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GAP FILLING METHOD FOR ETM+-OFF IMAGES BASED ON THE *WAVELET* TRANSFORM

Método para Preenchimento de Falhas do Sensor ETM+-off Baseado na Transformada Wavelet

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ABSTRACT

An unexpected and undesired failure of the Scan Line Corrector in the ETM+ instrument on board of Landsat 7 caused gaps. Lost data are difficult, impossible, to restore, because of their uniqueness, which turned these images unusable in some regions of the Earth. Some research was dedicated to partially compensate this problem. The solutions can be single source, when non-gapped pixels are used to derive a new value, or multi-source, when the value is derived from another image, which is supposed to be very similar to the problem image. In this paper, anew multi-source gap filling technique, based *on wavelet* analysis for application to LANDSAT ETM+ imagery, is presented. First, the noisy ETM-off image is filled repeating the previous valid line. Then the wavelet transform is applied systematically to both images, the noisy ETM+-off image and an ancillary highly correlated image. As it happens in some *wavelet*-based fusion approaches, the representation of the ancillary image is substituted by the representation of the noisy image. Then the inverse transform is applied, using the wavelet coefficients that were computed for the noise free image, which produces a hybrid image. In the last step, the gaps of the ETM-off image are replaced by the values of the hybrid image. The method is illustrated with real Landsat data. The results show that the method is valid and able to combine information of the noisy image and the ancillary data.

Keywords: Destriping, ETM+ SLC-off, Image Processing. Gap Filling.

RESUMO

Uma falha inesperada e indesejada do corretor de varredura no instrumento ETM + a bordo do Landsat 7 causou a ocorrência de lacunas nas imagens obtidas por este sensor. Dados perdidos são difíceis, impossíveis, de recuperar, o que transformou estas imagens inutilizáveis em algumas regiões da terra. Algumas pesquisas foram dedicadas para compensar parcialmente este problema. As soluções podem ser usando uma fonte única, quando se usa pixels válidos na imagem para preencher as falhas da mesma; ou usando várias fontes, quando um novo valor é derivado de outra imagem, que é supostamente muito semelhante à imagem com problema. Neste trabalho, é apresentado um novo método baseado em múltiplas fontes para o preenchimento de falhas nas imagens LANDSAT ETM+, com base na análise de *wavelet*. Primeiro, a imagem com falhas é preenchida repetindo a linha anterior válida. Em seguida a transformada *wavelet* é aplicada sistematicamente para ambas as imagens, aquela com falas e uma imagem auxiliar altamente correlacionada com a mesma. Como acontece em algumas abordagens de fusão baseadas em *wavelet*, a representação da imagem auxiliar é substituída pela representação da imagem barulhenta. Então a transformação inversa é aplicada, utilizando os coeficientes *wavelet* que foram computados para a imagem livre de ruído, que produz uma imagem híbrida. Na etapa final, as lacunas da imagem ETM-fora são substituídas pelos valores da imagem híbrido. O método é ilustrado com dados reais do Landsat. Os resultados mostram que o método é válido e capaz de combinar a informação da imagem barulhenta e os dados auxiliares.

Palavras chave: Preenchimento de Falhas, ETM+ SLC-off, Processamento de Imagens, Sensoriamento Remoto.

1. INTRODUCTION

In 2003 NASA reported the failure of the Scan Line Corrector (SLC) in the ETM+ instrument on board of Landsat 7, which has the purpose to compensate for the sensors forward motion in order to produce transversal parallel scans. Without the system, the recorded images show a “zig-zag” pattern that has two problems: the central areas of the image are registered twice and data are lost at the borders of the image. According to Zang et al. (2007) about 22% of the total image is lost. Since then, several researches have been performed aiming at eliminating this problem, although the lack of data can in reality not be fully compensated. The main proposed methods aim at performing a cosmetic image processing step in order to reduce the visual effect of the blanks, more of them using other information source to fill the gaps.

