ERS Tandem Data for Earthquake Prediction: Preliminary Results

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Abstract

First results related to the research activity carried out in the framework of the ESA Project AOT.I302 "Use of ERS-1/ERS-2 Tandem Data for Earthquake Prediction in Tectonic Active Areas" are presented. The project is aimed at integrating spaceborne techniques to measure ground deformation with traditional means of seismic activity monitoring. The Sannio-Matese area, one of the most earthquake-damaged zones in southern Italy, has been chosen as test-site and equipped with 20 corner reflectors, located by means of GPS measurements, and 16 GPS benchmarks, in order to have high-coherence ground control points suitable for DEM validation and phase analysis. Fringe maps and coherence analysis for three available tandem datasets (single-look complex images acquired from May to June, 1996) are presented, together with preliminary results on landuse classification and parameters extraction based on the coherent information gathered by the SAR sensors. The capability of measuring small crustal deformation by means of differential SAR interferometry (DINSAR) is also investigated by analyzing non-tandem datasets.
Keywords: SAR Interferometry, Coherence, Classification, Differential SAR interferometry.

Introduction

This paper presents some preliminary results related to the activity which is being carried out in the framework of the ESA project "Use of ERS-1/ERS-2 Tandem Data for Earthquake Prediction In Tectonic Active Areas" (AOT.I302, in response to an ESA's Announcement of Opportunity AO-Tandem issued January 16, 1996), aimed at monitoring and forecasting small crustal deformations and tectonic movements in the area of the Matese Chain (Campano-Molisano Apennines, Southern Italy), which extends from Isernia to Benevento, along the direction NW-SE, and is known as one of the most seismically active segments of the Apennine chain (Siro and Slejko 1989, Barbano *et al*., 1989), being subject to destructive earthquakes of intensity up to XI MCS (in 1688) and, in the last three centuries, to many other strong events (X MCS in 1702, 1732 and 1805, IX MCS in 1962, X MCS in 1980). The project, planned on three-year work packages and started in January, 1997, focuses its objectives on processing methods, validation and science in the areas Interferometry/Land topography, Land classification and Land motion detection with differential phase analysis. Co-ordinated by the Department of Aersopace Engineering of the Second University of Naples, Italy, the project involves national (Consortium for Research and Development of Advanced Remote Sensing (CO.Ri.S.T.A., Naples), Dept. of Space Science and Engineering, University of Naples, Italy) and European (Wageningen Radar Surveys, Wageningen, The Netherlands) partners. The main activities to be performed can be grouped into the following categories:

- Generation of digital elevation models (DEM) from interferometric Synthetic Aperture Radar (SAR) data;
- Attitude and orbit determination, and baseline components estimation from raw data analysis;
- Quality image analysis and improvement by means of SAR simulation;
- Differential SAR interferometry;
- Characterization/classification of land use by using interferometric radar information (coherence maps) and multi-temporal SAR products;
- Characterization of a tectonically sensitive area located in Southern Italy by means of seismotectonic models, derived from historical seismicity, tectonics and geodynamical modeling.

The final goal is the exploitation of the potentiality of conventional and differential SAR interferometry to measure terrain movements, and the integration of SAR observations and Global Positioning System (GPS) measurements and classical techniques of ground deformation measurements (high-precision leveling and tilt monitoring) and earthquake prediction. Results are foreseen both in a short-term analysis, through the study of historical and actual seismicity and of ground deformations which precede and accompany earthquakes, and in a long-term study involving the analysis and characterization of geodynamical processes which affect the Matese Chain.

The project has its predecessor in an international joint research, funded by the Commission of the European Communities (CEC), conducted from 1994 to mid 1996, which involved partners from Italy (Dept. of Space Science and Engineering, University of Naples, Consortium CO.Ri.S.T.A., Vesuvius Observatory), Germany (Institut für Navigation, University of Stüttgart) and France (Bureau de Recherche Gèologiques et Mineraries, Marseille) (Luongo *et al*., 1996). During this programme, the principal seismogenetic areas around the Matese Chain have been identified, and the Sannio-Matese test-site has been equipped with suitable instrumentation for ground deformation measurement with differential GPS and SAR techniques, as described later, collecting seismic data from May, 1994 to August 31, 1996.

