Multi Baseline Interferometric Techniques and Applications

A.Ferretti, A. Monti Guarnieri, C.Prati and F.Rocca

Dipartimento di Elettronica e Informazione (DEI) Politecnico di Milano (POLIMI), Piazza Leonardo da Vinci 32, 20133 Milano, Italy
aferre@elet.polimi.it monti@elet.polimi.it
http://www.elet.polimi.it

Abstract

Multi baseline interferometric data can be exploited for generating DEM, to estimate volumetric scattering and to get resolution on areas affected by foreshortening and layover. Moreover, multi baseline data allow to increase the elevation ambiguity interval, to detect and reduce atmospheric artifacts and to get high resolution coherence maps (i.e. an ensemble average is used instead of a space average). Results of the improvements achievable from multi baseline ERS-1 and Tandem data will be presented for the area of Bonn (ERS-1 images taken at 3 days interval during March 92) and Naples (4 Tandem pairs on Mt. Vesuvius, 1995-1996, have been used).
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Introduction

The aim of this paper is to present some results that can be achieved in SAR interferometry using multi baseline techniques, i.e. when more than one interferogram is available.

The difficulties related to this kind of approach are essentially due to the lack of precise satellite ephemerides and good estimation of the phase noise power superimposed on each interferogram. The former issue can be overcome by using optimization algorithms and good reference ephemerides (e.g. German PAF precise orbits), the latter using a local coherence estimation.

Precise location of the flight paths together with a good estimation of the standard deviation of the phase noise allow, in fact, the use of powerful statistics techniques, such as Maximum Likelihood (ML) and Maximum A Posteriori (MAP), to accurately estimate the height difference of each pixel with respect to a reference one with known elevation.

The same concept can be exploited to estimate the coherence using an ensemble average instead of a space one. The achieved coherence map highlights what remains unchanged during the time interval between the first and the last acquisition and could be exploited for image segmentation and classification.

Moreover, multi baseline techniques can be usefully exploited to get a DEM that is less affected by artifacts by averaging the uncorrelated atmospheric contributions coming from the single interferograms. When the ML DEM is generated it is possible to get the phase difference with respect to each interferogram. These phase residues are proportional to targets motion and/or atmospheric changes. In conclusion, the proposed technique can provide:

- a multiple interferograms averaged DEM - an ''atmospheric'' noise map for each interferogram - a multiple interferograms averaged coherence map, that gives a measure of SNR on a fine spatial resolution.

Maximum Likelihood Unwrapping and Mapping Algorithm

The image is divided in small patches (or blocks) such that:

1. The orbits can be considered linear. 2. The phase to height conversion function can be well approximated, for each interferogram, by a linear function:
$$dh = A * dr + B * dy + C * dphi \quad (1)$$

where:

dh is the height variation dr is the range variation dy is the azimuth variation dphi is the interferometric phase variation.

All these variations are defined with respect to a reference point chosen inside the block. The reference point will be a pixel having high coherence value in all the interferograms.

The parameters A, B and C are iteratively optimized as more and more points are unwrapped. A LMS optimization algorithm is used to minimize the error between the elevation values obtained from the interferograms and a reference DEM. If no *a priori* information is available (i.e. a rough DEM or GCPs) the baselines are optimized relative to one of the input interferograms, considered the reference for the other ones: the phase to height conversion function is considered fixed and known for this interferogram and at the end of the processing the final (combined) DEM will be affected by a systematic error due to the inaccurate estimates of the acquisition system geometry and a low frequency distortion due to atmospheric effects (the impact of this kind of distortion on the final DEM depends upon the mean value of the normal baseline of the reference interferogram: the higher the baseline, the lower the DEM distortion).

