An Improved Atmospheric Phase Compensation Approach to Ground-based SAR Interferometry for Landslide Monitoring

Zhenzhu Zha\(^1\), Yue Yang\(^1\), Xinyu Chen\(^1\), Keyu Long\(^2\) and Qun Wan\(^{1,*}\)

\(^1\)School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu, China, 611731
\(^2\)The Second Research Institute of CAAC, Chengdu, China, 610041

\(^*\)E-mail: wanqun@uestc.edu.cn

Abstract. Ground-based synthetic aperture radar (GB-SAR) interferometry is an increasingly popular terrestrial remote sensing technique for landslide monitoring. However, in actual application, the atmospheric phase screen (APS) seriously affects the accuracy of GB-SAR interferometry. Therefore, it is necessary to estimate the APS accurately. This paper develops an improved APS compensation method based on a 2D-polynomial regression model (2D-PRM) with a two-step estimation process using GB-SAR measurements. In this paper, permanent scatterer (PS) points which are selected by a joint method using amplitude, amplitude deviation and correlation coefficient are used to roughly estimate the model parameters. Then, by imposing the condition of the standard deviation of the fitting error, the outliers whose values enormously affect the estimation of parameters are filtered out of the estimation process. A more efficient estimation of the APS is finally achieved by using the remaining pixels based on 2D-PRM. At last, a landslide monitoring experiment is carried out to verify the performance of the proposed method.

1. Introduction
Landslide is one of the frequently occurred natural disasters in China. Once it occurs, it will cause serious loss to the lives and property of the people in the surrounding areas. Therefore, it is necessary to accurately and timely monitor the deformation information of the potential landslides. Recently, GB-SAR interferometry has gained an increasing interest as a deformation monitoring tool and has been widely applied in the field of landslide monitoring [1]. Compared with spaceborne SAR and airborne SAR, GB-SAR has the advantages of shorter data acquisition time, more flexible observation angle, and higher stability of sensor platform. These make GB-SAR interferometry a promising alternative to airborne and spaceborne radar interferometry in some cases. Noted that in spite of the very short range, the APS in GB-SAR measurement cannot be neglected either. As a result, the estimation and correction of the APS is a crucial procedure in GB-SAR interferometric process. In [2], the authors propose a method based on in site acquired meteorological data and an initial calibration of the humidity function. By using a priori knowledge of the scene, a new compensation algorithm is presented in [3], where the APS information from known motionless ground control points (GCPs) (e.g. corner reflectors). In [4, 5], the APS is modeled as a quadratic function of the distance, and is
further estimated by using two PS points. A similar approach is proposed in [6] based on a linear model with the high-coherence scatterers.

In this paper, an improved APS compensation method based on 2D-PRM with a two-step estimation process is proposed using GB-SAR measurement. This model is based on range and cross-range two dimensional. In addition, this paper applies the PS point technology to avoid the effect of temporal decorrelation. Firstly, PS points which are selected by a joint method using amplitude, amplitude deviation and correlation coefficient are used to roughly estimate the model parameters. Then, by imposing the condition of the standard deviation of the fitting error, the outliers are filtered out of the estimation process. A more efficient estimation of the APS is finally achieved by using the remaining trustworthy pixels free of outliers and its effects are verified by using real measured data.

2. GB-SAR Interferometric Principle

SAR images contain the geometric information related to distance between the radar and the target in the monitoring scenario. This kind of information, which can be translated as the differential phase calculated by two images acquired at different times, can be well used. Figure 1 shows the physical model of deformation measurement. And \( \phi_1 \) and \( \phi_2 \) represent the phases of the same target at different moments. Therefore,

\[
\Delta \phi = \frac{4\pi (r_2 - r_1)}{\lambda} = \frac{4\pi \Delta r}{\lambda}
\]

where \( \Delta \phi \) is the differential phase of two SAR images, \( \Delta r \) is the line-of-sight physical displacement of the target, and \( \lambda \) refers to the wavelength of the transmitted signal. And assuming that the propagation properties in the transmission medium are the same in both acquisitions.

\[ \Delta \phi = \Delta \phi_{\text{ATM}} + \phi_{\text{Noise}} + 2n\pi \]  

\( \Delta \phi_{\text{ATM}} \) refers to the differential phase caused by APS, \( \phi_{\text{Noise}} \) represents the disturbance of noise. And we can see the term \( 2n\pi \) with \( n \) unknown, which shows a phenomenon that phase is wrapped. Therefore, before the estimation and compensation of APS, some pre-processing should be done here.

