Multibaseline phase unwrapping for INSAR topography estimation (*)

A. FERRETTI(**), C. PRATI(***) and F. ROCCA(****)
Dipartimento di Elettronica e Informazione - Politecnico di Milano

(ricevuto il 22 Ottobre 1999; approvato l'11 Maggio 2000)

Summary. — Multibaseline Synthetic Aperture Radar (SAR) Interferometry (INSAR) can be successfully exploited for automatic phase unwrapping and high quality Digital Elevation Model (DEM) reconstruction. The information coming from several interferograms with different baselines increases the elevation ambiguity interval and allows automatic phase unwrapping. The height of each pixel in the image is considered as a random variable: a Maximum-Likelihood (ML) estimation of the height is carried out by exploiting the probability density function of the interferometric phase, that depends on the local coherence value. After phase unwrapping is possible to combine all the information available, getting a combined DEM that is more reliable than each single DEM. Results obtained using ERS-1/2 SAR data gathered over Vesuvius and Etna are presented. In both cases an accuracy better than 8 meters was obtained.

PACS 91.10.Jf – Topography: geometric observations.
PACS 91.10.Da – Cartography.
PACS 84.40.Xb – Telemetry: remote control, remote sensing; radar.

1. – Introduction

The theory of topographic mapping using SAR interferograms and the difficulties related to phase unwrapping of INSAR data have already been presented in some detail in recent review papers [1-3], reports [4] and books [5, 6]; in this section we only review the main results to establish notation.

Two radar antennas, M (master) and S (slave), gather the data of the same area from different acquisition positions. The distance B between them is called baseline. The

(*) Paper presented at the Workshop on Synthetic Aperture Radar (SAR), Florence, 25-26 February, 1998.
(**) E-mail: aferre@elet.polimi.it
(***) E-mail: prati@elet.polimi.it
(****) E-mail: rocca@elet.polimi.it

Fig. 1. – Geometry of interferometric SAR system. Two satellites both illuminate the same patch of ground. H is the altitude of the master satellite above a tangent plane at P_0, y_0 and r_{M0} the azimuth and range coordinates of the reference point, θ the off-nadir angle, B_n the baseline component normal to the look direction in $y = y_0$.

phase ψ of each pixel in the focused image is related to the sensor-target distance r as well as to the local reflectivity. The complex images, once focused, are registered: one of them, called the "master image" (M), is arbitrarily used as a geometric reference and the "slave image" (S) is resampled on the former. The two images are then cross-multiplied, in order to compensate for the local reflectivity phase contribution. In the ideal case of no noise and no artifact due to changes in the propagation medium, the interferometric phase ϕ of each pixel is proportional to the travel path difference, that is a function of the local topography. Since the quantity that can be measured from the interferometric image is not the phase ϕ, but its principal value ϕ_{w}, the value of ϕ has to be determined by means of a 2-D phase-unwrapping procedure. The quality of the final DEM is strongly dependent on this processing step.

Conventional orbit determination is not precise enough for absolute phase retrieval and usually the final DEM is a map where all the values are computed with respect to a reference point P_0 of known elevation z_0. Therefore, the datum used for DEM generation is not the phase ϕ of the generic pixel P, but the unwrapped *phase difference* between P and P_0:

$$\begin{aligned}\Delta\phi(P) &= \phi(P) - \phi(P_0) = \phi_{\mathrm{w}}(P) - \phi_{\mathrm{w}}(P_0) + k \cdot 2\pi \\ &= \Delta\phi_{\mathrm{w}}(P) + k \cdot 2\pi\,,\end{aligned} \tag{1}$$

where k is an integer.

