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A simultaneous inversion for deformation rates and topographic errors of DInSAR data utilizing linear least square inversion technique ☆

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ABSTRACT

We demonstrate here a computer code for calculation of time series and also mean and linear deformation rates from a set of coregistered unwrapped differential interferograms using a linear least-squares inversion technique based on the small baseline subset (SBAS) algorithm. The computer code is written in C and uses a singular value decomposition (SVD) routine from the LAPACK library and the fast Fourier transform for spatial filtering from the FFTW library. Various offset estimation and topographic correction algorithms are implemented, including simultaneous inversion for deformation rates and residual topographic error. This approach is particularly useful when applied to ALOS PALSAR interferograms that are coherent even at large perpendicular baselines and acquired with orbital parameters correlated with the time of acquisition. This methodology is applied to produce time series of ground deformation at Tauhara and Wairakei geothermal fields (Taupo Volcanic Zone, North Island, New Zealand) from 12 ALOS PALSAR images acquired between July 2007 and December 2009. We also present here a high-resolution deformation map of the ground subsidence caused by the extraction of geothermal groundwater for power generation, with maximum rates of subsidence of about 7 cm/y.

1. Introduction

Differential synthetic aperture radar interferometry (DInSAR) (Massonnet and Feigl, 1998; Rosen et al., 2000) is a tool for measuring ground deformation over a large area with subcentimeter accuracy and high spatial resolution. It has been successfully used for mapping seismic (Burgmann et al., 2000; Fialko, 2006) and volcanic (Kwoun et al., 2006; Fernandez et al., 2005) deformation, anthropogenic deformation caused by mining, and oil/gas and groundwater extraction (Schmidt and Burgmann, 2003; Hole et al., 2007; Gourmelen et al., 2007) and more recently for monitoring of deformation associated with carbon sequestration and melting of permafrost (Short et al., 2009; Rabus et al., 2009). A differential interferogram is calculated from two synthetic aperture radar (SAR) images acquired by the same or similar satellites at two different times using the following processing steps: image co-registration, interferogram formation, removal of earth curvature and topographic phases, filtering, and phase unwrapping. The result of the DInSAR processing is a high-resolution map of the line-of-sight deformation that has occurred between the two SAR acquisitions. A complete three-dimensional deformation field can be reconstructed from DInSAR either by using data sets acquired in different orbital geometries or by using other geodetic data, such as GPS (e.g., Samsonov and Tiampo, 2006; Samsonov et al., 2007, 2008).

The accuracy of DInSAR measurements depends on a variety of parameters including acquisition geometry (e.g., perpendicular baseline), time span between two acquisitions (temporal baseline), satellite wavelength, land cover, and atmospheric conditions. Coherence, which is the magnitude of cross correlation between two SAR images, is used to describe the quality of the interferogram. Coherence decreases with the increase of spatial and temporal baselines and also depends on the type of land cover and satellite wavelength. Volume scattering in densely vegetated areas significantly decreases coherence, often below the level at which a DInSAR image can be reconstructed (e.g., unwrapped). The loss of coherence due to vegetation is the most significant for short-wavelength sensors (X- and C-band). However, their ability to map slow deformation over a short period of time is higher than that of long-wavelength sensors (L-band).

Atmospheric noise does not decrease coherence of the interferogram; however, it may produce signals of similar magnitude

☆ Code available from server at: http://www.insar.ca/ccount/click.php?id=4.

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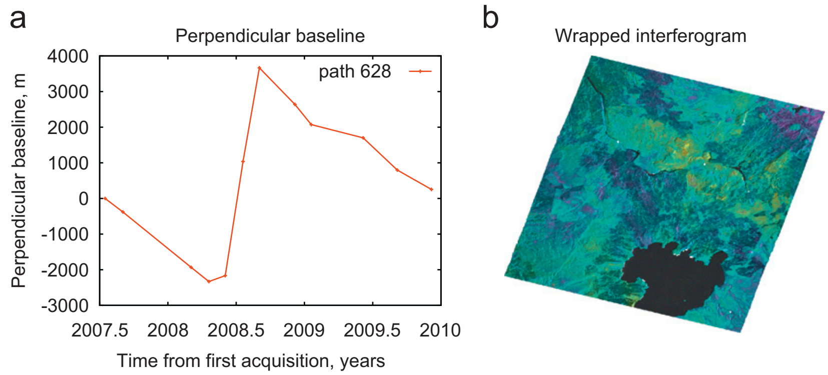

