Enhanced Model for Generating 3-D Images from RADAR Interferometric Satellite Images

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Abstract: The advent of interferometric SAR for geophysical studies has resulted in the need for accurate methods of two-dimensional phase unwrapping. Main approaches for phase unwrapping begin with the measured gradient of the phase field, which is subsequently integrated to recover the unwrapped phases. They also incorporate residue identification and cuts hence limiting the possible integration paths.

In this paper, first principal components of different quality maps are used to guide the processes of phase unwrapping. Principal component analysis seeks directions in feature space that best represents the data in least squares sense. It is a way of expressing data to highlight their similarities and differences.

Four types of quality maps are introduced, including Pearson coefficients, pseudo-correlation, phase derivate variance, and maximum phase gradient. The proposed scheme depends on quality maps to guide the placement of branch cut. It depends on the assumption that the residues are confined to a low quality regions and a quality map guides the integration path.

The proposed model using different quality maps is verified. It was found that the branch-cut algorithm is quite accurate but does not produce estimates in regions of highly phase noise. A new synthesis model, combining the cuts and the outputs of principal component transformation offers greater spatial coverage with less distortion in many instances.

Key-Words: - Phase Unwrapping, Radar Images, Interferometry, Quality maps, Principle Component

1 Introduction

Airborne and spaceborne Synthetic Aperture Radar (SAR) platforms have been used for many years to study the earth's surface [1]. When two radars on a single platform or two passes of single radar map the same area, an interferogram can be produced from the difference in phase measured by each radar or pass. An interferogram is a pictorial representation of the phase differences measured at each pixel. Since the measured phase differences lie between $-\pi$ and π, the phase is said to be wrapped [2]. A SAR interferogram contains fringes. These fringes are the locations on the interferogram where a 2π discontinuity exists. The interferogram resembles a topographical contour map where a line of constant elevation corresponds to a fringe. When no noise is present, the fringes can easily be located and the data adjusted by adding multiples of 2π to produce an unwrapped phase image [1, 2]. However, real-world data are always contaminated with noise, hence there is a need to develop sophisticated phase unwrapping algorithms. Successful phase unwrapping is the key to the extraction interferometric SAR phase image. The remainder of the paper is organized as follows: Section (2) focuses on branch cut method for phase unwrapping. Section (3) describes different quality maps. Section (4) emphasizes the proposed model for improving branch cut method using for quality maps. Section (5) describes the results and evaluation. Section (6) summarizes the conclusion.

2. Phase Unwrapping Technique by Branch Cut Method

The branch cut method solution is derived from integrating the fringes. The unwrapped phase is obtained directly by moving along the wrapped phase map while adding or subtracting 2π when a fringe is crossed. The branch cut method is a technique to compensate for the noise in the interferogram. First, phase inconsistencies, in the form of residues are located. Pairs of residues are connected to form branch cuts and phase is unwrapped by adjusting the integration path or by modifying the fringe information. This approach is intuitively appealing, but offers its own set of difficulties. Although the concept is straightforward, the difficulty of the branch cut method becomes apparent when connecting branch points. First of all, the residues must be connected in pairs (i.e. positive to negative), and there is no guarantee that the interferogram will contain an equal number of positive and negative residues. It is very likely that single poles will remain after a branch cut algorithm has been run. Incorrect treatment of these single poles will result in errors. Another difficulty occurs when the residue density is high, it is rarely obvious which residues should be connected to form a branch cut. The question of the best way to connect a given set of residues is still open [3]. Since noise will create pairs of residues (one positive and one negative) the connection method must favor connections of residues close to each other. If all the residues reside completely within the edges of the SAR interferogram, the connections can be made in a fairly straight forward manner to the edge, and any errors that result tend to be local in nature. However, in a SAR interferogram the data is truncated and some of the residues's corresponding matches are not included in the SAR interferometry data set. The way that connection scheme deals with this problem determine the algorithm's accuracy. Schemes based on connecting only nearest neighbors have been used to unwrap SAR interferograms [4], [5]. This method can lead to uncompensated residues that require manual operation to fix.

