Application Research of Extracting Slope DEM Data by GB-SAR

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Abstract: Ground-based Synthetic Aperture Radar (SAR) adopts the step-frequency continuous wave technology, synthetic aperture radar technology and interferometric measurement technology, to achieve all-weather, non-contact, high-accuracy deformation monitoring on the target. The slope DEM data may be extracted by increasing the radar vertical baseline and constructing the geometric model between the target slope and the radar. In this paper, the geometric model of the radar with vertical baseline and the target is analyzed firstly; the factors affecting the accuracy of target DEM data are summarized secondly; and the technology is verified through the use of the measured slope data finally. The results show that GB-SAR can extract the slope DEM data quickly, and the generated DEM data may be used to assist the recognition of the target radar image.

1 Introduction
As a microwave active detection technology, GB-SAR overcomes the limitation of spaceborne radar, such as long observation period, low spatial resolution and fixed imaging angle, and can acquire high-resolution deformation information of the target object within a short time. Therefore, it has been one of the research hotspots of scholars at home and abroad in recent ten years, and widely used in the deformation monitoring of the targets such as dams, bridges, and landslides. In order to obtain high-accuracy deformation information of the target, GB-SAR often uses the zero baseline mode for observation. In this case, the acquired radar image is a 2D image based on the distance between the target and the radar. In addition, the interference phase acquired in this mode is mainly composed of the atmospheric disturbance phase, target deformation phase and noise, which is conductive to the high-accuracy extraction of the target deformation phase. However, when recognizing the target area, it needs to make a comprehensive interpretation using the feature points, radar images and site map in the target scene, which increases the difficulty of recognition and is not...
This paper presents the method to acquire the target’s DEM model by using GB-SAR. By constructing the geometric relationship between GB-SAR with spatial baseline and the target, extracting the target DEM model by utilizing the unwrapped interference phase, and merging the DEM data and the target’s deformation data, a 3D deformation map of the target area may be generated. Besides, the paper also analyzes the accuracy of the method, summarizes the accuracy requirements upon which GB-SAR acquires the target DEM model, and verifies the feasibility of the technology through experiments combined with the measured data.

2 GB-SAR Generating Target DEM model

When GB-SAR is performing measurement, the radar unit is placed on the horizontal guide rail to slide so that the phase information of the target can be obtained. In the generated radar image, the origin of coordinates is the center point of the radar guide rail, and the spatial baseline is normally 0, which means that, the height of the radar relative to the center of the guide rail is unchanged at the beginning of each measurement. In this mode, only the displacement information of the target relative to the direction of the radar’s line of sight under different observation periods, and the height information of the target cannot be obtained. In order to obtain the target’s DEM model, it is necessary to increase the radar vertical baseline $B$ manually under different observation periods, namely, the height information of the radar on the guide rail is changed, and the relationship between the interference phase and the target height is used to calculate the height information of the target.

![Figure 1 Geometric Relationship during GB-SAR Observation](image)

The geometric relationship between the GB-SAR with spatial baseline and the target is shown in Figure 1. Where, O is the position of the radar phase center. During the measurement, the radar height is $H$, the X axis is the direction of the radar guide rail, the Y axis is perpendicular to the direction of the radar guide rail, and the Z axis is at the plumb position. The spatial baseline between the two observations is $B$. The height information of the target is mainly affected by the component $B_h$ in the Y axis and the component $B_v$ in the Z axis of the baseline $B$. $R_1$ and $R_2$ are respectively the distances between the target point P and the radar acquired under different observation periods, $\gamma$ is the angle between the target point P and the radar center point in the radar image polar coordinate system. From Literature [9], it is known that the relationship between the height $z$ of the target point and the radar phase $\phi$ is as follows:
Where, $\lambda$ is the radar wavelength.

