

# Advances of Multibaseline Phase Unwrapping Technique in InSAR Signal Processing

Hanwen Yu <sup>\*</sup>, Yang Lan <sup>†</sup> and Mengdao Xing <sup>‡</sup>

<sup>\*</sup> University of Houston, Houston, USA

E-mail: yuhanwenxd@gmail.com

<sup>†</sup> Xidian University, Xi'an, China

lanyangxd@hotmail.com

<sup>‡</sup> Xidian University, Xi'an, China

xmd@xidian.edu.cn

**Abstract**—Synthetic aperture radar (SAR) interferometry (InSAR) is utilized in many remote sensing applications and has created a new class of radar data which has significantly evolved over the last couple of decades. Most of the current InSAR applications, such as, topographic mapping and deformation monitoring, typically use a technique called phase unwrapping (PU). It is well known that the traditional single-baseline PU procedure (i.e., traditional 2-D PU) is the most delicate step in InSAR signal processing chain, because it is an ill-posed problem. However, the recent research reveals that the multibaseline (MB) PU technique has potential to improve the InSAR PU problem from the ill-posed to the well-posed by means of the InSAR baseline diversity. In this special session paper, advances of the innovative MB PU technique are reviewed. We hope this special session paper will provide guidelines to future researchers to enhance further MB PU algorithmic developments.

## I. INTRODUCTION

Synthetic aperture radar (SAR) interferometry (InSAR) is a well-established and powerful remote sensing technique applied to measure many important geophysical parameters, such as, surface height or deformation of the topography. InSAR detects absolute phase changes, which can be converted to geophysical parameters, between two or more SAR acquisitions that have been achieved from slightly different positions [1]. Unfortunately, InSAR system only can directly acquire the wrapped phase but not the absolute phase itself. The wrapped phase is equal to the absolute phase modulo  $2\pi$  whose value range is from  $-\pi$  to  $\pi$ . The InSAR measurement of a target can be expressed by

$$\varphi(s) = \psi(s) - 2k(s)\pi \quad (1)$$

where  $\varphi(s) \in (-\pi, \pi]$  and  $k(s) \in \text{integer}$

where  $\varphi(s)$  is the wrapped phase of the  $s$ th pixel,  $\psi(s)$  is the absolute phase of the  $s$ th pixel, and  $k(s)$  is called the ambiguity number of the  $s$ th pixel. It can be seen that the wrapped phase must be unwrapped before further use, i.e., we have to remove the  $2\pi$  ambiguity from  $\varphi(s)$ . This  $2\pi$ -ambiguity removal technique is called phase unwrapping (PU).

It can be seen that the difficulty for solving (1) mainly arises from that there are two unknowns ( $\psi(s)$  and  $k(s)$ ) in (1). Because it is impossible to solve two unknowns with just one equation, so we cannot directly use (1) to uniquely obtain the

absolute phase  $\psi(s)$ . Under this condition, directly solving (1) is an ill-posed inverse problem. To be specific, multiple  $\psi(s)$ s could be obtained by  $\varphi(s)$  with different  $k(s)$ s. In order to obtain the unique PU solution, the traditional single-baseline (SB) PU makes use of the phase continuity assumption, which essentially requires the measured areas have spatial continuity, to estimate the absolute phase difference between neighboring pixels. Then the final PU result can be obtained through an integration process, theoretically. However, the phase continuity assumption cannot be considered as the truth. For some kinds of terrains, the phase continuity assumption cannot be satisfied, e.g., valleys and steep mountains. In other words, the SB PU is not applicable to the terrain with the violent phase change.

To overcome the limitation of the conventional SB PU, PU researchers invent and design the multibaseline (MB) PU technique. To be specific, MB PU takes advantage of InSAR baseline diversity to significantly increase the ambiguity intervals of interferometric phases, so it can conquer the limitation of the phase continuity assumption. In this special session paper, we will compare the SB PU with MB PU. Then, the advances of the MB PU will be introduced.

The rest of this paper is organized as follows. In Section II, the principle of the SB PU is reviewed. Then, Section III provides an introduction to the MB PU. Section IV shows the effectiveness of MB PU by a set of experiments. Finally, Section V guides some potential future research directions and concludes this paper.

## II. PRINCIPLE OF SB PU

In this Section, we will introduce the principle of SB PU and its limitations. As described in the last Section, SB PU needs the phase continuity assumption.