Once the phase unwrapping step has been carried out, it is possible to obtain the elevation of each pixel in the image. The phase-to-height conversion function $z = z_0 + g(\Delta\phi)$ can be computed if the acquisition geometry is known. In general $g(\Delta\phi)$ is a non-linear relation involving, besides $\Delta\phi$, the acquisition positions (*i.e.* the satellite orbits), the coordinates of the reference point, the range and azimuth variations between

P and P_0 and the system wavelength. In fig. 1 the area of interest is a small patch of ground around P_0, the satellites trajectories are considered linear and the phase-to-height conversion function can be well approximated by a linear relation:

$$\Delta z = z - z_0 = g(\Delta\phi) \tag{2}$$
$$\backsimeq \mathcal{A} \cdot \Delta r + \mathcal{B} \cdot \Delta y + \mathcal{C} \cdot \Delta\phi\,, \tag{3}$$

where $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$ are constant parameters, $\Delta r = r(P) - r(P_0)$ and $\Delta y = y(P) - y(P_0)$ (*i.e.* the variations between the two pixels in range and azimuth direction, respectively).

The linear approximation is useful because it highlights the main features of the acquisition geometry. $\mathcal{A}$ depends on the off-nadir angle. $\mathcal{B}$ is usually small but not negligible, and the orbits cannot be supposed parallel. $\mathcal{C}$ is inversely proportional to the normal baseline B_n in $y = y_0 = y(P_0)$. The height difference corresponding to a phase variation of one cycle is the so-called altitude of ambiguity $h_{2\pi}$:

$$h_{2\pi} = \mathcal{C} \cdot 2\pi = \frac{\lambda}{2}\frac{r_{M0}}{B_n}\sin\theta\,, \tag{4}$$

where θ is the antenna off-nadir angle and r_{M0} is the distance between P_0 and the master trajectory (fig. 1).

From eq. (4) it follows that the greater the baseline, the greater the interferometric phase difference between two points and therefore the unwrapping process will be more difficult, due to the higher probability of phase aliasing. Moreover, geometric decorrelation strongly limits the SNR in high baseline interferograms [7]. On the contrary, low baseline interferograms show good fringes, are usually easy to unwrap, but have poor topographic accuracy [8]. If more than one interferogram of the same region is available, phase unwrapping should be carried out *simultaneously* on all the data set, taking advantage of all the available information. The underlying idea of the multibaseline approach is then the following: *the interferograms are different measures of the same physical variable: the topography.* In the next sections we will see how, following this idea, it is possible to overcome most of the difficulties encountered in INSAR DEM reconstruction, increasing the final product accuracy [9, 10].

2. – Multi-baseline phase unwrapping

If no *a priori* information about the topography is available, phase unwrapping of a single SAR interferogram is an ill-posed inverse problem. Even in high-coherence areas, the presence of phase aliasing can produce serious artifacts on the estimated topography. If NI interferograms of the same region are available, with different baseline values, it is possible to combine the data to eliminate phase aliasing.

Theoretically it would be enough to have two interferograms with baselines that are prime with respect to each other to remove phase ambiguities (Chinese remainder theorem [11]). In a practical case, where data are noisy and baselines random, the use of multiple interferograms increases significantly the elevation ambiguity level. The Bayesian inference gives a rigorous framework for the estimation, taking into account the possible *a priori* information about the DEM.

Let P_0 be a point of known elevation (GCP — Ground Control Point). The target is then to compute the elevation of each point P in the area of interest with respect to P_0. Let $z(P)$ be the height variation between P and P_0. This quantity can be considered as a *random variable*, its value can be estimated from the available NI measures. If $f(z/\Delta\phi_{\mathrm{w}}^{i})$ is the probability density function (p.d.f.) of the variable z conditioned to the wrapped phase value $\Delta\phi_{\mathrm{w}}^{i}$ (where the apex specifies the interferogram used for the estimation), from the Bayes rule, the p.d.f. *a posteriori* conditioned to all the available data is

$$f(z/\Delta\phi_{\mathrm{w}}^{1},\cdots,\Delta\phi_{\mathrm{w}}^{NI}) = \frac{f(\Delta\phi_{\mathrm{w}}^{1},\cdots,\Delta\phi_{\mathrm{w}}^{NI}/z)}{f(\Delta\phi_{\mathrm{w}}^{1},\cdots,\Delta\phi_{\mathrm{w}}^{NI})} f_{\mathrm{ap}}(z) \tag{5}$$