The patching of the unwrapped regions inside each block is operated only when all the blocks are processed. The algorithm starts from the reference point, as in a region growing algorithm (Hock et al., 1995), and it looks among the neighbor pixels for the most "reliable" point to be unwrapped. The unwrapping operation is reliable if all the interferograms estimate the same height variation for the running pixel with respect to the reference point. The dispersion "r" of the probability density function (p.d.f.) of the random variable dh(i,j) around the maximum is an indication of the "reliability" of the pixel P(i,j). The narrower the p.d.f. the more reliable the unwrapping.

In order to compute the p.d.f. of this random variable we use the coherence maps associated to each interferogram. From the absolute value of the coherence it is possible to achieved the expression of the p.d.f. of the interferometric phase (Lee J.S. et al., 1994) (Bamler R. and Just D., 1993) and thus of the elevation. The data from the "N" interferograms are "N" independent measures of the same physical variable (elevation), and we can compute its "a posteriori" p.d.f.(f), i.e. the p.d.f. of dh conditioned to the data:

f(dh/dphi1,dphi2,..,dphiN) = K* g(dphi1,dphi2,..,dphiN/dh)*ap(dh) = g(dphi1/dh) * g(dphi2/dh) * .. * g(dphiN/dh) * ap(dh) (2)

where:

K is a normalization constant g(dphin/dh) is p.d.f. to observe the value dphin for the interferometric phase of the interferogram "n" when the actual height variation is dh. ap(dh) is the *a priori* information (this function is a constant if no reference DEM of the region is available).

The estimated value of dh (dh_est) maximizes the likelihood function f. When the value of dh_est is determined it is easy to choose the value of 2pi 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 this way is then possible to compute the reliability (r) associated to each transition from the edge of the already unwrapped region to the neighbor pixels.

Many different measures of confidence can be considered for the "a posteriori" p.d.f. ; we have chosen a very simple one:

r = integral[dh_est-M,dh_est+M] f(dh) d(dh) (3)

being M a parameter that fixes the range of allowed altitude variation (e.g. to avoid aliasing, as will be discussed below). The reliability is then the probability that the correct value of the height variation lies inside the interval [dh_est-M,dh_est+M]. It is a positive value less than 1 and can be considered a measure of the multi image "topographic" coherence.

The algorithm will unwrap a point only if

1. This reliability is the maximum value among all the points around the edge of the region already unwrapped. 2. The reliability is greater than a threshold: r(i,j) > THR_REL

When a new point is unwrapped we can carry on the optimization of the geometric parameters and we can compute the reliability values for the neighborhood of this new point. Again the algorithm will look for the more reliable pixel to be unwrapped and so on.

When all the image blocks are processed, the reference point with the highest value of coherence is chosen has the reference point for all the image and the block of this seed point is considered the reference block. The algorithm proceeds unwrapping the blocks exactly in the same way it had unwrapped the points inside each block.

The benefits of this algorithm are twofold. In the first place the coherence information is properly exploited: the coherence maps highlight the best path for the unwrapping algorithm and give an estimation of the standard deviation of the error on the final DEM. In the second place there is less risk of aliasing with respect of conventional single interferogram phase unwrapping (Goldstein R.M et al., 1988) (Prati C. et al., 1990). Theoretically it would be enough to have three interferograms with baselines that are prime with respect to each other to remove ambiguities (Chinese remainder theorem). In a practical case, where data are noisy and baselines random, the use of multiple interferograms increases significantly the elevation ambiguity level.

Atmospheric Effects and Multi-Image Coherence Estimation

Once the Digital Elevation Model is available (ML DEM) it is possible to compute N differential interferograms between the original data and the synthetic version obtained from the ML DEM and the optimized baselines values. These phase difference maps can highlight interesting changes in the phase of some targets and/or atmospheric effects due to the change in the refraction index from one acquisition to another. Both effects are clearly visible in the phase error maps we got from the region around Bonn and Mt. Vesuvius (see next paragraph).