3. Quality Maps

The main idea is to use anther estimator (quality map) to guide the integration path in the phase and residue data [6]. Quality map can be defined as an array of values that define the goodness or badness of each pixel of the given phase data. There are different types of quality maps used in phase unwrapping problem including:

3.1 Pearson Coefficient

The Pearson Product Moment Correlation Coefficient (*r*) is used to measure a correlation or association [7]. The product moment part of the name comes from the way in which it is calculated, by summing up the products of the deviations of the variables from the mean. Pearson Coefficient is defined as:

$$r = \frac{\Sigma\left(X - \mu_x\right)\left(Y - \mu_y\right)}{N\sigma_x\sigma_y} \quad (1)$$

where the numerator of this formula is the sum up of the products of the deviations of a variable X from the mean of the Xs and the deviation of the variable Y from the mean of the Ys. This summation of the product of the deviation scores is divided by the number of variables (N) times the standard deviation of the X variables times the standard deviation of the Y variables. The regions due to layover, shadow, and miss-registration will produce de-correlated regions of the unwrapped phase data.

3.2 Pseudo-Correlation.

Pseudo-correlation marks the steep terrain as low quality regions [6], even though the phase data are well defined and noiseless. This is because the high terrain slopes are regions of high phase variations and thus the phase data are not well correlated with one another. Pseudo-correlation is defined as:

$$\frac{\sqrt{\sum(\cos\psi_{i,j})^2 + \sum(\sin\psi_{i,j})^2}}{k^2} \quad (2)$$

This is evaluated in k x k neighbourhood of each pixel Ψ(i, j) in phase data. The low values indicate low correlation (low quality areas) which indicate where the noise regions of phase exist, and vice versa.

3.3 Maximum Phase Gradient.

The maximum phase gradient at a pixel is defined to be average of two values:

$$\max\{|\Delta^x_{i,j}\}| \;,\; \max\{|\Delta^y_{i,j}|\} \quad (3)$$

It measures the magnitude of the largest phase gradient (partial derivative or wrapped difference) in the K x K neighbourhood of each pixel [6]. Where the maxima are evaluated in K x K neighbourhoods of the given pixel. The terms $\Delta^x_{i,j}$, $\Delta^y_{i,j}$ are the partial derivatives of the phase in x and y direction, respectively. In regions of noisy phase, the gradient tends to be large however, in steep terrain slop (highly varying but noiseless phase), maximum phase gradient also yields low quality values. The maximum phase gradient is negated so that it becomes a measure of good quality phase.

3.4 Phase Gradient Variance.

It is defined as:

$$\frac{\sqrt{\sum(\Delta^x_{i,j} - \overline{\Delta^x}_{m,n})^2} + \sqrt{\sum(\Delta^y_{i,j} - \overline{\Delta^y}_{m,n})^2}}{k^2} \quad (4)$$

where:

$\Delta^x_{i,j}$ and $\Delta^x_{i,j}$ are the partial derivatives of the phase. The terms $\overline{\Delta^x}_{i,j}$ and $\overline{\Delta^y}_{m,n}$ are the averages of these partial derivatives in the k x k windows. It measures statistical variance of phase derivative [6]. It marks highly varying phase (steep terrain). The phase derivative variance highlights the regions of de-correlated phase caused by SAR layover (in this case phase derivative variance exhibits constant phase variation). Same conclusion is achieved in the case of tilted plan.

4. The Proposed Model for Improving Phase Unwrapping

In this paper, phase unwrapping is performed through integration of continually growing area of unwrapped phase, growing into regions of high quality phase as indicated by quality maps. A quality map is an additional array of values indicating the quality of the corresponding phase values. They are derived from the phase data, regions of smooth phase are assigned high quality values whereas others are considered to indicate low quality. Four schemes to derive quality maps from phase data [6] are used, and discussed below. The four output quality maps are stacked and transformed using principal component analysis to use the advantage of compacting redundant information in quality maps. The first principal component is then used as a quality measure, containing the highest variation within the input data (different quality maps), in phase unwrapping. Figure 1 shows the flow diagram of the proposed phase unwrapping scheme.

