ESTIMATION OF EARTH DEFORMATION CAUSED BY THE NUCLEAR TEST PERFORMED IN NORTH KOREA

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ABSTRACT

This study aims at estimating the Earth deformations due to the nuclear test carried out by North Korea on the 3rd of September 2017 by processing a time series of synthetic aperture radar images acquired by the COSMO-SkyMed satellite constellation. For active satellite sensors working in the X-band, phase information can be unreliable if scenarios with dense vegetation are observed. This uncertainty makes difficult to correctly estimate both the interferometric fringes and the information phase delay generated by the variation in the space-time domain of the atmospheric parameters. To this end, in our research we apply the Sub-Pixel Offset Tracking technique, so that the displacement information is extrapolated during the coregistration process. The results reveal an accurate estimate of the spatial displacement of similar pixels due to the nuclear explosion. The work also reveals a hypothetical underground tunnel network.

Index Terms— Displacement-field, Nuclear tests, Persistent Scatterers Interferometry, SAR Interferometry, Synthetic Aperture Radar, Sub-pixel correlation, Sub-Pixel Offset Tracking.

1. INTRODUCTION

On the 3rd of September 2017, the Democratic People’s Republic of Korea (DPRK), or North Korea, announced the successful test of a thermonuclear device. Different seismological agencies reported body wave magnitudes of well above 6.0, consequently estimating the explosive yields a quantity of the order of hundreds of kilotons. Earthquakes induced by underground nuclear explosions, given the enormous amount of energy emitted, can produce possibly considerable ground displacements that, hence, can be estimated using satellite synthetic aperture radar (SAR) data.

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The most-widley used technique for displacement estimation is based on the persistent scatterers interferometry SAR (PS-InSAR) [1]. Unfortunately, this method has some limitations, such as the need of many interferometric images to obtain a reliable atmospheric phase screen and it cannot be applied to areas completely covered by vegetation.

A different approach exploits Differential InSAR (DInSAR) inversion strategy assisted by Small BAseline Subset (SBAS) [2]. Results demonstrate the effectiveness of the proposed technique to retrieve the full 4-D displacement field associated with active rifting affected by very large-magnitude deformation, but in [3] it has been shown that SBAS method had also limited benefits.

Sub-Pixel Offset Tracking (SPOT) is a promising alternative method for Earth displacement estimation. This technique has previously been applied to different scenarios overcoming technical defects and limitations of conventional DInSAR techniques [4].

In this paper, we apply the SPOT technique for estimating the Earth displacement caused by the underground nuclear explosion occurred on the 3rd of September 2017 in North Korea. A temporal series of interferometric SAR images, acquired from the COSMO-SkyMed (CSK) satellite constellation are processed. Experimental results confirm the presence of a large area with strong displacement and demonstrate the effectiveness of the method in estimating the location where the explosions began.

The outline of this paper is the following. In Section 2 we provide a description of the nuclear test site. In Section 3 we explain the applied methodology to estimate the Earth displacement and in Section 4 we discuss the experimental results.

2. THE PUNGGYE-RI NUCLEAR TEST SITE

North Korea established its only known underground nuclear test site 17 kilometers north of the village of Punggye-ri, at the foot of Mt. Mantap in North Hamgyong Province. Between

October 2006 and September 2017, six declared underground tunnel-emplaced nuclear explosive tests have been conducted from this site. All of these events generated seismic waves that were recorded at regional and teleseismic distances and all took place within a few km of each other at the Punggye-ri nuclear facility, which is visible on the Google Earth platform at 41.279°N, 129.087°E. The Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and the United States Geological Survey (USGS) have reported a systematic increase in the body wave magnitude from 4.3 to 6.3 for these events [5]. After the last nuclear test, in September 2017, a series of aftershocks hit the site, which seismologists believe collapsed part of the mountain's interior. Table 1 provides more information about the six nuclear events [6].

Since the 2006 nuclear test, numerous satellite images have revealed on-going construction, excavation, and movement at the facility prior to testing [7, 8]. Based on satellite imagery and according to a multitude of recent news reports [9], it has become clear that North Korea has probably modelled their nuclear test tunnels after old designs proven by the US, France and Pakistan [10]. The designs shall include "zig-zag" tunnels terminating in the shape of "fish-hooks" to encourage the self-sealing of molten rock due to detonation. An expected configuration of the tunnel network forming Punggye-ri nuclear test site is depicted in Figure 1.

3. METHODOLOGY

The total displacement of the sub-pixel normalized cross-correlation, is described by the chirp-Doppler complex quantity $\mathbf{D}^{(i,j)}$ [11, 12], for the (i,j)th interferometric pair. More precisely, considering a temporal series of N interferometric pairs, the total offset can be expressed as:

$$\mathbf{D}^{(i,j)} = \mathbf{D}_{\text{disp}}^{(i,j)} + \mathbf{D}_{\text{topo}}^{(i,j)} + \mathbf{D}_{\text{orb}}^{(i,j)} + \mathbf{D}_{\text{cont}}^{(i,j)} + \\ + \mathbf{D}_{\text{atm}}^{(i,j)} + \mathbf{D}_{\text{noise}}^{(i,j)} \quad \text{for} \quad (i,j) = 1, \dots, N, \tag{1}$$

where:

- $\mathbf{D}_{\text{disp}}^{(i,j)}$ is the quantity of interest to be estimated and indicates the possible spatial displacement;

Table 1. Identification, dates and estimated locations of the six nuclear tests performed in North Korea.

