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Multipass SAR interferometry. A tool for geologic analysis(*)

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Summary. — This paper investigates how the information content of repeat pass satellite SAR interferometric (INSAR) data can be used to provide the geologist with a tool which can improve his ability and efficacy in the geologic analysis of SAR imagery. INSAR processing produces interferometric fringes, coherence and amplitude images. To produce an interferometric DEM phase unwrapping is a critical step. For phase unwrapping, we propose the WLMS (Weighted Least Mean Square) estimation of the phase, which is a generalization of the least-mean square method. The crucial step in WLMS approach is the weighting procedure. We propose a weighting algorithm based on the fusion of *a priori* information extracted from different interferometric products. These different information channels—DEM, amplitude and coherence—can be effectively fused to convey information to the geologic interpreter using 3D stereoscopic visualization; SAR stereo pairs were artificially generated using the interferometric DEM and the intensity image or the coherence image of the area overlaid. In order to ascertain the performance of the procedure a number of tests were carried out over various sites in Matese (Southern Italy), which has a fairly demanding topography, using ERS SAR tandem data. The results demonstrate that WLMS unwrapping method is sufficiently robust in capturing the morphology of the area and that stereoscopic visualization greatly facilitates geologic interpretation and the observation of detailed features of the terrain.

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1. – Introduction

It is widely recognized that spaceborne imaging radars are a valuable remote-sensing tool to rapidly survey areas and carry out specific geologic investigations in addition to

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other traditional techniques. Amplitude SAR images are usually interpreted by conventional methods of photogeology using image tone, texture and shading but great care is necessary because many factors affect radar backscatter. A significant improvement in geologic interpretation can be achieved using stereo-pairs and stereoscopic viewing to elicit depth and certain aspect details.

Recent space missions offered the opportunity to acquire SAR interferometric pairs with short-time separation such as 1 or 2 days for the SRL-2 mission and 1 day for the ERS 1/2 tandem. This short lapse of time between the data takes reduces significantly the changes of the scattering properties observed inside a given resolution cell so that coherence is generally high and DEM (Digital Elevation Model) generation becomes effective also in hilly areas with vegetation cover.

These repeat-pass spaceborne SAR interferometric data contains a great wealth of information. The phase interferogram provides information on terrain elevation and can be exploited to produce a DEM, phase coherence (which depends on land cover, signal-to-noise ratio, repeat pass interval, etc.) provides land surface information and the amplitude of the radar return is related not only to land surface characteristics but also to morphology. These two last information channels—amplitude and coherence—can be exactly draped over the interferometric DEM without co-registration problems.

To fuse, at pixel level, the information content of the DEM and of the amplitude or coherence images we propose the use of stereo interpretation. In this way image understanding can be effectively improved because the interpreter can combine depth information with other cues such as shading or other surficial characteristics of the area.

The main objectives of this work are the generation of a robust interferometric DEM and the production of SAR stereo pairs, simulating satellite stereo acquisition, to be used in geologic applications, first of all for geomorphology and prospective structural geology.

In the first part of this paper the proposed algorithms for phase unwrapping and the generation of artificial SAR stereo pairs are presented. The second part discusses the geologic interpretation of simulated SAR stereo imagery.

2. – Test area

Considering the interest for geological applications, we have carried out a number of tests over various sites in Matese (Southern Italy).

The use of these areas for test site was largely a consequence of other geological investigations recently carried out [1, 2] in the area and of the availability of many ERS SAR tandem images.

In particular, the test refers to the Boiano area, a hilly area covered with vegetation, which is located to the north of the Matese massif (UL corner: $\phi = 41\,°35'$N, $\lambda = 14\,°15'$E; LR corner: $\phi = 41\,°10'$N, $\lambda = 14\,°45'$E), between the central and southern part of the Apennine orogenic segments. These tests have involved ascending path SLC ERS tandem SAR data (table I).

