ISPRS Journal of Photogrammetry and Remote Sensing xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Measurement of ground displacement from optical satellite image correlation using the free open-source software MicMac

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ARTICLE INFO

Article history:
Received 28 September 2013
Received in revised form 4 March 2014
Accepted 7 March 2014
Available online xxxx

Keywords:
Satellite image
Ground displacement
Image correlation
COSI-Corr
Medicis
MicMac

ABSTRACT

Image correlation is one of the most efficient techniques to determine horizontal ground displacements due to earthquakes, landslides, ice flows or sand dune migrations. Analyzing these deformations allows a better understanding of the causes and mechanisms of the events. By using sub-pixel correlation on before- and after-event ortho-images obtained from high resolution satellite images it is possible to compute the displacement field with high planimetric resolution. In this paper, we focus on measuring the ground displacements due to seismotectonic events. The three sub-pixel correlators used are: COSI-Corr – developed by Caltech, a free, closed-source correlator, dependent on commercial software (ENVI) and widely used by the geoscience community for measuring ground displacement; Medicis – developed by CNES, also a closed-source correlator capable of measuring this type of deformation; and MicMac – developed by IGN, the free open-source correlator we study and tune for measuring fine ground displacements. We measured horizontal ground deformation using these three correlators on SPOT images in three study cases: the 2001 Kokoxili earthquake, the 2005 dyke intrusion in the Afar depression and the 2008 Yutian earthquake.

1. Introduction

Measuring the fine displacements associated with an earthquake represents a key issue in seismotectonics, offering information about the geometry of the ruptured fault and the energy released by the earthquake (Van Puymbroeck et al., 2000).

The most common method for measuring these displacements is based on field measurements. However, the fault area is often hard to access and complex fault ruptures are not easy to detect in the field; depending on the extent of the fault slip, it can be measured only in a limited number of locations (Leprince et al., 2007a).

Another technique for measuring this type of displacement is by using permanent Global Navigation Satellite System (GNSS) receivers. This technique can only provide sparse coverage and it is impossible to have measurements if the area is not kept under surveillance. As the area of co-seismic ground displacement is *a priori* unknown, it is not always possible to have measurements before the event.

Satellite imagery using synthetic aperture radar (SAR) or optical satellites can overcome some of the limitations of the techniques mentioned before. The satellite images cover a large area – the fault rupture is partially or totally visible.

Compared to the optical sensor, the interferometric SAR technique can be used in all weather and nighttime acquisitions (Massonnet and Feigl, 1998). However this technique is unable to provide displacement maps in the near-field of the fault because the large amplitudes of the displacements present in this area cause the decorrelation of the interferometric phase, so the displacements cannot be estimated. Furthermore, SAR correlation gives low resolution planimetric results, and InSAR provides mainly the near-vertical component.

High-resolution optical satellite imagery provides detailed images of the ground and most importantly, it can resolve the near-fault displacement (Van Puymbroeck et al., 2000). The displacement field can be measured using the correlation of images acquired before and after the event (therefore the temporal baseline is one of the main issues of the correlation).

Optical satellite imagery has extended archives which allows measurements of old earthquakes and could also provide the before-event images when an earthquake occurs. Unlike with InSAR

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http://dx.doi.org/10.1016/j.isprsjprs.2014.03.002
0924-2716/

data, the combination of different archives is possible (Hollingsworth et al., 2012) and is a major advantage of using optical satellite images.

Numerous studies on sub-pixel correlation applied to high-resolution satellite images such as SPOT have shown the efficiency of this technique for measuring ground displacements due to earthquakes (Michel and Avouac, 2002; Dominguez et al., 2003; Binet and Bollinger, 2005; Klinger et al., 2006; Leprince et al., 2007b), landslides (Delacourt et al., 2004; Casson et al., 2005), ice flows (Scambos et al., 1992) and sand dune migrations (Hermas et al., 2012). Analyzing these deformations allows a better understanding of what triggered the event (e.g. analyzing the faults and the displacement field caused by an earthquake can supply extremely important information about the seismic mechanisms).

Sub-pixel detection capability is required in order to measure the displacements which are generally smaller than the image pixel size. In theory, the sub-pixel correlation method using a pair of SPOT panchromatic images could provide fault slip measurements with an accuracy of 0.1 px (Michel and Avouac, 2002; Dominguez et al., 2003). Therefore, using images with a ground pixel size of 2.5–10 m, the smallest displacements that may be measured are 0.25–1 m. However, the sub-pixel detection is highly dependent on the quality and the noise level of the data. Important matters to take into account when doing correlation are the texture of the images and factors causing great changes in aspect between the two images due to diachronism (the period of time between the two image acquisitions). Seasonal variations could generate changes in the landscape, which might cause decorrelation. In order to avoid parallax problems due to digital elevation model imprecision, it is preferable to use satellite images acquired with very similar incidence angles, close to nadir.

