Analysis of Baseline in Spaceborne InSAR System

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Abstract. Based on principle of spatial image system by interferometric synthetic aperture radar (InSAR), height error is discussed. The relation between signal-to-noise ratio (SNR), range resolution and baseline design are analyzed. The optimal baseline expression is derived from the relationship between variance and baseline based on target height. The simulation results coincide with the baseline of the system in practice. The derived optimal baseline expression is of significance to optimized design of performance of spaceborne InSAR system.

Introduction

InSAR is a new space-to-ground observation technology which has developed in recent years. Together with space technology including global positioning system (GPS), Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR), they make principal part of modern space-to-ground observation technology. Seasat-SAR launched by Jet Propulsion Laboratory (JPL) in 1978 was the first spaceborne SAR in application to interferometry [1], it is expected that InSAR technology shall be extensively applied to measurement of deformation field such as earthquake, volcano, glacier and landslide as well as ground detection and ground target detection and recognition [2]. Baseline plays an important role in InSAR data process, it influents the feasibility and precision of InSAR data process [3].

Influences of baseline on measurement error of system height and relation between baseline and system relevancy are designed in reference [4, 5]. References [5] and [6] present effective baseline and ultimate baseline, the relation between baseline and optimal performance of system are discussed. Since baseline is key parameter in InSAR system, having immediate influence on InSAR system imaging, determination of optimal baseline is of significance to image coherence of InSAR system and high sensitivity of phase.

Basic Principle for InSAR

In consideration of practical problem, height measurement of InSAR is comparatively complex, in order to facilitate analysis, supposing that the height measurement of InSAR is conducted in idealized state in the following discussion [7, 8] and that work mode is single emission and double receiving (double emission and double receiving is similar to it in terms of principle), fig.1 shows geometric model for interferometric space imaging, A1 is also used for launching, when A1 is in operation, slant range \(R_1\) of point target \(P\) can be obtained. The function of another antenna A2 is to determine another location parameter of point \(P\) within the plane (slip angle \(\theta\)).
A1 and A2 represent 2 antennae to observe the same surface, achieving parallel motion within the normal plane vertical to track, with locational relation between antennae represented by vector $\mathbf{B}$. $P$ is ground target to be measured, $h$ is ground target height to be measured, $H$ is height from radar platform to ground surface, $R_1$ and $R_2$ are range from A1 to target and range from A2 to target respectively, slip angle $\theta$ is included angle between $R_1$ and axis $z$, $\alpha$ is dip angle. It can be derived from Fig. 1 and cosine law

$$h = H - R_1 \cos \left( B^2 - \frac{2R_1 + \frac{\phi \lambda}{2\pi} \frac{\phi \lambda}{2\pi} + \alpha}{2BR_1} \right)$$

(1)

It is observed from formula (5) that height $h$ of point $P$ can be obtained as long as phase difference $\Phi$ is acquired based on the condition of baseline $B$, dip angle $\alpha$ and slant range $R_1$. In a similar way, horizontal range of point $P$:

$$y = \sqrt{R^2 - (H - h)^2}$$

(2)

Spatial position of point $P$ can be determined by $h$ and $y$.

**Estimation of Optimal Baseline Length in InSAR**

**Analysis of Height Measurement Error of InSAR**

Since baseline component along track makes no contribution to height measurement of baseline component, it is defined that aperture component perpendicular to radar to target ray within the normal plane vertical to cross track shall be effective baseline length, which can be expressed as follow equation.

$$B_\perp = B \cos(\theta - \alpha)$$

(3)

Since height measurement based on InSAR is a complex process, therefore, many factors in measurement process are likely to result in measurement error [4]. In general, height error is related to $R, B_x, B_y, H$ and $\phi$. The analyses of error components in these 5 parameter errors are as follows:

Since $R_1, R_2 >> B$, therefore, all are approximate to:

$$\phi = \frac{2\pi}{\lambda} (B_x \sin \theta - B_y \cos \theta)$$

(4)

Where, $B_x = B \cos \alpha, B_y = B \sin \alpha$. 

Figure 1. Principle of InSAR space imaging.
\[\delta_h^{<1>} = \delta_R \cos \theta \]  
(5a)

\[\delta_h^{<2>} = \frac{d\theta}{d\theta} \cdot \frac{d\phi}{dB} = \frac{R \sin^2 \theta}{B_x \cos \theta + B_y \sin \theta} \delta_{b_i} \]  
(5b)

\[\delta_h^{<3>} = \frac{R \sin \theta \cos \theta}{B_x \cos \theta + B_y \sin \theta} \delta_{b_i} \]  
(5c)

\[\delta_h^{<4>} = \delta_{\theta} \]  
(5d)

\[\delta_h^{<5>} = \frac{\lambda R \sin \theta}{2\pi (B_x \cos \theta + B_y \sin \theta)} \delta_{\theta} \]  
(5e)

Based on which, height measurement error due to every parameter error can be estimated in a simple way, in formula from (5a) to formula (5e), \(B_x \cos \theta + B_y \sin \theta = B \cos(\theta - \alpha)\) is length \(B_x\) of effective baseline in effect, in which \(\delta_R\) does not mean system range profile resolution but error of system clock in system due to factors such as atmosphere and ionospheric propagation delay. In practical measurement, height measurement error is mainly as a result of phase measurement error, which is under the influence of various factors such as system SNR, decorrelation due to system baseline length and image registration precision.

It is observed from (5e) that the longer effective baseline \(B_x\) is, the phase is more sensitive to height change, the height obtained is less sensitive to phase error \(\Delta \phi\). It is observed from formula that longer the baseline \(B_x\) is to result in the higher height measurement precision, but it is not the real case, regarding selection of effective baseline length \(B_x\), there is contradiction between phase height or sensitivity and image coherence.

