Accuracy of low relief topographical map derived from JERS-1 SAR Interferometry in Hanoi

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Abstract

The Synthetic Aperture Radar (SAR) techniques have been applied in many fields such as DEM generation, change detection and soil moisture determination. We analyzed four images acquired successively at an interval of 44 days by the synthetic aperture radar instrument on the JERS-1 satellite and generated three sets of Digital Elevation Model (DEM) in and around Hanoi city, Vietnam. DEMs estimated from three interferometric pairs are similar to each other and represent the major feature of flood plain along the Red River. In the least square fitting of baseline using 36 ground control points, the RMS error is about 3 m. This indicates that errors of about 3 m are included in the estimated DEM. Although the estimated height itself might not be accurate enough to represent the details of low relief topography in the Hanoi area, the similarity of three DEMs suggests a possibility that the present results can be used to investigate factors affecting the interferometric phases such as artificial objects, water body or vegetation. As an example, we compared the heights estimated from interferometric phase with a topographic map at ten random points in the urban area and the suburbs in order to evaluate the influence by artificial constructions. The comparison indicates that the height is overestimated by about 3.5 m in the urban area due to the effect of artificial constructions and that the JERS-1 interferometric phase has a potential to detect the effect of artificial constructions. Further consideration remains as the subject of a future study after we will construct the DEM based on a topographic map.

Key-words: InSAR, L band, coherence, multi-look, baseline, GCP, Digital Elevation Model.

1. Introduction

The Radar technology has been developed long steps during last two decades. The invention of synthetic aperture sensor improved the resolution of radar image significantly. The Synthetic Aperture Radar (SAR) techniques is an established technique combining two SAR images of the same scene acquired at different times from different viewpoints or from two antennas mounted on the spacecraft. Graham (1974) introduced a synthetic aperture radar technique for topographic mapping using data supplied by the first civilian remote sensing satellite SeaSAT. Zebker and Goldstein (1986) presented the first results from side looking airborne observation by two SAR antennas mounted on an aircraft with 11.1m from each
other. Since then many Interferometric SAR (InSAR) systems were designed for a variety of geodetic purposes such as surface deformation studies (Massonet et al., 1993) and ice flow analysis (Goldstein et al., 1993).

The InSAR techniques were applied in many fields such as DEM generation, change detection and soil moisture determination. Surface topography can be reconstructed from two dimensional phase field measurements using precise spatial relationship of the two imaging orbits. In the present study, we analyzed four images successively acquired by the synthetic aperture radar instrument on the JERS-1 satellite to generate a Digital Elevation Model (DEM) in and around Hanoi city, Vietnam and discussed the capability of DEM generation in the area of low relief topography.

2. Methodology

2.1. Synthetic Aperture Radar.

Radar (radio detection and ranging) is done with systems that use an antenna fixed below an aircraft (or spacecraft) and pointed to the side (Figure 1). Such systems are usually termed side-looking radar (SLR). The SLR system moves at uniform speed \( v \) and altitude \( H_r \) along the flight path. The system transmits the pulse of microwave in the direction orthogonal to the flight path at a look angle \( \theta \) along slant range \( r \). The returned echoes are sampled for the coherent signal processing (Richard and Jia., 1999).

A radar system is usually characterized by its resolution in the azimuth (along-tract) and range (cross-tract) directions. Range resolution is determined by the length of the transmitted microwave pulse and look angle, while azimuth resolution depends on the physical length of the antenna. The longer the antenna and the shorter the pulse length, the finer the image resolution (Elachi., 1987). In practice, restrictions on the antenna length and the power of the microwave pulse are considerable problems to achieve a fine resolution. For example, to achieve a 10m azimuth resolution with a C band (wave length \( \lambda = 5.6 \) cm) radar on a satellite 800km away, the length of antenna is required to be over 3 km, which is practically impossible. This deficiency is overcome in the SAR (synthetic aperture radar) systems. SAR is a data recoding and processing technique that significantly improves the resolution of point targets on both azimuth and range directions.

