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A simple and effective method for filling gaps in Landsat ETM+ SLC-off images

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ABSTRACT

The scan-line corrector (SLC) of the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor failed in 2003, resulting in about 22% of the pixels per scene not being scanned. The SLC failure has seriously limited the scientific applications of ETM+ data. While there have been a number of methods developed to fill in the data gaps, each method has shortcomings, especially for heterogeneous landscapes. Based on the assumption that the same-class neighboring pixels around the un-scanned pixels have similar spectral characteristics, and that these neighboring and un-scanned pixels exhibit similar patterns of spectral differences between dates, we developed a simple and effective method to interpolate the values of the pixels within the gaps. We refer to this method as the Neighborhood Similar Pixel Interpolator (NSPI). Simulated and actual SLC-off ETM+ images were used to assess the performance of the NSPI. Results indicate that NSPI can restore the value of un-scanned pixels very accurately, and that it works especially well in heterogeneous regions. In addition, it can work well even if there is a relatively long time interval or significant spectral changes between the input and target image. The filled images appear reasonably spatially continuous without obvious striping patterns. Supervised classification using the maximum likelihood algorithm was done on both gap-filled simulated SLC-off data and the original "gap free" data set, and it was found that classification results, including accuracies, were very comparable. This indicates that gap-filled products generated by NSPI will have relevance to the user community for various land cover applications. In addition, the simple principle and high computational efficiency of NSPI will enable processing large volumes of SLC-off ETM+ data.

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1. Introduction

The Landsat series of satellites provides an unparalleled data source for land surface mapping and monitoring (Byrne et al., 1980; Cohen & Goward, 2004; Hansen et al., 2008; Healey et al., 2005; Masek et al., 2008; Vogelmann et al., 2001). The Landsat sensors include the Landsat 5 Thematic Mapper (TM), the Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and the Landsat 1–5 Multispectral Scanners (MSS). The high value of the data from Landsat can be attributed in part to long-term repeat coverage (1972–present) and relatively high spatial resolution (30 m for the TM and the ETM+, and 80 m for the MSS sensors). Both Landsat 5 and Landsat 7 are still functioning, although both have substantially exceeded their planned design lives.

On May 31, 2003, the scan-line corrector (SLC) for the ETM+ sensor on board Landsat 7 failed permanently. The SLC compensates for the forward motion of the satellite, and without an operating SLC, images have wedge-shaped gaps that range from a single pixel in width near the image-nadir, to about 12 pixels towards the edges of the scene. Missing pixels comprise about 22% pixels of these images (Arvidson et al., 2006; Ju & Roy, 2008). The deteriorated image quality resulting from SLC failure has become a major obstacle for Landsat ETM+ data applications. Accordingly, images acquired before the SLC failure are designated SLC-on images, while those acquired after the SLC failure are designated SLC-off images.

Soon after SLC failure, a joint United States Geological Survey/National Aeronautics and Space Administration (USGS/NASA) Landsat team explored a number of different options for filling in the data gaps in the SLC-off images. One method developed was a local linear histogram-matching method using one or more SLC-off or SLC-on images (USGS, 2004). This method applies a local linear histogram matching in a moving window of each missing pixel to derive the re-scaling function. This re-scaling function is then used to convert the radiometric values of one input scene into equivalent radiometric values of the scene being gap-filled, and the transformed data are then used to fill the gaps of that scene. This method is very simple and easy to implement, and can resolve many of the missing-data problems if the input scenes are of high quality (e.g., negligible cloud and snow cover) and represent comparable seasonal conditions (USGS, 2004).

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As an alternative to this method, Roy et al. (2008) proposed to use the information observed by MODIS to estimate reflectance of the un-scanned pixels. Maxwell et al. (2007) developed another approach, whereby multi-scale segmentation was used to fill gaps in the Landsat 7 ETM+ SLC-off images. This approach was applied to three different areas, demonstrating that the filled products were useful for a wide variety of applications, such as general land cover mapping and visual assessment (Bédard et al., 2008). Geostatistics based methods have also been employed (Zhang, et al., 2007; Pringle, et al., 2009), in which kriging or co-kriging techniques have been used to fill the data gaps. The case studies showed that these geostatistical methods can also be very effective for interpolating the missing pixels in the SLC-off imagery.

While the above methods can restore the un-scanned gaps in ETM+ SLC-off imagery, sometimes with very good results, it should be noted that the above methods also suffer from a number of limitations that have precluded their widespread use, especially for quantitative application. For instance, the local linear histogram-matching method can yield satisfactory results in homogenous regions such as forests, but it tends to have difficulty with heterogeneous landscapes where the size of surface objects are smaller than the local moving window size (USGS, 2004). In general, using information from non-Landsat sensors is constrained by spectral compatibility and spatial resolution issues. Few instruments with high spatial resolution are spectrally similar to ETM+; one sensor that has comparable spectral bands is MODIS, but this sensor has much coarser spatial resolution (Roy et al., 2008). The multi-scale segmentation approach has a disadvantage in having lower reflectance prediction accuracy at the pixel level, especially for narrow or small objects, such as roads and streams (Maxwell et al., 2007). The geostatistical interpolation methods also have two major drawbacks. First, these methods do not predict the reflectance well at the pixel-level, and thus are not optimal for small and discrete objects. Secondly, these geostatistical approaches are very computationally intensive, which limit their implementation for mass production (Zhang, et al., 2007; Pringle, et al., 2009).