The morphology of the eastern hills is simpler than that of the western ones which is more articulated. The low slopes on the eastern part are expression of erodable lithology as tender/cemented sandstones, marl and conglomerates. On the left, instead, there is a more articulated morphology expression of cemented terranes as limestones except some part. The drainage pattern is caused by several factors among which lithology, rocks attitude, tectonic structures. In the case of mixed lithologies, the rivers dig preferably in the clay. The drainage pattern of the eastern hills (the slope of the sides is about $10\,°$) is subdendritic, typical of tender rocks and sub-horizontal layers; some irregularities could

TABLE I. – *ERS-1/ERS-2 tandem acquisitions over the Matese area.*

Date (E1-E2)	Orbit number (E1-E2)	ESA's baseline
Aug. 01-Aug 02, 1995	21159-1486	56 m
Sept. 05-Sep 06, 1995	21660-1987	100 m
Nov. 14-Nov 15, 1995	22662-2989	91 m
Feb. 27-Feb 28, 1996	24165-4492	190 m
Apr. 02-Apr 03, 1996	24666-4993	120 m

be due to a local presence of rocks more cemented or/and permeable. This pattern is not subject to any control by the structures. The drainage of the western hills is influenced by lithologic differences: there are two drainage patterns, an angular one—due to fractured terrains—and a subdendritic one—due to flysch terrains.

From a structural point of view the area is affected by important faults that caused the Boiano plain [3].

3. – SAR data processing

The procedure used for processing a repeat-pass SAR interferometric pair (single-frequency data set) can be summarized as follows: 1) slant range and azimuth filtering of the complex SAR images; 2) registration; 3) interferogram and coherence map generation; 4) flattening; 5) coherence and amplitude (average of the two amplitude images, which presents a reduced speckle for a given pixel dimension); 6) phase noise reduction; 7) phase unwrapping; 8) generation of the ground range DEM; 9) SAR stereo pair simulation.

3·1. *Phase unwrapping.* – For what concerns the phase unwrapping procedure, although a great deal of research has been carried out in the recent years, unwrapping of noisy interferograms still represents a challenge.

Phase unwrapping of SAR interferograms of hilly terrains generally is difficult also because of the side-looking configuration of SAR which may cause shadow and layover. A number of phase unwrapping algorithms for SAR interferograms have been proposed [4-6]. However, these algorithms do not give satisfactory results when noisy and/or dense fringes occur. Two phase unwrapping algorithms have been considered: the LMS (Least Mean Squares) and the Weighted-LMS [7]. The LMS is a well-known method as a counterpart to branch-cut/ghost-lines or residues tying strategies. By minimizing the difference (in a least-mean-squares sense) between the partial derivatives of the wrapped and the unwrapped phase, which turns into the Poisson equation, it always provides a solution. However, since it considers the scene as a whole and it does not allow greater than π phase jumps in the unwrapped phase, the solution may suffer from serious averaging problems around the phase discontinuities. This is because LMS provides only the irrotational component of the phase field [8]. The rotational part, not present in the LMS solution, contains the residues and therefore the phase discontinuities greater than π. LMS can be implemented in a very efficient way by using FFTs and performs well when dealing with not too rough relief areas.

The weak point of LMS is the inadequate treatment of inconsistent data, which occur in regions with concentrated and distributed phase noise, phase aliasing and areas where the phase is not reliable. Using the WLMS algorithm we can prevent the noisy phase

Fig. 1. – Weighting procedure scheme.

values from having any influence on the result simply by assigning a weight between 0 (not reliable) and 1 (reliable) to each sample of the phase map. This is equivalent to weighting each equation in the Poisson problem. Therefore, the linear system cannot be solved by using FFTs. The new weighted linear sparse system is solved iteratively with a Picard iterative method [7].

The crucial step in WLMS approach is the weighting procedure, *i.e.* the automatic procedure to detect and partition the inconsistent regions. The proposed weighting algorithm is based on the fusion of *a priori* information extracted by different interferometric products (fig. 1). First of all, the residues and coherence maps were used to link the singularities of opposite signs with the intent to locate zones which most probably contain aliasing lines (ghost lines) [6]. These lines are usually placed in lowest coherence areas.

Precisely, for all the opposite residues the taxi-cab distance and the average coherence in a box neighborhood, having the residues in the opposite corners, is computed. Then the closest end points were connected with a line whose thickness is proportional to the distance of the residues and inversely proportional to the average local coherence. Precisely, the thickness of the line is chosen according to the equation

$$Th = \left[\frac{d}{6}\right] + 1 - [4\bar{c}]\,,$$

if $Th > 1$ and $Th = 1$ in the other cases, where d is the distance of the closest residues, $\bar{c}$ is the average coherence before mentioned and the square brackets indicate the integer part because the thickness must be an integer number.