SAR is the coherent imaging system that records both phase and intensity information of the microwave field back-scatter by all objects within the correspondent resolution cells on the ground. Each SAR image is composed of a regular grid of complex value that will be decomposed into an amplitude \( I \) and a phase \( \phi \). The intensity provides information on surface roughness of the illuminated targets, while the phase composed of scattering part \( \phi_{sc} \) and a propagation part \( \phi_{prop} \) contains useful information on surface and propagation path.

2.2 DEM generation from InSAR

SAR interferometry (InSAR) is a relatively new signal processing technique that combines two or more SAR radars over the same area recorded by imaging radar systems onboard satellite platform. InSAR operates on the principle of extracting the phase change between two images over the same area taken from different positions to measure the difference in the path length. The differences can then be related to important parameters such as terrain height, deformation of the Earth surface and excess atmospheric delay (Goldstein et al., 1988). Figure 2 illustrates the basic geometrical configuration of InSAR. Both of two radar systems \( S_1 \) (master or reference) and \( S_2 \) (repeat) illuminate the same ground patch of the Earth. \( B \) is the distance between the two antennas, called baseline, \( \theta \) is the look angle, \( r_1 \) and \( r_2 \) are slant ranges to a point \( P \) on the ground, and \( \alpha \) is the angle between baseline and the horizontal.

Fig. 1. Three-dimensional view of scanning configuration for a side looking SAR system.
As $(r_1 + r_2) = 2r_1$, we have from (2.5)

\[
\delta r = r_1 - r_2 = -B \sin(\theta - \alpha)
\]

Then the equation (2.3) for repeat pass becomes

\[
\phi = -\frac{4\pi}{\lambda} B \sin(\theta - \alpha)
\]

The derivative of phase with respect to range \( r \) is

\[
\frac{\partial \phi}{\partial r} = -\frac{4\pi}{\lambda} B \cos(\theta - \alpha) \frac{\partial \theta}{\partial r}
\]

This phase derivative depends on two terms; the perpendicular component of the baseline \( B = B \cos(\theta - \alpha) \) and the derivative of look angle \( \theta \) with respect to range \( r \). The look angle usually increases with range, so \( \partial \theta / \partial r > 0 \). However when the local terrain slope exceeds the look angle, an increase in look angle does not produce a corresponding increase in range (Price and Sandwell., 1998).

Applying the law of cosines to a triangle \( S_1 P_1 \), the look angle \( \theta \) to a point \( P \) on the ground surface is expressed as

\[
\cos \theta = \frac{H^2 + r^2 - x^2}{2rH}
\]

where \( r \) is the range to the point \( P \), and \( H \) and \( x \) are the distances of the satellite and the point \( P \) from the center of the Earth \( O \) respectively. To see the relation between the interferometric phase and the local topography, let us consider a point \( P_0 \) which is located at the same range as the point \( P \) on the reference ellipsoid and would appear in the same position on the SAR image from a satellite \( S_1 \) (Figure 3). Let \( x_0 \) be the local Earth radius of the reference ellipsoid, \( \theta_0 \) be the look angle. Then using the law of cosines, we find

\[
\cos \theta_0 = \frac{H^2 + r^2 - x_0^2}{2rH}
\]

Using (2.10) and (2.7) we can derive the interferometric phase \( \phi_0 \) from the point \( P_0 \), called the flat Earth phase, as follows

\[
\phi_0 = -\frac{4\pi}{\lambda} B \sin(\theta_0 - \alpha)
\]
The actual distance \( x \) is usually greater than the radius of the reference ellipsoid \( x_0 \). The difference \( x - x_0 \) provides the geometric elevation. The phase due to the actual topography \( \phi(x) \) can be expanded in a Taylor Series about \( x_0 \):

\[
\phi(x) = \phi(x_0) + \left( \frac{\partial \phi}{\partial x} \right)_0 (x - x_0) + \frac{1}{2} \left( \frac{\partial^2 \phi}{\partial x^2} \right)_0 (x - x_0)^2 + \cdots
\]