where $f_{\mathrm{ap}}(z)$ is the possible *a priori* information about z. If the measures are statistically independent, we simply have

$$f(z/\Delta\phi_{\mathrm{w}}^{1},\cdots,\Delta\phi_{\mathrm{w}}^{NI}) = \frac{1}{C}\prod_{i=1}^{NI} f(z/\Delta\phi_{\mathrm{w}}^{i})\cdot f_{\mathrm{ap}}(z)\,, \tag{6}$$

where C is a normalization constant. The maximum *a posteriori* (MAP) estimation, $\widehat{z}$, of the variable z maximizes this p.d.f. When the value of $\widehat{z}$ is determined, it is easy to choose the value of 2π to be added to each interferogram: the correct value of the phase will correspond, in fact, to the height value nearest to the estimated one.

In order to compute $f(z/\Delta\phi_{\mathrm{w}}^{i})$, we use the coherence maps associated to each interferogram. The coherence is

$$\gamma = \frac{E[u_i u_j^*]}{\sqrt{E[|u_i|^2]}\sqrt{E[|u_j|^2]}}\,, \tag{7}$$

where we have indicated with u_i, u_j the complex values of the correspondent pixels in the two images. Its estimate is

$$\widehat{\gamma} = \frac{\sum_{l=1}^{L} u_{il}u_{jl}^*}{\sqrt{\sum_{l=1}^{L}|u_{il}|^2}\sqrt{\sum_{l=1}^{L}|u_{jl}|^2}}\,. \tag{8}$$

¿From the absolute value of the local coherence γ and the number of looks in the interferogram (the number of degrees of freedom in the estimate of $\Delta\phi$) , it is possible to compute the expression of the p.d.f. of the interferometric phase [12] and thus of the elevation. The conditional density function of the elevation for each interferogram $f(z/\Delta\phi_{\mathrm{w}}^{i})$ is periodic with a different period (the altitude of ambiguity) dependent on the baseline. In each period the higher is the quality of the fringes (the coherence) the sharper is the histogram. The product of the conditional densities shows a neat peak whenever the coherence is not close to zero and the baseline errors are not too high. The sharper is the global peak, the higher is the reliability of the result, *i.e.* the probability that the correct value of the height variation lies inside a given interval. In fig. 2 it is shown an example of this kind of computation, where three interferograms with three different baseline values are considered.

Many different measures of confidence can be considered for the MAP estimation; we have chosen a very simple one

$$\rho = \int_{\widehat{z}-T}^{\widehat{z}+T} f(z/\Delta\phi_{\mathrm{w}}^{1},\cdots,\Delta\phi_{\mathrm{w}}^{NI})\cdot \mathrm{d}z\,, \tag{9}$$

Fig. 2. – Example of p.d.f. *a posteriori* computation. Three independent interferograms are considered (normal baseline values are 106, 146 and 230 m). The coherence value is supposed to be the same and equal to 0.5 (3 looks).

being T a fixed parameter. ρ is called *reliability* of point P. The reliability is then the probability that the correct value of the height variation lies inside the interval $[\widehat{z}-T, \widehat{z}+T]$. It is a positive value less than 1 and can be considered a measure of the multi-image *topographic* coherence.

The benefits of the multibaseline approach are twofold. First, combining all the information it is possible to limit the impact of the noise. Besides, there is minor risk of aliasing with respect to conventional single interferogram phase unwrapping: *working simultaneously on more interferograms, phase unwrapping is possible even if the phase is undersampled.* Of course the higher the noise, the worse the reliability and the more likely the phase unwrapping errors.

3. – Application to repeat-pass interferometry

If we knew exactly the phase-to-height conversion function for each interferogram, the implementation of the algorithm would be straightforward. All we should do is to compute the p.d.f. *a posteriori* conditioned to the data for each pixel in the image. Unfortunately, this is usually not the case. First of all, the satellite trajectory is not exactly known: only an estimation of the phase-to-height conversion function is available. Of course, attitude errors are systematic and usually introduce a tilt, or more generally a polynomial distortion, on the DEM [8]. Nevertheless, they cannot be neglected.