The inconsistent regions so extracted are combined with other regions obtained in the following way. An average of the amplitudes of the two SLC images, used for the interferogram generation is computed. Through this image we can localize regions with an unreliable phase, *i.e.* pixels with low amplitude that are often related to shadow areas, especially when they are grouped in connected regions. For this reason, a thresholding algorithm that cuts off pixels with very low amplitude is used. Then an erosion morphological operator, with a structure of 3×5 elements (to respect the different pixel spacing

Fig. 2. – Two-dimensional weighting array (a) of interferometric fringes (b); unwrapped phase with WLMS method (c) and its principal value ("rewrapped value") (d).

of ERS 1-2 SLC images) is applied to filter out isolate pixel in the mask (usually related to the speckle present in single look images). Finally, weights are assigned to the mask, obtained as logical union of the two described masks, through the multiplication of this mask by a quantized coherence map. We have found that the results of the investigations show that the WLMS approach, with this weighting procedure, performs better if the coherence map is quantized only in four levels. The introduction of different weight levels permits the reduction of the masking errors in high-coherence area. Their choice is completely image dependent and must be made after a thorough analysis of coherence values nearby the residues.

This general procedure was applied to produce a DEM of the test area. Figure 2

Fig. 3. – LMS and WLMS residuals.

shows a two-dimensional weighting array (a) of the interferometric fringes (b), the phase unwrapped (WLMS) image (c) of a subset of the full area and its principal value ("re-wrapped value") (d).

The residuals [9] of LMS and WLMS unwrapping methods related to the same area of fig. 2 are shown on fig. 3. At the right top of the LMS residual image there is a wide fringe between two noisy zones. It appears clearly that the WLMS algorithm performs better than the LMS one.

The WLMS DEM of the area with the amplitude image overlaid, related to fig. 2, is presented in fig. 4.

3·2. SAR *stereo pair simulation*. – Stereo vision provides a direct way of inferring depth information by using two images, which are recorded with a difference in the view angle, destined to the left and right eye, respectively.

Fig. 4. – WLMS DEM with SAR amplitude overlaid. The altitude is exaggerated.

Fig. 5. – SAR stereo pair of the test area. a) Original SAR amplitude image; b) simulated SAR amplitude image.

An artificial stereo pair is generated by processing a single original image by using a simulator [10] which permits the user to choose significant parameters such as the height of the sensor and the inclination angle of the simulated image in order to modulate the stereoscopic exaggeration factor.

Concerning ERS SAR stereo pairs both images, amplitude or coherence, have the same side looking geometry but with a certain separation simulating left and right stereo images. These images are flashed alternatively on the computer monitor and a system of LCD glasses synchronized with the display is used to provide each eye with the proper image.

A stereo pair of the SAR amplitude image of the test area is shown in fig. 5.

4. – Geological evaluation of SAR data products

4·1. *General considerations*. – Morphology is represented by slope articulation; in recent orogenic areas, surficial geomorphic features such as valleys, gradients, and gradient changes indicate the erosional expression both of geologic structures (such as high angle faults, fractures, etc.) and of lithology and bedding. Hence, for morpho-structural analyses, it is of primary importance that DEM should keep gradient changes. On the other hand, a high altimetric accuracy of the DEM is not absolutely necessary for large-scale studies, *i.e.* morpho-structural analyses. Therefore, it is of the uppermost importance that in the generation of an INSAR DEM the phase unwrapping procedure should avoid error propagation. In fact, if the error is localized, on the whole, the morphology will not be altered.

In geologic investigations DEM's are usually used to generate gradient maps, and shaded-relief images [11] with various solar illumination angles and different perspective views. These products are generally useful because they allow the photointerpreter to visualize the characteristics of the relief, which are

Fig. 6. – Comparison of topographic and WLMS DEM profile.

– The slope. It gives information on the lithology (*i.e.* to high slopes correspond not much erodible terranes such as limestones, while to low slopes correspond more erodible terranes such as flysch facies) and on the geological structures (*i.e.* high angle faults).