The paper is structured as follows. After a description of the Sannio-Matese area from a seismotectonic viewpoint, the monitoring network is presented. Successively, the activities performed on the ERS tandem pairs are summarized, and the interferograms are shown. Results on the coherence analysis and a simple, straightforward unsupervised classification scheme based on the coherence maps are presented. Moreover, a feasibility study on the possibility of detecting small surface changes is performed, showing potentialities of the DINSAR technique on the test area. Concluding remarks describe the future steps of the research activity.

Description of the test-site and ground equipment
Historical seismicity and current seismic events of the Sannio-Matese area

The first phase of the activity related to the project has been an overall assessment of the seismic characteristics of the area: in this section such a charatcerization is briefly summarized. Figure 1 shows the main tectonic characteristics of the Matese complex, which is a transitional area from the structure of the Calabro Arch and the Umbro-Marchigiano-Toscano Arch, affected by complex regional stress fields and by significant variations of the deformation fields, due to stress fields acting in the southern and middle-northern parts of the Apennines (Hippolyte *et al.*, 1994, Lavecchia, 1988).

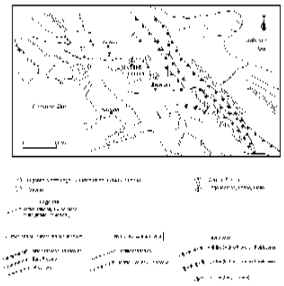
 (click here for full-size image)

Figure 1. The Sannio-Matese area and its main tectonic features.

The focal mechanisms are mainly dip-slip for earthquakes of major energy, and strike-slip for the others (Westaway, 1987). The dip-slip mechanisms show the tensile axis perpendicular to the chain due to the rifting process migrating from the Tyrrhenian coast to the chain, whereas strike-slip mechanisms can be related to strike slip movements perpendicular to the chain axis. In short, the analysis of historical seismicity of the area under investigation shows that:

The isoseismals are extended in the direction of the chain and follow the principal tectonic features, and the magnitudo of historical events, assessed by comparing areas damaged by past and recent earthquakes, ranges from 6.2 and 7.5 (Table 1).

Date	***Magnitudo***	***L (km)***
1456, Dec. 5	7.5	100
1688, Jun. 5	6.8	45
1694, Sep. 8	7.0	53
1732, Nov. 29	6.8	45
1805, Jul. 26	6.8	45
1857, Dec. 16	7.0	53
1930, Jul. 23	6.8	45
1980, Nov. 23	6.8	45

Table 1. Major seismic events in the Sannio-Matese area.

The maximum length of seismogenetic faults, L, reaches the value of 100 km. Periods of seismic activity are separated by periods of inactivity sometimes very long.
In major earthquakes, complex rupture mechanisms are prevailing, as inferred from the earthquake of 1456 (Luongo *et al.*, 1991). The numerous fractures in the medium account for the complexity of the rupture mechanism; the structures longitudinal to the chain can be significantly divided into fault segments that are generated by rotation and migration of the peninsula towards East.
The structures transverse to the chain can be triggered by earthquakes along the axis of the chain itself, or they may have the function of channels of seismic energy.
The seismic activity is mostly found on the eastern side of Matese and the mechanisms are prevailingly extensive, with the main planes in the NW-SE direction.

As far as the current seismicity is concerned, low-energy earthquakes have characterized the period 1980-1991, with the majority of seismic events located in a narrow strip of the peninsula, with focal depths reaching up to 20 km. Seismicity sources are various, not necessarily linked to the Apennine fault, as a confirmation of the complexity of the stress field acting on the area (Alessio *et al.*, 1995). Four main seismogenetic areas have been identified:

Southern Abruzzo, with mid/low-level energy of seismic activity in historical and recent times;
Molise, with past high-energy earthquakes and recent seismic activity in swarms vith low energy;
Area of Benevento, with strong earthquakes in the past (>X grade) and current low-level but frequent seismic events;
Campania and Basilicata, with high-intensity events in historical times and recently (for example, the 6.8-magnitudo earthquake occured in Irpinia in 1980).