Moreover, even if the orbits were not affected by any indetermination, another low-frequency contribution should be taken into account in repeat-pass interferometry: a phase distortion α due to random refractive index variations in the propagation medium [8, 13, 14]. The power of this kind of distortion cannot be estimated from the local coherence, since the correlation length of these phenomena (usually more than 1 km) is far longer than the estimation window used for γ and large ground regions will exhibit a common error.. So the final topography can show strong distortions in spite of high coherence values.

Atmospheric effects and baseline errors can strongly reduce the effectiveness of the multibaseline approach outlined above. In order to unwrap correctly the phase values, a good matching between the topographic profiles coming from each interferogram is necessary. These low-frequency phenomena make a straightforward implementation of the multibaseline approach unfeasible. The "resonance" of the p..d.f.'s relative to the interferograms would become more and more unreliable, while considering pixels more and more distant from the reference point P_0.

In order to compensate for possible baseline errors and atmospheric distortion, the phase-to-height conversion functions are iteratively optimized as more and more points are unwrapped. A RLMS optimization is used to minimize the error between the elevation values obtained from each datum. Since the new baseline values compensate not only for orbit indeterminations but for atmospheric distortions too, we will call them *effective baselines.*

3˙1. *Two resolutions, three processing steps.* – If no approximation could be done in phase-to-height conversion, the need for optimization procedures would make the implementation of the algorithm cumbersome and very time consuming. For that reason the processing is carried out on two different resolution levels.

The image is divided into small blocks (about 1×1 km^2) such that: 1) orbits can be considered linear; 2) phase distortion due to possible atmospheric effects can be considered linear; 3) the phase-to-height conversion function can be well approximated, for each interferogram, by a linear function (eq. (3)):

$$\Delta z^i \backsimeq \mathcal{A}^i \cdot \Delta r + \mathcal{B}^i \cdot \Delta y + \mathcal{C}^i \cdot \Delta \phi^i + \mathcal{D}^i \,, \tag{10}$$

where the apex specifies one of the NI interferogram. As already mentioned, all these variations are defined with respect to a reference point chosen inside each block. The reference point will be a pixel having high coherence value in all the interferograms. The $\mathcal{D}^i$ parameter compensate for phase noise on $\phi^i(P_0)$.

Inside each block it is then possible to carry out a *linear* recursive optimization, fast and effective. Though we work on two resolutions level (*intra* and *inter*-block), the program can be divided into three steps:

1) Phase unwrapping inside each block (first resolution level–Algo I).

2) Phase unwrapping of the blocks (second resolution level–Algo II).

3) Phase unwrapping of the pixel not reached by the first algorithm (Algo III).

In the next sections we describe in more detail the two resolution levels used during the processing and we highlight the need for a last step in the processing chain. The implementation of the algorithm follows closely this description.

1) *Algo I*
Three different pixel classes are defined in the processing: 1) Not-processed Pixels (NPs); 2) Processed Pixels (PPs); 3) Unwrapped Pixels (UPs).

Fig. 3. – The algorithm starts from a reference point, as in a "region growing" algorithm, and it looks among the neighbor pixels (Processed Pixels) for the most reliable point. At the end of each processing cycle only the most reliable pixel is unwrapped and added to the unwrapped area.

The distinction between UPs and PPs limits the probability of error propagation while phase unwrapping is in progress. PPs correspond to the neighborhood of the already unwrapped area (fig. 3). The algorithm starts from a reference point, as in a "region growing" algorithm, and it looks among the neighboring pixels (PPs) for the most reliable point to be unwrapped. If its reliability value is greater than a threshold, the pixel is unwrapped, structures identifying UPs and PPs are updated and a step of the optimization routine is performed, otherwise the cycle stops and a new block is considered. Therefore the path for phase unwrapping is *not* deterministic: *in each block, a statistically optimum route is found.*

