NEW IMPROVEMENTS OF THE EMCF PHASE UNWRAPPING ALGORITHM FOR SURFACE DEFORMATION ANALYSIS AT FULL SPATIAL RESOLUTION SCALE

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ABSTRACT

We present an effective space-time phase unwrapping (PhU) algorithm that allows us to analyze (large) sequences of multi-temporal differential Synthetic Aperture Radar (SAR) interferograms at the full spatial resolution scale for the generation of surface deformation time-series. The core of the proposed technique is represented by the Extended Minimum Cost Flow (EMCF) PhU algorithm. The method relies on the joint exploitation of both the spatial and temporal relationships among a set of properly selected multi-master differential interferograms. In particular, the key idea is to split the complex MCF network problem into that of simpler sub-networks. Accordingly, we start by identifying and solving a primary network involving a proper selection of the coherent pixels common to the computed interferograms, representing the backbone structure of the overall network. Afterwards, this result is applied for constraining the solution of the sub-networks connected to the primary one, and involving the whole set of analyzed pixels. This task is achieved by solving a constrained optimization problem based on the computation of a Constrained Delaunay Triangulation (CDT) in the Azimuth/Range domain. The experimental results, obtained by applying the proposed method to a dataset consisting of European Remote Sensing (ERS) SAR data acquired from June 1992 to August 2007 over the Napoli (Italy) bay area, confirm the effectiveness of the proposed PhU approach..

Index Terms— Deformation time-series, Differential SAR interferometry, Small BAseline Subset (SBAS), Phase unwrapping (PhU)

1. INTRODUCTION

Differential synthetic aperture radar interferometry (DInSAR) is a well-known technique for the generation of spatially-dense surface deformation maps of large areas on Earth [1]. To achieve this task, the phase difference between SAR data pairs corresponding to temporally-separated observations is exploited, obtaining a measurement of the ground deformation projection along the radar line of sight (LOS) with centimeter to millimeter accuracy.

In this work, we concentrate on the advanced DInSAR technique referred to as Small Baseline (SB) subset that was originally developed for analyzing multi-look interferograms [2] and subsequently adapted to the full resolution case [3]. Within this framework a critical problem to be faced is the Phase Unwrapping (PhU) operation that represents the retrieval process of the absolute phase signals from their (measured) modulo-2π restricted components. In particular, we focus on the technique referred to as Extended Minimum Cost Flow (EMCF), representing the space-time extension of the basic Minimum Cost Flow (MCF) PhU algorithm [4].

The EMCF technique, which is well integrated in the SBAS processing chain, is based on the computation of two Delaunay triangulations. The former accounts for the SAR data acquisition distribution in the Temporal/Perpendicular baseline plane through a set of points, whereas the latter involves the coherent pixels common to the generated interferograms. It is worth to remark that the selection of the proper SAR data pairs via a triangulation in the temporal/perpendicular baseline plane may unfortunately lead to generate interferograms with large temporal and/or spatial baselines, which may be drastically corrupted by decorrelation phenomena. Accordingly, to avoid these effects, we also impose constraints on the maximum allowed interferogram baseline values, and we discard from the triangulation all the triangles involving at least one “large baseline” interferogram. Equivalently, we also remove triangles which involve SAR data pairs characterized by doppler centroid differences exceeding a selected threshold. Therefore, after the triangle removal step, we obtain the SAR data pair distribution, as the one shown in Fig. 1(b).

