Accuracy analysis of multi-baseline InSAR height inversion

YinYing Hao1*, YuanZhi Hui2
1Laboratory of Radar Remote Sensing Applications, Changsha University of Science and Technology, HuNan, 410114, ChangSha
2Laboratory of Radar Remote Sensing Applications, Changsha University of Science and Technology, HuNan, 410114, ChangSha
*Corresponding author’s e-mail: yuanzihui@csust.edu.cn

Abstract. Digital elevation model (DEM) is of great significance in commercial and scientific applications, and the accuracy of elevation inversion represents the quality of DEM. With reference to the height measurement accuracy formula of single-baseline interferometric SAR, the mathematical relations between elevation accuracy and platform height, lower viewing angle, target oblique distance, baseline strip number, baseline length and baseline roll angle are established, and the variation of elevation accuracy with system parameters (especially the number of base lines and baseline length) is quantitatively analyzed, and the optimal range of multi-baseline InSAR system parameters is obtained. It provides a theoretical basis for the optimal design of system parameters.

1. Introduction

Interferometric synthetic Aperture Radar (InSAR) is a high-precision earth observation technology to estimate ground elevation information and deformation information by interfering the data received by InSAR system. Multi-baseline InSAR technology is a new surveying and mapping technology developed on the basis of traditional single-baseline InSAR technology[1,2]. Due to the fusion of multiple interferograms, the multi-baseline InSAR technique can increase the non-ambiguous interval of the interference phase, but it requires higher system parameters. Among them, flight altitude, radar range, base line side roll angle, baseline length, phase noise and terrain slope are the main factors affecting elevation accuracy[3-5].

For the problem of single-baseline height inversion, many scholars have analyzed and simulated a large number of parameters related to elevation accuracy by using satellite data such as TanDEM-X, SRTM, Envisat, etc., and proved the influence of system parameters on elevation accuracy, and made some analysis and improvement on them[6-8]. For multi-baseline elevation inversion problems, they can be roughly divided into two categories. The first is based on mathematical statistics, which takes the terrain elevation as the parameter to be estimated in the statistical distribution framework, and estimates[9,10]by maximum likelihood (ML) or maximum a posteriori standard (MAP). The second kind is based on non-mathematical statistics, which directly uses the combined information of interferograms with different baseline lengths for elevation inversion, and does not need to use the interferometric phase probability density function to establish a statistical distribution framework. Reference [11] proposed a phase unwrapping method based on CA (Cluster analysis), which uses CA to establish a formula between the interferometric phases of different baselines to estimate the absolute phase. A phase unwrapping method related to Kalman filter has been proposed in reference [12,13], which can be used for phase unwrapping at the same time of filtering. The method of phase
unwrapping using deep convolution neural network is proposed in reference [14]. These methods can not only improve the unwrapping efficiency and obtain much higher unwrapping results than the single baseline, but also greatly improve the accuracy of elevation inversion.

Therefore, this paper mainly analyzes the accuracy of multi-baseline elevation inversion based on non-mathematical statistics, and establishes the expression of elevation accuracy and multi-baseline InSAR system parameters to analyze the relationship between elevation accuracy and system parameters, which provides a theoretical basis for optimizing the parameter setting of multi-baseline InSAR system.

2. Accuracy of multi-baseline InSAR height inversion

Using the Dem linear combination method, there are $K$ interference baselines, and the height of the same position calculated by each interference baseline is $h_k$, then the final DEM is:

$$h = \sum_{k=1}^{K} \rho_k h_k$$

(1)

Where $\rho_k$ is the weighting coefficient of the $k$-th baseline, different combinations of weighting coefficients will have different height accuracy. The analysis is as follows:

(1) $\rho_k = 1/K, \; k = 1, 2, \cdots, K$ is the final DEM and the arithmetic mean value of DEM corresponding to each interference baseline. At this point, the final height error is:

$$\sigma_h = \frac{1}{K} \sum_{k=1}^{K} \sigma_{h_k}$$

(2)

Where $\sigma_{h_k}$ is the height error corresponding to the $k$-th interference baseline:

$$\sigma_{h_k} = \frac{\lambda r \sin \theta}{2\pi pB_{\perp k}} \sigma_{\phi_k}$$

(3)

Where $B_{\perp k}$ is the vertical baseline length corresponding to the $k$-th interference baseline, and $\sigma_{\phi_k}$ is the interference phase error corresponding to the $k$-th interference baseline. The relationship between height accuracy and multi-baseline InSAR system parameters can be established from formulas (4).

$$\sigma_h = \frac{\lambda r \sin \theta}{2\pi pK} \sqrt{\sum_{k=1}^{K} \frac{\sigma_{h_k}^2}{B_{\perp k}^2}}$$

(4)

The curve of the relationship between the height error in this case and the parameters of the multi-baseline InSAR system (especially the length of each baseline) can be obtained.