Event	Date	Estimate coordinate
DPRK 1	9/10/2006	41.294° N, 129.094° E
DPRK 2	25/05/2009	41.303° N, 129.037° E
DPRK 3	12/02/2013	41.299° N, 129.004° E
DPRK 4	6/01/2016	41.300° N, 129.047° E
DPRK 5	9/09/2016	41.287° N, 129.078° E
DPRK 6	3/09/2017	41.343° N, 129.036° E

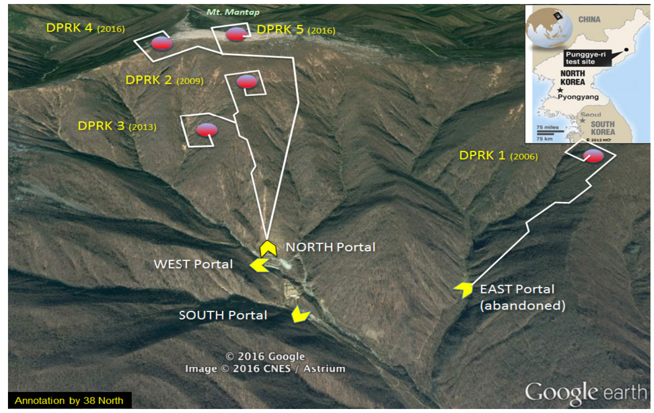

Fig. 1. Google Earth image of the Punggye-ri nuclear test site looking down from south-southeast of Mount Mantap. Numbers mark the estimated locations of the six nuclear tests vis-à-vis tunnel portals with conjectured tunnel projections.

- $\mathbf{D}_{\text{topo}}^{(i,j)}$ represents the residual topography induced phase due to a non perfect knowledge of the actual height profile;
- $\mathbf{D}_{\text{orb}}^{(i,j)}$ accounts residual errors in satellite orbit information;
- $\mathbf{D}_{\text{cont}}^{(i,j)}$ accounts attitude and control errors of the flying satellite trajectory;
- $\mathbf{D}_{\text{atm}}^{(i,j)}$ denotes the phase components due to the change in the atmospheric and ionospheric dielectric constant between the two master/slave acquisitions;
- and $\mathbf{D}_{\text{noise}}^{(i,j)}$ accounts for decorrelation phenomena such as: spatial, temporal, thermal, etc..

Therefore, solving (1) with respect to $\mathbf{D}_{\text{disp}}^{(i,j)}$, would lead to a compensation of all the other offset components as described in [13, 14]. Figure 2 shows the graphic representation of the displacement estimation concept by the coregistration procedure. Figure 2 (left) represents the focused pixel of the master image while Figure 2 (right) is the same pixel located on the slave image. Writing $\mathbf{D}^{(i,j)} = \left|\mathbf{D}^{(i,j)}\right| \exp\left(\jmath\theta^{(i,j)}\right)$, where the magnitude is the distance between the master and slave pixel centers is estimated by two-dimensional cross-correlation and the phase, considered respect to the horizontal axis, is an harmonic parameter indicating the direction of displacement [15].

Figure 3 shows the applied processing workflow, which is made by several consecutive steps. Starting from the image databases where the master and slave SAR images are stored, the first step performs the coregistration of a single interferometric pair. The next steps perform the displacement estimation and the geocoding process, respectively. The workflow is repeated for each $(i,j) = 1, \dots, N$ interferometric pair and then averaged.

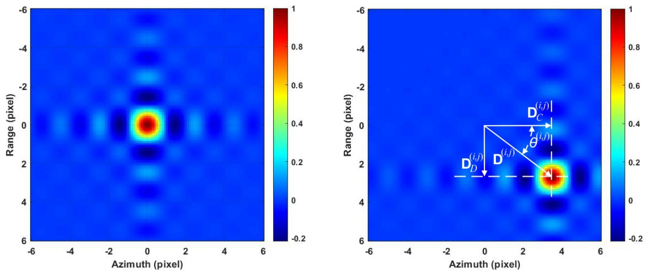

Fig. 2. Vectorial representation of the total interferometric displacement: master image (left) and slave image (right).

4. EXPERIMENTAL RESULTS

The experimental results are derived by processing the interferometric time series of SAR Spotlight data acquired by CSK satellite constellation. Specifically, we consider 27 images, of which 13 are pre-events and 14 are post-events. In this study we are not interested in the estimation of a displacement time series because a nuclear explosion occurs in a very small amount of time and we assume that after this event no other geological force caused significant movement at the Earth's surface. The main objective is to analyse the displacement generated by the enormous forces due to nuclear blasting. Through the geocoded data we are able to estimate the position where the explosion occurred. In addition, we try to analyse a possible network of underground tunnels, probably some of them even disused, characterizing the whole test site.

