

Development and Application of Pseudo-SAR Image Simulator

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Abstract— In recent years, Japan has experienced a lot of accidental heavy rains inducing landslides. To reduce damage from landslides, it is necessary to take appropriate countermeasures through constant monitoring of ground deformation. Among various methods for monitoring ground deformation, SAR is superior in that it can observe a wide area with high accuracy. However, SAR image analysis is not always appropriate for some geomorphological conditions. In this study, we develop a simulator to generate pseudo-phase components in SAR images with arbitrary topography and ground deformation and show the usefulness of the simulator. It is confirmed that the pseudo-SAR images, generated based on the basic equation of phase variation caused by reflections from features, can be applied to existing ground deformation estimation methods in the same way as authentic SAR images. We also simulated some cases in which the topography and ground deformation were rotated relative to the satellite orbit. The experiments found that the characteristics and range of the ground deformation, which can be predicted from the line-of-sight (LOS) deformation estimated by PSInSAR, differed depending on the relationship between the satellite orbit and the direction of the movement.

Keywords—ground deformation, road management, simulator, synthetic aperture radar (SAR).

I. INTRODUCTION

In recent years, damage to civil engineering infrastructures caused by frequent heavy rains inducing landslides has become a serious problem. In August 2019, a large-scale landslide occurred around Takeo JCT (Saga Prefecture) on the Nagasaki Expressway. The road surface was uplifted, and it required about a year for complete recovery. Although the main factor causing the landslide at Takeo JCT was the continuous heavy rainfall in 2019, Susaki et al. pointed out that the ground deformation in the surrounding area may have shown signs of a landslide more than a year ago [1]. This indicates that constant monitoring of civil engineering infrastructures and the surrounding ground is very important to minimize the human and economic damage caused by landslides.

GNSS surveying is one of the major monitoring methods used by many civil engineering infrastructure companies, including highway companies. While recent improvements in observation technology have made it possible to observe ground deformation with high accuracy by GNSS, there are also issues such as observation of ground deformation over a wide area and installation of equipment when the surrounding

area is privately owned. In these circumstances, the usage of Synthetic Aperture Radar (SAR) is gathering attention for ground deformation prediction. SAR is an active microwave radar aboard satellites that can observe the earth's surface regardless of time and weather conditions. However, in general, the deformation estimated by SAR image analysis is limited to the direction of radar irradiation. Because of this restriction, SAR image analysis is less useful in some situations, depending on the satellite's orbit, the direction of the ground deformation, and the environment of the observation area. In addition, L-band SAR images used to ground monitoring, which is observed with a relatively long wavelength, tend to be expensive. Therefore, for the spread of civil engineering infrastructure monitoring technology using SAR image analysis, it is required a measure to consider the applicability of SAR image analysis to the target area in advance.

This study shows the development of an L-band pseudo-SAR image simulator and its application in the investigation of the usefulness of SAR image analysis for monitoring civil engineering infrastructures and surrounding areas. Generally, SAR data are distributed in Single Look Complex (SLC) format, which contains both amplitude and phase information of reflected waves from features. Since this paper considers Interferometric SAR analysis (InSAR), which mainly uses phase information, only the observed phase components produced by the diffuse reflection of arbitrary geographic objects were generated. Considering the application of simulated SAR images, an arbitrary topography and ground deformation were given and rotated with respect to a fixed satellite orbit to investigate how the sensitivity of SAR image analysis to the deformation of the target ground differs depending on the relationship of the topographical condition and the direction of the satellite orbit.

The remainder of this paper is organized as follows. Chapter 2 shows the principle of the simulator and the pseudo-SAR images generated by it. In Chapter 3, the experiments to consider the usefulness of the simulator are demonstrated. The validity and usefulness of the simulator are discussed in Chapter 4. Finally, Chapter 5 concludes the paper.

II. SIMULATION OVERVIEW

A. Principle

This simulator generates pseudo-SAR images containing only the phase component. The relationship between the slant range (the distance from the satellite to the feature) and the

phase of waves reflected back from the feature is expressed by (1).