(2.12)

where \( \phi(x_0) \) is the flat Earth phase \( \phi_0 \) given by (2.11). Because the second derivative is very small, \( \phi(x) \) is well approximated by the first two terms in the series:

\[
\phi(x) = \phi(x_0) + \left( \frac{\partial \phi}{\partial x} \right)_0 (x - x_0)
\]

(2.13)

The first term is the flat Earth phase \( \phi_0 \) given by equation (2.11), and the second term can be derived from equations (2.7) and (2.9). From (2.7), we have

\[
\left( \frac{\partial \phi}{\partial x} \right)_0 = -\frac{4\pi}{\lambda} B \cos(\theta - \alpha) \left( \frac{\partial \theta}{\partial x} \right)_0
\]

(2.14)

and from (2.9), we have

\[
\left( \frac{\partial \theta}{\partial x} \right)_0 = \frac{x_0}{rH \sin \theta_0}
\]

(2.15)

Substituting (2.14) and (2.15) into (2.13), we have an equation to estimate the height \( h \) from the reference ellipsoid

\[
h = x - x_0 = \frac{-\lambda r \sin \theta_0}{4\pi \lambda \cos(\theta - \alpha)} \left( \phi - \phi_0 \right)
\]

(2.16)

3. DEM generation of Hanoi from JERS-1 SAR interferometry

3.1 Geography and climate of Hanoi

Hanoi is the second largest city in Vietnam situated in a flood plain of the Red River. The Hanoi city is located at latitudes 20°53' - 21°23' N and longitudes 105°44' - 106°02' E. Most of the Hanoi area is flat with elevations below 20 m except the northern mountainous part up to 400 m height. The climate is typical of the Red River Delta region, i.e., sunny and tropical along with heavy monsoon. The average annual rainfall in Hanoi is about 1,600 mm. Normally, over 80% of rainfall occurs from May to October. Heavy rains and typhoons happen in July. The dry season prevails from November to April. December, January and February are the driest months. The annual average temperature is around 24°C. January is usually the coldest month, while it is usually the hottest in July with average temperatures of 34°C. Being situated near the river and due to strong monsoons, high relative humidity of about 70% prevails during most of the year (Mai et al., 2004).

Fig 4. Lists of information for four images and their image pairs. *calculated from the least square fitting of GCPs.

Fig 5. Study area. (a) JERS-1 frame over Hanoi. (b) Study area on JERS-1 multi look image.
3.2 Data sources

We have produced the Digital Elevation Model (DEM) from JERS-1 SAR images. JERS-1 is the Japanese satellite with the repeat periods of 44 days and the nominal altitude of 568 km. JERS-1 SAR uses L band with \( \lambda = 23.5 \) cm, and the off-nadir angle is 35 degree. We analyzed four SAR images acquired successively during the period from May to September in 1995. Four images are called here Images A, B, C, and D. We used image combinations of Images A and B, B and C, and C and D to produce three interferograms. They are called here Pairs 1, 2 and 3. Figure 4 summarizes basic information for four images and three image pairs.

We processed NASDA facility raw images along range and azimuth to get the files called single look complex (SLC). The Single look complex uses all the signal returns from a ground target to create a single image. The image contains speckles but achievable resolution is high. The SLC image has a slant range pixel spacing of 8.78 m and an azimuth pixel spacing of 4.51 m. The data are recorded in a complex format with 4 bytes for each of the real and imaginary parts. One complex scene is composed of 5,546 range elements and 15,850 lines.

Our research focuses on the urban area and its suburbs. Figure 5 shows (a) JERS-1 frame over Hanoi city on map and (b) study area on JERS-1 multi look image. In the study area, we can easily recognize the Tay Lake, the biggest lake in the northern part, and the Red river that meanders from North West to South East. Other water bodies are also shown in dark. Bright parts in and around the center of the city represent reflections from artificial constructions.