**Estimation of Optimal Baseline Length of InSAR**

It is observed from above mentioned analysis that shorter \(B_x\) is to make phase less sensitive to height change but result in better coherence; on the contrary, that longer \(B_x\) is to make phase more sensitive to height change but result in better coherence; namely the height measurement error due to uncertainty of phase difference and baseline length is getting smaller, but the coherence is getting poorer, in case that \(B_x\) is in excess of certain ultimate length, the 2 images are deprived of coherence, accordingly, it is impossible to obtain interferometric phase related to height and baseline length is defined as ultimate baseline \(B_c\), therefore, optimal baseline shall be in the length range from zero to ultimate baseline to enable spaceborne InSAR system to operate in optimal state. In case of taking no account of external factors such as weather and environment, it is defined that optimal baseline of spaceborne InSAR is space baseline to achieve minimum estimated variance of target height.

Estimated variance of target baseline \(\sigma_h\) is

\[\sigma_h = \sqrt{(\sigma_R \cos \theta)^2 + (R \sigma_\theta \sin \theta)^2} \]  
(6)

In which, \(\sigma_R\) is variance of slant range \(R\), \(\sigma_\theta\) is variance of slip angle \(\theta\). When scattering points in resolution cell are subject to uniform distribution, the following is obtained.

\[\sigma_R = \rho_{IN}/\sqrt{12} \]  
(7)

It is defined that parameter \(\rho_{IN}=c/(2\times B_{w, \text{InSAR}})\) is range resolution in interferometric system and that \(B_{w, \text{InSAR}}\) is signal bandwidth of interferometric system, \(\rho_i\) is ground range resolution.
\[ \sigma_{\theta_1} \approx \frac{0.6W}{R} = \frac{0.6\rho_{\text{w}}}{R \tan(\theta - \chi)} \]  
\[ \sigma_{\theta_2} \approx \frac{\Delta \theta}{\sqrt{\text{SNR}}} \]  

In which, SNR is signal to noise ratio of InSAR system, which is defined in reference [9].

According to analysis of formula (7) and formula (10), the range resolution is getting poorer with the increase of baseline \( B \) length and the decrease of SNR in interferometric system and that the influence of baseline on SNR and range resolution shall be different due to different system operation wavebands. When length of system baseline increases, the influence of phase error and baseline error on system precision decreases, the interferometric fringe capability to reflect target height is enhanced. Moreover, the SNR of the system decreases and the range resolution becomes poorer.

According to the above analysis, the expression of slip angle variance of InSAR system can be expressed as follow equation:

\[ \sigma_{\theta}^2 \approx (0.6W/R)^2 + \left( \frac{\Delta \theta}{\sqrt{\text{SNR}}} \right)^2. \]  

(10)

To evaluate partial derivative of \( B \), suppose it is zero to obtain determination formula for optimal baseline: (to simplify calculation, suppose \( \alpha=0^\circ, x=0^\circ \))

\[ B_{\text{opt}} = \frac{-3a + 4\sqrt{\frac{9a^2}{4^3} + (a^2 - 4c^2)2d}}{(a^2 - 4c)}, \]  

(11)

Where,

\[ a = R\lambda \sin \theta, \quad d = \frac{1}{12} \cos^2 \theta + 0.36 \frac{\sin^2(\theta - \alpha)}{\tan^2(\theta - \chi)}. \]  

(12)

We can conclude that on certain topographical condition \( x \), optimal baseline is codetermined by slip angle \( \theta \), baseline dip angle \( \alpha \), SNR and system signal bandwidth \( B_w \). In practical design of InSAR system, baseline length should be smaller than ultimate baseline and approximate to optimal baseline length to a great extent so as to enable system to operate in optimal condition.

**Simulation Analysis**

On the premise of constant terrain inclination, system SNR=20 dB and signal bandwidth of interferometric system \( B_w=16 \) MHz, for SIR-C/X-SAR satellite (\( \lambda=0.0312 \) m, \( \rho_r=7.90 \) m) in waveband X, ERS-1 satellite (\( \lambda=0.0567 \) m, \( \rho_r=9.37 \) m) in waveband C, SEASAT satellite (\( \lambda=0.0243 \) m, \( \rho_r=10.2 \) m) in waveband L, the relation between estimated variance of target height and the baseline in InSAR is subjected to simulation, the result of which is as shown in Fig.2. It can be concluded from simulation results that 1) optimal baseline within the range should be smaller than ultimate baseline \( B_{\text{opt}} \) on the premise of terrain with certain slope. 2) with the decrease of operating frequency of system, the length of optimal baseline \( B_{\text{opt}} \) should increase.

The optimal baseline of SIR-C/X-SAR in waveband X at slip angle of 23\(^\circ\) is 80m, which talls with the range of variation of baseline from 60m to 110m in different terrain; the optimal baseline of ERS-1 in waveband X is 550m, with ultimate baseline up to 980m, baseline length up to 600m, ultimate baseline up to 1100m, which tally with practical result; the optimal baseline of SEASAT in waveband L is 1300m, research by LI shows that when baseline is 1200m, interferometric fringe is clearest, the simulation result tallies with the practical result on the whole.
Conclusion

Baseline in InSAR system has been analyzed, with optimal baseline deduced and optimal baseline of InSAR system in various wavebands subjected to simulation calculation, having obtained better result and solved the problem on optimal baseline. Baseline design plays a vital role in spaceborne InSAR system design, with baseline length serving as the basis for interferometry of 2SAR images. Baseline length is associated with system SNR and range resolution, increase of baseline is to decrease system SNR and range resolution. Baseline affects spaceborne interferometric SAR image coherence, therefore, it is preferred that the length no more than ultimate baseline and approximate to optimal baseline be selected for baseline design.

References