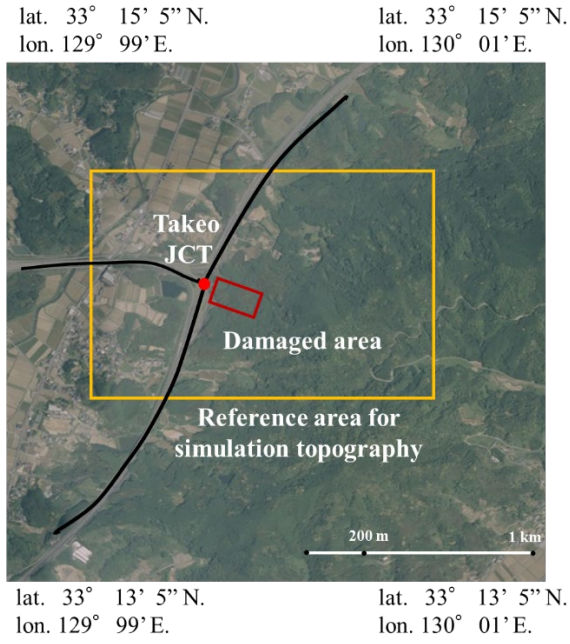
$$\phi = \frac{2\pi}{\lambda} \cdot 2 \cdot R \quad (1)$$

Where ϕ : the observed phase, λ : the microwave wavelength (150 to 300 mm in the L-band), and R : the slant range. Also, ϕ should be wrapped around $-\pi$ to π .

B. Creating Simulation Images

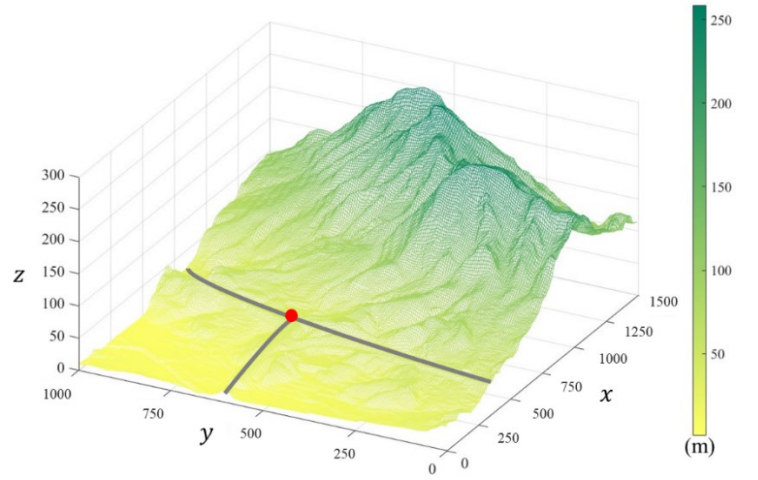
The conditions used to create the pseudo-SAR images were as follows. The topography was modeled after the area around Takeo JCT in Saga Prefecture (1.5 km east-west $\times$ 1 km north-south) where a large-scale road surface uplift

occurred in 2019 (Fig. 1(a)). The coordinate axes were set as shown in Fig. 1(b). The deformation was set so that the mountain slope continued to move in the direction of the landslide at a constant velocity (Fig. 2). The resolution was 5 m. The observation wavelength was L-band and the frequency was approximately 1.2 GHz. The satellite orbit was Ascending orbit (along the y -axis in this chapter) navigating from south to north and the irradiation direction was right. The orbit was maintained in a tube [2] with a radius of approximately 500 m from the reference orbit. The acquisition interval for each SAR image was 50 days, and a total of 10 pseudo-SAR images were generated. As an example, the first five images are shown in Fig. 3.



(a) Aerial view around Takeo JCT [3]

(Red frame: Area affected by heavy rain in August 2019, Yellow frame: Reference area for simulation topography)



