A METHOD FOR OBSERVING SEISMIC GROUND DEFORMATION FROM AIRBORNE SAR IMAGES

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ABSTRACT

Observation of seismic ground deformation is one of the fundamental topics in remote sensing. A Synthetic Aperture Radar (SAR) has been used to obtain images representing geometrical properties of the ground surface. SAR images can be taken in nearly all weather conditions and in nearly all time. This paper proposes a ground deformation observation method using image correspondence matching, which employs phase-only correlation to estimate displacement between two SAR intensity images with sub-pixel accuracy. Through experiments using airborne SAR intensity images of the Kumamoto Earthquake, we demonstrate that the proposed method exhibits the efficient performance in observing seismic ground deformation.

***Index Terms*—** airborne SAR, seismic ground deformation, image matching, phase-only correlation

1. INTRODUCTION

Synthetic Aperture Radar (SAR) is one of microwave imaging systems used in the field of remote sensing, which has been used to obtain images representing geometrical properties of the ground surface [1]. The advantage of using SAR is to take images in nearly all weather conditions and in nearly all time, since microwaves have a cloud-penetrating capability and an active system has a day and night operational capability. SAR has been implemented on an artificial satellite or an airplane. A spaceborne SAR has the advantage of collecting images over a larger area than an airborne SAR and providing consistent viewing geometry, although a spaceborne SAR does not have flexibility in data collection from different look angles and directions. An airborne SAR has the advantage of the flexibility in data collection, since images can be taken from different look angles and directions, and in anywhere and anytime as long as weather and flight conditions, although an airborne SAR may be susceptible to imaging geometry problems due to the variation of look angles within a scene. The use of the airborne SAR is suitable for our objective due to its data collection flexibility, since we focus on seismic ground deformation in this paper.

A major approach of observing ground deformation using SAR images is Differential Interferometric SAR (DInSAR) [2]. DInSAR measures the degree of ground deformation from the phase difference of SAR images before and after ground deformation. The accuracy of DInSAR is high, although there are two drawbacks that DInSAR can measure the degree only in the slant-range direction and DInSAR cannot be used in the case that the degree of deformation is much larger than the wavelength. Addressing the former drawback, Multiple Aperture Interferometry (MAI) was proposed [3]. MAI estimates the deformation degree in the azimuth direction using backward and forward InSAR, while the accuracy of MAI is lower than DInSAR. DInSAR cannot be always used for the airborne SAR, since it is difficult for the airborne SAR to keep the consistent viewing geometry among different flights. In addition, the major drawback of DInSAR is not used in the case that two images are not taken in the short-time difference such in the earthquake, in other words, DInSAR is not always used for observing seismic ground deformation.

Another approach is to utilize image matching [4, 5]. The advantage of this approach against InSAR is that image matching can be used for SAR images taken in different timing and can measure seismic ground deformation in the azimuth and slant-range directions, since image matching finds pixel correspondence between two images. SAR images taken in the different timing include large geometric modulation such as foreshortening, which has to be normalized so as to obtain accurate observation. These methods [4, 5] have been proposed for spaceborne SAR, since the effect of geometric modulation in the spaceborne SAR is smaller than that in the airborne SAR.

Addressing the above problem, this paper proposes a novel method for observing seismic ground deformation from airborne SAR images. The proposed method employs Phase-Only Correlation (POC) [6] to obtain accurate corre-

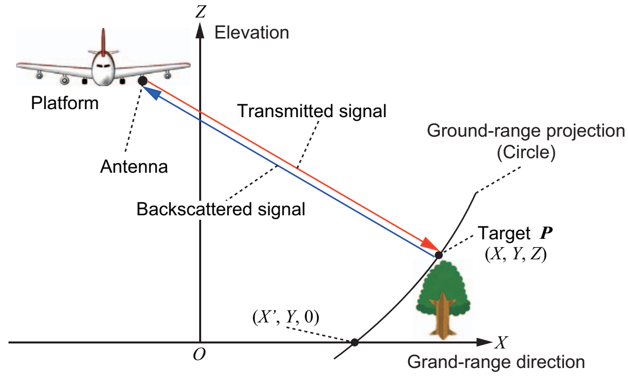


Fig. 1. Projection model of an airborne SAR image.

spondence between SAR images taken before and after the earthquake. We also propose two performance improvement techniques of the proposed method: (i) canceling foreshortening in the ground-range direction and (ii) removing periodic deformation in the azimuth direction. Through the experiment using the airborne SAR images taken before and after the Kumamoto Earthquake in 2016, we demonstrate that the proposed method exhibits the efficient performance on observing the seismic ground deformation.