Some observations are now in order:

i) Since the interferogram with the largest normal baseline value is less sensitive to orbital parameters errors and atmospheric artifacts, this is usually assumed as a reference and its orbital parameters are supposed to be correct. The phase to elevation relation of the remaining $NI-1$ interferograms are optimized to minimize the average (weighted with the coherence) elevation difference with respect to the topographic profile of the reference one.

ii) The p.d.f. *a posteriori* is computed considering an "allowed elevation interval" (AEI) fixed by the user. The computation window is centered around the elevation value of a neighbor pixel already unwrapped.

iii) Although the processing is sequential, phase unwrapping is *not* performed by means of an integration of the phase variations between adjacent pixels: we always consider $\psi(P)$ and $\psi(P_0)$ and the neighbor point are used only to center the AEI.

iv) In order to reduce the computational burden, the samples of the probability density function, for different coherence values, are computed only once at the beginning of the processing, filling a look-up table.

2) *Algo II*
Once all the blocks have been processed, the unwrapped areas should be phase aligned. The reference point $P_{0\mathrm{best}}$ with the highest value of coherence is chosen as the reference pixel valid all over the image: the phases of all the points in the

Fig. 4. – Phase alignment between block B_i and B_j is accomplished processing more than one pixel: each one gives an estimation of the correct values of 2π to be added to the reference point P_{0j}.

image must be unwrapped with respect to this point. However, since the pixels within the generic block n have been already unwrapped with respect to $P_0^{(n)}$, phase alignment is carried out simply by unwrapping all the $P_0^{(n)}$ with respect to $P_{0\text{best}}$. The patching between the blocks is then performed using the same strategy used within the block (ML estimation). Again, the algorithm starts from $P_{0\text{best}}$ and it looks among the neighbor *blocks* for the most reliable one, minimizing the probability of error propagation. To better explain the strategy used in this second processing step, let us consider just two blocks, B_i and B_j (fig. 4). Suppose we want P_{0i} be the reference point for both. Whatever pixel P is considered in B_j, if we succeed to unwrap it correctly, we can immediately unwrap P_{0j} and consequently all the pixels in B_j, in fact

$$\Delta\phi_{P_{0j}-P_{0i}} = \Delta\phi_{P_j-P_{0i}} - \Delta\phi_{P_j-P_{0j}} \,, \tag{11}$$

where the second term on the right-hand side has been already unwrapped by the first processing step (Algo I) performed on each block.

Since we can use more than one pixel, we have more than one estimation of the number of 2π to be added to the reference point P_{0j}. This allows a more reliable

Fig. 5. – In order to unwrap correctly two blocks B_i and B_j, a set of edge points are selected in the two unwrapped areas as shown in the figure. Each pair of pixels gives an estimation of the number of 2π to be added for phase alignment.

choice to be accomplished. On the other hand, possible errors in Algo I give rise to a wrong estimation (eq. (11)). For these reasons the unwrapping of block B_j with respect to B_i is carried out as follows:

i) NP pairs of pixels are selected (as in fig. 5).

ii) From each pair of pixels is then possible to get an estimation of the unwrapped phase value between P_{0j} and P_{0i}:

$$\Delta\phi_{P_{0j}-P_{0i}} = \Delta\phi_{P_j-P_i} + \Delta\phi_{P_i-P_{0i}} - \Delta\phi_{P_j-P_{0j}}\,. \tag{12}$$

iii) Since different pairs can estimate different $k\cdot\, 2\pi$, only the most reliable value should be chosen. The reliability of the unwrapping of P_{0j} with respect to P_{0i}, with a number of 2π to be added equal to $\overline{k}$, is defined as follows:

$$\rho_{II}(P_{0i} \Rightarrow P_{0j}|\overline{k}\cdot 2\pi) = \frac{1}{N_P}\sum_{m=1}^{M} \rho_I(P_{mi} \Rightarrow P_{mj})\,, \tag{13}$$

where $\rho_I(P_i \Rightarrow P_j)$ is the reliability as defined in eq. (9), the sum extends only over pixel pairs estimating $\overline{k}$ as the correct value (M) and N_P is the total number of pixel pairs. $\rho_{II}(P_{0i} \Rightarrow P_{0j})$ ranges from 0 to 1. A block is unwrapped only if the reliability $\rho_{II}(P_{0i} \Rightarrow P_{0j})$ is greater than a threshold level provided by the user.