3.3 Data processing procedure

The software GAMMA was used in this research. This software provides image-processing modules in the field of microwave remote sensing. The processing follows some main steps:

- Co-registration of SLC data
- MLC image for speckle reduction
- Interferogram generation and flat earth phase removal
- Coherence estimation
- Phase unwrapping
- Baseline estimation by GCPs
- Phase to height conversion
- Geocoding of height map

Image coregistration

Before the interferometric processing of complex SAR data that combines two images into an interferogram, it is necessary to co-register two images at sub-pixel accuracy. We co-registered Images A, B, C and D to each other in order to produce three pairs of images. The co-registration of image was performed by applying the bilinear function that maximizes the local spatial correlation in the real valued image intensity to each small area of 32 x 32 pixels throughout the image.

MLC image for speckle reduction

After the co-registration, the multi-look over 2 pixels in range and 6 lines in azimuth was performed to improve the quality of the interferometric phase. After the multi-look for speckle reducing, the resolution became 17.56 m in range and 27.06 m in azimuth. The size of the image was reduced to 2,773 pixels in range and 2,640 lines.

Interferogram generation and flat earth phase removal

The array of phase differences or interferometric phases is obtained from the multi-looked images. Let \( u_1 \) and \( u_2 \) be the complex values at a pixel of the master image and at the corresponding pixel of the slave image respectively. Then they are expressed by

\[
\begin{align*}
    u_1 &= A_1 e^{i\phi_1} \\
    u_2 &= A_2 e^{i\phi_2}
\end{align*}
\]

So we have

\[
I = u_1\bar{u}_2 = A_1 A_2 e^{i(\phi_1 - \phi_2)}
\]

where \( \bar{u}_2 \) shows the conjugate complex number of \( u_2 \). Therefore the phase difference between corresponding pixels is obtained by

\[
\phi = \Phi_1 - \Phi_2 = \arctan \left( \frac{\text{Im}(I)}{\text{Re}(I)} \right)
\]

where \( \text{Im}(I) \) and \( \text{Re}(I) \) are the real and imaginary parts of the complex number \( I \). The phase difference depicted as a raster image is called an interferogram or fringe image. Figure 6 (a), (b), (c) show three interferograms: \( \phi_1 \) for Pair 1 (Images A and B), and \( \phi_2 \) for Pair 2 (Images B and C), and \( \phi_3 \) for Pair 3 (Images C and D). This fringe phase is called a raw interferogram. It is noted that the phase difference can be estimated only in the interval \( (-\pi, \pi) \), i.e. the phase is wrapped.

It is necessary to remove the flattened phase to get the so-called flattened interferogram.

\[
\phi_{fl} = \phi - \phi_0
\]

where \( \phi_0 \) is the flat Earth phase given by the equation (2.11). Figure 6 (d), (e), (f) show the flattened interferograms of three pairs. As we observe in Figure 6, the flattened interferogram shows much less variation than
the raw interferogram, indicating a very low relief.

**Coherence estimation**

To evaluate the quality of the interferogram, we computed the coherence $\gamma$ of two complex SAR images within the study area of $1025 \times 834$ pixels by

$$\gamma = \frac{\sum u_1 \bar{u}_2}{\sqrt{\sum |u_1|^2 \sum |u_2|^2}}$$

(3.6)

where $u_1$ and $u_2$ are corresponding complex values from two images. Summation in equation (3.6) was performed over each shifting windows of 5 x 5 pixels. Figure 7(a), (b) and (c) show coherence images for Pairs 1, 2 and 3 respectively. The coherence is the product of all the various factors affecting signal correlation, including thermal noise, atmospheric effect and temporal change noise. Zero value means that two images are totally uncorrelated while one means that there is no change between two images. Figure 7 (d) shows relative cumulative distribution curves of coherences for three pairs. According to Madsen and Zebker (1998), the interferogram can be ranked as a good quality if pixels with coherence greater than 0.5 covers 80% of a full scene and more. The pixels with coherence greater than 0.5 cover 83% in Pair 1, 86% in Pair 2 and 89% in Pair 3. Thus three pairs of images have high coherence except for water and vegetation areas. It is reasonable to consider that almost all objects did not change during a short repeat period of 44 days.