(b) Topography used in simulation

Fig. 1. Topography in the simulation

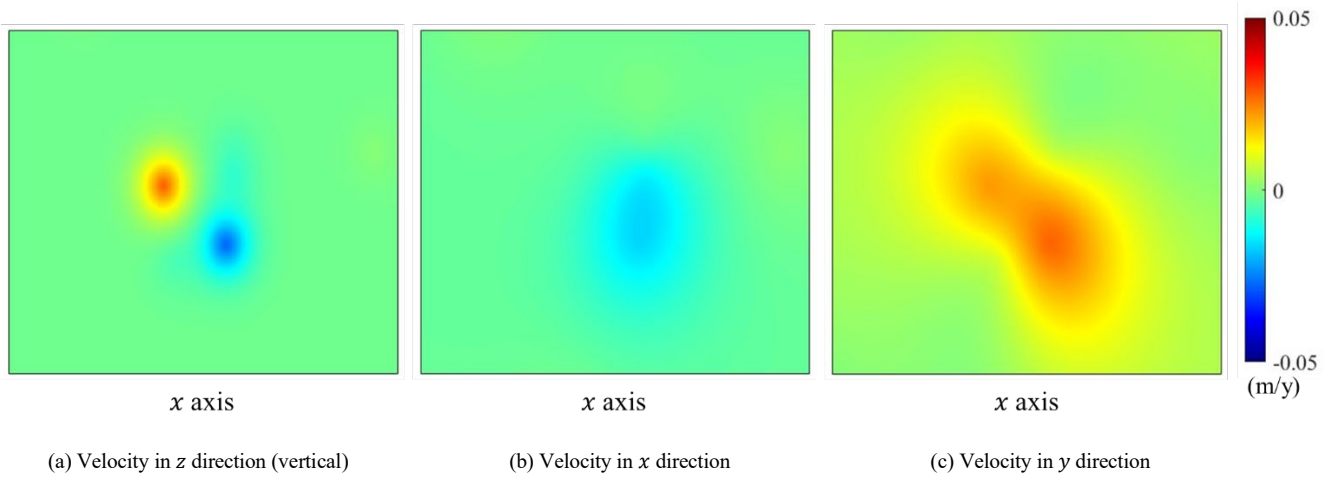


Fig. 2. Ground deformation velocity (from the sky) assumed in the simulation.

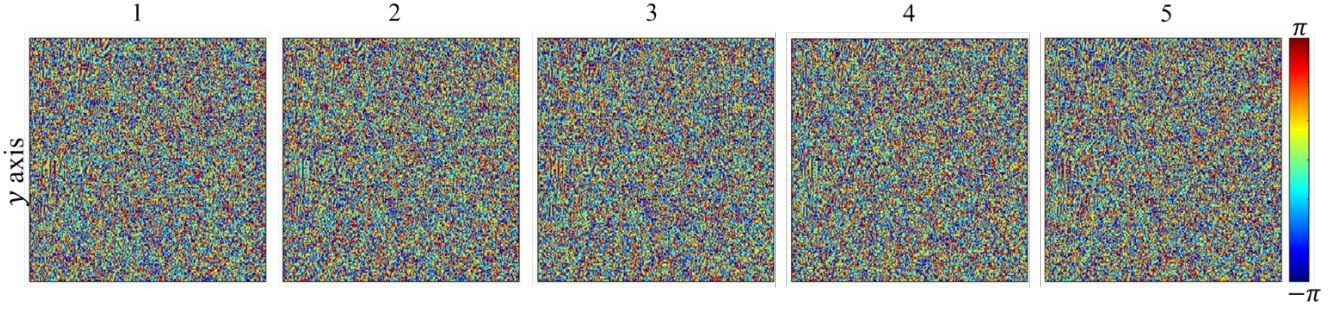


Fig. 3. Generated pseudo SAR images

III. APPLICATION OF SIMULATED SAR IMAGES

In this chapter, we demonstrate the usefulness of the simulator in considering whether SAR image analysis is effective for the target area and for the expected ground deformation in advance. By pseudo-SAR images simulated with rotated topography and ground deformation (used in Chapter 2) relative to the Ascending orbit, the velocity in the line-of-sight (LOS) direction was estimated. For each rotation angle, we evaluate the effectiveness of SAR image analysis to capture the characteristics of ground deformation from the estimated ground deformation velocity in the LOS direction (the direction of radar irradiation). When estimating the ground deformation velocity, we used Permanent Scatterers InSAR (PSInSAR) [4]. We did not decompose the velocity in the LOS direction into vertical and horizontal directions because we want to assess the effectiveness of applying SAR image analysis to the target area easily.

A. PSInSAR

We estimated the average ground deformation velocity in the target area. The flow of PSInSAR used in this study is shown in Fig. 4. Normally, Permanent Scatterers (PS) candidates are selected based on the amplitude component. However, in this experiment, 4000 PS candidates were randomly selected since the simulator did not generate an amplitude component. We assumed that the DEM error followed a standard normal distribution, and the orbital information included an error of a 1-meter radius. Equation (2) was used to select the master image [5].

$$\min \left(\frac{1}{N-1} \sum_{k=0}^{N-1} g(B_{\perp}^{k,m}, a_1) \cdot g(T^{k,m}, a_2) \right) \quad (2)$$

Where

$$g(x, c) = \begin{cases} 1 - \frac{|x|}{c} & \text{if } |x| < c \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

N : total number of images, m : master image, k : slave image, $B_{\perp}^{k,m}$, $T^{k,m}$: vertical baseline length, time baseline length between m th and k th SAR images, a_1 , a_2 : critical vertical baseline length, critical time baseline length.