Monitoring and ground equipment

Currently, the deformations in the Matese area are being measured through analysis of seismicity data and ground slow motion. Seismicity is monitored through a number of stations of the national seismic network, managed by the National Institute of Geophysics (ING, Istituto di Geofisica Nazionale), together with a regional network monitored by the Vesuvian Observatory (OV, Osservatorio Vesuviano) and a set of temporary stations installed by the Department of Geophysics and Volcalonogy (DGV) of the University of Naples, to increase the number of monitoring points (Fig. 2). Ground motion is monitored by high-precision leveling and inclination measurements with a suitable leveling route, 129.300-km long, equipped with 164 benchmarks, of which 61 have horizontal displacement monitoring capability, and 103 are able to measure vertical components of ground displacements. Last August, 1996, a preliminary leveling campaign has been performed (Luongo *et al.*, 1996): currently, a correlation between the experimental data gathered and seismotectonic models of the area is being performed.

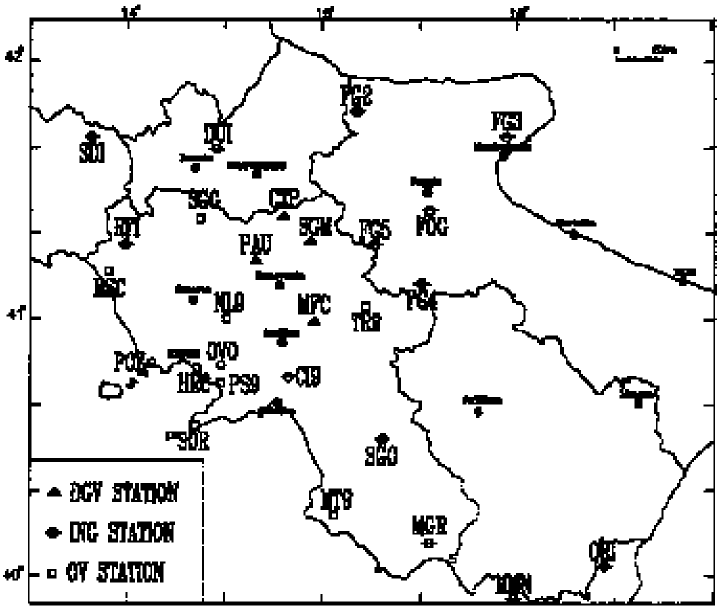


Fig. 2. Seismic network of the Sannio-Matese area.

Moreover, twenty triangular trihedral corner reflectors (CR) and sixteen GPS benchmarks have been installed (Fig. 3): the CRs, deployed by a team headed by Prof. P. Murino (Dept. of Space Science and Engineering, University of Naples, Italy), are suitable ground control points for image registration, can give reliable and stable radar cross-section values, thus giving radiometric standards for absolute image calibration, and can be exploited as phase references when monitoring height variation and horizontal slips by means of differential interferometric data, whereas the GPS benchmarks, fixed to the ground by excavation and concrete cages, enable to determine with good accuracy the horizontal component of the displacement field, by means of ionosphere-corrected differential GPS measurements. Recent campaigns conducted in the area (November 1994 and June/July 1995, Luongo *et al.*, 1996) gave a first statement of stability of the site, with differential displacements not greater than 10 mm.

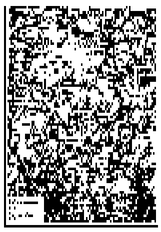
 (click here for full-size image)

Fig. 3. Deployment configuration of corner reflectors and GPS benchmarks.

Interferometric SAR products generation

The availability of several tandem acquisitions over the Sannio-Matese area during the last three years has greatly improved the possibility of obtaining highly correlated SAR datasets, due to the one-day ground-site revisiting period. The criterion adopted for tandem pair selection was aimed at finding sets of at least three passes at the shortest time intervals, and with suitable baseline components. The consequent constraints on the baseline component perpendicular to the line of sight, B_{perp}, lock the suitable values of $|B_{perp}|$ to be in the range from 70 to 130 m, for efficient phase unwrapping and avoiding baseline decorrelation (Li and Goldstein, 1990, Prati and Rocca, 1990): as a consequence, only the tandem pairs with such values of B_{perp} have been selected from the listings provided by the ESA Guide and Directory Service (GDS) Internet site. The datasets analyzed in this work are reported in Tab. 2. The tracks of interest are labeled 129 and 358: both are ascending passes, and to obtain a reasonable superposition of the ground swaths, the second quarter of the track 129 (frame 819) and the first quarter of the track 358 (same frame) have been selected. Fig. 4 depicts the imaged area.