**Phase unwrapping**

The flattened interferogram is usually filtered to reduce noises in the fringe before the next phase-unwrapping procedure. Among many types of filters, we applied the adaptive filter (Goldstein and Werner, 1998), which is a low-pass filter suitably adapted to avoid a loss of useful phase. The interferogram is segmented into overlapping rectangular patches and power spectrum PS for each patch is computed by the two-dimensional FFT. The response of adaptive filter $F$ is then computed from the power spectrum by $F = |PS|^\alpha$. No filtering is applied for $\alpha = 0$, while filtering is strongest for $\alpha = 1$. Useful values of $\alpha$ lie in the range 0.2 to 1. It is generally known that the window size from 32 to 246 pixels leads to good result and $\alpha$ should be large values in the case of flat terrain (Wegmüller et al., 2001). In the present study, we chose 64 pixels as the window size and 0.7 as the parameter $\alpha$ considering that the topography is very flat and the correlation is high.

As the raw interferometric phase varies within a range from $-\pi$ to $\pi$ resulting from applying the arctangent function, we have to determine the relative phases for all the points in the flattened interferogram using the so called "phase unwrapping" technique, which adds the proper

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Fig 6. Raw interferogram of (a) Pair 1, (b) Pair 2 and (c) Pair 3. Flattened interferogram of (d) Pair 1, (e) Pair 2 and (f) Pair 3.
Fig 7. Coherence image of (a) Pair 1, (b) Pair 2 and (c) Pair 3. (d) Cumulative distribution curves of coherence.

Fig 8. Phase unwrapping image and frequency distribution. The ordinate gives number of pixels at an interval of 0.00357 (rad). (a) Pair 1. (b) Pair 2. (c) Pair 3.
Accuracy of low relief topographical map derived from JERS-1 SAR Interferometry in Hanoi

Fig 9. Ground control points.

Fig 10. Estimation errors of 36 ground control points.

(a) Pair 1. (b) Pair 2. (c) Pair 3.

Height map generation and geocoding

The equation (2.16) gives the relation between the phase difference $\phi - \phi_0$ and the elevation $h$. In this equation, the wavelength $\lambda$, the range $r$ and the distance of satellite $H$ can be derived from Radar system parameters. The phase difference has been obtained from phase unwrapping procedure of the flattened interferogram (Figure 8). Thus the height map will be obtained if we have an accurate perpendicular baseline $B = B \cos(\theta_0 - \alpha)$. Exactly speaking, the perpendicular baseline varies slightly with look angle across a typical SAR image and further changes with time along the track since the orbits are not exactly parallel. Thus the baseline determined from the orbit data is generally not accurate enough to convert the unwrapped interferometric phase to topographic height. In order to determine the accurate perpendicular baseline, we used 36 ground control points (GCPs) sampled from topographical map of 1/10,000 scale (Figure 9). The phase value at corresponding point is extracted from a file of unwrapped interferogram. Based on (2.16), we calculated the best fit baseline by Least Square Fit algorithm in GAMMA. The refined perpendicular baselines at the center of images are -154.30 m, 198.03 m and -38.59 m for Pairs 1, 2 and 3 respectively (See Figure 4). The estimated heights and errors at 36 GCPs are summarized in Table I.

Figure 10 shows the estimation errors of heights at 36 GCPs. As Table I and Figure 10 show, most of errors for three pairs are restricted within a range of 6 m. The RMS of errors is about 3 m; 3.10 m for Pair 1, 2.41 m for Pair 2 and 3.00 m for Pair 3. It is noted that the error is least for Pair 2 of the longest baseline (198.03 m) and the error is not large even for Pair 3 of the shortest baseline (38.59 m).