Equation (4) was used to calculate the average ground deformation velocity and DEM error that maximize the absolute value of time coherence γ .

$$\arg\max \left(|\gamma| = \left| \frac{1}{N} \sum_{k=1}^N \exp \{ i(\Delta\varphi_{Flat} - \varphi_{Defo} - \varphi_{TopoErr}) \} \right| \right) \quad (4)$$

Where

$$\varphi_{Defo} = \frac{4\pi}{\lambda} T_k \cdot v \quad (5)$$

$$\varphi_{TopoErr} = \frac{4\pi}{\lambda} \frac{B_{\perp}^{k,m}}{R} \left(\frac{1}{\sin\theta} + 1 \right) \Delta h \quad (6)$$

$\Delta\varphi_{Flat}$: phase difference component of the interferometry image, in which the effects of baseline length and DEM were removed, φ_{Defo} , $\varphi_{TopoErr}$: phase changes caused by the ground deformation and DEM errors, T_k : time difference from the master image, v : the average ground deformation velocity, Δh : DEM error, θ : off-nadir angle.

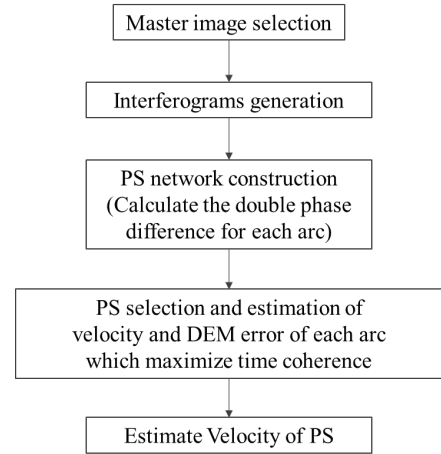


Fig. 4. Process flow of PSInSAR

B. Result

The basic simulation condition was the same as in the previous chapter. The topography was rotated clockwise through 0° , 45° , and 90° . The positional relationship between the satellite orbit and topography in each case is shown in Fig. 5. The ground deformation was fixed to the topography. The accuracy of the velocity estimation in each case was better than 3.5 mm/y in RMSE, which is considered sufficient for capturing the approximate ground deformation. Fig. 6 shows the estimated radar LOS deformation velocity estimated from the pseudo-SAR images for each topographical condition. A positive value and a negative value mean close to and move away from the satellite respectively.