The relationship between the polar coordinates ($\gamma$, $R$) of the radar image and the Cartesian coordinates ($x$, $y$) is as follows:

$$
\begin{pmatrix}
x \\
y
\end{pmatrix} = \sqrt{R^2 - z^2} \begin{pmatrix} \sin \gamma \\ \cos \gamma \end{pmatrix} z
$$

(2)

The ground-based radar adopts the measurement method different from that for the spaceborne radar and airborne radar. Therefore, if the radio between the azimuth and the range direction of the target is small for the spaceborne radar and the airborne radar in the generated radar image with the beam width of -3dB, it may be considered as $\gamma = 0$ approximately. For the ground-based radar, the ratio between the azimuth and the range direction of the target is large, and the elevation is affected by the angle between the target and the radar.

3 Analysis of Model Accuracy

GB-SAR often acquire the target’s DEM model by increasing the baseline in the vertical direction [10]. In Formula (1), $B_h$ is normally 0, so the accuracy of the target’s DEM model is mainly affected by the radar wavelength $\lambda$, baseline component $B_v$, radar height $H$ and noise. According to the law of covariance propagation, when the influence factors are independent of each other, the mean square error $\sigma_z$ of the target height $z$ is:

$$
\sigma_z = \sqrt{\left(\frac{\partial z}{\partial \phi} \cdot \sigma_\phi\right)^2 + \left(\frac{\partial z}{\partial B_v} \cdot \sigma_{B_v}\right)^2 + \left(\frac{\partial z}{\partial \lambda} \cdot \sigma_\lambda\right)^2 + \left(\frac{\partial z}{\partial H} \cdot \sigma_H\right)^2}
$$

(3)

The above error propagation coefficients are respectively:

$$
\frac{\partial z}{\partial \phi} = \frac{\lambda}{4\pi} \cdot \frac{R_i}{B_v}
$$

$$
\frac{\partial z}{\partial B_v} = \frac{1}{2} \cdot \frac{R_i \cdot \lambda \phi}{B_v^2 \cdot 4\pi}
$$
In order to facilitate the analysis and calculation of the above-mentioned variation trend of the error propagation coefficient, \( R_i = 1000m \), \( \gamma = 0^\circ \) and \( \phi = 4\pi \) are taken, and IBIS is considered as the radar coefficient, \( \lambda = 17.58mm \), and the curve indicating that each error propagation coefficient varies with the baseline is as shown in Figure 2 (They are \( \frac{\partial z}{\partial \lambda} \), \( \frac{\partial z}{\partial B_v} \), \( \frac{\partial z}{\partial \phi} \) and \( \frac{\partial z}{\partial H} \) respectively in the sequence from top to bottom and from left to right):

**Figure 2** Error Factor Propagation Coefficients affecting the Accuracy of DEM Model

From Figure 2, it can be seen that the error propagation coefficient of the radar height is 1 as a constant value, and the error factor is not affected by the baseline \( B_v \); the radar wavelength and phase error have the largest influence coefficient, which is mainly affected by the frequency stability of the radar signal, so the radar signal frequency stability has the most significant influence on the target DEM accuracy. Under the premise that the other influence factors are not taken into account, when \( B_v = 0.25m \), to make the target elevation accuracy at 1000m from the radar is 0.1m, \( \sigma_\phi < 1^\circ \), \( B_v < 1.4mm \), \( \sigma_\lambda < 0.025mm \) and \( \partial H < 0.1m \) are required.
4. Slope Experiments
The experimental team used GB-SAR to carry out experiments on the excavated slope during the construction of a Hydropower Station in Yunnan. GB-SAR was located at the bottom of the opposite slope of the target slope. The time taken to acquire a radar image was about 5 minutes, and the vertical baseline was artificially increased by 0.1 m between two radar image observation periods. The slope site is as shown in Figure 3, where, the target area includes two special parts, one is the reinforced slope (the area defined by the red border), at which, a landslide happened before the experiment, and then the slope was reinforced. The construction was still going on in the area during the experiment. The other slope is a slope with complex environment (the area defined by the yellow border), at which, there are some vegetation, stacked construction materials, and multiple construction transportation routes, and construction vehicles often pass by. Figure 4 is a radar interference image of the target area with a spatial baseline of 0.1 m. There are several obvious linear data-free areas in the figure. The areas refers to the roads in the target area. Within the range of the roads located, there is no radar reflection signal due to the influence of the imaging geometry of the radar and the target slope. In addition, as seen from Figure 4, within the range of the slope with complex environment and the reinforced slope, there are many abnormal phase units which are inconsistent with the surrounding environment, and most of them are located in the right lower part of the reinforced slope and the lower part of the slope with complex environment. Combined with the site situation, it is known that the abnormal phase point is caused by the sporadic gravel on the surface of the slope, the parking of the construction vehicle and the construction materials. The radar phase change trend in the bottom of the target area is generally uniform, and the sporadic abnormal phase points are mostly located on the edge position of the target areas segmented by the road, and the radar interference phase of the target area has a significant phase winding phenomenon.