Stripes are an old problem in remote sensing images. For instance Landsat TM L0 images had stripes because individual detectors appear lighter or darker than the others. This is a calibration problem of different relative detector gains and was solved by image processing. The stripes problem can be solved for instance by histogram analysis (HORN & WOODHAM, 1979 or WEGENER, 1990). Missing lines were already visible in some Landsat TM images, but they were not systematic and also small. Methods to fill blanks, caused by missing lines in an image, were proposed using another correlated image of the same sensor obtained at the same time, as described in Chuvieco (1996).

In the case of ETM+ on Landsat 7 the stripes problem is different, because the SLC fault wide stripes of missing data. Because the missing lines occur in all ETM+ bands systematically, image processing solutions were proposed to fill the blanks. A recent comprehensive survey is introduced by Suling et al. (2015) or Jabar et al. (2014). The main approaches are described as single or multi-source approaches.

In the single source approaches, the pixels of the affected image are divided in two sets: with gaps and valid (non-gapped) pixels. The valid pixels are used to derive a statistic that can be used to replace the gaps. For example, the mean value of the valid pixels around a missing pixel can be used to replace its value (CHUVIECO, 1996). Some improvements of this proposal can be found in the literature that consider using a weighted average, interpolation methods as the cubic convolution that is used in image registration or interpolation methods based on the partial derivative (SINGH et al., 2015).

Other approaches compute global statistics from the non-gapped pixels in order to predict the missing digital values.Authors like Zhang et al. (2007), Pringle et al.. (2009) or Zhu et al. (2012) proposed geo-statistical interpolation methods. Here, the variogram of the valid pixels is computed and used to fill the gaps based on the spatial correlation of the pixel values.

The other group of approaches uses a high correlated image to fill the missing pixels. Such methods are therefore called multi-source methods. An ancillary image is used as basis to derive a new value for the missing pixels, for instance a previous Landsat 7 ETM+ with SLC on (STOREY et al., 2005; MAXWELL et al., 2007, BOOLORANI et al., 2008) or even an image of another sensor that has the same spectral characteristics (CHEN et al., 2011). Among them, the method proposed by Storey et al. (2005) is widely used and recommended by NASA and USGS to process ETM+-off data.

Following the principle of USGS/NASA product, Boloorani et al. (2008) proposed what they called the multispectral projection transformation method based on the Principal Component Transform. The basic idea behind this method is to fill gap areas in multispectral images using statistics from another SLC-on image applying the fore- and backward principal component transform. First, the mean, correlation matrix and Eigenvalues needed to perform the Principal Components transform are computed from the SLC-on image. So, the fore- and backward transform matrices are available. Then a new set of statistics is computed for the SLC-off image and the principal components transform is applied to it. In the last step, the former backward transform is applied to the principal components set and the new values are used to replace the missing pixels in the SLC-off image (BOLOORANI et al., 2008b)

In this paper a multi-source method is introduced, which is based on the wavelet transform. In a general manner it resembles the multispectral projection transformation method but the wavelet transform is used instead of the principal components transform. In the following section the proposed method is described.

2. METHOD

The continuous *wavelet* transform of a signal f (x) isgiven by Equation (1).

$$\mathrm{WT(f)} = \frac{1}{\sqrt{\mathrm{a}}}\int \mathrm{f(x)}g_{ab}\mathrm{(x)dx} \tag{1}$$

where is a *wavelet* function with the scale and translation parameters *a* and *b*, respectively, as described in Equation (2)

$$g_{ab}(x) = g\left(\frac{x-b}{a}\right) \tag{2}$$

According to Holschneider (2000), the inverse *wavelet* transform can be computed as:

$$f(x) = \iint h(a,b)g_{ab}(x)dadb \tag{3}$$

The discrete form of the *wavelet* transform is often applied in image processing, for example in the pan-sharpening method described by Luo et al. (2008) or Mitianoudis (2010). The traditional *wavelet*-based image fusion can be performed in two steps. First, it is performed the decomposition on the two input images separately into approximate coefficients and detailed coefficients. In the second step, the high detailed coefficients of the multi-spectral image are replaced by those of the pan image and the inverse transform is applied to the new set. Torres & Infante (2001) proposed a similar approach that consists of the systematic application of the wavelet transform to the noisy image to detect the striping patterns. Then, the coefficients related to the stripes are eliminated at selected levels and finally the image is reconstructed.