**Phase Continuity Assumption:** The absolute phase difference between any two neighboring pixels in the scene is less than  $\pi$  [2].

We can see that the purpose of the phase continuity assumption is to request the scene has phase spatial continuity. In other words, the sampling rate of the wrapped phases in the scene must be high enough. Under this condition, the SB PU technique can use the whole data of the scene to

solve the PU problem. To be specific, if the phase continuity assumption can hold, there will be no ambiguity existing in the gradient information of the absolute phase between any two adjacent pixels, i.e., the absolute phase difference can be truly estimated. The absolute phase gradient can be obtained by

$$\Delta_{\psi}(s, s-1) = \begin{cases} \varphi(s) - \varphi(s-1) & |\varphi(s) - \varphi(s-1)| \leq \pi \\ \varphi(s) - \varphi(s-1) - 2\pi & \varphi(s) - \varphi(s-1) > \pi \\ \varphi(s) - \varphi(s-1) + 2\pi & \varphi(s) - \varphi(s-1) < -\pi \end{cases} \quad (2)$$

where  $\Delta_{\psi}(s, s-1)$  is the estimated absolute phase gradient between adjacent pixel  $s-1$  and pixel  $s$ . Based on the result of (2), the final PU result can be obtained through an integration process with a known reference point. However, for some scenes, it is difficult for InSAR to get enough wrapped phase samples, e.g., steep mountains or building edges. Under this condition, the gradient results between some adjacent pixels obtained from (2) will be intrustable. Worse, the phase gradient estimation error may spread to the whole scene through the integration process. In this case, essentially, almost all the SB PU methods can be considered as a kind of criterion that minimizes the difference between the unwrapped phase gradient and the estimated gradient obtained by (2) with different objective functions to obtain the final PU solution. However, [2] indicates that finding the correct objective function for the SB PU is as difficult as finding a ghost. In other words, it is impossible to find one uniform objective function that can be effectively used on all the scenes.

In short, as an ill-posed problem, 2-D PU in InSAR is an impossibly fully solving problem for the SB PU techniques. In addition, the requirement of the phase continuity assumption also brings some extra limitations on applications of InSAR. For example, in the wetland study [3], [4], the rivers usually fully cut off the input interferogram as several pieces, so multiple ground control points (GCP) are needed to recover the absolute water change of the wetland (InSAR-derived result only represents spatially relative water level changes in the wetlands), but obtaining multiple proper GCPs in the wetland areas is not easy. In addition, in the large-scale PU study [5], [6], [7], [8], due to the requirement of the sampling rate, we cannot sample down the large-scale input interferogram to reduce the PU problem size. In order to overcome the limitation of the conventional SB PU, PU researchers invent and design the MB PU technique. We will introduce the MB PU technique in the next Section.

### III. PRINCIPLE OF MB PU

For simplicity, we will introduce the principle of the MB PU under the dual-baseline (DB) case in the following paragraphs. The relation between the terrain height and the absolute phase is shown as,

$$h(s) = \frac{\lambda \cdot r(s) \cdot \sin(\theta)}{B_i \cdot 4\pi} \cdot \psi_i(s) \quad (3)$$

where  $h(s)$  is the terrain height of the  $s$ th pixel,  $r(s)$  is the slant range of the target from the master channel of the  $s$ th pixel,  $\theta$  is the incidence angle,  $\lambda$  is the wavelength,  $B_i$  and  $\psi_i(s)$  are the normal baseline length and absolute phase of the  $s$ th pixel in the  $i$ th ( $i = 1, 2$ ) interferogram, respectively. If we combine the absolute phases of two interferograms by (3) which is

$$B_2 \cdot (\varphi_1(s) + 2k_1(s)\pi) = B_1 \cdot (\varphi_2(s) + 2k_2(s)\pi) \quad (4)$$

where  $k_i(s)$  and  $\varphi_i(s)$  are the ambiguity number and wrapped phase of the  $s$ th pixel in the  $i$ th ( $i = 1, 2$ ) interferogram, respectively. In (4), there are two unknowns (i.e.,  $k_1(s)$  and  $k_2(s)$ ), so we cannot simultaneously solve them only using (4), theoretically. However, because  $k_1(s)$  and  $k_2(s)$  are integers, the Chinese Remainder Theorem (CRT) offers us an option to ensure the uniqueness of the solution to (4) under some special combination of the normal baseline length [3]. Under this condition, we can find the solution of (4) by an integer programming model which is