When a good DEM is available with the same resolution of the original SAR images, it is also possible to compute a multi image coherence map. In this case the increased number of freedom degrees (due to the multiple interferograms) allows to get high resolution coherence maps (say 40 x 40 m). These maps are actually computed by compensating for the estimated interferogram phases, and then averaging all the interferograms. The final result highlights what actually remains unchanged in all the images.

Experiments

The multi baseline approach to phase unwrapping and DEM reconstruction was tested with two different data sets. During March 1992, ERS-1 surveyed ten times (i.e. every three day) the region around Bonn. One image was chosen as the "master" image and 4 different interferograms were produced using 4 other images of this data set. The baselines values are 93, 110, 150 and 162 meters (the altitudes of ambiguity about 97, 82, 60 and 55 meters).

The topography presents no particular difficulty, but the presence of the river and low coherence forested areas make this area suitable for testing the feasibility of automatic phase unwrapping of not connected blocks (Figure 1).
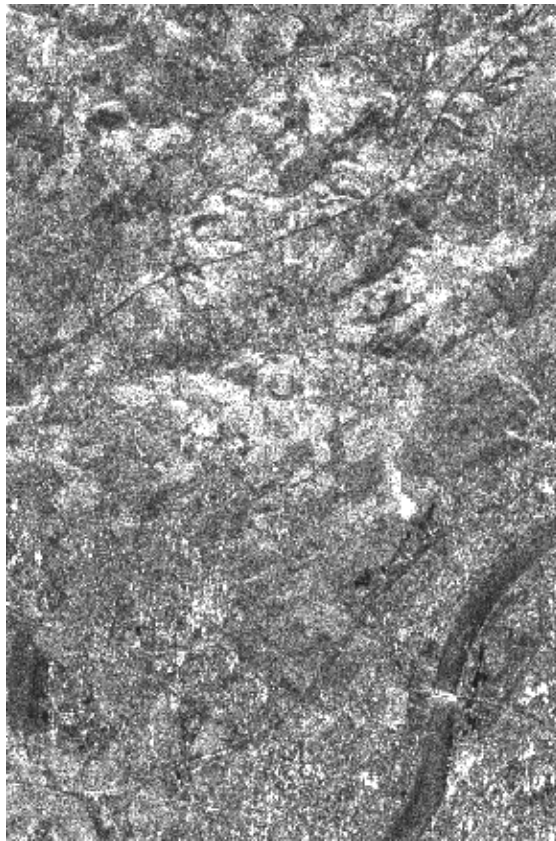
Figure 1: Bonn area: Amplitude Image - Dimensions:
600 (range) x 2000 (azimuth).

The ML DEM we obtained at the end of the processing (Figure 2) is smooth and presents no relevant phase unwrapping error.
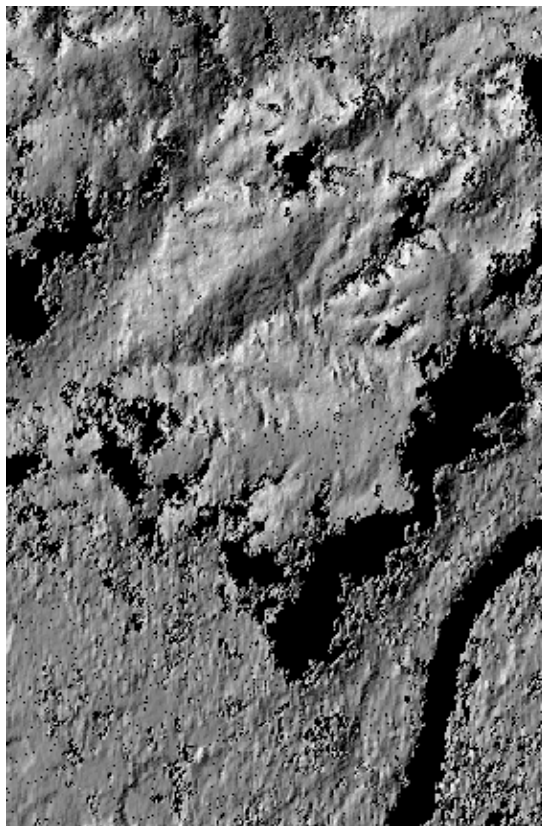

Figure 2: Bonn area: Maximum Likelihood DEM.