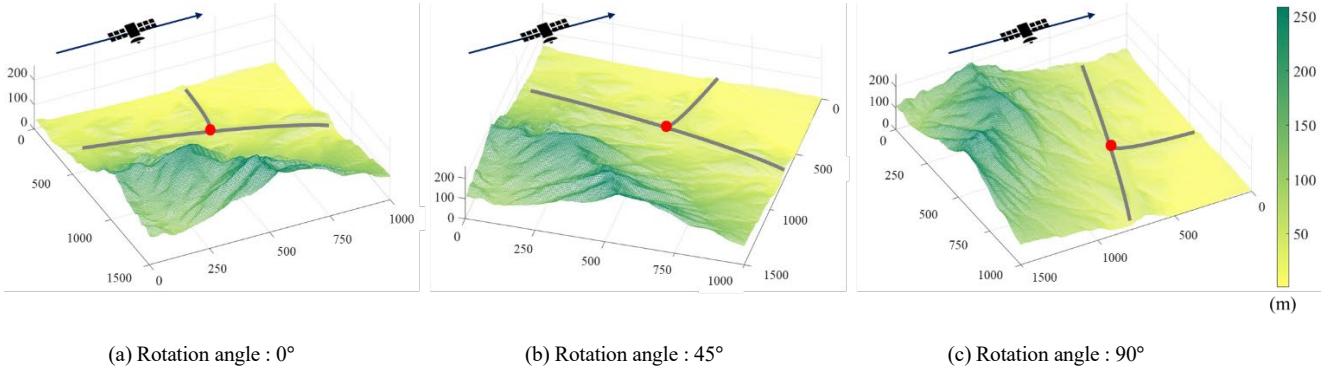


Fig. 5. The positional relationship between the satellite orbit and topography

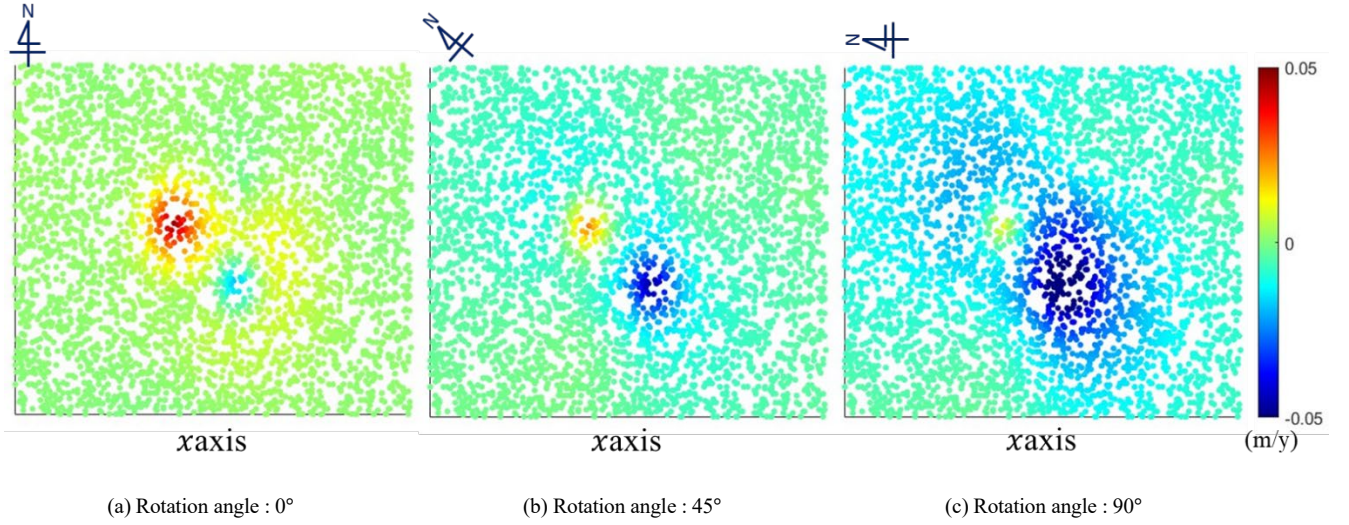


Fig. 6. Estimated velocity in LOS direction from pseudo SAR images

IV. DISCUSSION

The simulation of SAR images was generally successful. It was shown in Chapter 3 that the pseudo-SAR images generated by the simulator can be treated in the same way as real images and applied to existing ground deformation estimation methods, like PSInSAR. On the other hand, the simulator in this study is not able to consider the changes in amplitudes affected by land cover and geometric effects that may be a concern for more complex topography.

Next, we discuss the results of ground deformation estimation using the pseudo-SAR images. The characteristic of the ground deformation in this experiment is that the lower part of the slope is uplifted due to the collapse of the upper part of the mountain slope. First, comparing Fig. 5(a) to 5(c), it can be seen that the scale and trend of estimated ground deformation vary greatly depending on the LOS direction of SAR, even for exactly the same topography and deformation. Theoretically, deformation in the direction perpendicular to the LOS direction of SAR cannot be observed. Therefore, a rotation angle of 0° (Fig. 5(a)) could not capture the deformation in the y -direction. But the tendency of uplifting and subsiding was observed. In addition, when comparing the rotation angles of 45° (Fig. 5(b)) and 90° (Fig. 5(c)) with the velocity (Fig. 2(a)) actually given in the vertical direction (z -direction), the scale and amount of uplift at the point assumed

to be the Takeo JCT are not captured. This is because the uplift component in the z -direction and the component in the y -direction cancel each other out when the deformation velocity components in each direction are aggregated in the satellite's LOS direction. This indicates that there are cases in which SAR-based ground deformation estimation does not show significant results depending on the relationship between the topography, the direction of deformation, and the satellite orbit.

V. CONCLUSION

In this study, we developed a simulator to generate pseudo-SAR images in the context of promoting the use of SAR image analysis in the monitoring of civil engineering infrastructures. The simulator allows the user to change the topography, ground deformation, satellite orbit, observation frequency, etc., as desired, and the generated pseudo-SAR images can be treated and applied to ground deformation estimation methods in the same way as real SAR images.

Considering applications, we showed the usefulness of the simulator in the assessment of the effectiveness of SAR image analysis in the target area. In addition, this simulator will help other kinds of research. Due to cost issues, especially in the L-band SAR image usage, it is difficult to experiment with abundant SAR images. In terms of ground deformation

analysis, accurate data on actual ground deformation are rarely available and it makes it tough to evaluate the validity of the proposed method. Therefore, we expect that this simulator will have a wide range of potential applications, such as machine learning and validation of the new methods.

In our future work, it is necessary to improve the simulator to generate pseudo-SAR images with closer to the real SAR images. The variation and attenuation of amplitude components are essential. Differences in reflectance between vegetation and artificial objects may affect the accuracy of ground deformation estimation in civil engineering infrastructure monitoring, especially in mountainous areas. Geometric effects are also an inherent part of real images. In particular, much of the civil engineering infrastructures in Japan are located in mountainous areas, and the effects of shadows and foreshortening cannot be avoided. We plan to improve the simulator to make it possible to generate pseudo-

SAR images as closely as possible to look like actual SAR images.

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