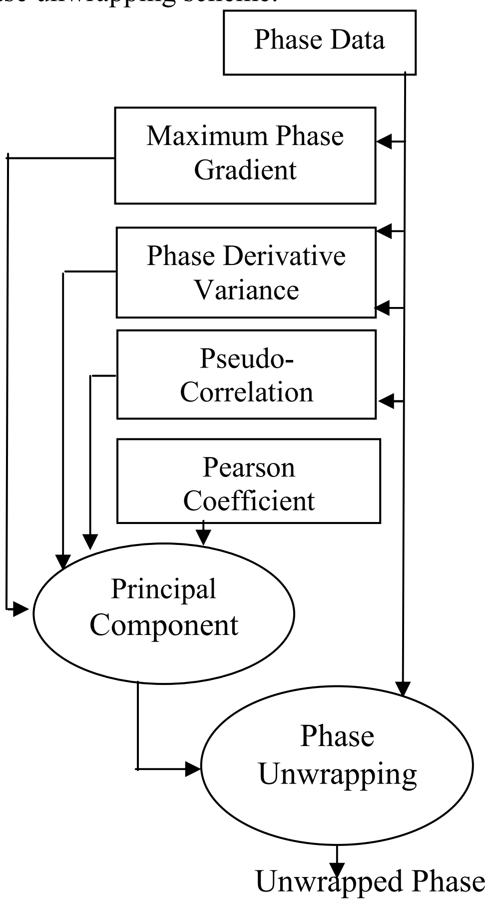
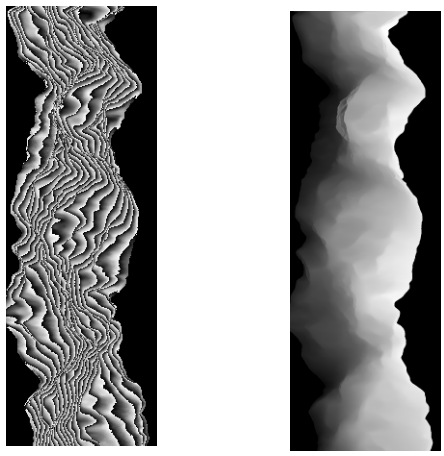


Figure (1) System flow chart for proposed phase unwrapping scheme

5. Results

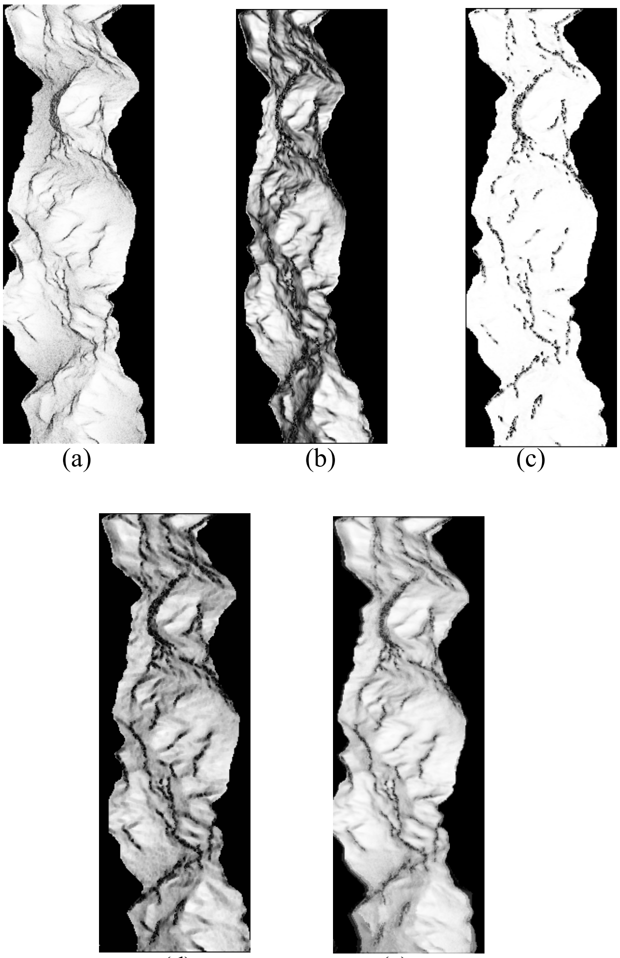
In this study, simulated interferometric SAR (InSAR) example is used. The data set was generated on the basis of a real digital elevation model of mountainous terrain around Long's, and isolation Peak Colorado, united state, using a high-fidelity InSAR simulator that models the SAR point spread function, InSAR geometry, speckle noise, layover and shadow phenomena [6]. The size of the image in pixels is 458 (azimuth) × 152 (range). The estimated surfaces are compared with the reference digital elevation model. Figure (2) shows the input phase data and reference unwrapped phase. In order to evaluate the effect of proposed model on phase unwrapping, we consider the determination of the phase field estimation, firstly without aid of any quality maps, then by using each of quality maps separately. The output results are compared with the reference data shown in Figures (3 a-e). Mean square error (MSE) is used to check the over all errors distributed along the whole images. Then some scattered points are evaluated and plotted against their reference values to measure the performance of the algorithms over faulty regions.