In the present study a multi-source method for the elimination of ETM+ SLC-off gaps based on the *wavelet* transform is introduced. For this purpose we use two images: The noisy ETM+ image, referred as NI, and an ancillary image without noise (NF). The second image can be a Landsat ETM-on image or a Landsat 8 image with similar spectral band. It is also assumed that the noisy image and the ancillary image are very similar, which means that the land cover on both images is similar, without great land cover changes. Therefore, it is better if both images are obtained with small time difference or at least they are obtained in the same season of the year.

Figure 1 illustrates the method. Here, NI is the noisy image, NF is the noise-free image, WT stands for the *wavelet* transform and WT^{-1} is the inverse transform. The parameters are stored in the sub-images ch_i (horizontal), cv_i (vertical) and cd_i (diagonal).

In order to achieve a better starting point the null values in the noisy images are filled with a value derived from the neighbourhood, as it happens in the single source approaches. Although there are many options for such interpolations, in a simple case the valid digital value of the previous line is repeated. This first step has the purpose to soften the changes at the borders of the stripes.

Similar to the fusion methods described above, the method continues applying the *wavelet* transform to both images. As proposed by Torres & Infante (2001), the wavelet transform is applied systematically to both images, producing a wavelet representation of the noisy image and the ancillary image.

As it happens in the image fusion approaches, after obtaining the approximation of the image and the corresponding coefficients in different levels with the *wavelet* transform, two approximations of the scene are available. The first one is derived from the noisy image (M_3 in Figure 1) and the second one is computed from the ancillary image (O_3 in Figure 1). As it is assumed that the images are highly correlated, it is reasonable to substitute the representation of the ancillary image by the representation of the noisy image, obtaining a new set of approximation and coefficients. The inverse transform is then applied to the new set, using the wavelet coefficients that were computed for the noise free image. Because the detail is stored in the coefficients, the resulting image inherits the properties of the original image but also the filled lines of the ancillary image.

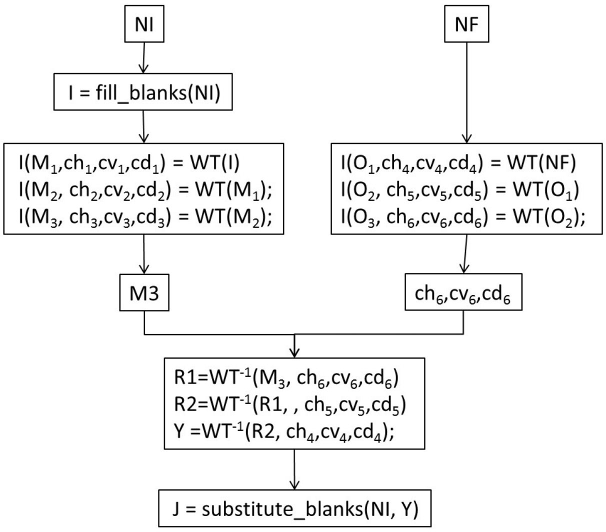

Fig. 1 – Steps of the substitution method. NI is the noisy image. First their blanks are filled with a simple method and then the *wavelet* transform is applied. The ancillary image is also transformed by the wavelet transform. The results are then combined and a hybrid image (Y) is obtained after the inverse transform is applied. In the last step, the blanks are filled with the hybrid image.

In a final step, the missing pixels of the original noisy image are substituted by the corresponding pixels of the hybrid image (Y in Figure 1), filling the gaps.

3. EXPERIMENTS

The method was applied to real Landsat ETM+ images with SLC-off. An example is described in this section. Two images are used in the experiment: A noisy image (Figure 2a) of the Landsat 7 ETM+ and an image without noise of Landsat 8 (Figure 2b), both covering the near infrared spectral band of the spectrum.