The strategy used to perform the alignment of the blocks is then very similar to that used in Algo I, provided that a different reliability measure is defined.

3) *Algo III*

The need for a last processing step can be easily justified looking at fig. 6. Here

Fig. 6. – After phase alignment of the blocks a last processing step is needed. In fact, only connected pixels are unwrapped inside each block by the first algorithm (Algo I). This last processing eliminates the artifacts due, for example, to very low coherence cuts (see picture).

Fig. 7. – Vesuvius: multi-image reflectivity map. Image dimensions: 600 [rg] $\times$ 540 [az]. The full-resolution image was averaged by a factor of 5 in azimuth.

Fig. 8. – Vesuvius data set: estimated DEM in each block after the first step of the multibaseline phase unwrapping program.

Fig. 9. – Vesuvius: combined DEM. The topography is estimated using the unwrapped phase maps generated by the Multibaseline Phase Unwrapping Program developed at POLIMI. Seven TANDEM interferograms were processed.

nine blocks are considered. Since only connected pixels are unwrapped inside each block by the first algorithm (Algo I), it can happen that some pixels are not reached by the processing: in fact a river or an area in foreshortening make it impossible to reach all the pixel of the block by means of a connected path from the reference point.

Algo III eliminates this kind of processing artifacts as follows:

i) For each block the eight neighbor blocks are considered. We call this structure *macro-block*.

ii) The best reference point is chosen as the reference pixel of the *macro-block.*

iii) The phase-to-height conversion function for each interferogram can *not,* in general, be considered linear in the *macro-block.* An optimization procedure has been adopted to maximize the elevation consensus from all the unwrapped interferograms. If no *a priori* DEM is available, again the largest baseline is assumed as a reference (it is less sensitive to orbital parameters errors and atmospheric effects) and its orbital parameters are supposed to be correct. The phase-to-elevation relation of the remaining $NI-1$ interferograms is first approximated up to the second order, then the parameters are changed to minimize the average (weighted with the coherence) elevation difference with respect to the reference elevation map.

iv) Once the geometric parameters have been found, all the remaining non-unwrapped pixels are processed computing the p.d.f. (ML estimation) as usual. Only points with reliability value higher than a threshold provided by the user are unwrapped.

Fig. 10. – Error map (SAR coordinates) of the multibaseline INSAR DEM relative to a reference SPOT DEM. White pixels correspond to not unwrapped areas (reliability values under threshold). Error standard deviation: 8 m.

4. – Test data sets

The multibaseline approach to phase unwrapping was tested with several different data sets, ranging from the smooth topography around Bonn (Germany) [9], Ancona (Italy) [15] and Pomona (California) [16] to the more difficult areas around the two main Italian volcanoes: Vesuvius and Etna. Here results concerning the last two test areas will be presented.

All the unwrapped phase maps where obtain averaging the interferograms only by a factor 5 in azimuth direction (3 effective looks were considered for p.d.f. computation), maintaining full resolution data in slant range. The final resolution cell is about 20×20 m^2 for flat terrain. We remember that the reconstructed unwrapped phase is identical to the original wrapped phase when unwrapped. In order to assess the reliability of the results *a priori* DEM of both test sites were used.

4·1. *The vesuvius data set.* – The multi-image reflectivity map (incoherent average of the co-registered SAR data) of the region around Mt. Vesuvius is shown in fig. 7. Maximum height variation is 1281 m (from sea level to the top of the volcano). Seven Tandem interferograms were used, the baseline values range from 39 to 253 m (table I). No *a priori* information was exploited during the processing. In fig. 8 the estimated topography after the first processing step (Algo I) is reported. The blocks are still

Fig. 11. – Etna: multi-image reflectivity map (incoherent average of all the available data). Image dimensions: 1600 [rg] $\times$ 1360 [az]. The full-resolution image was averaged by a factor of 5 in azimuth.