$$\begin{aligned} \arg \min_{k_1(s), k_2(s)} & |B_2 \cdot (\varphi_1(s) + 2k_1(s)\pi) \\ & - B_1 \cdot (\varphi_2(s) + 2k_2(s)\pi)| \\ \text{s.t.} & L_{k_1(s)} \leq k_1(s) \leq U_{k_1(s)} \\ & L_{k_2(s)} \leq k_2(s) \leq U_{k_2(s)} \\ & k_1(s), k_2(s) \in \text{integer} \end{aligned} \quad (5)$$

where  $(L_{k_i(s)}, U_{k_i(s)})(i = 1, 2)$  are the CRT searching windows of  $k_i(s)(i = 1, 2)$ . From (5), it can be seen that MB PU is not based on the phase gradient between adjacent pixels of the whole scene, so MB PU does not need high spatial sampling rate. In other words, MB PU is based on the repeated observations with different system parameters which is like phototopography. These characteristics make MB PU technique unwrap phase pixel by pixel. More importantly, (5) does not need any assumption or constraint condition. We can see that the MB PU is well-posed but not ill-posed, so MB PU has a wider application scope. For example, it is applicable to the terrain with the violent phase change.

The MB PU technique has been drawing more and more attention as the icebreaking MB research achievements are increasing. For example, there are two critical questions to MB PU: 1) what is the best normal baseline length for MB PU; 2) how to manually obtain the best baseline length in the repeat-pass based MB InSAR system. For these two scientific questions, [9] proposes an optimal baseline design criterion for all the CRT-based MB PU methods. In addition, [10] introduces a method to manually change the normal baseline length of the repeat-pass based MB InSAR system through using the motion compensation algorithm. It can be seen that the door appears open for improving the InSAR technique from an ill-posed problem to a well-posed problem through using the MB PU. It is fair to say that the MB PU technique starts to be ready to be used in the practical applications. In the next Section, we will use a set of experiment results to show the advances of MB PU.

TABLE I  
MAJOR INTERFEROMETRIC PARAMETERS OF EMPLOYED REAL DATA SET OF ALOS PALSAR

Orbit Altitude	Incidence Angle		Wavelength	
691.65km	34.3°		0.236m	
Interferogram	Fig. 1(a)		Fig. 1(b)	
Normal Baseline	192.99m		112.96m	
Image Size	500 × 500 pixels		500 × 500 pixels	
Channel	Master	Slave	Master	Slave
Date	August 18 2007	July 03 2007	August 18 2007	October 03 2007
Interferogram	Fig. 1(c)		Fig. 1(d)	
Normal Baseline	404.78m		439.95m	
Image Size	500 × 500 pixels		500 × 500 pixels	
Channel	Master	Slave	Master	Slave
Date	August 18 2007	January 03 2008	August 18 2007	October 08 2009