2. PROJECTION MODEL

Fig. 1 illustrates a projection model of an airborne SAR image. A SAR antenna receives radar echoes while radar pulses are transmitted from the SAR antenna. A SAR intensity image is generated by recording the intensity of radar echoes reflected from targets in order of time. The location of a target P is determined by a traveling time of a radar pulse between the antenna and the target. The target is represented by the rader coordinate system (X, Y, Z), where the origin O is located at sea level, and the axes for X, Y and Z correspond to the ground-range direction, the azimuth direction and the elevation direction, respectively. We use the images projected onto the $X - Y$ plane, that is, the ground-range images in this paper. The ground-range image is represented by the image coordinate system (u, v), where the origin is located at the upper left, and the horizontal axis u and the vertical axis v correspond to the azimuth direction and the ground-range direction, respectively. The target position P is projected onto X' in the radar coordinate system, which is an intersection between the $X - Y$ plane in the radar coordinate system and the circle centered at the antenna, that is, the target position on ground-range images is displaced toward the antenna depending on its height. This phenomena is one of geometric modulation caused in SAR images and is called forethortening [1]. The relation between (u, v) and (X', Y) is defined by

$$v = \alpha_v X', \;\; u = \alpha_u Y, \tag{1}$$

where α [pixel/m] is the inverse of the image resolution.

3. PROPOSED METHOD

The proposed method consists of 4 steps: (i) target area registration, (ii) image correspondence, (iii) foreshortening cancellation and (iv) periodic deformation removal.

3.1. Target Area Registration

The area between two SAR images has to be aligned so as to observe the degree of ground deformation using image matching. Such global displacement can be approximated by rotation and translational displacement between SAR images. Let the flight path 1 and 2 be before and after the earthquake, respectively. Assuming that the image coordinate of SAR images taken by flight path 1 and 2 is indicated by (u_1, v_1) and (u_2, v_2), respectively, the target area can be aligned by

$$\begin{bmatrix} u_1 \\ v_1 \end{bmatrix} = \boldsymbol{R} \begin{bmatrix} u_2 \\ v_2 \end{bmatrix} + \boldsymbol{t}, \tag{2}$$

where $\boldsymbol{R}$ is a 2×2 rotation matrix and $\boldsymbol{t}$ is a translation vector. $\boldsymbol{R}$ and $\boldsymbol{t}$ are estimated from the latitude-longitude location of image corners using singular value decomposition. The resultant $\boldsymbol{R}$ and $\boldsymbol{t}$ are converted from the radar coordinate system to the image coordinate system using Eq. (1).

3.2. Image Correspondence

The disparity between two SAR images is obtained using the image correspondence method using POC [6]. POC is the image matching technique using phase information obtained by Discrete Fourier Transform (DFT) of given images, can estimate the translational displacement between two images with sub-pixel accuracy, and is robust against noise. These characteristics are important in processing SAR images compared with other image matching methods such as Sum of Absolute Differences (SAD), Sun of Squared Differences (SSD) and Normalized Cross-Correlation (NCC). The resultant disparity includes not only the degree of ground deformation but also image modulation by foreshortening and periodic deformation by SAR imaging. We introduce the subsequent two steps to refine the disparity for observing only seismic ground deformation.

3.3. Foreshortening Cancellation

The disparity includes the offset in the ground-range direction, which is caused by foreshortening. Fig. 2 illustrates foreshortening caused in SAR images taken in the different flights. The offsets observed in SAR images are different from each other, since the geometric relation between the antenna and the target is different due to a slight difference between flight paths. Hence, the offsets by foreshortening have