(1) Interferogram and coherence image generation: Each interferogram is a complex image, with the magnitude corresponding to the reflected signal intensity of the target and the phase indicating
scattering properties [7, 8]. Then the interferometric phase is usually computed: \( \varphi_{ms} = \arg(M \cdot S^*) \), where \( \varphi_{ms} \) is the wrapped interferometric phase \( \varphi_m - \varphi_s \), \( M \) is the master image and \( S^* \) is the complex conjugate of \( S \). The result is an image where each pixel contains the wrapped difference of phases between the image \( M \) and the image \( S \).

(2) Phase filtering [9] and 2D phase unwrapping [10]: Noise phase leads to the discontinuity of interferometric phase and critically affects the phase unwrapping, so the noise phase filtering should be implemented. The wrapped interferometric phases of the generated interferograms are unwrapped, i.e. the unwrapping constant \( n \) of equation (2) is estimated.

(3) PS point selection: In order to obtain enough high-quality PS points, a method that uses amplitude value, amplitude dispersion index and correlation coefficient (see [11, 12]) all at once has been applied to pixels of the SAR images.

In this context, we actually have twice selection processing for PS points. The second time selection will be proposed by defining a variance error of the differential phase in Section 3.

3. The proposed atmospheric phase compensation method

The unwrapped differential phase \( \Delta \varphi_i \) satisfies for a single spatial point \( i \) a 2D-PRM [13]:

\[
\Delta \varphi_{x,y} = p_0 + p_1 (x-x_0)^2 + p_2 (x-x_0)(y-y_0) + p_3 (y-y_0)^2 + \varepsilon
\]

(3)

where \((x, y)\) are the pixel coordinates of a given pixel, \( \Delta \varphi \) is the observation of the differential phase and \( \varepsilon \) is the random observation error, \( p_i \) are the polynomial parameters, \((x_0, y_0)\) are the coordinates of the reference point. The observations to estimate the above model parameters are pixels which are located in stable areas. Then considering all PS points in the observed area, the following matrix equation is obtained:

\[
\Delta \psi = AP + \varepsilon
\]

(4)

where \( \Delta \psi = (\varphi_1; \varphi_2; \cdots; \varphi_n) \), \( A = (a_1; a_2; \cdots; a_n) \), \( a_i = (1; (x_i-x_0)^2; (x_i-x_0)(y_i-y_0); (y_i-y_0)^2) \), \( P = (p_0 \ p_1 \ p_2 \ p_3)^T \), where \(^T\) indicates the transposed of the matrix, and \( \varepsilon = (\varepsilon_1; \varepsilon_2; \cdots; \varepsilon_n) \).

The unknown parameter vector \( P \) is then derived from a least squares regression by the expression: \( P = (A^*A)^{-1}A^* \Delta \psi \), where \(^*\) indicates the transposed conjugate of the matrix \( A \). Consequently, the estimated expression of the APS of 2D-PRM model is given by

\[
\hat{\Delta \psi}_{ATM} = AP
\]

(5)

Then the APS can be removed by the following way: \( \Delta \psi_{comp} = \Delta \psi - \hat{\Delta \psi}_{ATM} \). Considering the fact that there are some high-quality but phase-instable scatterers, usually referred to outliers whose values enormously effect the estimation of parameters. So we improve the method and introduce the unbiased estimator of the variance error by the following expression [5]:

\[
S^2 = \frac{\Delta \psi^* \Delta \psi - P^* A^* \Delta \psi}{n-3}
\]

(6)

The filtering condition of outliers is given by the following inequation:

\[
\Delta \varphi_i - \hat{\Delta \psi}_{ATM,i} < 2S
\]

(7)

By imposing this condition of the standard deviation of the fitting error, the outliers can be filtered out of the estimation process. This process is called the second time PS point selection. Then the remained pixels can be recognized as high-trusty PS points and are used to the second step estimation, i.e. equation (4) and equation (5) are computed again. Finally, equation (5) is used to estimate (predict) the atmospheric phase term over the nonstable areas. This term is then subtracted from the original
phases to obtain phases cleaned by APS for the whole interest area so that we can extract the real deformation characteristic.