The anomalous phase of the slope with complex environment and the reinforced slope will directly affect the subsequent phase unwrapping accuracy, the radar interferogram in the target area needs to be filtered. In view of the distribution characteristics of the phase anomaly points, Goldstein filtering was adopted for the filtering of the radar interferogram in this paper. In order to facilitate the subsequent phase unwrapping, the data was interpolated by the bilinear interpolation method for the blank area of the radar interferogram. Finally, the least square phase unwrapping method was used to perform the unwrapping on the winding phase, based on the phase value of the bottom of the target area. The phase after unwrapping is as shown in Figure 5. According to the geometric relationship between the interference phase and the target height in Formula (1), the unwrapping phase was used to solve the height information of the target area, then a DEM model was generated, as shown in Figure 6. It can be seen from Figure 6 that the overall change of the DEM model in the target area is relatively gentle. Since there was a part of the radar interferogram without radar reflection signal, the phase interpolation processing was used during the generation of DEM data in this area, so the DEM data of the area shows a linear change. The details of the slope could not be accurately expressed, while the areas where the radar signal was unobstructed, the DEM data can show more details of the target area. By comparing the known elevation information of the four burying points within the reinforced slope (with TP-01 point as the reference) and the generated DEM data, as shown in Table 1, the results show that the generated DEM data can acquire a height difference information of the target better than 2m, reflecting the slope characteristics of the target area relatively accurately.
Figure 3 Slope Site Map

Figure 4 Radar Interferogram

Figure 5 Unwrapping Phase Diagram

Figure 6 Slope DEM Model

Table 1 Difference between Target Point DEM Data and Actual Height Difference

| Measurement Point Number | Burying Height Difference (m) | DEM Height Difference (m) | Difference (m) |
|--------------------------|-------------------------------|--------------------------|----------------|
| TP-01                    | 0                             | 0                        | 0.00           |
| TP-02X                   | -36.6                         | -35.2                    | 1.40           |
| TP-06X                   | -18.1                         | -19.6                    | -1.50          |
| L13                      | -63.6                         | -62.7                    | 0.90           |

5 Conclusion

The experimental results show that the measurement accuracy of extracting the DEM data of the target through the use of the ground-based radar interferogram with spatial baseline is mainly affected by the measurement accuracies of phase, wavelength, etc. When the spatial baseline is less than 0.5 m, higher measurement accuracies of the wavelength, phase and baseline are required, and their error propagation coefficients decrease rapidly with the increase of the length of the baseline. In addition, the phase and wavelength accuracies have the greatest influence on the DEM accuracy. When the spatial baseline is greater than 0.5m, the change trend that the error propagation coefficients of the wavelength, phase, baseline and other factors decrease with the increase of the length of the baseline become gentle. When GB-SAR is used to extract the high-accuracy DEM data of the target, the spatial
baseline length shall be greater than 0.5m. The ground-based radar has a short wavelength and high measurement accuracy, its interference phase is prone to the influence of the interference factors in the observation environment. In the complex environment, more abnormal phase points often generate, which affects the accuracy of the phase unwrapping results. Therefore, the radar interferogram must be effectively filtered before phase unwrapping. The height difference information of the target area may be calculated by using the geometric relationship between the radar and the target and the interference phase after unwrapping. According to the measured data, it is known that the DEM data superior to 2m in the target area of the complex environment may be obtained in the range of 800m through effective filtering and phase unwrapping.

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