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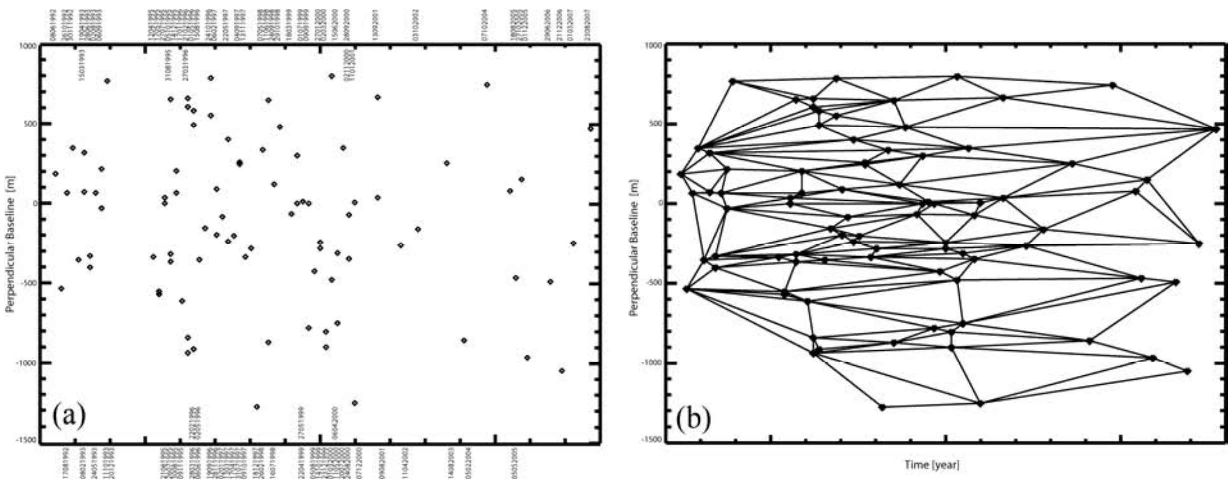

Fig. 1 SAR data representation in the temporal/perpendicular baseline plane for the ERS-1/2 SAR data analyzed in the following experiments, relevant to the Napoli (Italy) bay area. (a) SAR image distribution. (b) Delaunay Triangulation after the removal of triangles with sides characterized by spatial and temporal baseline values, as well as doppler centroid differences, exceeding the selected thresholds (corresponding in our experiments to 400 m, 1500 days and 1000 Hz, respectively).

The unwrapping operation is performed as follows: first of all, for each arc connecting neighboring pixels in the azimuth/range plane, the unwrapped phase differences are estimated by applying the MCF technique in the temporal/perpendicular baseline plane. Subsequently, these estimates are used as the starting point for the spatial unwrapping operation, implemented again via the MCF approach, but in the Azimuth/Range plane.

In this work, we propose to exploit the highly efficient EMCF algorithm as the core procedure to unwrap sequences of large single-look DInSAR interferograms suitable for the generation of deformation time-series through the SBAS approach. This PhU approach allows us to directly apply the SBAS inversion to the unwrapped full resolution DInSAR phase sequences, with no need to pass through the analysis of the corresponding sequences of multi-look DInSAR interferograms [3]. To properly solve this PhU problem, we suggest to apply an effective divide-and-conquer approach to the space-time phase unwrapping problem. The key idea is to divide the complex minimum cost flow network problems, implementing the whole PhU step, into that of simpler sub-networks, which are solved by applying the EMCF approach. More precisely, we start by identifying, and solving, a primary network that involves a selected set of very coherent pixels in our interferograms. The results of this primary network minimization, representing the backbone structure of the overall network, are subsequently used to constrain the solution of the remaining sub-networks, including the entire set of coherent pixels. To achieve this task, the second EMCF PhU step relies on the generation of a Constrained Delaunay Triangulation (CDT) [5], whose constrained edges are relevant to the set of successfully unwrapped pixels analyzed during the first PhU operation. We remark that our approach has some similarities with [6] where a two-scale strategy was also suggested to unwrap large interferograms; however our strategy is similar but inverted because in our scheme the primary PhU step is used to figure out a (global) PhU solution, and the secondary one to locally "propagate" the PhU solution in low coherent areas.