(a) (b)

Figure (2) Input and reference data (a) Wrapped input phase for isolation peak (b) Reference DEM for Isolation Peak

Figure (3) shows the different quality maps for isolation peak simulated InSAR problem of figure 2(a). Figure 3(a) depicts an output of Pearson coefficient, low correlation coefficient are shown as dark pixels and height correlation coefficients as light pixels. The low correlation regions along the mountain peaks correspond to the regions of de-correlated phase, which were induced by SAR layover

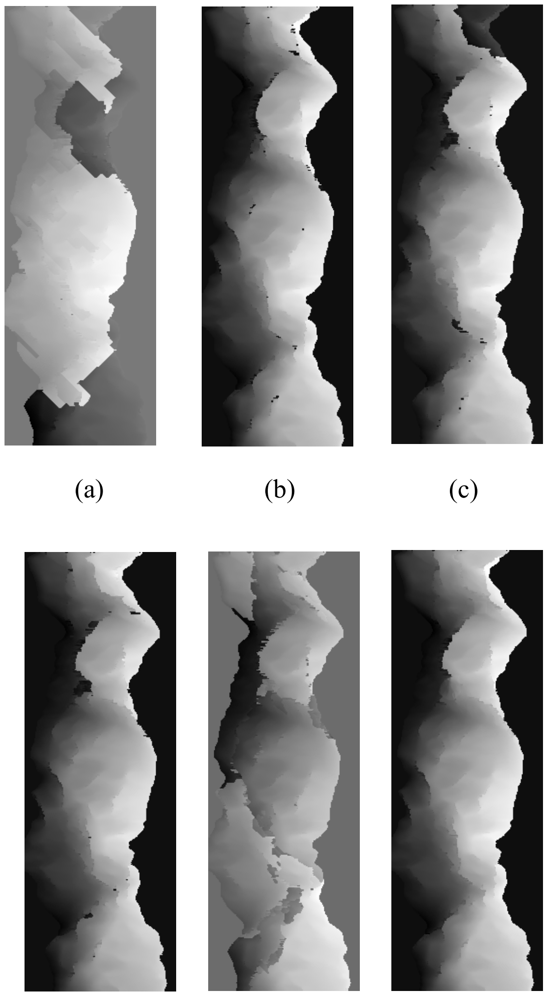


(a) (b) (c)

(d) (e)

Figure (3) Different quality maps for isolation peak (a) Pearson coefficient map , (b) Pseudo- correlation, (c) Gradient variance, (d) Maximum phase gradient, (e) First principal component

The pseudo correlation map shown in Figure (3-b) is quite different from the Pearson coefficient map. The dark regions indicate the regions of highly varying phase as well as regions of high terrain variation. The phase derivative variance map is shown in Figure (3-c), the dark pixels indicate regions of de-correlated phase due to layover. Unlike Pearson coefficient and pseudo correlation, the phase derivative variance does not mark the regions of steep terrain as low quality unless the phase data are de-correlated. The maximum phase gradient map is shown in Figure (3-d), the dark pixels indicate steep gradient, which tend to be noisy pixels. Figure (4) shows the different unwrapped phase using different quality maps discussed in section 3. Mean square error, MSE, is the performance measures used to quantify the performance of various quality maps in phase unwrapping process. Table (1) lists different MSE values for different quality maps. In general, it can be stated that the MSE using principal component is the lowest one with slight difference of phase gradient variance and Pearson coefficient.