The black areas are not unwrapped areas: the reliability was under threshold in these regions. The two banks of the river have been correctly unwrapped even if there is no path between them. It is interesting to compare the ML DEM with that obtained using only a single interferogram: the former looks smoother and less noisy because of the optimum combination of all the information available. It is then possible to compare one of the coherence map associated to one of the input interferogram with the "reliability map" obtained at the end of the processing (Figure 3) again it is clear that combining multi baseline interferograms we can improve the resolution of the final product.
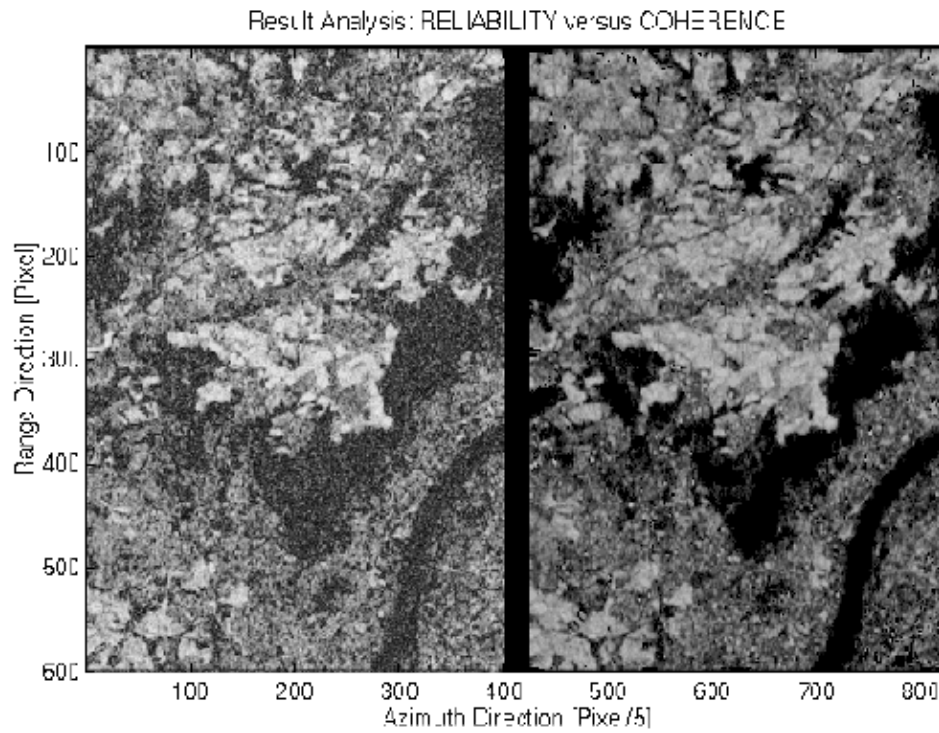
Figure 3: On the left hand side one of the input coherence maps, on the right hand side the final reliability map.