The data set covers the Campo Verde – MT municipality in Mato Grosso, Brazil. The Landsat Worldwide Reference System coordinates are path 226, and row 70. The noisy image is the Landsat 7 ETM+-off, band 4, obtained on May, 8th of 2014, while the ancillary image is band 5 of OLI on board of Landsat 8, obtained on Mat, 14th. 2014. A small 512 by 512 part of the image is used to illustrate the experiment.

(a)

(b)

Fig.2 – (a) Noisy image and (b) ancillary Image (enhanced by contrast stretching)

In order to reduce the marked influence of the stripes on the coefficients, in the first step the gaps were filled by substituting the missing pixels by the previous valid line. The result is a rough transformation, as it can be seen in figures 4 and 5. Comparing figures 4b and 4c, or figures 5b and c. the repetition of the previous valid pixel is visible.

This filled image is the start point for the *wavelet* fusion procedure. The *wavelet* transform using the *Daubechies* 1 wavelet was applied to this filled image and a set of coefficients in three different levels were obtained. Figure 3 illustrates the *wavelet* transform of the noisy image after 3 steps. The stripes are visible especially in the first vertical and diagonal coefficients of the resulting image set. The same wavelet transform was also applied to the Landsat 8 image, also in three steps, in order to obtain the corresponding coefficients.

In the final steps the wavelet approximations were combined and the inverse transform applied in the three levels, leading to a hybrid image. The resulting image is produced when the missing pixels of the ETM+ image are substituted by the pixels of the hybrid resulting image.

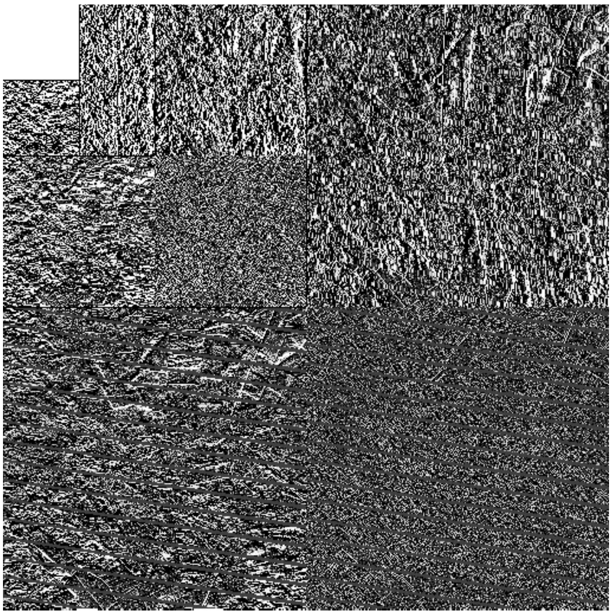

Fig. 3 – Wavelet transform of the noisy image, after gray level contrast stretch.

As the image size is too big to be displayed in detail in this paper, only selected areas are used to illustrate the different steps of the procedure. In figures 4 and 5, four images are displayed. The first one is the ancillary Landsat 8 image (a). The second one (b) is the Landsat 7 ETM+-off image. The third image (c) is the noisy image after filling the gaps with the available data of a previous line. Finally, image (d) shows the resulting image after using the hybrid image to fill the gaps.

The effect of the substitution is visible when comparing figures 4b and 4d. The black line in the centre of the image, a small river, is highly affected by the gaps in image 4b. After the procedure, the line is spatially coherent and the river well defined.

The same analysis can be applied to the results displayed on Figure 5. In this case the image shows more areal features of agriculture. The dark field in the centre of the image, affected by the gaps, was corrected, but two situations are visible. At the left side, the border is continuous, while the right border appears somehow blurred. A possible explanation for this effect is the high contrast between the two neighbouring fields and the use of the *Daubechies* 1 wavelet, which is very hard. The inverse wavelet transform gives a pixelated appearance to the fused image and this effect becomes more evident at borders and especially when the border has strong contrast. When comparing the gaps with the filled areas (figures 5b and 5d), it can be noticed that the gap is filled with new values that trend to form squares. Nevertheless, when spatial detail is present in the ancillary image the transform replaces the missing pixels by new reasonable values.

