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Correlation of satellite image time-series for the detection and monitoring of slow-moving landslides

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ABSTRACT

Slow-moving landslides are widespread in many landscapes with significant impacts on the topographic relief, sediment transfer and human settlements. Their area-wide mapping and monitoring in mountainous terrain, however, is still challenging. The growing archives of optical remote sensing images offer great potential for the operational detection and monitoring of surface motion in such areas. This study proposes a multiple pairwise image correlation (MPIC) technique to obtain a series of redundant horizontal displacement fields, and different multi-temporal indicators for a more accurate detection and quantification of surface displacement. The technique is developed and tested on a series of monoscopic and stereoscopic Pléiades satellite images at a test site in the South French Alps. Empirical tests confirm that MPIC significantly increased detection accuracy ($F-measure = 0.85$) and that the measurement error can be reduced by averaging velocities from all pair combinations covering a given time-step (i.e. when stereo-pairs are available for at least one date). The derived inventory and displacement fields of 169 slow-moving landslides show a positive relationship between the landslide size and velocities, as well as a seasonal acceleration of the largest landslides in response to an increase in effective precipitation. The processing technique can be adapted to better exploit increasingly available time-series from a variety of optical satellites for the detection and monitoring of landslide displacement.

1. Introduction

Landslides constitute a major natural hazard and a dominant geomorphic agent in many mountainous landscapes with diverse impacts on topographic relief, sediment transport and human settlements. Rapid slope failures triggered by earthquakes and rain storms account for the vast majority of related casualties (Petley, 2012) but also continuously active, slow-moving landslides are a widespread phenomenon causing severe damages to infrastructure and alterations of the sediment budget (Mackey and Roering, 2011; Mansour et al., 2011). Landslide inventory maps are, therefore, fundamental for the quantification of sediment budgets and natural hazards but their elaboration through field work and visual image interpretation often remains a tedious task (Guzzetti et al., 2012).

Consequently, considerable research efforts have already been dedicated to the development of more automated remote sensing techniques for landslide inventory mapping. Studies on the analysis of optical satellite data, focus predominantly on the mapping of rapid landslides which typically lead to a removal of the vegetation cover in post-failure state (e.g. Behling et al., 2016, 2014; Joyce et al., 2009; Kurtz et al., 2014; Li et al., 2016; Lu et al., 2011; Martha et al., 2010, 2012; Mondini et al., 2011; Stumpf and Kerle, 2011; Stumpf et al., 2014a). For the detection and monitoring of very slow and extremely slow landslides (Cruden and Varnes, 1996), in contrast, Interferometric Synthetic Aperture Radar (InSAR) has proven to be particularly suitable (e.g. Handwerger et al., 2013; Lauknes et al., 2010; Zhao et al., 2012). The use of InSAR is typically limited to landslides slower than $1.0\ \mathrm{m \cdot yr^{-1}}$, on slopes without dense vegetation cover, with favorable slope exposition, and with significant displacement along the line-of-sight of the satellite (Wasowski and Bovenga, 2014). The detection and frequent monitoring of slow-moving landslides with such techniques remains challenging (Schlögel et al., 2015a).

Template-based matching of optical remote sensing images is used frequently to measure surface displacement related to geomorphological and tectonic processes at sub-pixel precision (Leprince et al., 2008; Stumpf et al., 2016, and references therein). Despite the sub-pixel precision of available image correlation algorithms (e.g. Debella-Gilo and Kääb, 2011; Leprince et al., 2007; Rosu et al., 2015),

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a number of potential error sources still often lead to false detections or biased measurements. Limitations can arise from imperfect sensor models, co-registration and orthorectification residuals linked to the DSM (Digital Surface Model) errors, but also from the study site characteristics such as the presence of a dense vegetation cover, cast shadows, low contrast areas or apparent movement caused by specular reflectance features and strong soil surface state changes (Stumpf et al., 2014b). Such factors often impact the accuracy of the calculated displacement fields and impose the need for careful post-processing to correct for geometric errors, outliers and noise.

Proposed techniques for the correction of geometric errors include for example destriping to correct for orbital and sensor errors (Leprince et al., 2007), and the modeling of systematic DSM errors (Scherler et al., 2008). Calibration techniques used for the latest generation of optical satellites can compensate for sensor misalignments and orbital jitter (Lebegue et al., 2012). However, non-systematic DSM errors and decorrelation due to changes in the surface aspect remain critical issues, especially for the orthorectification of very-high spatial resolution (VHSR) images acquired at variable incidence angles. Post-processing thus frequently includes masking based on the correlation coefficient (Berthier et al., 2005) or signal-noise-ratio (Scherler et al., 2008), and the application of low-pass denoising filters to filter out false matches (Heid and Kääb, 2012; Stumpf et al., 2014b). For gravitational processes such as landslides and glaciers, filters related to the direction and maximum velocity of the motion have also proven useful to remove outliers (Kääb, 2005; Scherler et al., 2008; Stumpf et al., 2014b). For surfaces with dense vegetation cover such filters can be complemented by vegetation masks obtained from multi-spectral images (Stumpf et al., 2014b) which, however, incur the possibility of not detecting surface motion in vegetated areas.

