matching between the PAN image and the ith band of the MULTI image.

The Wavelet method provides a lower spectral ERGAS value than obtained for the Fourier method (table 2). Nevertheless, the spatial ERGAS index, as well as the average ERGAS is lower for all fused images by the proposed method.

Figure 3(c) displays RGB colour compositions of the fused image with the filters that provide a lower average ERGAS value (3.0696).

5. Conclusions

A new methodology for fusing multispectral images, based on tailored filtering in the Fourier domain, has been proposed. An objective criterion, which depends only on the source image characteristics, has been established for designing the FIR filters. The results showed that the Wavelet method provides a lower spectral ERGAS value than obtained by the Fourier method. Nevertheless, the spatial ERGAS index as well as the average ERGAS value is lower for the proposed method in all considered cases. Moreover, it has been shown that the proposed method establishes a better trade-off between the spectral and spatial quality of the fused images than the Wavelet method and it carries out implicitly the radiometric

Table 2. ERGAS indices.

Fusion method	Radiometric correction	M	Spectral ERGAS	Spatial ERGAS	Average
Wavelet	–	–	1.6761	7.0577	4.3669
Fourier	Yes	4	4.2474	3.9575	4.1024
	Yes	2	2.9201	3.3158	3.1193
	No	4	4.2217	3.7445	3.9831
	No	2	3.0386	3.1007	3.0696

correction required by other fusion methods. Two important consequences are derived from this point. First, the subjectivity of this correction is eliminated and also the computational complexity of the determination of the ω_c values is noticeably reduced, since a unique filtering of the PAN is required.

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