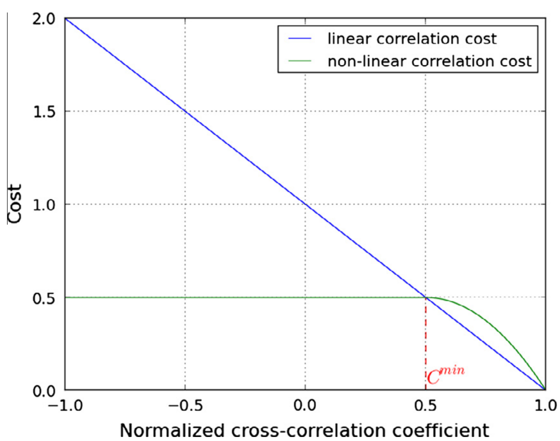

Fig. 1. Linear and non-linear correlation cost in MicMac. By default the correlation cost is linear ($Cost = 1 - Cor$, where Cor is the normalized cross-correlation coefficient). When dealing with images with great inhomogeneity, a non-linear cost is used in order to limit the impact of the noisy signal on the whole measurement: $Cost = \left(1 - \left(\frac{Max(Cor, C^{min}) - C^{min}}{1 - C^{min}}\right)^{\gamma}\right) * (1 - C^{min})$, where C^{min} is the correlation threshold (below this value, the correlation has no influence) and γ determines the influence of the correlation scores (in our studies, $C^{min} = 0.5,\ \gamma = 2$).

The purpose of this article is to present free open-source software, MicMac, capable of measuring the two-dimensional displacements by optical image correlation and free from most of the drawbacks of the correlators used up until now (e.g. not open-source and hence not easily adaptable to specific cases, lack of robustness in cases where the time interval between the two image acquisitions is very significant or dependent on commercial softwares). In this paper we present the sub-pixel correlation results obtained with MicMac, compared with those obtained using two other correlators, COSI-Corr and Medicis, both of which are used by the geoscience community. The horizontal displacements induced by seismotectonic events were measured using pre-event and post-event SPOT ortho-images. The three study cases are the Kokoxili earthquake ($M_w \sim 7.8$, November 2001, Tibetan Plateau), the September 2005 rifting event of Afar (Ethiopia) and the Yutian earthquake ($M_w \sim 7.1$, March 2008, Tibetan Plateau).

2. Methodology

2.1. Image correlation

The basic parameters of the correlation are the "sliding window", the "search space" (the correlator computes a correlation score for every position given by the "discretization step" in the search space and keeps the best one; the discretization step defines the sub-pixel precision of the correlation results) and the "step" (distance in pixels between two consecutive parallax estimations, defining the correlation image size). The spatial resolution of the displacement is directly related to the size of the correlation window. The use of a small correlation window implies a result with a higher spatial resolution, which is extremely important if a fine description of the near-fault area is desired. However, the noise

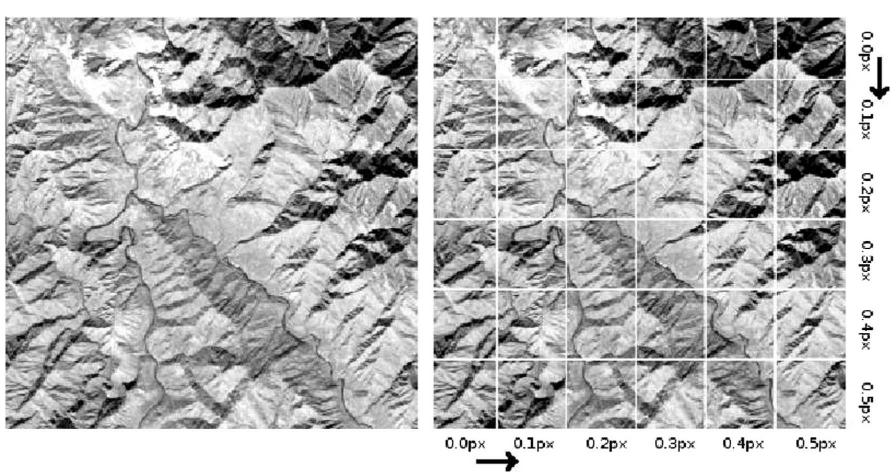

Fig. 2. Synthetic displacement field to retrieve by correlation: the slave image was created using the reference image, a QuickBird satellite image, by dividing it into blocks and moving them along columns and lines, creating successive offsets of 0.1 px per block. The synthetic offsets values go from 0 px to 0.5 px. The correlation results obtained using COSI-Corr, Medicis and MicMac are in Figs. 3 and 4.