The constantly growing archives of optical remote sensing images (e.g. Landsat, SPOT-Satellite Pour l'Observation de la Terre, ALOS-Advanced Land Observation Satellite, Sentinel-2) bear a great potential to study seasonal and long-term patterns of surface motion with image correlation techniques. Given the above-mentioned limitations, however, image correlation is currently mainly suitable for the quantification of surface displacements which are coherent over large areas (e.g. coseismic slip), localized in flat terrain (e.g. dune migration) or in areas with little vegetation cover (e.g. alpine glaciers). While SAR interferometry time-series processing methods have been developed for two decades to better deal with coherence loss and atmospheric noise (Hooper et al., 2012), the fusion of time series from optical data has only recently been demonstrated to improve the coverage and accuracy of glacier flow estimates over large areas (Dehecq et al., 2015; Fahnestock et al., 2015; Rosenau et al., 2015). Applications to landslides have focused mainly on the investigation of known active landslides (Casson et al., 2005; Delacourt et al., 2004; Leprince et al., 2008; Stumpf et al., 2014b; Yamaguchi et al., 2003). Lacroix et al. (2015) demonstrated the potential of optical image correlation for the detection and quantification of landslide activations due to seismic shaking, whereas comprehensive automatic methods for the analysis of optical Satellite Image Time Series (SITS) are, to the best of our knowledge, still lacking. The usefulness of image correlation as a reliable tool for the detection and monitoring of slow-moving landslides, which can remain inactive for several years or develop on previously stable slopes, remains limited by numerous false detections.

To fill this gap, the objective of this work is to propose and test several approaches for the exploitation of optical SITS in order to improve the measurement accuracy and reduce false detections. They are based on the hypothesis that landslides feature a displacement which is more coherent in space and time than residuals resulting from imperfect co-registration, orthorectification and false matches. The technique takes advantage of multiple-pairwise image matching (MPIC) to increase the redundancy of the measurements and exploits the resulting stack of displacement fields to quantify the displacement coherence over time. The effectiveness of several multi-temporal indicators and the accuracy of the resulting velocity fields is assessed in the Ubaye valley (South French Alps) with a multi-temporal dataset of Pléiades satellite images.

The paper is structured as follows. Section 2 introduces a multiple-pairwise image correlation scheme and the techniques to jointly analyze the resulting stack of velocity fields. The section also describes the study site along with the analyzed datasets, and the experimental protocol for assessing the sensitivity and accuracy of the proposed processing techniques. Section 3 presents the results of the sensitivity analysis, provides a discussion of the accuracy and limitations of the best performing technique, and gives an interpretation of relationships between landslide kinematics and variations of the seasonal precipitation. Finally conclusions are drawn in Section 4.

2. Methods and data

2.1. Multiple-pairwise image correlation

The processing strategy (Fig. 1) is based on the image correlation algorithm implemented in the MicMac open-source library (Pierrot-Deseilligny et al., 2015; Rosu et al., 2015). It enables parallel processing and is employed for batch-processing on High-Performance Computing (HPC) infrastructure. The algorithm follows a hierarchical matching scheme using normalized cross-correlation (NCC) with a non-linear cost function and spatial regularization to eliminate outliers. Sub-pixel resolution is achieved through step-wise interpolation of the input images which is computationally expensive but also more precise than interpolation of the correlation surface or peak-fitting methods (Debella-Gilo and Kääb, 2011). NCC-based correlation is better adapted for the use of smaller matching windows targeting small landscape features (Heid and Kääb, 2012). The proposed analysis technique, however, does not depend on a particular correlation algorithm and can be easily extended using other image correlation algorithms (e.g. Heid and Kääb, 2012; Leprince et al., 2007) for pairwise matching. The MicMac correlator has a number of parameters which can be adapted to the particular application. This comprises the size of the template window ω and the sub-pixel resolution as a parameter to negotiate between sub-pixel precision and computational runtime. The matching cost function is evaluated from the normalized cross-correlation coefficient taking into account only correlation coefficients $C \geq C_{\min}$. The exponent γ can be used to increase the relative influence of high correlation values (Rosu et al., 2015). The most likely match for each pixel is determined considering the cost-function at the pixel and the gradient to the displacement of neighboring pixels along a defined number of scan directions n_{dir}. The influence of the gradient can be adapted with a regularization parameter *reg* and enforces a spatial smoothness on the displacement field which allows to reduce noise and outliers. The settings used in this study are summarized in Table 1. For ω, n_{dir}, *reg* the default values of the implementation were used. The threshold parameter $C_{\min}$ was set to 0.3 to account for typically stronger surface changes of landslides with respect to the default value of 0.5 targeting in particular measurements of co-seismic slip (Rosu et al., 2015). The sub-pixel resolution was decreased from its default of 0.05 pixel to 0.1 pixel to reduce the computational costs.

Given a sequence of orthorectified and co-registered monoscopic images and stereo-pairs acquired at n different dates over the same area, a possible strategy is the correlation among only the multi-temporal pairs with the smallest spatial baselines to minimize the differences in incidence angles and the influence of DSM errors. This leads to a sequence of $m = n - 1$ measurements or $m = \sum_{i=1}^{t}(n - i)$ if the matching is not only performed sequentially but over a range of t subsequent dates. If the sequence includes multiple images per date, (e.g. stereo-pairs) each date can be denoted as a tuple of the