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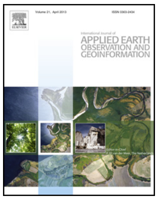

Evaluation of a rule-based compositing technique for Landsat-5 TM and Landsat-7 ETM+ images

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ABSTRACT

Image compositing is a multi-objective optimization process. Its goal is to produce a seamless cloud and artefact-free artificial image. This is achieved by aggregating image observations and by replacing poor and cloudy data with good observations from imagery acquired within the timeframe of interest. This compositing process aims to minimise the visual artefacts which could result from different radiometric properties, caused by atmospheric conditions, phenologic patterns and land cover changes. It has the following requirements: (1) image compositing must be cloud free, which requires the detection of clouds and shadows, and (2) the image composite must be seamless, minimizing artefacts and visible across inter image seams. This study proposes a new rule-based compositing technique (RBC) that combines the strengths of several existing methods. A quantitative and qualitative evaluation is made of the RBC technique by comparing it to the maximum NDVI (MaxNDVI), minimum red (MinRed) and maximum ratio (MaxRatio) compositing techniques. A total of 174 Landsat TM and ETM+ images, covering three study sites and three different timeframes for each site, are used in the evaluation. A new set of quantitative/qualitative evaluation techniques for compositing quality measurement was developed and showed that the RBC technique outperformed all other techniques, with MaxRatio, MaxNDVI, and MinRed techniques in order of performance from best to worst.

1. Introduction

Image compositing is a popular technique used to reduce large datasets of satellite imagery, with often redundant or contaminated observations, into single datasets of uncontaminated and "valid" data (Gutman et al., 1994). The techniques are traditionally applied to low earth orbiting meteorological satellite imagery such as Advanced Very High Radiometer (AVHRR) and Moderate Resolution Imaging Spectro-radiometer (MODIS) (Chuvieco et al., 2005) products and have recently gained popularity in compositing higher resolution Landsat imagery, as the rich archive of historical imagery is of particular value for longitudinal studies and time series analyses (Roy et al., 2010a). The compositing of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) imagery in forest monitoring has recently gained popularity due to a good balance between image acquisition frequency and forest dynamics (Potapov et al., 2011). The use of Landsat ETM+ imagery with the scan line correction failure artefact (Roy et al., 2011b) makes compositing highly desirable. Although there are a number of existing compositing techniques, there is no consensus on what the best techniques are for Landsat TM and ETM+ imagery (Dennison et al., 2007). Many of the existing techniques were developed for other sensors or have specific limitations that reduce the quality of the resulting products.

A common technique for image compositing is to use observations from an image which has the highest Normalised Difference Vegetation Index (NDVI) value of all the images in the stack (Gutman et al., 1994). The assumption is that observations with a higher component of haze or cloud will have a higher response in the red band and thus a lower NDVI value. This compositing method, commonly referred to as Maximum Value Compositing (MVC), is widely used and was initially developed for AVHRR and MODIS data (van Leeuwen et al., 1999). MVC is applied by Roy et al. (2011a,b) for Web-Enabled Landsat Data (WELD), while Roy et al. (2010a) used a combination of MVC, based on NDVI and brightness temperature, to generate Landsat composites after a preliminary cloud and cloud shadow masking. This technique is henceforth referred to as the maximum NDVI compositing or MaxNDVI.

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Although MaxNDVI compositing is known to be ineffective at excluding haze, shadow and bidirectional reflectance distribution function (BRDF) artefacts, it is very useful for the generation of a single band NDVI product as implemented by Maxwell and Sylvester (2012) and Kross et al. (2011) who used it to monitor the greening phenology in the boreal forests of Canada (using AVHRR data). To overcome some of the shortcomings of using maximum NDVI to create multiband composites, (Brems et al., 2000; Maxwell and Sylvester, 2012) used a median value of several spectral observations on imagery corrected to At Surface (AS) reflectance with the MC-FUME method. The main drawback of this method is that it relies on AS reflectance imagery.

Hüttich et al. (2011) used a combination of maximum NDVI and the mean value of several cloud-free observations in their compositing for MODIS time-series data, producing monthly composites for a land cover classification in Namibia. Pouliot et al. (2011) found that a 6–8 day MaxNDVI for AVHRR or Medium Resolution Imaging Spectrometer (MERIS) data is optimal, while 10–14 day averaged composites are suitable for the detection of green-up periods in Canada. Breaker et al. (2010) established an objective basis for finding the correct compositing timeframe, characterised by the phonological response, without losing too much temporal information. They concluded that, when images were taken daily along the coast of California, the best compositing window was 3.2 days. A blending approach that weighs acquisitions according to their quality was used to produce composites.