2. EMCF-BASED PHU TECHNIQUE

The key idea of the proposed approach is to split our complex MCF network problem into that of simpler sub-networks. This solution can be efficiently implemented, as shown in the following, through two subsequent processing steps that are both carried out by using the EMCF technique. Basically, the first PhU step is carried out on a set of very coherent pixels, used to compute a Delaunay triangulation in the Azimuth/Range plane, and the achieved PhU results are eventually exploited to successfully unwrap the remaining pixels. To achieve this task we solve a "constrained optimization problem" based on the computation of a Constrained Delaunay Triangulation (CDT) in the plane from the grid of the overall coherent pixels. To clarify this issue, let us provide some basic information about the CDT, which is a triangulation of a given set of vertices with the following properties [5]: 1) a pre-specified set of non-

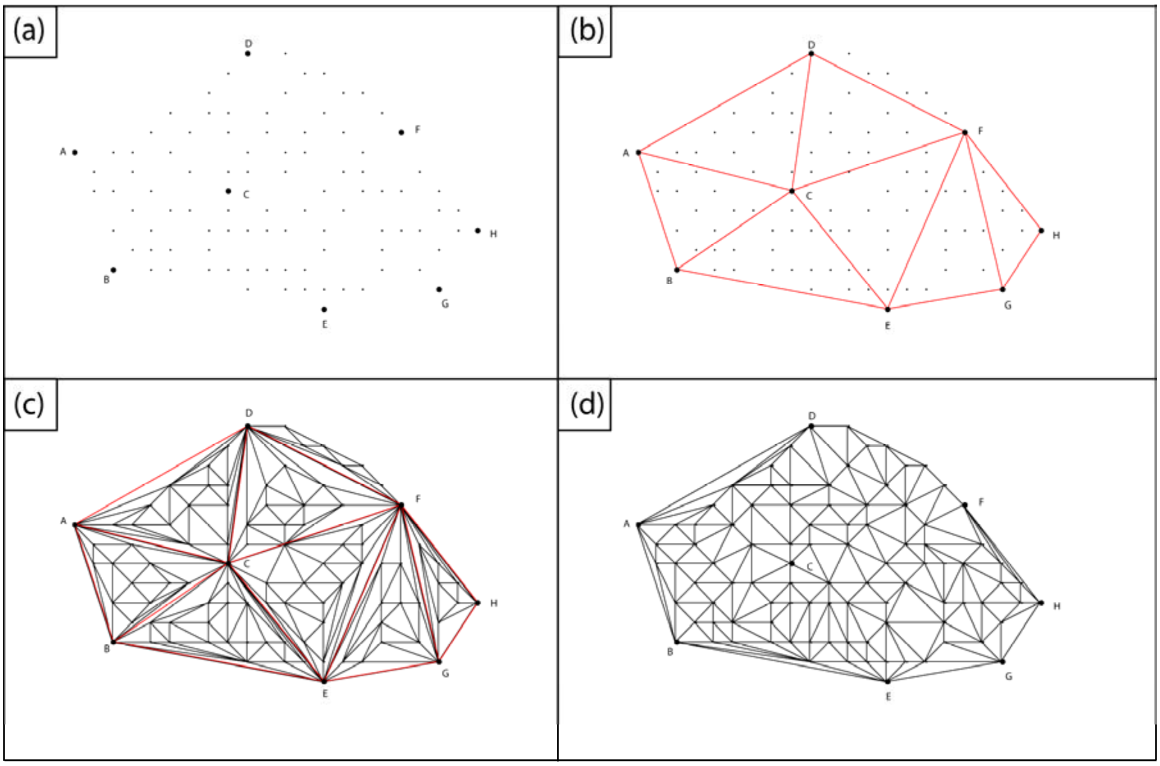

Fig. 3 Examples of Triangulations. (a) Dataset of 96 points with highlighted 8 of them, labeled to as A, B, C, D, E, F, G, H, respectively. (b) The 8-points Delaunay triangulation drawn with red lines (c) Constrained Delaunay Triangulation generated from the set of points of (a), and by using as constraints the triangulation of (b). (d) Delaunay triangulation computed from the 96 points in (a).

crossing edges (referred to as constraints, or constrained edges) is included in the triangulation, and (2) the triangulation is as close as possible to a Delaunay one. As an example, in Fig. 2, it is shown a simple CDT relevant to a set of 96 points, see Fig. 2(a); in this case the selected constraints are represented by the 14 edges of the Delaunay triangulation generated from an eight-points subset of the originally 96 ones, see Fig. 2(b); the computed CDT is shown in Fig. 2(c), whereas the corresponding Delaunay triangulation is presented in Fig. 2(d).