Using the refined baselines, we derived three sets of Digital Elevation Models from interferograms. As it is difficult to show the detailed feature of the low relief topography by default color table in GAMMA, we the frequency distribution of unwrapped phases. As showed in the frequency distribution, the phase values accumulate within a very narrow zone. The means are 0.861, 1.256 and 0.105 and the standard deviations are 0.062, 0.072 and 0.015 for Pairs 1, 2 and 3 respectively. As the equation (2.16) shows, the estimated height is proportional to the product of the perpendicular baseline length and the standard deviation of topographic height. The standards deviations 0.062, 0.072 and 0.015 for Pairs 1, 2 and 3 are nearly proportional to the perpendicular baselines 148.7 m, 197.9 m and 39.5 m respectively. Considering the relation between the interferometric phase and the height given by the equation (2.16), it is expected that the standard deviations of topographic heights are similar to each other.

GAMMA software provides two unwrapped phase methods: Branch cut algorithm (BC) (Goldstein et al., 1988) and Minimum cost flow algorithm (MCF) (Costantini, 1998; Wegmüller et al., 2002). In the BC algorithm, locations of all residuals in an interferogram are identified and then the residuals are connected through "branch cuts" to prevent the existence of integration paths that can encircle unbalanced numbers of positive and negative residues. In the MCF algorithm, the unwrapped phases are calculated in a triangular irregular network by sum of phase along the path of integration and adjustment of phase for different flows into the arc crossing the path.

We applied the MCF algorithm to three pairs of images. Figure 8 gives the result of phase unwrapping together with the frequency distribution of unwrapped phases. As showed in the frequency distribution, the phase values accumulate within a very narrow zone. The means are 0.861, 1.256 and 0.105 and the standard deviations are 0.062, 0.072 and 0.015 for Pairs 1, 2 and 3 respectively. As the equation (2.16) shows, the estimated height is proportional to the product of the perpendicular baseline length and the standard deviation of topographic height. The standards deviations 0.062, 0.072 and 0.015 for Pairs 1, 2 and 3 are nearly proportional to the perpendicular baselines 148.7 m, 197.9 m and 39.5 m respectively. Considering the relation between the interferometric phase and the height given by the equation (2.16), it is expected that the standard deviations of topographic heights are similar to each other.

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Using the refined baselines, we derived three sets of Digital Elevation Models from interferograms. As it is difficult to show the detailed feature of the low relief topography by default color table in GAMMA, we
Fig 11. Geocoded height map in Grass6.0. (a) Pair 1, (b) Pair 2 and (c) Pair 3. (d) JERS-1 multi look image.

Fig 12. Frequency distribution of estimated heights. The ordinate gives number of pixels at an interval of 0.38 m.

Pair 1: Mean=6.61 m. Standard deviation=3.45 m. Pair 2: Mean=7.01 m. Standard deviation=3.18 m
Pair 3: Mean=7.70 m. Standard deviation=3.37 m
Fig 13. Comparison of three DEM on X-X’ profile. (a) Profiles of three DEMs and correlation between (b) Pair 1 - Pair 2, (c) Pair 2 - Pair 3, (d) Pair 1 - Pair 3. Correlation coefficient: 0.94 for Pair 1 - Pair 2, 0.93 for Pair 1 - Pair 3, and 0.86 for Pair 2 - Pair 3.