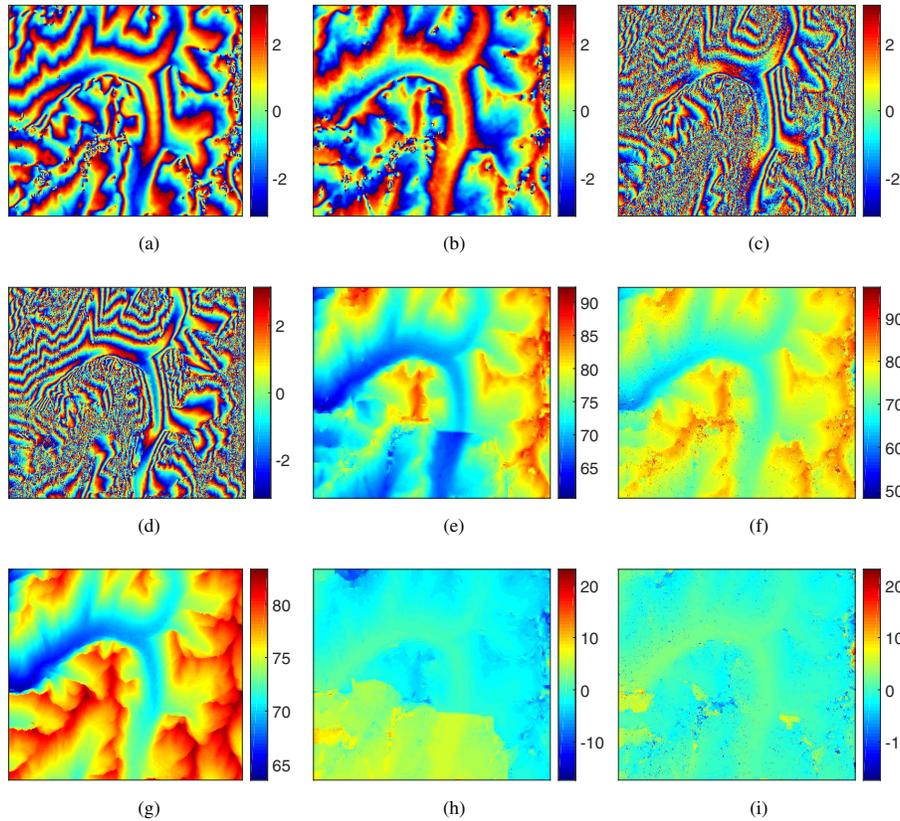


Fig. 1. (a) ALOS PALSAR interferogram 1. (b) ALOS PALSAR interferogram 2. (c) ALOS PALSAR interferogram 3. (d) ALOS PALSAR interferogram 4. (e) PU solution of (a) obtained by the SB MCF PU method. (f) PU solution of (c) obtained by the MB TSPA PU method. (g) Reference unwrapped phase of (a). (h) Errors between (e) and (f). (i) Errors between (e) and (g).

IV. EXPERIMENT

In this experiment, we choose the Minimum-Cost Flow (MCF) SB PU method [11] to compare with the two-stage programming based MB PU method (TSPA) [12]. MCF and TSPA are both representative PU methods in SB and MB PU domains, respectively. The SAR images employed in this experiment are acquired by the ALOS PALSAR from the Himalayan mountain area. The major interferometric parameters of this real repeat-pass data are listed in Table I. Figs. 1(a)-

(d) are filtered interferograms with different normal baseline lengths. Fig. 1(e) is the absolute phase, obtained by the MCF SB PU method, of Fig. 1(a). Fig. 1(f) is the absolute phase, obtained by the TSPA MB PU method, of Fig. 1(a). We can see that Fig. 1(a) has very complicated fringe patterns, so the phase continuity assumption may not be satisfied. Under this condition, there are some obvious long cutting lines (i.e., discontinuous phase jumps) in Fig. 1(e). We know that the phase fringe in the interferogram is analogous to a contour

map, so the absolute phase on the same fringe should be the same. Through comparing Fig. 1(e) with the fringe trend of Fig. 1(a), we know that these discontinuous variations should be SB PU artifact errors from the MCF method (the discontinuous phase jumps cut off the phase fringe). However, because the TSPA MB PU method does not need to obey the phase continuity assumption, the PU result shown in Fig. 1(f) seems more credible than that shown in Fig. 1(e). Fig. 1(g) is the reference unwrapped phase of Fig. 1(a), which is generated by the PALSAR DEM. Fig. 1(h) shows the errors between Fig. 1(e) and Fig. 1(g) with MSE of 11.12. We can see that the PU error spreads over the lower part of Fig. 1(e). Fig. 1(i) shows the errors between Fig. 1(f) and Fig. 1(g) with MSE of 4.38. It is worth mentioning that, in order to effectively and fairly compare the performance, the same reference point, scale, and range of the colorbar are applied in Figs. 1(h) and (i). The colorbar range is from the minimum pixel value of Figs. 1(h) and (i) to the maximum pixel value of those. It can be seen that the MB PU much outperforms the traditional SB PU.

## V. CONCLUSIONS

MB PU is a growing and exciting PU technique for InSAR, which can give InSAR the wider application scope on the study area with violent phase change. Unlike SB PU, MB PU does not need any presumption, so the door appears open for improving the InSAR technique from an ill-posed problem to a well-posed problem through using the MB PU. Although the research achievements on MB PU look exciting, rapid advancement is still expected in some fields of MB PU in the upcoming years. For example, the MB PU needs to process multiple interferograms simultaneously, the scale of the input interferograms will pose unique challenging when it exceeds the limit of computational capabilities. Therefore, how to greatly reduce the time and memory consumption of the well-established small- and medium-scale MB PU methods still needs research. However, in general, it is fair to say that the MB PU technique starts to be ready to be used in the practical applications.

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