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Improving Terrain Height Estimates from RADARSAT Interferometric Measurements

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ABSTRACT

We describe two methods of combining two-pass RADARSAT interferometric phase maps with existing DTED (digital terrain elevation data) to produce improved terrain height estimates. The first is a least-squares estimation procedure that fits the unwrapped phase data to a phase map computed from the DTED. The second is a filtering technique that combines the interferometric height map with the DTED map based on spatial frequency content. Both methods preserve the high fidelity of the interferometric data.

INTRODUCTION

The SAR research community has shown a great deal of interest in the use of interferometric methods for topographic mapping. Orbital SARs such as SEASAT, ERS-1 & -2, and RADARSAT would seem to be excellent sensors for such applications, owing to their moderate resolution, large scene size, and the possibility for repeat orbital geometry.

Unfortunately, several shortcomings have conspired to reduce the impact of these systems in terrain mapping applications. One of the most serious of these is the lack of precise positional information on the sensor. Interferometric terrain solutions are highly sensitive to the precise position and orientation of the interferometric baseline between observations. Errors in this knowledge propagate into very large systematic errors of terrain height. A second critical error source is due to electromagnetic propagation effects. Height estimation errors due to this source are typically not as large as those resulting from baseline errors, but are less systematic.

In this paper, we briefly describe these two error sources and then develop two very general techniques for circumventing the associated problems. These methods make use of existing, albeit low resolution, terrain elevation data. Level 1 Digital Terrain Elevation Data (DTED), available from the National Imagery and Mapping Agency (NIMA) [formerly Defense Mapping Agency], cover a large percentage of the earth's landmass. Exhibiting a typical 100m post spacing and 20m LE-90 height accuracy, these data do not contain the fine

detail to be found in the interferometric SAR data. However, they do provide a means to remove the systematic errors that plague the raw IFSAR measurements.

SENSOR POSITION ERRORS

Consider the imaging geometry shown in Figure 1. Here a and b denote the separation of aperture phase centers parallel and orthogonal to the line of sight to a scene-center reference point at depression angle ψ_0 . Vectors $\vec{r}_1$ and $\vec{r}_2$ are line of sight vectors from each phase center to a certain point $\vec{p}$ on the terrain surface, and ψ is the depression angle to point $\vec{p}$. The corresponding interferometric phase at $\vec{p}$ may be written:

$$\begin{aligned}\phi_I(\vec{p}) &= \frac{4\pi}{\lambda} (|\vec{r}_1| - |\vec{r}_2|) \\ &\approx \frac{4\pi}{\lambda} (a \cos(\psi - \psi_0) - b \sin(\psi - \psi_0))\end{aligned}\quad (1)$$

Figure 1. Imaging geometry.

If parameters a and b are known precisely, we can easily solve Equation (1) for ψ in terms of ϕ_I and from this result derive the corresponding elevation of the terrain. Conversely, any errors in our knowledge of the baseline parameters will

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translate into errors in our estimate of terrain elevation that often prove to be unacceptable. Other errors common to most interferometric topographic mapping efforts are a constant phase ambiguity and linear error terms arising from imprecise aperture alignment in processing of the image pair. These linear errors typically give rise to intolerable tilts in the computed height map if they are not removed.

Our method of dealing with the errors described above is to estimate them by comparing the measured phase data with phases computed for a set of known ground control points (GCPs). Rather than using a small number of surveyed GCPs as other practitioners have done [1] to estimate the phase bias and tilts, we employ the entire Level 1 DTED map as ground control data.

PARAMETER ESTIMATION

The parameter estimation problem is formulated as follows. We write the measured unwrapped phase as:

$$\begin{aligned}\phi_M(\bar{p}) &= \phi_I(\bar{p}) + p_0 + p_x(x - x_c) + p_y(y - y_c) \\ &= \frac{4\pi}{\lambda} [a_1 + a_2(y - y_c)] \cos(\psi - \psi_0) \\ &\quad - \frac{4\pi}{\lambda} [b_1 + b_2(y - y_c)] \sin(\psi - \psi_0) \\ &\quad + p_0 + p_x(x - x_c) + p_y(y - y_c).\end{aligned}\quad (2)$$

Here x and y are the cross-track (range) and along-track (azimuth) image coordinates of $\bar{p}$, while x_c and y_c denote the scene-center coordinates. Equation (2) incorporates the constant phase ambiguity p_0 and linear phase tilts p_x and p_y in the cross-track and along-track directions. The baseline parameters a and b are allowed to vary linearly in the along-track direction to account for slightly non-parallel satellite orbits.