– Gradient changes. They could be related to changes of lithology (*i.e.* from bedrock to debris or from limestones to marl) and presence of structures. At the same time the changes in slopes visualize drainage patterns, valleys and ridges which represent the surficial expression of lithology types, structures, etc. Therefore, for morphostructural studies, the respect of the relative slopes is very important.

Obviously the information obtainable depends on the DEM scale. While for great morphostructural studies, a large-scale DEM can be used, for detailed geomorphological analyses, a small-scale DEM is necessary.

In stereo interpretation, amplitude or coherence image draped on the interferometric DEM permit to fill in small morphologic errors and to enhance subtle morphologic features.

4·2. *Results of the tests*. – Altimetric accuracy tests of WLMS DEM have been carried out by comparing a number of topographic and WLMS DEM profiles. Figure 6 shows two of these profiles which result to be very close. The WLMS DEM reproduces the topography of the area fairly well, the topographic errors remain localized and therefore the morphology of the area is well represented.

Concerning the analysis of a single SAR amplitude image we have:

– if the study area is sufficiently wide, the differences between lithology types may be, to some extent, delineated because of different brightness, texture and shading (morphology). If the area is small, the discrimination is extremely difficult;

– the variations of texture among terrains having a different mechanical behavior are not well visible on the sides (having a low backscatter) dipping in the same direction of the SAR look direction;

Fig. 7. – Nadir view of the amplitude SAR image. The Biferno river, east to the plain, is well evident with its bight. The deviation of “Bifern” (B) coincides with the “Fosso delle Cese” tributary (A) and with an orthogonal ditch to the east. The rivers on the Plain of Boiano are not well visible.

– only to a great scale there is correspondence between radar image texture and morphology/lithology;

– even if the amplitude image is related (on the average) to morphology, it does not allow a correct evaluation of the slopes. Therefore, it is difficult to correctly set the structural elements and to estimate the attitude of the layers, which can be inferred from the asymmetry of the slopes;

– ditches and hatches parallel to the look direction or not deeply embanked are difficult to detect (fig. 7).

Coherence and SAR amplitude images give synergistic, and in some case complementary, information respect to the geology of the area. Indeed while amplitude imagery is particularly sensitive to surface roughness and to morphology, coherence gives particular information on the e.m. scattering stability of the surface.

In coherence image even small ditches, hatches, rivers are well expressed as result of strongly contrasting dark (low coherence) to light (high coherence) tonal differences.

The discrimination among these dark linear features can be performed draping coherence data on DEM. The low values of coherence are not only due to the presence of water, but also to the vegetation along the course of the rivers. Therefore, using the coherence information it is possible to identify ditches and rivers that are not deeply embanked.

In fig. 8, 9 the rivers (1,2) on the Plain and the “Fosso delle Cese” tributary (A) stand out clearly.

Fig. 8. – Interferometric coherence image of Boiano plain. Dark linear features are well evident.

Fig. 9. – Perspective view of the elevation map of the area with coherence image overlaid.

The synergistic stereoscopic viewing of DEM with amplitude or coherence image overlaid provide a sharp detail. Texture, patterns and other morphologically expressed features, such as morphology, strike features, faults lineaments are strongly enhanced and well interpretable. It must be pointed out that even in a stereoscopic pair the illusion of depth is influenced by the shadow direction. It is appropriate therefore that shadows fall toward the observer.

5. – Conclusions

The WLMS unwrapping method showed to be sufficiently robust in avoiding error propagation and therefore in reproducing correctly the morphology of an area.

The use of DEM with coherence or amplitude image overlaid allow the interpreter to obtain a better description of the geologic characteristics. In particular coherence images proved to be an interesting cue in geomorphic studies; for instance, it is possible to identify waterways that are not clearly visible on shaded relief or amplitude images only.

Considering an experienced interpreter, stereoscopic interpretation of SAR stereo pairs produces markedly improved results over monoscopic interpretation. The usefulness of this tool consists, for instance, in a correct evaluation of strikes, dips, landslides, that greatly improves morphologic and structural analyses. The gain in geological interpretation is well worth the extra steps of computer processing required to generate stereo pairs.

In particular this methodology can be used to investigate remote areas with dense vegetative cover or which are under cloud cover or where access is difficult or impossible.

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