The differential interferograms (Figure 4) between the data used for the processing and the synthetic interferogram obtained using the optimized baseline values show interesting features in the image and highlight the regions where the reflectivity changed from one image to another due to atmospheric effects (low frequency effects) and antropogenics causes (single fields).
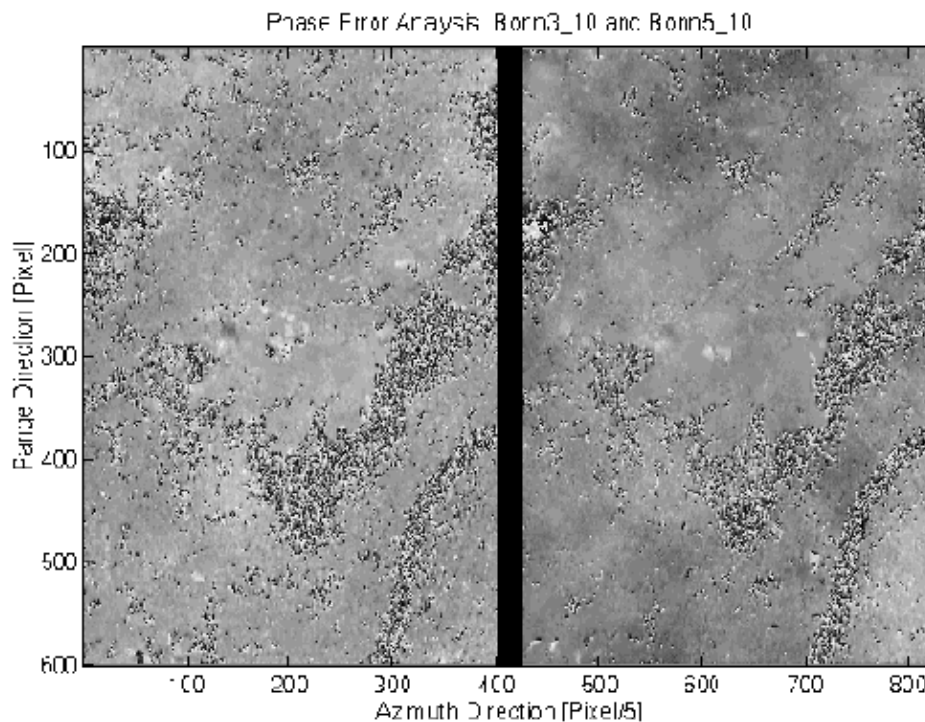

Figure 4: Two phase error maps (in radians [0..2pi]). The baselines values of the two input interferograms used to produce these images are 150 (on the left hand side) and 110 meters (on the right hand side).

In Figure 5, we can see another interesting comparison. On the left hand side we have a multi-image coherence maps obtained using 6 different images and the ML DEM to compensate the phase of each pair. The coherence is estimated using an ensemble average instead of a space one.
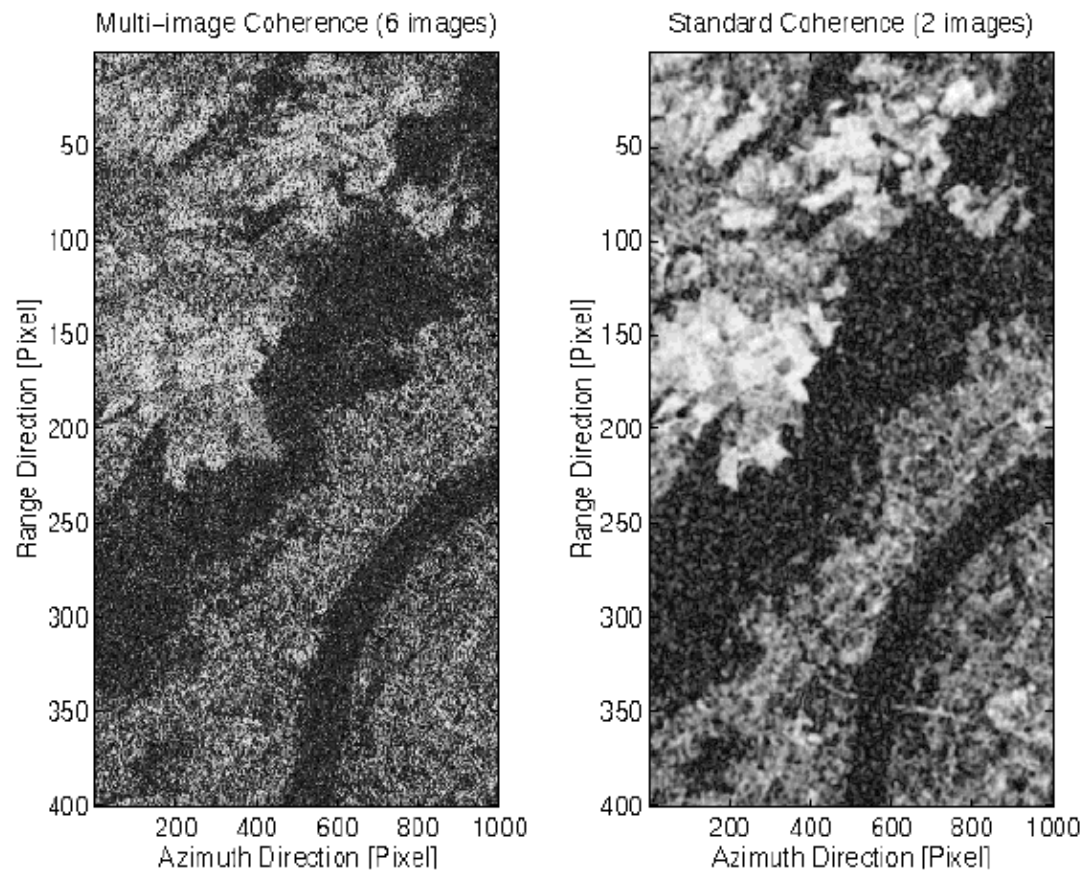
Figure 5: Bonn: Multi-image and standard coherence maps.