Similarly to the case of Figure 2, we compute a CDT for the spatial grid of the pixels , whose constrained edges are the arcs of the previously identified primary network . Since the EMCF Phase Unwrapping algorithm can work with generic triangular irregular grids, not necessarily Delaunay triangulations, it can be also applied to the irregular spatial grid obtained via our CDT. However, in this case we must solve a constrained optimization problem because we want to preserve, for each interferogram, the unwrapped phase values already obtained by solving the primary network. Accordingly, we perform the second unwrapping step again through the EMCF approach but applying the temporal PhU step only to the unconstrained arcs of the generated CDT. Moreover, the spatial PhU step is carried out on each single interferogram via the basic MCF approach but, in order to preserve the unwrapped phases relevant to the primary network, the weights used for the spatial MCF minimization must be properly set. If we refer to the generic PQ arc, this is achieved by imposing:

$$w_{PQ} = \begin{cases} L & PQ \in \{G_{Constrained}\} \\ 100 & \{PQ \notin \{G_{Constrained}\}\} \cap \{Cst_{\min} < \rho\} \\ 1 & \{PQ \notin \{G_{Constrained}\}\} \cap \{Cst_{\min} > \rho\} \end{cases} \qquad (1)$$

where $\{G_{Constrained}\}$ is the set of constrained edges, and $Cst_{\min}$ is the temporal minimum network cost relevant to the given spatial arc. Moreover, L is a very large integer number, and ρ is a threshold value that is typically set not greater than 5% of the total number of interferograms. Based on (11), the flow into the constrained MCF network is automatically forced not to cross the constrained arcs and, as a consequence, the estimates of the primary network unwrapped phases are fully preserved. In other words, the