Acquisition date	***Orbit numbers***	***B_{perp} (m)***
May 7-8, 1996	25167 (ERS-1) / 5494 (ERS-2)	122
May 23-24, 1996	25396 (ERS-1) / 5723 (ERS-2)	81
June 27-28, 1996	25897 (ERS-1) / 6224 (ERS-2)	78

Table 3. Tandem pairs analyzed and correspondent baseline estimates. The theoretical value of B_{perp} suitable for interferometry applications is of the order of 100 m.

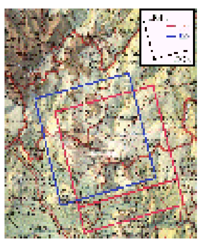
 (click here for full-size image)

Fig. 4. Sketch map of the ground swaths of ERS Tracks 129 (Quarter 2) and 358 (Quarter 1), Frame 819. The approximate co-ordinates of the test area are 41°33' N, 14°04' E (upper left corner), 41°33' N, 14°52' E (upper right), 41°01' N, 14°04' E (lower left), 41°01' N, 14°51' E (lower right). The extension is about 1800 km^2.

Single-look complex (SLC) images, processed by ESA/ESRIN, have been requested for the investigation. The average dimensions of each frame is of the order of 15000 lines of 2200 range samples. Fig. 5 shows, as an example, one of these images, multilooked by a factor 5 in the azimuth direction in order to get a square pixel (about 20x20 m^2), and mirrored about its horizontal axis, to obtain a north-south image, canceling the effect of the ascending passage. The Matese Chain and the Matese Lake are well visible on the central portion of the frame, and a division of the massif into three blocks with respect to the NW-SE-oriented Matese Lake-Letino structure is suggested by the radar image. In particular, since the radar illumination is almost orthogonal to the main morphostructures of the massif, the ascending passage is suitable for geological analysis of the area (lithologies, principal structural lineaments, faults direction recognition, etc.).

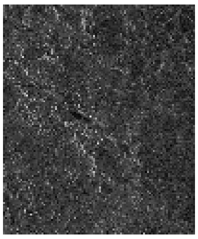
 (click here for full-size image)

Fig. 5.SAR SLC image of the Sannio-Matese area, gathered on May 7, 1996 by the ERS-1 AMI instrument (orbit number 25167, frame 819, track 129), processed by ESA-ESRIN (© ESA 1996).

The capability of producing DEMs on different 10x10-km^2 subareas of the test-site has already been accomplished by using November 1995 and February 1996 ERS tandem pairs and implementing an efficient end-to-end procedure, from geometric registration to baseline components estimation from the propagated state vectors available in each CEOS formatted SLC header (Rufino et al., 1996). Here, the logic flow of the operations needed for obtaining fringe maps of the three tandem pairs analyzed is reviewed:

- Coarse registration by rigid translation. A number of visually-inspected bright points common to both images has been used to eliminate crude non-overlapping areas, obtaining a residual misregistration of the order of three pixels.
- Fine registration by localization in each 512x256 pixel subset of the brightest point target as a Ground Control Point (GCP). The evaluation of the pixel shifts to be applied for registration has been performed by 10-time oversampling each subset (cubic B-splines have been used for interpolation) and cross-correlating the GCP amplitudes. The average number of suitable GCP, after elimination of poorly correlated subsets and inconsistent shifts derived from the procedure, has found to be from 150 to 200, depending on the size of the images: such an high number, as compared to past experience with 3-day ERS-1 pairs (Moccia et al., 1994), can take account for possible nonlinearities due to the pointing geometry and/or attitude differences.
- Co-registration by means of bicubic polynomials, whose coefficients have been computed with least-square approximations, by using as input the sub-pixel shifts. As a remark, we noted that the range and azimuth residual shifts are quite constant for the three pairs analyzed, with a slight increase of azimuth sub-pixel displacement from near to far range, probably due to small differences in attitude (i.e. pointing geometry) between the two passes, or to non perfectly parallel orbits.
- Complex product between the co-registered SLC images (the second one being complex conjugated). No common spectral band filtering before computation of the fringe map has been performed, thus leaving a residual baseline decorrelation.
- Coherent multilook for coherence enhancement and maximum likelihood estimation of the interferometric phase (Werner et al., 1992). Fig. 6 shows one of the resulting interferograms: the shorter ERS-1/ERS-2 temporal baseline gives good quality fringes, and comparatively small decorrelated areas.