Based on the shortcomings in the above methods, the aim of this study is to demonstrate the application of a simple and effective method to fill the gaps in SLC-off ETM+ imagery. This new method, which we will refer to hereafter as the Neighborhood Similar Pixel Interpolator (NSPI), has the potential to interpolate the value of pixels located in the gaps accurately, especially improving results in heterogeneous landscape areas. In this paper, we will first describe this approach and the algorithm, and later on we will demonstrate its use and performance on simulated and actual SLC-off images.

2. Algorithm development

It is reasonable to assume that neighboring pixels in close proximity to SLC-off gaps share similar spectral characteristics and temporal patterns of changes with the missing pixels located within the gaps, if they belong to the same land cover type. Thus it is logical to make use of the information of the same-class neighboring pixels to restore spectral reflectance of missing pixels. Here, for convenience in this paper, the SLC-off image that will be filled is defined as the target image, while the other images that are selected to fill the gaps in the target image are referred as the input images. There are two data sources that can be used to fill the gaps in target image: (1) an appropriate TM image or SLC-on ETM+ image, and (2) SLC-off images acquired at different dates, whereby the scanned parts of these images partly overlap with the gaps in the target image. The steps for gap filling implementation for these two data sources will be introduced respectively below. Since the local atmospheric conditions are usually relatively homogenous, pixels within a given neighborhood will normally be under similar atmospheric effects. The NSPI can be applied either (1) to top-of-atmosphere radiance or DN value (if the radiometric calibration formula is the same between input and target images), or (2) to top-of-atmosphere reflectance or reflectance products after the atmospheric correction.

2.1. Using a single TM or SLC-on ETM+ image

A TM image acquired reasonably close to the date of the target image can be used as the input image. Target images that are the most similar to the input images in seasonality and acquired under comparable sun illumination conditions are the best scenes to use. Similarly, an SLC-on ETM+ image can also be used, assuming that there has not been a significant amount of land use and land cover change between data acquisition times. Before implementing the filling process, the input image must be geometrically rectified to match the target image. Fig. 1 presents a flowchart of the gap filling method using a single input image. All steps will be discussed in detail below.

2.1.1. Selection of neighboring similar pixels

Based on the assumption that the same land cover class pixels in close proximity to the gaps have similar spectral characteristics and temporal patterns of change with the target missing pixel, it is necessary to search for similar pixels near the gaps. We assume that no major land cover changes occurred during the period between acquisitions of the input image and target image. Assuming that the time interval between input and target scene acquisitions is short, we think that this assumption will generally be valid. Accordingly, we can select the similar pixels from the input image and assume that these pixels are also spectrally similar with the target missing pixel at the target image. Here, an adaptive moving window searching procedure is employed. As shown in Fig. 2, all common pixels that are located in the moving window but outside the gaps with valid values both in target and input images are selected. When using TM or SLC-on ETM+ images as input images, the gaps only exist in the target image within the window (black part in Fig. 2). Similar pixels are then selected from these common pixels according to spectral similarity. Here the spectral similarity is defined as root mean square deviation (*RMSD*) between each common pixel and the target pixel as Eq. (1). The target pixel is a pixel located in the gaps of the target image without a valid value.

$$RMSD_i = \sqrt{\frac{\sum_{b=1}^{n} \left(L(x_i, y_i, t_1, b) - L(x, y, t_1, b)\right)^2}{n}} \tag{1}$$

$L(x_i, y_i, t_1, b)$ is the value of ith common pixel located in (x_i, y_i) in band b for the input image acquired at t_1, $L(x, y, t_1, b)$ is with same definition but for a target pixel, and n is the number of spectral bands. A large *RMSD* denotes a large spectral difference. Then, a threshold is used to identify similar pixels that have an RMSD values lower than the threshold. The threshold can be determined by the standard deviation of a population of pixels from the input image and the estimated number of land cover classes (Gao et al., 2006). If *RMSD* of the ith common pixel satisfies Eq. (2), the ith common pixel is selected as a similar pixel:

$$RMSD_i \le \left[\sum_{b=1}^{n} \sigma(b) \times 2 / m\right] / n \tag{2}$$

where $\sigma(b)$ is the standard deviation of the whole input image for band b, and m is the number of classes. The estimated number of classes (m) needs to be predefined. This value is an empirical threshold and varies with the complexity of the landscape. It can be estimated by visual interpretation of the input images, or using a prior land cover map. In this experiment we used the value of five for m. Use of a larger number of classes represents a stricter condition for

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