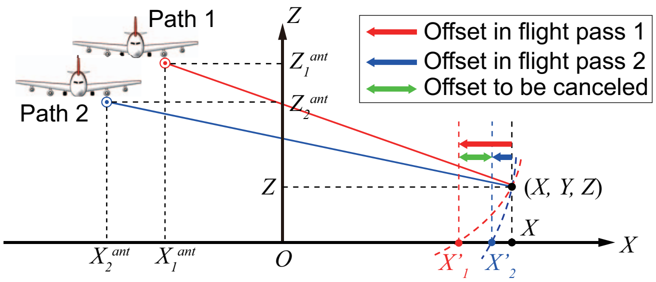
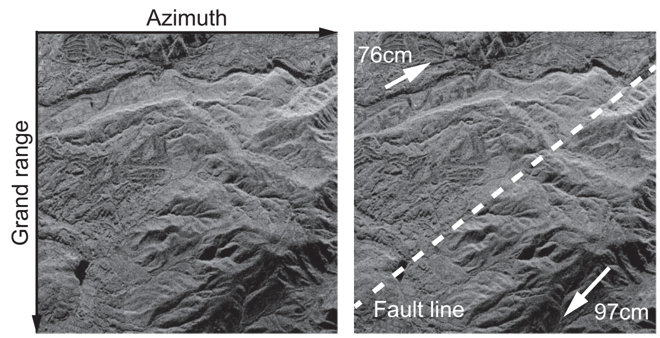


Fig. 2. Foreshortening caused in SAR images taken in the different flights.



(a) December 15, 2015 (Before the earthquake)
(b) April 17, 2016 (Before the earthquake)

Fig. 3. SAR images and a fault caused in the Kumamoto Earthquake: SAR image before the earthquake (a) and after the earthquake and the location of the fault (b).

to be canceled for accurate observation of seismic ground deformation. We consider a foreshortening cancellation method using the projection model of the airborne SAR. The offset can be calculated if the position of the target (X, Y, Z) is known. We use the Digital Elevation Model (DEM) to calculate the foreshortening offsets caused in the ground-range direction. The target (X, Y, Z) is projected onto $(X', Y, 0)$ in the $X - Y$ plane as shown in Fig. 2. X' is calcualted by

$$X' = \sqrt{(X - X^{ant})^2 + (Z - Z^{ant})^2 - (Z^{ant})^2} + X^{ant}, \tag{3}$$

where (X, Z) is the position of the target obtained from DEM and (X^{ant}, Z^{ant}) is the position of the antenna obtained from the metadata. Let X'_1 and X'_2 be the projected points of the flight path 1 and 2, respectively. The offset Δ to be canceled is calcualted by

$$\Delta = X'_1 - X'_2. \tag{4}$$

Δ represented in the radar coordinate system is converted to the image coordinate system using Eq. (1). The foreshortening offset included in the disparity is canceled by subtracting Δ from the disparity.

3.4. Periodic Deformation Removal

The periodic deformation is observed in the disparity. Such deformation may be included during the imaging process of the airborne SAR. However, its mechanism is not clear even now. The same problem has been reported in the conventional method using image matching [7]. The result reported in [7] includes the periodic deformation in a diagonal direction. Hence, this method reduced the effect of deformation by cutting the frequency components in the first and third quadrants. In the case of our results, the periodic deformation is observed in the azimuth direction of the disparity. We reduce the effect of periodic deformation by filtering the frequency components of the disparity as well as [7]. Let $d(u, v)$ and $D(k_u, k_v)$ be the disparity and its frequency components obteind by DFT of $d(u, v)$, respectively. We apply simple filtering to $D(k_u, k_v)$, which is $D(k_u, 0) = 0$ except for $D(0, 0)$, to reduce the periodic deformation in the azimuth direction.

4. EXPERIMENTS AND DISCUSSION

We evaluate the performance of the proposed method using the airborne SAR images taken before and after the Kumamoto Earthquake in 2016.

4.1. Dataset

SAR images used in the experiment are acquired by the airborne X-band SAR system developed by National Institute of Information and Communications Technology (NICT), Japan [8]. The target area is 6km×6km around Mt. Aso, Kumamoto Prefecture, Japan (N32°15'01" and E131°07'46"). The size of the ground-range image is 24,000×24,000 pixels. The SAR images were taken on December 15, 2015 and on April 17, 2016, where the Kumamoto Earthquake happened on April 16, 2016. Fig. 3 shows the SAR images used in the experiment. A slip on a fault was caused in the diagonal direction as shown in Fig. 3 (b). A field survey was observed that the upper area of the fault was moved to the upper right and the lower area was moved to the lower left. As shown in Fig. 3, it is hard to visually observe the difference between the two SAR images. We use the DEM provided by Geospatial Information Authority (GIA) of Japan[1] for foreshortening cancellation.