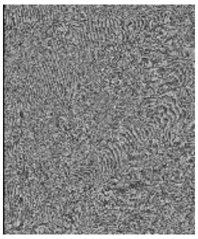
 (ERS-R) (click here for full-size image)

Fig. 6. 5-look interferogram obtained from the ERS tandem pair of May 7-8, 1996 (see Tab.3). The image dimensions are 2400x2400 pixels.

Coherence analysis and classification

Fringe quality has been evaluated by means of the correlation coefficient $\gamma = \frac{\left|p_{i1}p^{*}_{j2}\right|}{\sqrt{\langle p_1^2\rangle\langle p_2^2\rangle}}$, where * denotes complex conjugation, p_{i1} and p_{j2} are homologous pixels in the two co-registered images,and <> denotes the average operator. Coherence has been evaluated by using 5x3-pixel inspection matrices, in order to analyze a reasonable pixel number in azimuth and as little range pixels as possible, due to the range phase undersampling. Fig. 7 shows coherence histograms of the multilooked interferograms (2400x2400 pixels, on average), and Table 4 gives a statistical characterization of the correlation coefficient. The values found are quite good, as a consequence of the reduced temporal gap between the two observation, and it is expected that stripping off mountainous areas and zones in which layover due to high slopes occur could even increase the average coherence. As a remark, layover areas reduce the possibility of efficient phase unwrapping for DEM generation, as shown by analyses conducted on different pairs of the illuminated area by Rufino et al., 1996.

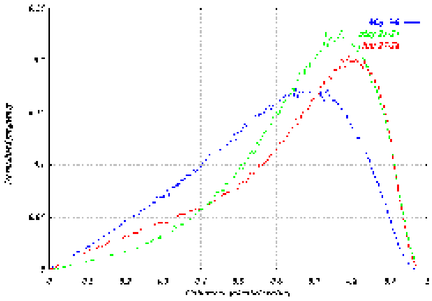
 (click here for full-size image)

Fig. 7. Histograms of coherence values for the three tandem pairs selected.

Tandem couple	**Average**	**St. dev.**
May 7-8, 1996	0.55	0.21
May 23-24, 1996	0.59	0.05
June 27-28, 1996	0.63	0.04

Table 4. Coherence statistics.

Fig. 8(a) shows the coherence image relative to the June 27-28, 1996 pair, and Fig. 8(b) is a color-composite image obtained by superimposing (red and blue channels) the interferogram to the coherence map, in order to visually inspect areas of low coherence. The Matese Chain, a densely vegetated mountanious area, shows, as expected, low coherence, whereas flat areas and bare soil exhibit larger correlation.

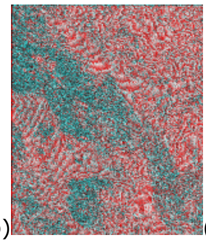
(a)(ERS-R) (click here for full-size image) (b)(ERS-R) (click here for full-size image)

Fig. 8. Coherence map (a) of the June 1996 ERS tandem pair. Brighter areas correspond to high coherence values. (b)Composite image of coherence+interferogram.

With respect to the corresponding SAR images (Fig. 5), some ground features are more identifiable: for example, rivers Volturno and Calore are clearly visible in the lower left part. Temporal decorrelation shows changes in land use, vegetation cover and moisture, as well as roughness and hydro-meteorological changes (Wegmüller *et al.*, 1995). This suggests strategies of classification based on feature extraction from the coherence maps. At this stage, a straightforward attempt has been performed, based on a common iterative, self-organized unsupervised clustering algorithm (ISODATA, ERDAS™, 1991). The initial number of clusters has been chosen to be 4, on the basis of available thematic maps of the area, and the corresponding broad classes have been labeled as woods and water courses, pasture, bare soils, sown areas. Fig. 9 shows the resulting classified area, with color-coding of the different classes. The comparison with thematic data is encouraging, even if refinements need to be done, for the identification of narrower classes, possibly by means of multi-source imagery (for example, woods and water basins are grouped in the same class in the coherency image, whereas are distinguishable in the backscatter image) and for accuracy evaluation.