The same algorithm was tested using a different data set: 4 Tandem pairs on Mt. Vesuvius, the Italian volcano near Naples, (Figure 6).
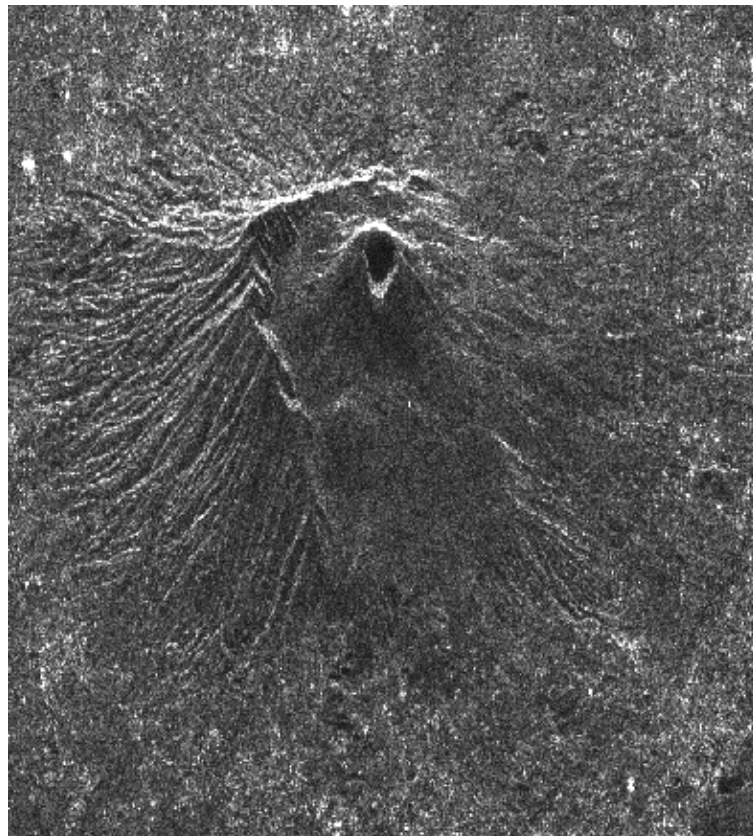

Figure 6: Vesuvius: Amplitude Image - Dimensions: 600 (range) x 2700 (azimuth).

