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# Generation of large-scale digital elevation models *via* synthetic aperture radar interferometry(*)

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**Summary.** — We investigate the possibility to generate a large-scale Digital Elevation Model by applying the Synthetic Aperture Radar interferometry technique and using tandem data acquired by the ERS-1/ERS-2 sensors. The presented study is mainly focused on the phase unwrapping step that represents the most critical point of the overall processing chain. In particular, we concentrate on the unwrapping problems related to the use of a large ERS tandem data set that, in order to be unwrapped, must be partitioned. The paper discusses the inclusion of external information (even rough) of the scene topography, the application of a region growing unwrapping technique and the insertion of possible constraints on the phase to be retrieved in order to minimize the global unwrapping errors. Our goal is the generation of a digital elevation model relative to an area of 300 km by 100 km located in the southern part of Italy. Comparisons between the achieved result and a precise digital terrain model, relative to a smaller area, are also included.

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## 1. – Introduction

Synthetic Aperture Radar Interferometry (INSAR) has been proven to be a powerful technique for high-resolution Digital Elevation Model (DEM) generation. This technique is based on imaging, *via* Synthetic Aperture Radar (SAR) systems mounted on board

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air- or space-borne platforms, the same area from two "slightly" different side looking angles, thus providing a stereoscopic scene vision [1-5]. Likewise SAR, INSAR is an all weather, all time system that works independently of the presence of sunlight or clouds, fog and rain.

Unlike similar stereometric systems, INSAR is a coherent device that requires sophisticated and sometime huge data processing aimed at extracting the phase difference signal between the two SAR image of the investigated zone [3, 4]. This phase signal is related to the observed scene topography, thus allowing, following its evaluation, to produce a DEM of the area. High resolutions in the ground coordinates are obtained by synthesizing a long antenna in the along track direction (azimuth) and by transmitting dispersed high bandwidth pulses in the across track direction (range) [3].

Unfortunately, the measured phase difference signal, usually referred to as interferogram or interferometric phase, is only known restricted (wrapped) to the $(-\pi, \pi)$ interval, while the wanted phase variations usually largely exceed this interval, if high system sensitivity to the target height is required. Reconstruction of the original (unwrapped) phase starting from the measured wrapped one is therefore needed and represents a critical point in the interferometric processing chain due to the high nonlinearity of the problem coupled with the sampled nature of the involved signals. This particular phase retrieval operation is usually referred to as phase unwrapping (PhU) [3, 6-13].

Despite the strong research efforts dedicated to the solution of the PhU problem, till now there are no fully unsupervised PhU algorithms that automatically solve this ill-posed problem [6]. As a result, INSAR DEMs are generally characterised by locally high height resolutions, but often suffer for the presence of global, low-frequency, errors [6].

The PhU problem becomes even more a challenge when one is interested in the generation of large-scale DEMs. In this case a data partitioning operation must be carried out in order to limit the computing requirements, if robust phase unwrapping techniques are applied. Indeed, several problems may arise when joining independently unwrapped phase obtained from the different data portions.

In this paper, in order to evaluate the potentialities of the INSAR systems, we investigate the problems related to the generation of large-scale DEMs by using ERS-1/ERS-2 tandem data. The area of interest covers large portions of the Italian regions of Campania, Molise and Abruzzo and the southern area of Lazio; the observed area shows a large variety of terrain patterns including large flat areas and extremely steep mountainous territories.

In particular, we specifically focus on the problem of using external information as rough knowledge about the DEM we want to reconstruct and on the problem of improving the performances of the phase unwrapping procedures. This latter includes application of region growing strategy to preserve reliable (*i.e.* nonsteep) areas from PhU errors and forcing the solution to known boundary phase values, when unwrapping very critical data sets, to guarantee phase continuity in between the data portions.

The paper is organized as follows. In sect. **2** we present a brief review of the interferometric processing for DEM reconstruction. In sect. **3** we discuss the PhU problem, the weighted and region growing based algorithms and the boundary condition problem. In sect. **4** we present the obtained results and discuss the phase flattening procedure we tried to apply in order to ease the phase unwrapping step by using a low-resolution DEM available on a web site. Moreover, a comparison of the retrieved DEM and an available high-precision DEM is also included.

Fig. 1. – SAR and INSAR reference geometry.