Figure 4 shows two subsidence maps. More precisely, Figure 4 (left) is the output obtained by processing only the SAR images observed before the nuclear tests, and it confirms that no significant subsidence phenomena are detected. Moreover, Figure 4 (right) represents the output obtained processing the SAR images acquired after the DPRK-6 event. In this result a very interesting subsidence phenomena can be observed. The displacement generated by the explosions can be seen as it is possible to observe that the north side of the mountain is in subsidence, characterized by a physical movement of the Earth's surface downwards of about -20 cm. Conversely, the south side has a positive subsidence of about $+50$ cm, which means a rise of the Earth's surface.

In Figure 5 we observe the subsidence effect caused by the nuclear explosion in which we aim to identify the chambers used both in the past experiments and in the experiment of 3 September 2017. Specifically, in Figure 5 (left) the estimated locations of DPRK 2, DPRK 3, DPRK 4, DPRK 5, and DPRK 6 events are represented as indicated by the USGS and listed in Table 1. In Figure 5 (right) we analyse in detail the DPRK 6 displacement location. This figure shows the 2-D displacement modulus with the core of the energy pulse source. Observing both figures we observe that the displacement has a main lobe with an asymmetric profile. This asymmetry could be due to a not perfect uniformity of the explosion inside the test chamber.

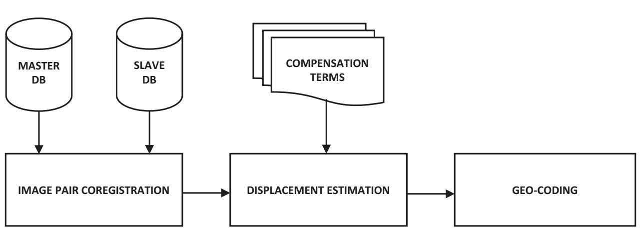

Fig. 3. Adopted processing chain workflow.

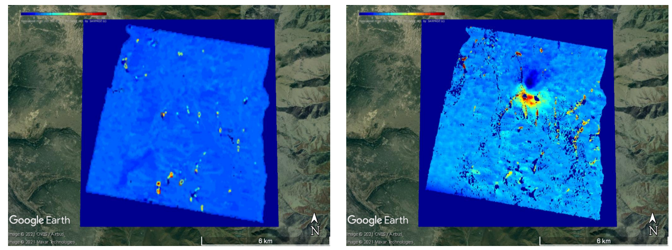

Fig. 4. A visual Earth displacement representation on the Google Earth platform before (left) and after (right) the six nuclear tests. Dark blue indicates a negative subsidence while the red areas depict a positive subsidence which mean a lowering and a rising of the Earth's surface, respectively.

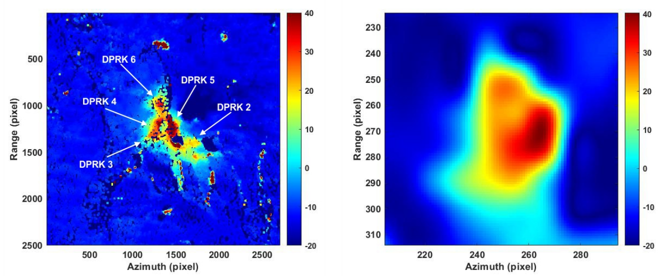

Fig. 5. Global view of the main explosion area (left), and a detailed view of the DPRK-6 site (right). Amplitude values are in centimetres.

In Figure 6 we show the displacement-field indicating both direction and intensity. This representation is useful to understand the origin of the force field that generated the displacement, i.e., the position of the nuclear weapon, and to give interesting information about the tunnel networks.

5. CONCLUSIONS

This study has the objective of estimating the Earth deformations due to the underground nuclear test carried out by North Korea on the 3rd of September 2017 by processing time series of multitemporal interferometric SAR images observed by the CSK satellite constellation. The pixel displacement

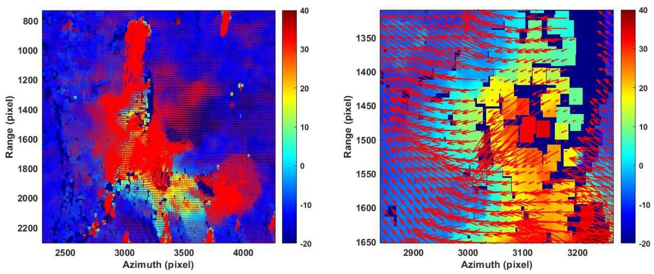

Fig. 6. Displacement-field over the area where the nuclear test explosions occurred (left), and a detailed view over the DPRK 6 event location (right). Amplitude values are in centimetres.

is estimated through the SPOT technique. The results show significant ground displacement located at the North Korean nuclear test site of Punggye-ri, revealing the exact location of the nuclear explosion site and the underground network of tunnels which stems from the generated displacement field.

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