The baselines values are 106, 146, 220 and 253 meters (the altitudes of ambiguity about 85, 62, 41 and 35 meters). No *a priori* information was exploited during the processing, the final result is presented in Figure 7.
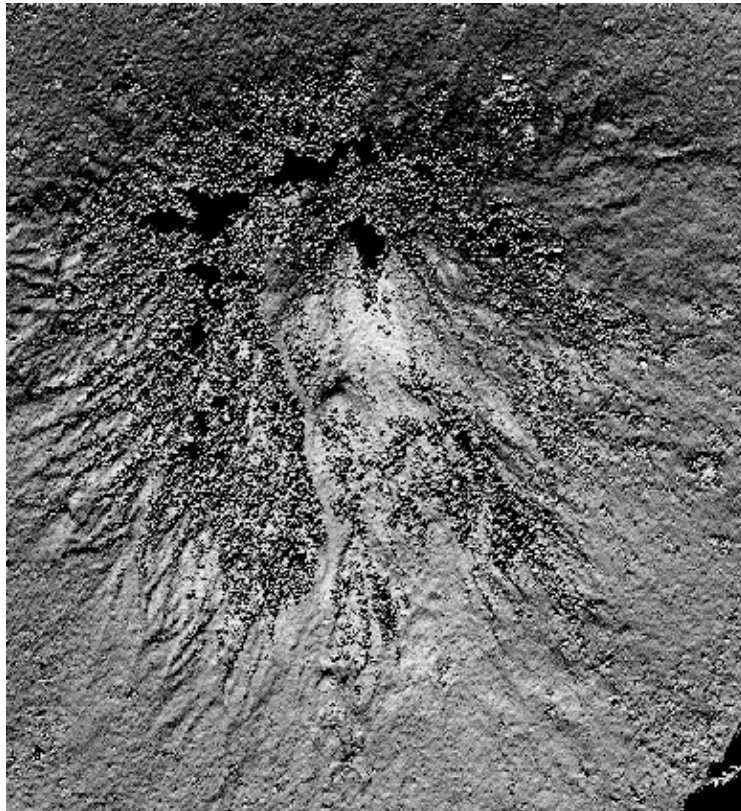

Figure 7: Vesuvius: Maximum Likelihood DEM.

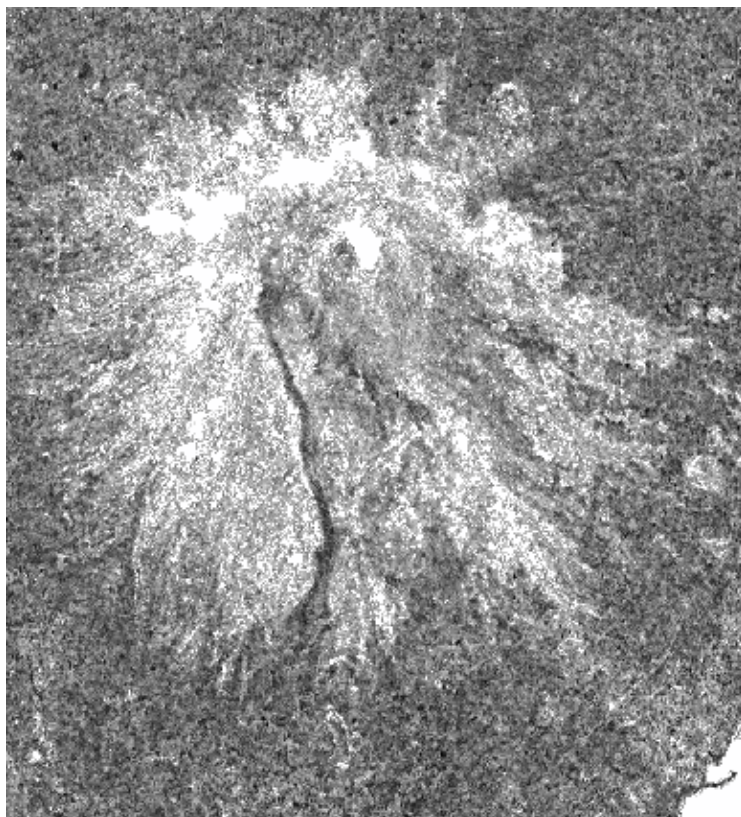The estimated error standard deviation map is reported in Figure 8.