Luo et al. (2008) developed a technique for generating 250 m resolution, seven band, clear sky composites of MODIS imagery of Canada using sun-satellite relative azimuth angles. This was conducted after a good pre-classification. Unfortunately hemispheric directional specific compositing techniques are not suitable for lower latitudes or for use with the nadir-acquired narrow swath width data produced by Landsat. Hemispheric directional compositing relies on considerable image overlaps and various acquisition angles. However, their comparison of different compositing techniques showed that the maximum ratio compositing technique (MaxRatio) [max(B4,B5)/B1] is a promising alternative to MaxNDVI, mainly because the latter performs poorly over water bodies as it gives preference to cloudy observations in such areas. Their class based compositing has inspired this work.

A computationally-intensive compositing technique developed by Dennison et al. (2007) uses the shape of the signature across the full spectral range of the input imagery to guide decision making about whether to include or reject an observation in a composite. This approach is promising, but its computational requirements limit its application to operational solutions.

All of the methods described above substitutes missing values in a composite and do not adjust the spectral values of valid picture elements, with the exception of the work done by Hüttich et al. (2011) which entailed a hybrid approach of averaging and substitution. Adjustments can produce a result that is visually more appealing, as demonstrated by the GLS 2005 gap-filled ETM+ imagery (Gutman et al., 2008). This approach uses a simple histogram matching of the master image (composite) needing substitution and the slave image to identify apparently invariant features. However, it has been shown that invariant features cannot be identified accurately enough by this technique. An alternative method is to match Landsat imagery to Spot VEGETATION data (Olthof et al., 2005), but the added complexity and instability of such approaches suggest that cosmetic adjustments of spectral values should be avoided, especially when using Landsat 7 ETM+ Scan Line Correction (SLC) OFF data.

Chuvieco et al. (2005) used the maximum values in the thermal band to optimise compositing of MODIS imagery for burnt area mapping. Earlier work on burnt area mapping by Barbosa et al. (1998) used MaxNDVI techniques on AVHRR albedo corrected data. This approach is expected to provide unreliable results for Landsat composites and forestry applications as forests are normally cooler than their surroundings and because the resolution of the thermal bands for both ETM+ (60 m) and TM (120 m) is significantly coarser than that of the multispectral bands (30 m). In addition, the poor relative calibration of the thermal detectors in the TM sensor is expected to introduce noise.

Image compositing techniques generated from wide swath data have to take into account large spectral distortions introduced by BRDF (Hu et al., 2000). Up to ten cloud-free observations, acquired for MODIS and Spot VEGETATION at different angles, are needed to accurately fit a BRDF function to each pixel. These functions are then applied to the observations candidates in the compositing window and often averaged for the composite (Hagolle et al., 2005; Cihlar et al., 2004). These compositing methods cannot be applied to Landsat data due to insufficient angular observations and a relatively low angular variability.

Maximum surface temperature compositing, as described by Liang et al. (2012), is known to produce good results by favouring the warmest observations for a composite. It was not considered in this study for the same reasons mentioned above for not using the method proposed by Chuvieco et al. (2005). With the overall objective of excluding haze, cloud and cloud shadow pixels, the Haze Optimised Transformation (HOT) developed by Zhang et al. (2002) can provide a valuable contribution to the exclusion of such observations from composites. HOT is discussed in more detail in Section 2.3.2.

This paper proposes a new rule-based compositing (RBC) technique that combines several existing pre-processing, pre-classification and compositing methods. The RBC technique is evaluated by a quantitative and qualitative comparison thereof to three existing compositing techniques, namely the maximum NDVI (MaxNDVI), minimum red (MinRed) and maximum ratio (MaxRatio) methods. The techniques are quantitatively and qualitatively compared using 174 Landsat TM and ETM+ images. To assess the transferability and robustness of the techniques for forestry applications, images from three sites and three different timeframes were chosen. The results of the evaluations are discussed in the context of finding an operational solution and recommendations are made for future research opportunities.

2. Materials and methods

2.1. Study areas

To demonstrate the transferability of the developed techniques, three study sites in different regions in South Africa were selected. The selection of test sites was based on the heterogeneity of the landscape and land cover classes and included bright bare areas, strong topographic relief areas, highly vegetated areas (e.g., forestry, sugarcane, dry-land and irrigated cultivation) as well as large urban areas. All three study sites are characterised by seasonal cloud cover and dry periods with smoke contamination from burning biomass which poses major challenges for compositing (Dennison et al., 2007). Each site covers a one degree square area and represents a different climatic zone (Fig. 1). Variations of elevation above sea level within each area were recorded from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). The three sites are defined as:

Site A (2430 Lowveld) extends from 30.5–31.5° E and 24.5–25.5°S and covers a large block of commercial forestry in South Africa. The area has a very distinct sub-tropical climate and summer rainy season, although rainfall is heavily influenced by the orographic effect of the escarpment (elevation in Site A ranges from 283 m to 2255 m above means sea level), which runs from north to