Table 1. GB-SAR System Parameters.

| GB-SAR System Parameters |
|---------------------------|
| Bandwidth(MHz)            | 320 |
| Center Frequency (GHz)    | 17.2 |
| Length of Synthetic Aperture(m) | 0.85 |
| 3dB Beamwidth             | 45° |
| Resolution of Range(m)    | 0.4688 |

4. The experimental results

In order to verify the effectiveness of the proposed method, a previous PRM method is described as follow: $\Delta \phi = h_0 + h_1 \times r + h_2 \times r^2$, $h_i$ is the model fitting coefficient, $r$ is the range distance between the targets and the sensor. This model only depends on range distance, compared with 2D-PRM that takes full advantage of the information of the range and the cross-range, losing a part of useful information.

In this section, PRM and 2D-PRM are applied to a real monitoring campaign that covers a temporal baseline of about eight hours. The GB-SAR system parameters are given by table 1. Considering that the observation period was not long, we assumed that the deformations of the PS points were zero. In order to illustrate the goodness of method proposed, in this paper, we set the coherence coefficient threshold $\gamma > 0.99$ and the amplitude dispersion index threshold $D_A < 0.02$. For the first time rough selection, we have 62 PS points, and for the second time selection, the number is 56.

Figure 2. The phases before and after preprocessing
Figure 3. The APS compensation results by using PRM and 2D-PRM

Figure 2 shows the phases after preprocessing. The left-up corner is the original phase. Notice that the original phase is rambling so that we can know nothing from it. And the right-up corner is the interferometric phase between two images. Notice the discontinuity of interferometric phase due to noise phase. Left-down corner and right-down corner of Figure 2 are the interferometric phase after filtering and the interferometric phase after 2D phase unwrapping, respectively.

Figure 3 illustrates the deformation retrieval results by using PRM and 2D-PRM. The PRM and the first step of 2D-PRM are based on the PS points selected from previous $n$ SAR images, that is PS point set 1. And the PS point set 2 after the second time PS point selection is used to the second step estimation of 2D-PRM. Observing the green line in Figure 3, it can be clearly seen that the deformation values of many points far exceed the accuracy of error (1mm), confirming the necessity of the second step estimation. Comparing the three lines, obviously, the improved 2D-PRM has the best APS compensation effects. By comparing the green line with the red line, it is obvious that the second step APS compensation result of 2D-PRM is more accurate than its first step. Looking further at the red line, it can be seen that the second step compensated phases are more concentrated near zero mean, what is expected to happen because of the absence of displacement. However, because of the presence of the outliers, the first step APS compensation result of 2D-PRM is even worse than of PRM. So we can explain the worst compensation behavior of the green line in Figure 3. The consistent result can also be seen in Figure 4. In Figure 4, the values of the red line are almost zero, indicating that after filtering out the outliers, the estimated APS is closer to the original interferometric phase. Figure 5 shows the temporal differential phase evaluation of a certain high-quality PS point. It is a temporal separation between measurements of around 6.2 min. The black line is the original interferometric phase, showing the severe atmospheric phase fluctuations during the observation. The blue line is the APS compensation result of PRM, and the green line and red line are the first step and second step APS compensation results of 2D-PRM, respectively. The comparison of the red line and the green line shows the goodness of the improved 2D-PRM based on the 8-hours data. In general, Figure 3, Figure 4 and Figure 5 show the consistent results. Owing to the absence of deformation, the
compensated differential phase along time presents a zero-mean value with a low standard deviation value, \( \sigma_{\text{max}} = 0.12 \), which corresponds to 0.167 mm.

![Graph showing the unbiased estimator of variance error](image)

**Figure 4.** The comparison of variance error of PRM and 2D-PRM.

![Graph showing the temporal evaluation of differential phase](image)

**Figure 5.** The temporal evaluation of differential phase.

5. **Conclusion**

In this paper, we improve the 2D-polynomial regression model using a two-step estimation process. And through the real monitoring experiment, the excellent performance is clearly verified. By analyzing the experiment results, we can conclude that the improved 2D-PRM has higher accuracy and better feasibility of the estimation and compensation than PRM and traditional 2D-PRM. Compared with the benchmark methods, our model uses a larger number of more reliable and stable...
PS points, making better fitted model parameters. In addition, due to the second step selection of PS points, our methods can better adapt to complex and changeable environment and the scope of application is wider.

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