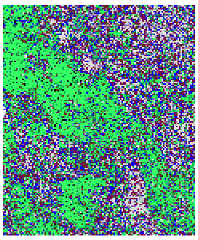
 (ERS-R) (click here for full-size image)

Fig. 9. Colour-coded classified map of a portion of the Sannio-Matese area. Classes are woods/water (green), pasture (blue), bare soils (indigo/white), sown areas (blue/red) (ERS-R).

Feasibility of differential SAR interferometry

The potentiality of differential SAR interferometry (DINSAR) for measuring small displacements (of the order of centimeters) occurred between the acquisition of three radar images has been widely demonstrated (Gabriel et. al., 1989, Prati *et al.*, 1993). The feasibility of double-difference interferograms, though, relies heavily on quantitative changes of the scattering mechanisms of the imaged area, i.e. on the well-known temporal and baseline decorrelation effects (Zebker and Villasenor, 1992), and therefore is strictly related to the terrain morphology and land use. Since the test-site is a densely vegetated area, with little urbanization and sparse bare-soil regions, the loss of coherence is significantly high even after few days, a constraint which gives non-tandem data of the area (e.g. ERS-1/ERS-1, ERS-2/ERS-2 pairs, or ERS-1/ERS-2 passages with more than 1-day separation) a relatively low information content. This section will justify quantitatively this observation, also showing the possibility of obtain DINSAR maps on some non-vegetated areas present in the illuminated scene.
The investigation has been conducted on two tandem pairs, namely, the May 23-24 and the June 27-28 couples (see Tab. 3), chosen because of their suitable B_{perp} values (81 and 78 m for the tandem pairs, about 80 m between non-tandem observations).

Fig. 10 shows the coherence histograms obtained from the processing of two non-tandem combinations of the available SLC products.

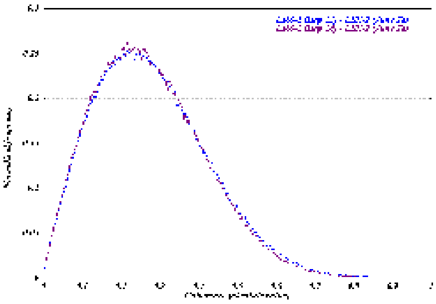
 (click here for full-size image)

Fig.10. Coherence histograms of the analyzed non-tandem pairs. Average values found are 0.28 and 0.27 for the ERS-1/ERS-2 and the ERS-2/ERS-2 pairs, respectively, with standard deviation of 0.02.

The interferometric correlation has dramatically decreased, due to the wide temporal baseline (34 and 35 days respectively) and to possible cultivation in vegetated areas (harvesting) during the time gap between the two acquisitions. As a result, only in little portions of the image fringes are visible. Fig. 11 shows an area in which some fringes survived, roughly corresponding to Mount La Gallinola (in the Matese Mount Maggiore unit, direction NE with respect to the Matese Lake, visible in Fig. 5), a non-vegetated site formed by milestones, clay and marl. We are exploring the possibility of obtaining DINSAR information in this small region: at the moment, no double-difference interferogram has been produced.

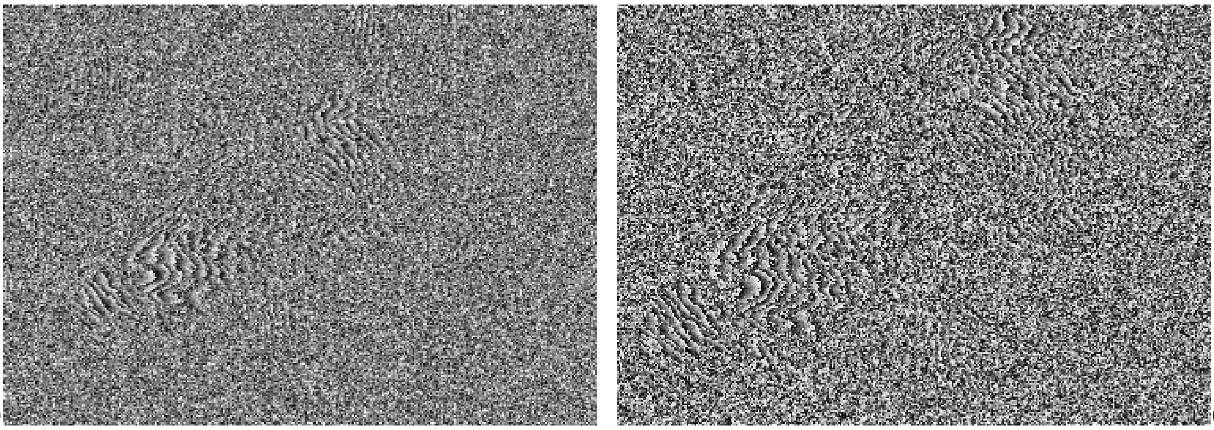
(a)  (b)