4.2. Experiment

The seismic ground deformation is estimated as a disparity map using the proposed method. The accuracy of results can be evaluated using the slip distance from the electronic reference points provided by GIA[1]. The electronic reference points are not located on the fault in the target area. Therefore, we use the electronic reference points close to the fault as a reference value for discussion.

[1]http://www.gsi.go.jp/

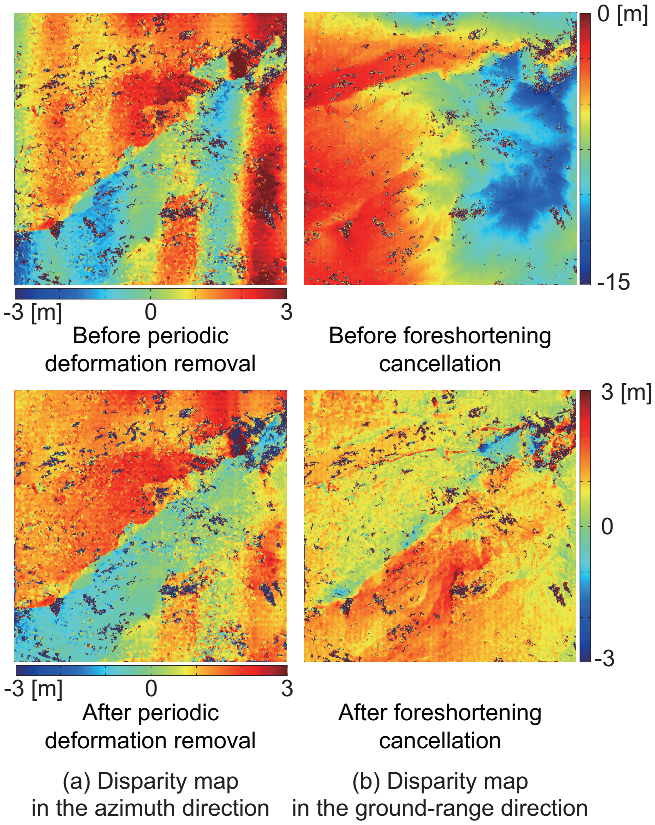


Fig. 4. Experimental result.

4.3. Result

Fig. 4 summarizes the results obtained using the proposed method. Fig. 4 (a) shows the disparity map in the azimuth direction before and after periodic deformation removal. Fig. 4 (b) shows the disparity map in the ground-range direction before and after foreshortening cancellation. In Fig. 4 (a), the positive value indicates the ground deformation towards the right and the negative value indicates the ground deformation towards the left. In Fig. 4 (b), the positive value indicates the ground deformation downward and the negative value indicates the ground deformation upward. As observed in Fig. 4, there is the gap between the upper and lower areas. The location of the gap is almost the same in the slip of the fault and the degree of the deformation is close to the value measured by the electronic reference point. The effect of periodic deformation is reduced by periodic deformation removal as shown in Fig. 4 (a), and the effect of foreshortening is reduced by foreshortening cancellation as shown in Fig. 4 (b). The use of the proposed method makes it possible to observe a slight deformation on the SAR images, which cannot be visually confirmed. The absolute degree of the ground deformation is not completely estimated by the proposed method. The effect of foreshortening remains as shown in Fig. 4 (b), since we employ the DEM to cancel the effect of foreshortening. The DEM represents the ground surface, while the SAR represents the ground surface with trees. As a result, there is a difference in the height of trees between DEM and SAR images. Digital Surface Model (DSM), which is an elevation model with trees, has to be used in foreshortening cancellation in order to improve the accuracy of the proposed method.

5. CONCLUSION

This paper proposed a novel method for observing seismic ground deformation from airborne SAR images. Through the experiment using the airborne SAR images taken before and after the Kumamoto Earthquake in 2016, we demonstrated that the proposed method exhibits the efficient performance on observing the seismic ground deformation. In the future, we will improve the accuracy of the proposed method using DSM in order to estimate the absolute value of seismic ground deformation.

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