## 2. – SAR **interferometry review**

As already anticipated in sect. **1**, SAR is a system that allows obtaining two-dimensional high-resolution radar images of the observed scene. The possibility to generate a 3D map of the observed area is offered by the INSAR configuration implying two antennas, usually referred to as master and slave. These are displaced in the across-track direction, see fig. 1, of a certain amount $b$ called *baseline* and form, with respect to the horizontal direction, an inclination angle $\alpha$, usually referred to as *tilt angle*. The two antennas can be either synthesized by two subsequent passes of a single antenna system or can be simultaneously present on-board the platform. In the former case the scene should be stable with respect to microwave scattering properties.

Let us start the following analysis by considering the cylindrical coordinate system of fig. 1 whose axis is represented by the master antenna trajectory, which is assumed to be a straight line. Presence of trajectory deviations, which are negligible for satellite systems, may be accounted for as presented in [14]. The two target spatial coordinates, *i.e.* the ones imaged by the SAR system, are the distance $r$ of the target from the antenna trajectory, usually referred to as *range*, and the target position with reference to the along track direction $x$ (*azimuth*).

High-resolution in the *across-track* (range) direction is achieved *via* transmission of large bandwidth pulses. Usually these are dispersed chirp signals which allow limiting the transmitting peak power: in this case a processing step in range direction of the received (raw) data is necessary to compensate for the linear distortion of the signal [3].

High resolution in the *along track* direction is again achieved *via* a raw data processing aimed, this time, at synthesizing an antenna (synthetic aperture) whose dimension is sensibly (100–1000 time) larger than the real one mounted on-board the platform. This allows increasing the radar image azimuth resolution as well [3, 14].

By referring again to fig. 1, it is evident that a single SAR system operating in a non-interferometric configuration is unable to uniquely localize the target. As a matter of fact, it discriminates only the target spatial coordinates (that are azimuth and range) of the cylindrical reference system and results “blind” with respect to the angular target coordinate $\vartheta$, usually referred to as target look angle [3].

Likewise stereometric system, SAR interferometry exploits angular diversity in the scene imaging to localize the target and therefore to obtain the digital elevation model of the observed scene. We still consider in the INSAR case $r$ be the target range with respect to the master antenna and indicate with $r + \delta r$ the target range at the slave antenna, $\delta r$ being the range (path) difference at the two imaging sensors (see fig. 1). Simple geometric considerations allow to demonstrate that, by knowing $r, \delta r$ and the orbital parameters ($b$, $\alpha$ and $H$), the target look angle can be found by

$$\sin(\vartheta - \alpha) = \frac{r^2 - (r + \delta r)^2 + b^2}{2br} \approx -\frac{\delta r}{b} \tag{1}$$

and the target height readily follows as

$$z = H - r\cos(\vartheta). \tag{2}$$

Key point of SAR Interferometry is therefore the measurement of the target path difference $\delta r$. However, differently from stereometric system, in the INSAR case this is obtained by extracting the phase difference between the target returns in the two focused images. As a matter of fact, it is known that the electromagnetic response of a generic scene target exhibits a phase component that is proportional, through the factor $4\pi/\lambda$ ($\lambda$ being the *wavelength* of the illuminating radiation), to the travelling path, *i.e.* $r$ and $r + \delta r$ for the master and slave antenna, respectively. Accordingly, letting $\varphi$ be the phase difference signal between the two images we have

$$\varphi = \frac{4\pi}{\lambda}\delta r, \tag{3}$$

showing that the INSAR system can get the target path difference measurement with an accuracy of the wavelength order (for instance, 5.6 cm for the ERS satellites). Letting $\sigma_\varphi$ be the standard deviation of the phase noise that corrupts the phase measure (again refer to fig. 1) we can express the accuracy of the reconstructed DEM by

$$\sigma_z = \sin\vartheta \frac{\lambda}{4\pi} \frac{r}{b\cos(\vartheta - \alpha)} \sigma_\varphi. \tag{4}$$

Equation (4) apparently suggests the use of large baselines. Unfortunately, there are physical limits to the baseline increase dictated by scattering mechanisms [3, 15]. Actually, the above presented discussion holds only when the phase of the backscattering component of the signal received at the two antennas does not change "too much" in the master and slave images [3, 15]. This phase change depends on the range system resolution, $c/2B$ ($c$ and $B$ being the *lightspeed* and the transmitted *bandwidth*, respectively), and can be described by following the stochastic signal theory approach [3,4]. In summary, it results that the baseline must satisfy the following limit [3]:

$$|b_\perp| = b|\cos(\vartheta - \alpha)| \leq \frac{\lambda}{2}\frac{2B}{c} r \tan\vartheta, \tag{5}$$

in order to retain a non-zero *correlation degree* between the two focused images and, therefore, a low $\sigma_\varphi$ value resulting from the phase difference evaluation. The maximum baseline component orthogonal to the look direction ($b_\perp$) for the ERS-1/ERS-2 sensors is of 980 m [3]; while the optimum one is of 370 m. However, much lower baselines are generally chosen in order to avoid significant errors in the PhU reconstruction.