Fig 14. Comparison of three DEM on Y-Y’ profile. (a) Profiles of three DEMs and correlation between (b) Pair 1 - Pair 2, (c) Pair 2 - Pair 3, (d) Pair 1 - Pair 3. Correlation coefficient: 0.92 for Pair 1-Pair 2, 0.84 for Pair 1 - Pair 3, and 0.91 for Pair 2 - Pair 3.
imported the results into the open source GIS software Grass6.0 and geocoded the map to WGS84 zone 48N of UTM system. Figure 11 (a), (b) and (c) give the geocoded height maps drawn by Grass6.0 for Pairs 1, 2 and 3 respectively. Figure 11(d) shows JERS-1 multi look image in the same area. Three DEMs shown in Figure 11 (a), (b), (c) are very similar to each other. The Red River and its river bank are clearly distinguished. City area is prominently displayed with red color as the higher part. The elevation reduces gradually to the southern part of the city that is conformable with the trend of river flow. Several extremely high or low spots are observed in the water area especially in the Red River where the coherence is low (See Figure 7). The bright parts in Figure 11(d) represent reflections from artificial constructions, which roughly coincide with the area of higher elevation displayed by red color in Figure 11 (a), (b) and (c). It is likely that the height is overestimated in the area due to the reflection from artificial objects.

Figure 12 shows the frequency distribution of estimated heights. The ordinates give number of pixels at an interval of 0.38 m. The distribution curves are very close to each other. The means are 6.61 m for Pair 1, 7.01 m for Pair 2 and 7.70 m for Pair 3. The standard deviations are 3.45 m for Pair 1, 3.18 m for Pair 2 and 3.37 m for Pair 3. This feature is consistent with the similarity of height maps shown in Figure 11.

Figure 13(a) and Figure 14(a) shows profiles for three DEMs along the line X-X’ and Y-Y’ showed in Figure 11(d) respectively. The distance in the profile X-X’ is measured from the west bank of the Red River in the direction toward the East and the distance in the profile Y-Y’ is also measured from south bank of the Red River in the direction toward the South. It is clearly observed in the profiles that general trends of three profiles resemble to each other within a range less than 3 m except for some isolated places across the Red River and other water areas. Figure 13 (b), (c), (d) and Figure 14 (b), (c), (d) show the correlation of estimated heights along the profiles X-X’ and Y-Y’ respectively. The correlation coefficients are higher than 0.84 for all pairs, especially high for combination of Pair 1 and Pair 2.

3.4 Accuracy of the Hanoi JERS-1 DEM

The length of the baseline determines the suitability of the data set for applications. The baseline is one of important factors to control the correlation between two pairs of image. The correlation between echoes decreases linearly from unity at zero baseline to zero or no correlation at the critical baseline (Price and Sandwell, 1998) given by

$$B_r = \frac{\lambda r}{2\Delta r} \tan \theta \quad (3.7)$$

where $\Delta r$ is the pixel width: $\Delta r < c / 2W$ ($c$ : velocity of light, $W$ : frequency of pulse). The critical baseline is measured in the direction perpendicular to the look direction because the component parallel to the look direction does not affect the decorrelation of images (Zebker et al., 1992). For optimal system performance, the baseline must be large enough to give sufficient phase sensitivity to height, and also be small enough to decrease decorrelation noise. As $W$ is 15 MHz for JERS-1, $\Delta r$ is less than 10 m, and so the critical baseline is approximately longer than 6800 m. It is known that spatial phase unwrapping of an interferogram becomes difficult for the perpendicular baseline longer than 25% of the critical value (Wegmüller et al., 2003). Therefore the baseline for JERS-1 interferometry analysis should be less than 1500 m. The baselines of the present three pairs are satisfactorily shorter than the critical value.

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RMS 3.90 RMS 2.41 RMS 3.80
From the equation (2.16), we have a relation between the phase error \( \sigma_p \) and the resultant height error \( \sigma_h \) as follows:

\[
\sigma_h = \frac{\lambda H \sin \theta}{4 \pi B \cos (\theta - \alpha)} \sigma_p
\]  

(3.8)

As shown in Figure 8 (d), (e), (f), the unwrapped interferometric phases are accumulated within a very narrow zone. The standard deviations are 0.062, 0.072 and 0.015 for Pair 1, 2 and 3 respectively. Substituting these values into \( \sigma_p \) in the equation (3.8), we have 3.67 m, 3.33 m and 3.56 m as the values of \( \sigma_h \) for Pair 1, 2 and 3 respectively. They are very similar to the standard deviations of estimated heights: 3.45 m (Pair 1), 3.18 m (Pair 2) and 3.00 m (Pair 3). This similarity proves that interferometric phases were correctly transformed into heights.