Fig. 11. Portion of the interferograms obtained from ERS-1 (May 23)/ERS-2 (June 28) images (a) and ERS-2(May 24)/ERS-2 (June 28) pairs (b). Poor-quality fringes are visible on a bare-soil area, which exhibits an average coherence of 0.4. The dimension of this subset are 128x128 pixels (a 5-look coherent summing has been applied in the azimuth direction).(ERS-R)

The lack of large and representative high-coherence areas seems to reduce the impact of change detection by means of DINSAR data and the possibility of collecting wide-area information on ground displacements phenomena which are precursory of seismic events. Nonetheless, the presence of a number of CR deployed on the test-site could allow us to obtain a correct phase sampling on a small subset of high-coherence points (the point target images), whereas GPS measurements on the absolute CR locations should permit the reconstruction of the absolute phase of each reflector, and, as a consequence, the possibility of detecting surface changes in the vicinity of the CRs. In a first attempt of this procedure, the identification of the CR responses in the images and the extraction of geometric and radiometric image quality parameters (range and azimuth resolutions, integrated and peak sidelobe ratio (ISLR, PSLR)) by means of appropriate algorithms (Moccia *et al.*, 1994, Rufino *et al.*, 1996), has allowed us to obtain a set of control points with good phase quality. The problem of retrieving the relative phase of the CRs is still open, because unfortunately the CRs are immersed in low-coherence areas. Simulation approaches are under study.

Conclusions and further work

First results relative to the analysis of ERS tandem pairs of the Sannio-Matese area have been presented in this paper. First, a description of the main tectonic structures of the site and of the instrumentation deployed for detection of small elevation changes (leveling route, GPS benchmarks, CRs) have been presented. Then, the study has been focused on three available SAR SLC couples, from May to June, 1996: good quality interferograms have been obtained, and the coherence analysis has shown reasonably good coherence values. A first approach in classifying land use from the coherence information has been presented, and critical analysis on the feasibility of differential interferometry on the area has shown potential application of the technique only in small subsets of the scene. In the future, the research activity related to the project will be concentrated on the following points:

- Development of differential interferometry by means of phase information derived from the installed CRs. We are investigating the approach proposed by Massonnet et al., 1996, who suggests to use a course DEM for generating synthetic fringes due to relief, and detect terrain displacements by overpassing the need for phase unwrapping. To this end, computer simulation of the SAR system will allow us to create artificial fringe maps, generate the reference function necessary to compress the raw data and enhance the interferogram coherence. The simulation technique has been successfully applied on SIR-C/X-SAR data (Ponte and Moccia, 1995), which shown better resolutions when compressed with the simulated 2D impulse response function.
- Correlation between GPS measurements and differential interferometry. Synergistic use of multi-source imagery (for example, SPOT data, SIR-C/X-SAR, ERS) for geological analysis.
- Refinement of baseline estimation methods and orbital modelling. Work is currently underway for producing efficient computer code for the extraction of the platform attitude during data acquisition, starting from the ERS restituted state vectors. A comparison with SIR-C/X-SAR attitude information (derived from the postflight attitude trajectory history (PATH) data) shows little interpolation errors in recostructing the attitude from the SAR raw data (Rufino and Ponte, 1997). The objective of such activity will be better estimation of the baseline components for phase unwrapping and DEM generation.
- Refinement of classification strategies based on coherence maps and SAR backscatter images. A promising multi-source approach, which does not require normal distribution of data and seems to improve classification accuracy, is the so-called evidential reasoning (Peddle, 1995). Study on the application of this theory to microwave signatures provided by INSAR products are being performed.

Development of three-dimensional seismo-tectonical models of the Sannio-Matese area, for a more precise definition of seismogenetic areas.

Acknowledgment

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