Figure 8: Vesuvius: Estimated Error Standard Deviation (for unwrapped areas the range of values is 1..7.5 meters - white corresponds to not unwrapped pixels).

Again, the reliability map highlights new features not visible in any of the coherence maps used (Figure 9).
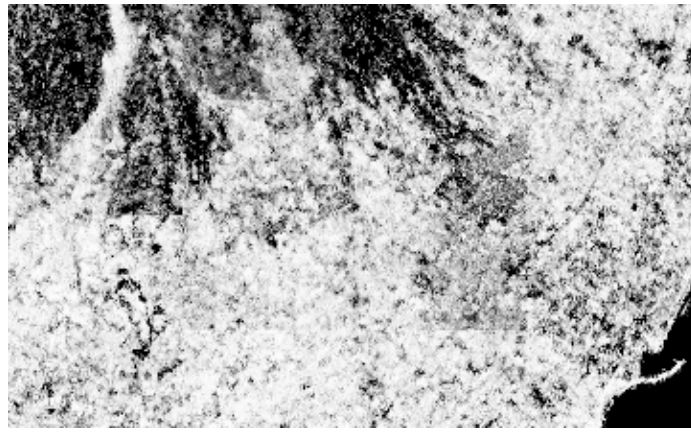
Figure 9: Vesuvius: Reliability Map (region around Torre del Greco).

The "residues" between the data and the synthetic interferograms have been obtained and no evidence of unwrapping errors is visible (Figure 10).
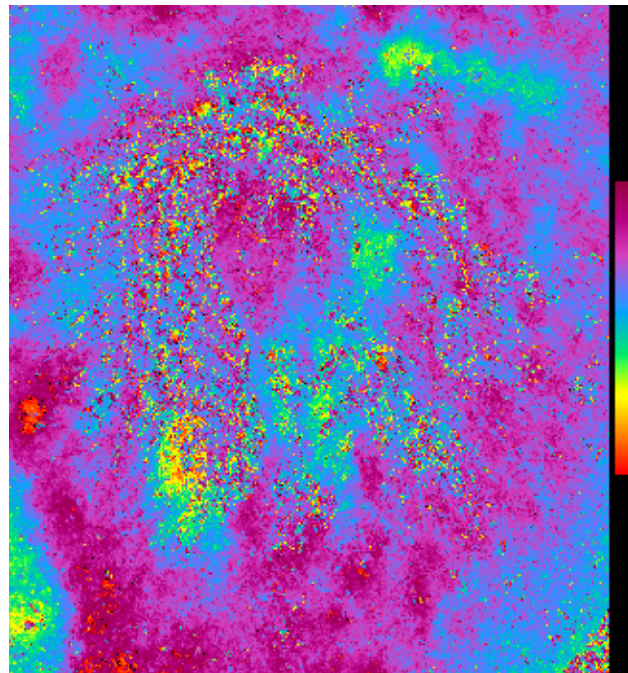

Figure 10: Vesuvius: one of the error maps (in radians [0..2pi]). Normal baseline value: 106 meters. Low frequency atmospheric effects are visible.

Conclusions

This paper describes a multi-baseline phase unwrapping technique for DEM generation. It is shown that the combination of more than two SAR images allows to get a robust technique and that coherence maps quality can be substantially improved. 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 first results on real data are encouraging. The computational burden is not as high as it can appear (both the 12 by 10 km maps shown in the paper have been obtained in less than 90 minutes, using a medium workstation). The next step will be to integrate this software with a geocoding algorithm to obtain a ML DEM on the UTM grid.

Acknowledgements

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