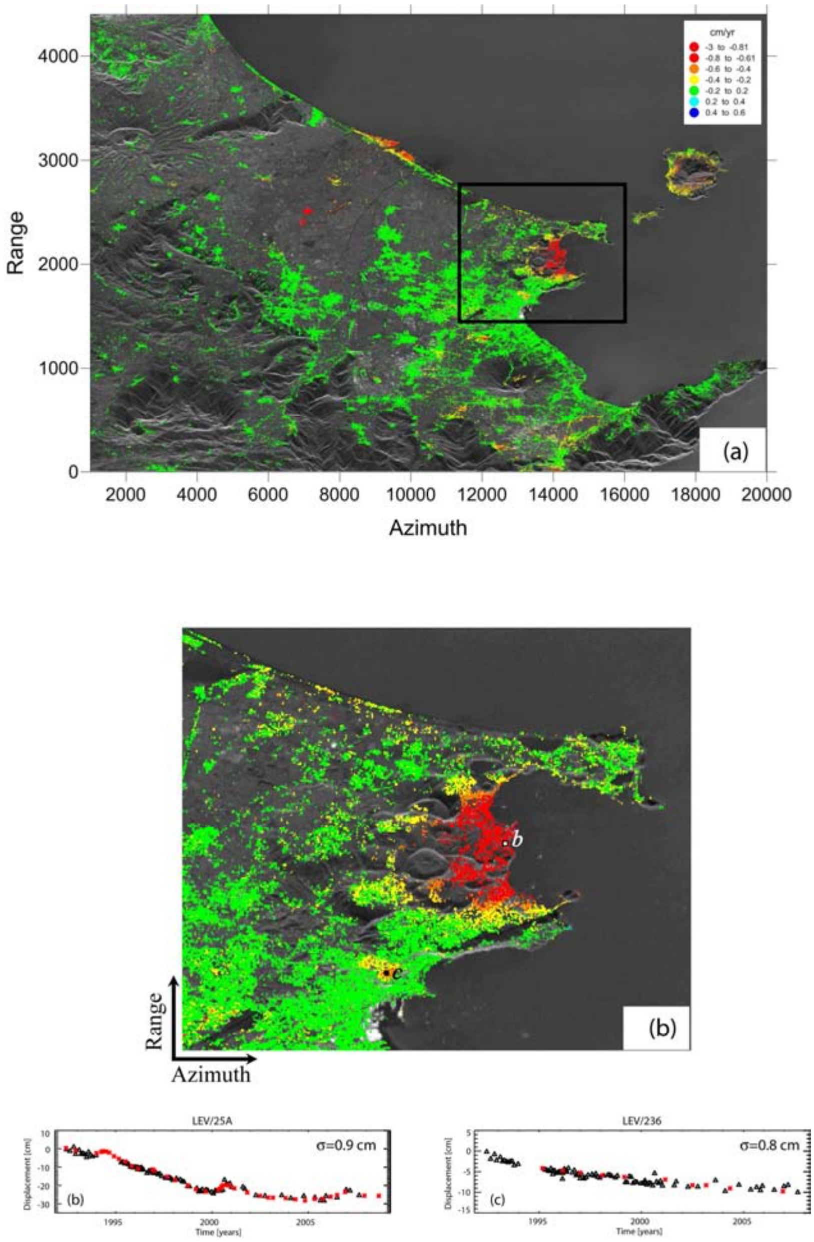

Fig. 3 ERS-1/2 DInSAR results. (a) Geocoded map of the mean deformation velocity of the investigated area (b) Zoomed view of the area of Napoli city and Campi Flegrei caldera (Italy) highlighted by the black box in (a). The plots show the DInSAR/leveling comparison of the deformation time-series corresponding to the pixels in (a) labeled as b (25A leveling benchmark) and c (236 leveling benchmark), respectively.

presented approach allows us to effectively "propagate" the unwrapped solution from the primary network to the connected sub-networks, largely improving the phase unwrapping performances, and drastically decreasing the overall computational burden.

3. RESULTS

The proposed approach was validated by analyzing a dataset of 86 ERS-1/2 SAR images acquired on descending orbits (Track 36, Frame 2781) between June 8, 1992 and August 23, 2007 [see Table I and Fig. 5(a)], over the Napoli

(Italy) Bay area. From these data, we identified a set of 234 data pairs characterized by perpendicular baseline values smaller than 400 m, and a maximum time interval of 1500 days. Precise satellite orbital information and a 3 arcsec SRTM DEM of the area were used to generate a sequence of single-look DInSAR interferograms. The computed interferograms were then unwrapped by applying the EMCF approach. To achieve this task, we first identified the spatial grid of all the coherent pixels to be unwrapped, composed of about 530 000 pixels, where 50 000 of them are very coherent. From the latter pixels, we generated, in the spatial plane, a Delaunay triangulation. The arcs of this triangulation represent the constrained edges of the implemented CDT: this structure connects the overall set of coherent pixels , and is essential for the second EMCF PhU step, leading to the final estimate of the unwrapped interferograms on the chosen spatial grid.

Figure 3 shows a false color map of the detected mean deformation velocity, where only points with high data quality are included, superimposed on a multi-look SAR amplitude image of the area. Moreover, in order to further investigate the achieved accuracy of the proposed approach, we focused on the Napoli city and surroundings, including Campi Flegrei caldera [see Fig. 3(a)] where independent geodetic information (leveling and GPS measurements) was available. In particular, for our analysis, we considered pixels located in correspondence to continuous GPS stations and leveling benchmarks and, for each of these points, we compared the retrieved DInSAR time-series with those obtained from the geodetic measurements, projected on the radar LOS. Note that, although we did not perform any filtering of the atmospheric phase artifacts affecting the DInSAR time-series, there is a good agreement between the SAR and the geodetic measurements. These results f confirm the effectiveness of the proposed phase unwrapping approach.

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