(2) $\rho_k = \gamma_k / \sum_{i=1}^{K} \gamma_i, \; k = 1, 2, \cdots, K$ is the weighted average of the coherence coefficient of the final DEM corresponding to each interference baseline DEM. At this point, the final height error is:

$$\sigma_h = \sqrt{\sum_{k=1}^{K} \left( \frac{\lambda r \sin \theta K}{\sum_{i=1}^{K} \gamma_i} \right) \sigma_{h_k}^2} = \sqrt{\sum_{k=1}^{K} \frac{\gamma_k^2 \sigma_{h_k}^2}{\sum_{i=1}^{K} \gamma_i}}$$

(5)
The curve of the relationship between the height error and the parameters of the multi-baseline InSAR system (especially the length of each baseline) can be obtained.

\[
\rho_k = \frac{\sigma_{h_k}}{\sum_{i=1}^{K} \sigma_{h_i}^{-2}} \left( \sum_{i=1}^{K} \left( \frac{\lambda r \sin \theta}{2\pi p B_{i,k}} \cdot \sigma_{\phi_i} \right)^{-2} \right)^{-1}
\]

(3)

\[
\sigma_{h_k} = \left( \frac{\sigma_{\phi_k}}{B_{i,k}} \right)^{-2} \left( \sum_{i=1}^{K} \left( \frac{\lambda r \sin \theta}{2\pi p B_{i,l}} \cdot \sigma_{\phi_i} \right)^{-2} \right)^{-1}
\]

\[
\rho_k = \frac{\sigma_{h_k}}{\sum_{i=1}^{K} \sigma_{h_i}^{-2}} \left( \sum_{i=1}^{K} \left( \frac{\lambda r \sin \theta}{2\pi p B_{i,k}} \cdot \sigma_{\phi_i} \right)^{-2} \right)^{-1}
\]

\[
\sigma_{h_k} = \left( \frac{\sigma_{\phi_k}}{B_{i,k}} \right)^{-2} \left( \sum_{i=1}^{K} \left( \frac{\lambda r \sin \theta}{2\pi p B_{i,l}} \cdot \sigma_{\phi_i} \right)^{-2} \right)^{-1}
\]

(6)

The curve of the relationship between the height error and the parameters of the multi-baseline InSAR system (especially the length of each baseline) can be obtained.

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3. Analysis of the influence of system parameters and height combination method on the accuracy of Multi-baseline InSAR height inversion

In the analysis of the third section, we analyze three kinds of weighting coefficients, the relative elevation accuracy of three different baselines under four slopes are set in the following experimental analysis. The baseline length is set to the combination of long and short baselines, \( B_1 = 90 \text{m} \) \( B_2 = 163 \text{m} \) \( B_3 = 237 \text{m} \). The short baseline \( B_1 \) is about half of the long baseline \( B_3 \), and the length \( B_2 \) is the intermediate value greater than the short baseline and less than the long baseline. The four terrain slope setting parameters are as follows:
Figure 1. The weighting coefficient is $\rho_k = 1/K, k = 1,2,\cdots, K$ : (a) Relative height error standard deviation corresponding to different baselines in the case of slope 1; (b) Relative height error standard deviation corresponding to different baselines in the case of slope 2; (c) Relative height error standard deviation corresponding to different baselines in the case of slope 3; (d) Relative height error standard deviation corresponding to different baselines in the case of slope 4.
Figure 2. The weighting coefficient is Lagrange multiplier: (a) Relative height error standard deviation corresponding to different baselines in the case of slope 1; (b) Relative height error standard deviation corresponding to different baselines in the case of slope 2; (c) Relative height error standard deviation corresponding to different baselines in the case of slope 3; (d) Relative height error standard deviation corresponding to different baselines in the case of slope 4.

Figure 3. The weighting coefficient is the normalized coherence coefficient: (a) Relative height error standard deviation corresponding to different baselines in the case of slope 1; (b) Relative height error standard deviation corresponding to different baselines in the case of slope 2; (c) Relative height error standard deviation corresponding to different baselines in the case of slope 3; (d) Relative height error standard deviation corresponding to different baselines in the case of slope 4.
Figure 1-figure 3 shows the curve relationship between different baselines and relative height accuracy obtained under different weighting conditions and different slopes. The weighting coefficient of fig. 1 is the normalized coherence coefficient of fig. 2, and the weighting coefficient of fig. 3 is the Lagrange multiplier. It can be seen from the whole that the height accuracy errors of different baselines are different under different weighting conditions, and the accuracy of height inversion can be improved by using appropriate weighting coefficients.

4. Conclusions
In the face of the problems of dense phase winding, multi-point ambiguity and complex terrain limitations in the traditional single-baseline InSAR technology, there are many deficiencies in accuracy and function. Multi-baseline InSAR technology can improve these problems and improve the accuracy of height inversion. For the analysis of the accuracy error of height inversion of multi-baseline InSAR technique, the main work of this paper is as follows:

1) The two main system parameters that affect the height accuracy are discussed, and the curve relationship between them and the height accuracy is given.

2) Based on the method that the DEM obtained from each baseline is weighted and then the final height value is obtained by linear combination, three different weighting coefficients are proposed, and the baseline lengths of different slopes are analyzed related to the height accuracy under the condition of different weighting coefficients.

3) Through the simulation and real DEM data, the height inversion of the interferogram with multi-baseline phase unwrapping is carried out, which confirms the necessity of the height inversion accuracy of phase unwrapping in complex areas such as large slope.

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