As summarized in the Table 1, the RMS errors at 36 GCPs are 3.1 m for Pair 1, 2.41 m for Pair 2 and 3.00 m for Pair 3. It should be noted that the errors are similar independently of the perpendicular baseline lengths. It is reasonable to consider that these errors are not due to random noises in phases arising from the observation system, which might generate height errors inversely proportional to the perpendicular baseline lengths. The result of the least square fitting indicates that errors of about 3 m are included in the estimated DEM. The misfit of estimated height suggests the effect of objects on the Earth surface. Although the estimated height itself might not be necessarily enough to observe the details of low relief topography in the Hanoi area, we consider from the similarity of three OEMs as well as the RMS errors at GCPs that the present results can be used to investigate factors affecting the interferometric phases such as artificial objects, water body or vegetation.

In order to evaluate the influence by artificial constructions, we randomly sampled check points in two regions A and B from topographical map of 1:10,000 scale (Figure 15). The region A lies in the center of the city while the region B is in the area of bare or crop land east of the city. As Table 2 summarizes, the means of difference are 4.84 m (Pair 1), 4.23 m (Pair 2) and 5.50 m (Pair 3) in the region A, and 0.74 m (Pair 1), 2.16 m (Pair 2) and 3.34 m (Pair 3) in the region B. This height is overestimated by 3.69 m (Pair 1), 3.49 m (Pair 2) and 3.34 m (Pair 3) in the region A compared to the region B. It is natural to consider that this overestimation is due to the reflection from the artificial constructions in the city area. This indicates that the JERS-1 interferometric phase has a potential to detect...
the effect of artificial constructions.

Further considerations on the factors affecting the interferometric phases could be made if we compare the estimated DEM with the exact DEM based on a topographic map. The problem remains as the subject of a future study.

4. Conclusion

We analyzed four images acquired successively from 1995/05/09 to 1995/09/18 at an interval of 44 days by the synthetic aperture radar instrument on the JERS-1 satellite to generate the Digital Elevation Model (DEM) in and around Hanoi city, Vietnam.

The coherences of three pairs were fairly high, the pixels with coherence greater than 0.5 cover 83% (Pair 1), 86% (Pair 2) and 89% (Pair 3). 36 ground control points were taken from topographical map 1/10,000 scale to determine the accurate perpendicular baseline. The refined perpendicular baselines at the center of images are -154.30 m, 198.03 m and -38.59 m for Pairs 1, 2 and 3 respectively. The RMS of errors is about 3 m; 3.10 m for Pair 1, 2.41 m for Pair 2 and 3.00 m for Pair 3.

DEMs estimated from three interferometric pairs are similar to each other and represent the major feature of floodplain along the Red River. The standard deviations are similar to each other: 3.45 m (Pair 1), 3.18 m (Pair 2) and 3.37 m (Pair 3) and the standard deviation is consistent with the height error evaluated from the standard deviation of unwrapped phase: 3.67 m (Pair 1), 3.33 m (Pair 2) and 3.56 m (Pair 3). The similarity of the standard deviation suggests that the interferometric phases were correctly transformed into heights in the present study.

Although the estimated height itself might not be necessarily enough to observe the details of low relief topography in the Hanoi area, the similarity of three DEMs suggests a possibility that the present results can be used to investigate factors affecting the interferometric phases such as artificial objects, water body or vegetation. As an example, we compared the heights estimated from interferometric phase with a topographic map. The problem remains as the subject of a future study after we will construct the DEM based on a topographic map.

References


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