TABLE I. – *Vesuvius data set: orbits, acquisition dates and baselines (in meters).*

Satellite	Orbit	Date	$\lvert B_n \rvert$
ERS-1	20794	07/07/95	
ERS-2	**1121**	**08/07/95**	**39**
ERS-1	21295	11/08/95	
ERS-2	**1622**	**12/08/95**	**57**
ERS-1	22297	20/10/95	
ERS-2	**2624**	**21/10/95**	**135**
ERS-1	22798	24/11/95	
ERS-2	**3125**	**25/11/95**	**220**
ERS-1	23299	29/12/95	
ERS-2	**3626**	**30/12/95**	**253**
ERS-1	23800	02/02/96	
ERS-2	**4127**	**03/02/96**	**146**
ERS-1	24802	12/04/96	
ERS-2	**5129**	**13/04/96**	**106**

Fig. 12. – Etna data set: reliability map.

Fig. 13. – Etna data set: coherence map associated to the TANDEM pair 5-6/09/1995.

Fig. 14. – Unwrapped phase interferogram relative to the October 1995 Tandem pass. Black areas correspond to not unwrapped pixels.

not unwrapped one with respect to the other. The final DEM was computed using the 7 unwrapped phase maps and the technique described in [8]. In order to reduce baseline errors, we used the ESA precise orbits products (processed at GFZ/D-PAF, Oberpfaffenhofen [17]) to propagate the satellite trajectory relative to each image. A 3-D perspective of the final result is shown in fig. 9. The error between the combined DEM and a reference (SPOT) topography (in SAR coordinates) is reported in fig. 10. White pixels correspond to not unwrapped areas (reliability under threshold). Error standard deviation is about 8 m. It should be noted that the SPOT DEM available to us has an estimated accuracy of 7–8 m, so multibaseline INSAR data allow a precise estimation of the topographic profile.

4·2. *The Etna data set.* – The third test was the region around Etna volcano. Eight interferograms were used (table II). The area selected is about 30×30 km^2. As usual, the images were averaged only by a factor of five in azimuth direction (fig. 11). An example of reliability map generated by the multibaseline phase unwrapping software is reported in fig. 12 while the best coherence map of the Etna data set is reported in fig. 13 for comparison. It should be noted that, using the multi-baseline approach, it was possible to unwrap the October 1995 Tandem pass, with a normal baseline of almost 400 m (fig. 14). The difficulties related to the unwrapping of this high baseline inteferogram can be appreciated analysing fig. 15, where a close up of the wrapped interferogram is reported. A perspective view of the final DEM, obtained from the combination of all the

Fig. 15. – Close-up of the wrapped interferogram relative to the October 1995 Tandem pass. This area corresponds to the white rectangle in fig. 14.

Fig. 16. – Etna data set: combined DEM.

Fig. 17. – Error histogram of the final INSAR DEM with respect to a reference (IPGP) topography. Error standard deviation is 7.5 m.

unwrapped phase data [8], is shown in fig. 16. In order to assess the reliability of the final estimated topography in fig. 17 the error histogram with respect to a reference DEM provided by IPGP (estimated accuracy 4 m) is also shown. Error standard deviation (computed for unwrapped pixels) is 7.5 m.

TABLE II. – *Etna data set: orbits, acquisition dates and baseline (in meters).*

Satellite	Orbit	Date	$\vert B_n \vert$
ERS-1	21159	01/08/95	
ERS-2	**1486**	**02/08/95**	**59**
ERS-1	21660	05/09/95	
ERS-2	**1987**	**06/09/95**	**106**
ERS-1	22161	10/10/95	
ERS-2	**2488**	**11/10/95**	**388**
ERS-1	22662	14/11/95	
ERS-2	**2989**	**15/11/95**	**176**
ERS-1	23163	19/12/95	
ERS-2	**3490**	**20/12/95**	**337**
ERS-1	24666	02/04/96	
ERS-2	**4993**	**03/04/96**	**125**
ERS-1	25167	07/05/96	
ERS-2	**5494**	**08/05/96**	**129**
ERS-1	37191	25/08/98	
ERS-2	**17518**	**26/08/98**	**341**