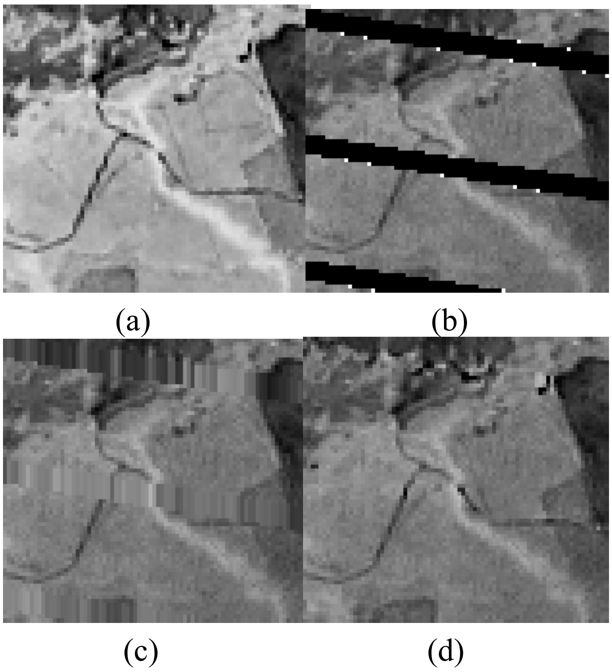

Fig. 4 - Detail of the procedure in the first area: (a) Ancillary image; (b) noisy image; (c) first correction; (d) final image.

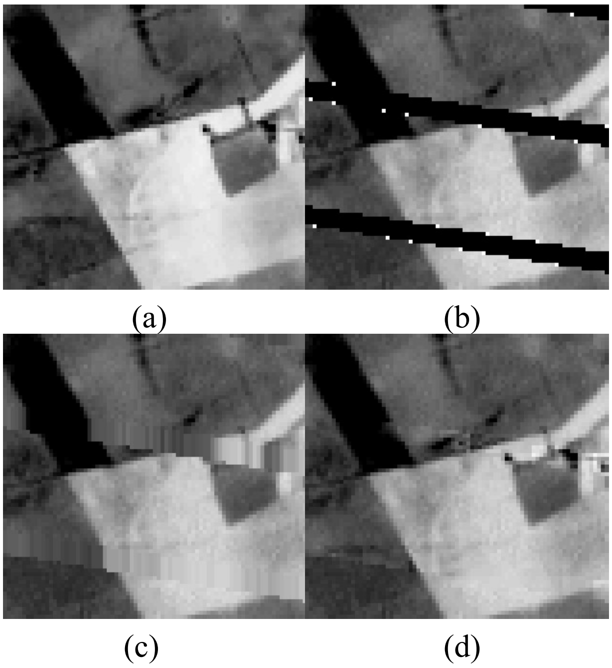

Fig. 5 - Second areain different steps:(a) ancillary image; (b) noisy image; (c) first correction; (d) final image.

CONCLUSIONS

In this paper we introduced a multi-source method for filling the gaps of Landsat ETM+-off images, which is based on the wavelet transform. The experiments prove that it is suitable to produce a better image, with some details that are inherited from the ancillary image. The success of the proposed method depends on the correlation of the ancillary image and the noisy data, as in other multi-source methods.

The method resembles the *wavelet* based fusion approaches and is able to combine information of both data sources: the noisy image and the ancillary data. As the spatial detail is stored in the coefficients of the wavelet transform, applying the fusion procedure enables to recover the spatial features, like lines and borders, from the ancillary data, filling the gaps. The brightness of the image is not affected, because the wavelet representation of the original image is used as starting point of the inverse transform.

As it happens in other gap filling methods, the missing pixels are replaced by a "reasonable" value, but in real terms this is only a cosmetic correction because nothing can replace the real lost value. The use of another image, the multi-source approach, depends on the similarity between the noisy image and the ancillary image. If there are real land use changes on the Earth's surface, the use of the ancillary image becomes risky and is not recommended.

Future research will be dedicated to evaluate the use of other *wavelet* functions and also verify if other sensors, like CBERS, can be used for this purpose.

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