The unknown parameters in Equation (2) are all linear with respect to the measured phase, so they may be estimated by the least-squares method. We construct parameter and coefficient vectors

$$\bar{v} = \begin{bmatrix} p_0 \\ p_x \\ p_y \\ b_1 \\ a_1 \\ b_2 \\ a_2 \end{bmatrix}$$

$$\bar{h}_i = \begin{bmatrix} 1 \\ x_i - x_c \\ y_i - y_c \\ -(4\pi/\lambda) \sin(\psi_i - \psi_0) \\ (4\pi/\lambda) [\cos(\psi_i - \psi_0)] \\ -(4\pi/\lambda) [\sin(\psi_i - \psi_0)] (y_i - y_c) \\ (4\pi/\lambda) [\cos(\psi_i - \psi_0)] (y_i - y_c) \end{bmatrix}$$

using i to index position in the image. The phase we expect to see at position i is:

$$\phi_i = \bar{h}_i^T \bar{v} \quad (3)$$

The unwrapped phase is sampled on a grid commensurate with the DTED post spacing. For each such sample ϕ_i , we transform its image coordinates (x_i, y_i) into the corresponding location in the DTED map. The DTED are interpolated to obtain the terrain height, which is then converted into a depression angle ψ_i . The three-space coordinates (x_i, y_i, ψ_i) allow us to compute the coefficient vector $\bar{h}_i$ corresponding to phase sample ϕ_i .

An overdetermined system of equations is constructed as follows for a complete set of unwrapped phases:

$$\bar{\Phi}_M = H\bar{v}, \quad \bar{\Phi}_M = [\phi_1, \phi_2, \dots]^T, \quad H = [\bar{h}_1^T, \bar{h}_2^T, \dots]^T \quad (4)$$

The least squares estimate of the parameter vector is just the solution to the matrix equation:

$$(\bar{H}^T \bar{H}) \bar{v} = \bar{H}^T \bar{\Phi}_M \quad (5)$$

Once the parameters are estimated, we can compute the interferometric phase from the measured phase using (2), and compute the actual depression angle to each scatterer using (1). The 3-space location of every phase sample is specified from its range and azimuth image coordinates and its depression angle. The final height map is thereby obtained at the sample rate of the unwrapped phase data, which is considerably denser than the Level 1 DTED.

PROPAGATION EFFECTS

Because these satellite sensors must propagate electromagnetic energy through the ionosphere and the troposphere, the radar pulses are subject to small variations in the index of refraction along the lines of propagation. These variations result from changes in the total electron content of the ionosphere, and turbulence (coupled with water vapor content) in the troposphere. For two-pass collections, changes in the electrical path length from one pass to the other introduce errors in the observed interferometric phase differences. Goldstein reported substantial errors from the tropospheric source, even in a region with a very dry climate [2]. These errors are quite random in nature, but exhibit a characteristic spatial spectrum that is power law with a slope of $-8/3$. Therefore, the height discrepancies that result have the most energy at low spatial frequencies.

Since we possess interferometric data that contains desired detail at high spatial frequencies but random low frequency errors and we have complementary Level 1 DTED with good large scale fidelity but poor (or non-existent) high frequency information, it seems reasonable to combine the two via filtering. This is also a useful technique for situations where the interferometric baseline is too large for the terrain slopes encountered. The subsequent aliased interferometric phase cannot always be unwrapped properly, resulting in isolated regions with one or more cycles of phase error. These large-area unwrap errors can likewise be addressed with a filter that combines the DTED map with the interferometric data.

Figure 2. Low Spatial Frequency Congruence Filter.

With reference to Figure 2, the filtering procedure proceeds as follows. Using the parameters estimated as described above, we can compute an *estimated* unwrapped phase function from the DTED height map. The difference between that and the actual unwrapped phase function is low-pass filtered and added to the actual phase function. The low-pass cutoff frequency is chosen such that only the low frequency errors are processed. The output phase function, which is then used for DEM production, therefore benefits from the large-scale fidelity of the DTED data as well as the fine scale detail of the interferometric height.

AN EXAMPLE

Figure 3 shows an example DEM that was generated from eight pairs of RADARSAT interferometric pairs collected over the South-Central region of Iran. The resultant map has a post spacing of 35m on a UTM projection. The fact that these eight pairs, with baselines ranging from about 80m to greater than 600m, mosaic together without discernable discontinuities at their boundaries can be attributed to use of the least squares estimation of the baseline parameters as well as the low-spatial-frequency congruence filter discussed in this paper.

Figure 3. An eight pair mosaic of RADARSAT interferometric DEMs.

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