Fig. 1. Temporal variation of perpendicular baseline for ALOS PALSAR path 628 over New Zealand (a) and wrapped geocoded differential interferogram calculated from ALOS PALSAR images (path 628 frame 4400, HH polarization) acquired on 15 July 2007 and 30 August 2007, $B_{\perp}=-380$ m (b).

and shape that cannot be distinguished from a true deformation signal in a single interferogram. Various techniques based on the redundancy principle (i.e., for overdetermined systems) have been developed to minimize the atmospheric contribution (Sandwell and Price, 1998; Ferretti et al., 2001; Berardino et al., 2002; Hooper et al., 2007; Hooper, 2008). For example, the stacking technique (Sandwell and Price, 1998) is used to calculate mean deformation rates and to achieve higher accuracy of measurements by averaging the atmospheric noise, which often can be considered random in time and space. This approach may not be very accurate in mountainous regions affected by particular weather patterns. It also is not able to capture the temporal pattern of deformation. Another approach is a linear least-squares inversion technique known as the small baseline subset or SBAS method (Berardino et al., 2002; Lanari et al., 2004a). This methodology selects interferograms with small spatial and temporal baselines, solves for deformation rates between subsequent SAR acquisitions, and then reconstructs cumulative displacements by integration. The advantage of this approach is that it can produce nonlinear time series of deformation over a long period of time using interferograms with short time spans, which are usually more coherent.

The residual topographic noise in interferograms is caused by inaccuracies or lack of resolution in the digital elevation model (DEM) used to remove the topographic phase during the differential processing. In most cases the residual topographic noise can be considered random in time because it depends on the perpendicular baseline, which usually varies randomly, and therefore can be successfully reduced during stacking or SBAS processing. However, in our previous work (Samsonov, 2010), we showed that in the case of the L-band ALOS PALSAR (Rosenqvist et al., 2007), the standard SBAS processing is less accurate because of significant residual topographic noise. This happens because the L-band ALOS PALSAR interferograms with large perpendicular baselines are coherent (e.g., Fig. 1b) and, therefore, can be used in SBAS processing and also because ALOS orbital parameters are not random in time (Fig. 1a). In Samsonov (2010) we proposed various topographic corrections that can be used to remove residual topographic noise in the case of strong and moderate correlation between time of acquisition and perpendicular baseline.

In this paper we describe our software code that implements the SBAS algorithm with various topographic corrections and can be used for everyday processing of DInSAR data, including, X-, C-, and L-band data. It is implemented in C language using an inversion routine from the LAPACK library[1] and the fast Fourier transform for spatial filtering from the FFTW library.[2] It can be run in both Windows and Linux environments. Various practical aspects of code implementation are described in this paper (e.g., offset estimation, filtering, and topographic correction), followed by an example where we reconstruct time series and also mean and linear deformation rates for the Tauhara and Wairakei geothermal fields, located in the central part of the Taupo Volcanic Zone (TVZ) in the North Island of New Zealand.

2. Methodology

The software code that we present here calculates deformation rates, reconstructs cumulative displacements (time series), and calculates mean and linear deformation rates. The input consists of a set of coregistered and unwrapped differential interferograms in binary 4-byte float format (little- and big-endian formats are supported). It is assumed that differential interferograms are successfully unwrapped, orbital ramps are successfully corrected, and regions with coherence below the chosen threshold are set to zero.

It is assumed that each k interferogram ϕ^k_{obs} consists of deformation ϕ^k_{def}, residual topographic ϕ^k_{topo}, and atmospheric ϕ^k_{atm} components:

$$\phi^k_{obs}=\phi^k_{def}+\phi^k_{topo}+\phi^k_{atm}, \tag{1}$$

and our goal is to estimate and remove the residual topographic ϕ^k_{topo} and atmospheric ϕ^k_{atm} components in order to achieve better accuracy in calculation of ground deformation ϕ^k_{def}. It is also assumed that the atmospheric term ϕ^k_{atm} contains all other sources of random noise (e.g., thermal noise). The flow chart diagram of the software presented here is shown in Fig. 2 and discussed in detail below.

2.1. High-pass filtering in the spatial domain

The optional high-pass filtering in a spatial domain allows for the removal of residual orbital ramp and other long-wavelength noise from interferograms. This high-pass filtering is performed in a spatial domain for each interferogram independently. For this, the fast Fourier transform using the FFTW library is calculated and high-pass filtering is applied using a Gaussian window (e.g., Gonzalez and Woods, 2001). The threshold frequency for

[1] http://www.netlib.org/lapack.

[2] http://www.fftw.org.