5. – Conclusions

This paper describes a multibaseline approach to phase unwrapping and a possible implementation. It is shown that the combination of more than two SAR images allows to get an automatic technique able to produce high-quality results. As already mentioned, the benefits of the multibaseline approach are twofold. First, combining all the information it is possible to limit the impact of noise and to reduce the probability of error propagation during the processing. Besides, there is minor risk of aliasing with respect to conventional single interferogram phase unwrapping. Moreover, the combination of many uncorrelated phase artifacts (mainly due to atmospheric changes) strongly reduces their impact on DEM accuracy. Even if some aspects of the processing chain must be still improved and optimized, the results on real data are good. Comparison with two reference DEMs of two different test sites showed a good quality of the final products, comparable to that obtained with optical data under good weather conditions.

REFERENCES

[1] Balmer R. and Hartl P., *Inverse Problems*, **14** (1998) R1-R54.
[2] Massonnet D. and Feigl K. L., *Rev. Geophys.*, **36** (1998) 441-500.
[3] Rosen P. A., Hensley S., Joughin I. R., Li F., Madsen S. N., Rodriguez E. and Goldstein R. M., *Proceedings of the IEEE* **88**, 8 March 2000, pp. 333–382.
[4] Prati C., Rocca F., Monti-Guarnieri A., Pasquali P., *Interferometric Techniques and Applications*, ESA Study Contract Report. Contract N.3-7439/92/HGE-I.
[5] Franceschetti G. and Lanari R., in *Synthetic Aperture Radar Processing* (CRC Press) 1999.
[6] Ghiglia D. C. and Pritt M. D., in *Two-Dimensional Phase Unwrapping - Theory, Algorithms, and Software* (John Wiley and Sons) 1998.
[7] Gatelli F., Monti-Guarnieri A., Parizzi F., Pasquali P., Prati C. and Rocca F., *IEEE Trans. Geosci. Remote Sensing*, **32** (1994) 855-865.
[8] Ferretti A., Prati C. and Rocca F., *IEEE Trans. Geosci. Remote Sensing*, **37** (1999) 705-715.
[9] Ferretti A., Monti-Guarnieri A., Prati C. and Rocca F., *Proceedings of the FRINGE 96 Workshop, Zurich, 1996*, http://www.geo.unizh.ch/rsl/fringe96/.
[10] Ferretti A., Monti-Guarnieri A., Prati C. and Rocca F., *Proceedings of the 3rd ERS Symposium, Florence, 1997*, http://florence97.ers-symposium.org/.
[11] Xu W., Chang E. C., Kwoh L. K., Lim H., Heng W. C., *Proceedings of IGARSS '94, Pasadena 1994* (IEEE, 94CH3378-7, 1994) p. 730-732.
[12] Lee J. S., Hoppel K. W., Mango S. A., and Miller, *IEEE Trans. Geosci. Remote Sensing*, **32** (1994) 1017-1028.
[13] Zebker H. A. and Rosen P., *J. Geophys. Res. - Solid Earth* **102** (B4) (1997) 7547-7563.
[14] Hanssen R., *Assessment of the role of Atmospheric heterogeneities in ERS Tandem SAR interferometry* - Delft University Press, DEOS Report no. 98.1, 1998, Delft, the Netherlands.
[15] Ferretti A., Prati C. and Rocca F., *IEEE Trans. Geosci. Remote Sensing* **39**, (2001) 8–20.
[16] Ferretti A., Prati C. and Rocca F., *IEEE Trans. Geosci. Remote Sensing* **38**, (2000) 2202–2212.
[17] Reigberg C., Xia Y., Kaufmann H., Massmann F., Timmen L., Bodechtel J. and Frei M., *Proceedings of the FRINGE 96 Workshop, Zurich, 1996* http://www.geo.unizh.ch/rsl/fringe96/.