(a) (b) (c)

(d) (e) (f)

Figure (4) Output DEM using different quality maps for isolation peak (a) Without quality maps, (b) Pearson coefficient map, (c) Minimum gradient, (d)Minimum variance, (e) Pseudo correlation, (f) First principal component

For the qualitative assessment of different quality maps used in phase unwrapping algorithm. Figure (4-a) shows that the algorithm without using quality maps incorrectly unwraps several regions. By contrast, using quality maps correctly unwraps most of those troublesome (dark) regions. These regions are those in which phase data exhibits a low quality values due to layover, shadow, or noise. Using non linear transformation of different quality maps based on principal component transformation appears to unwrap these troublesome regions correctly as shown in Figure (4-f).

For quantitative assessment of different quality maps used in phase unwrapping, mean square error of the derived unwrapped phase is calculated to estimate the over all performance as shown in table (1). Then ten random points are checked, evaluated and plotted against their reference values as shown in Figure 5.

Quality Map	**Mean Square Error (Meters)**
Pearson Coefficient.	220
Pseudo-correlation.	2651
Maximum phase gradient.	448
Phase gradient variance.	224
First Principal component.	208

Table 1. Mean square Error of Height Inversion of Input Interferogram using different quality maps

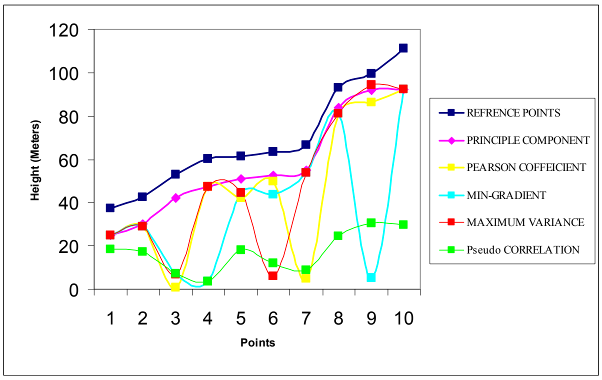


Figure (5) Graphical representation of the unwrapped values for different quality maps with respect to the reference values

Generally it can be stated that: First principal component produces the lowest MSE as indicated from table 1, followed by Pearson coefficient and phase gradient variance with slightly higher value of MSE. Pseudo-correlation comes with distorted output unwrapped phase with very high MSE value. By using quality maps, the phase data is correctly unwrapped, except of small patches (black holes in figure 5 and deep jumps in curves of Figure-5). The failure on that is due to the lack of a good quality estimation of pixel values in quality maps. On the other hand, using first principal component the algorithm unwraps these patches correctly.

6. Conclusions

A novel scheme for improving phase unwrapping problem is presented and evaluated in this study. The proposed scheme combines the different quality maps using principal component transformation to use the advantage of representing several spectral variables with little information loss. The first principle component produces a well defined quality measure (95 % of all input quality maps) used in phase unwrapping techniques

Phase unwrapping by means of branch cut algorithm without the aid of any quality maps fails due to nearest neighbour strategy which placed a branch cuts in undesired locations. In proposed scheme a new quality map is presented to exploit additional information form the phase data to determine where the branch cuts should lie.

Four quality maps are introduced in this study, Pearson coefficient, Minimum gradient, Minimum variance, and Pseudo correlation. In all cases the algorithm unwraps the phase data correctly except some small batches. The failure in these batches is due to misplacement of branch cut at these regions. First principal component of quality maps achieves noticeable improvements in overall performance of phase unwrapping problem.

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