The interferometric SAR data processing chain can be summarized as follows.

1) SAR focusing of the received raw signal at the master and slave antenna for the SAR images generation; the obtained results are usually referred to as Single Look Complex (SLC) images.

2) Geometric registration of the slave SLC image onto the master SLC grid.

3) Complex interference signal generation, flat earth phase removal, complex average (multilook) and phase difference extraction.

4) Phase unwrapping of the interference signal (interferogam).

5) Target localization and DEM geocoding starting from the interference signal.

We briefly describe the aim of these steps. Likewise SAR system for scene backscattering image generation, raw data focusing (step 1) is necessary to increase the spatial (*i.e.* azimuth and range) resolution of the processed data and, therefore, of the reconstructed DEM.

Step 2 carries out a slave image data *resampling* aimed at compensating, with respect to the master image, for geometric distortions induced by the different angular imaging geometry. As a matter of fact, target responses in the two images are located at different image pixels, while interference must be taken with respect to the same target.

Averaging in the third step is usually carried out to reduce, prior to the subsequent phase unwrapping, the phase noise content. Moreover, being the images in cylindrical geometry, flat earth gives a strongly variable phase signal that is conveniently eliminated before the phase unwrapping step, once the imaging geometry is known. This is usually implemented prior to the complex average to accommodate even in this step the high signal spatial variations.

Phase unwrapping is needed due to the fact that phase difference, being measured *via* the argument of complex signals, is only known restricted to the $(-\pi, \pi)$ interval while the wanted (absolute or true) phase signals always exceed this interval for high elevation accuracy systems. Finally, geo-localization is essentially the procedure that solves eqs. (1) and (2) in a Cartesian geocentric reference system and geocoding includes map projection procedures to generate the DEM in universal Cartographic reference systems [3, 16].

## 3. – Phase unwrapping

PhU is an important step in SAR Interferometry for DEM reconstruction that is usually complicated by the presence of critical areas. These appear whenever either high noise content or steep topography variations (*layover*) generate a true phase pixel-by-pixel variation exceeding the $(-\pi, \pi)$ interval (*aliasing*). Layover is rather frequent on ERS data due to the low system look angle (23°) [3].

Several PhU techniques have been developed over the past years [3-16]. They basically address the problem in two separated steps: a preliminary (non-linear) estimation ($\mathbf{s}$) of the wanted true phase gradient $(\nabla\varphi)$(1) carried out on the measured data and a

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(1) Gradients are substituted by pixel-to-pixel variations in the discrete domain case.

subsequent integration of the measured gradient. Indeed, instead of refering to **s** as to the measured gradient, that is rotational due to the above-mentioned aliasing effects, we should call it a pseudogradient. The nature of the pseudogradient integration, wherein critical areas may have large impacts, classifies two different PhU strategies: the local and the global (generally, Least Squares-LS) methods.

Local PhU techniques [6] simply integrate the measured gradient along paths connecting (in principle) all the image pixels. Path crossing of critical areas, where the gradient estimate is incorrect, generates a drastic error that propagates (without any attenuation) to all the subsequent integration points. Moreover, changes of the integration path may lead to different unwrapped phase patterns [3, 7].

Least-Squares algorithms are, on the other hand, based on global (*i.e.* two-dimensional) integration criteria: they minimize the distance, usually, in a square ($L^2$) norm, between the gradient estimated from the wrapped data and the gradient of the retrieved solution [7, 13]:

$$\varphi_u : ||\nabla\varphi_u - \mathbf{s}||^2 \to \min, \tag{6}$$

where $||\cdot||^2$ is the usual quadratic norm operator in the Hilbert space(²). The solution to this problem, in a rectangular domain, is obtained by projecting the equation $\nabla\varphi_u = \mathbf{s}$ through the divergence operator and equating on the domain boundary the normal derivative of $\varphi_u$ and the **s** normal component (Neumann condition) [3].

By using the first Green identity [3,8], LS techniques have been shown to include two-dimensional integration, thus resulting more robust than local integration methods [3, 7, 9]. Moreover, the solution is in any case unique [3, 7] and can be fast computed in the spectral domain [8]. Finally, as they do not "honor the data", in the sense that

$$\langle\varphi_u\rangle \neq \varphi_m = \langle\varphi\rangle, \tag{7}$$

where $\varphi_u$ is the retrieved unwrapped phase function and $\langle\cdot\rangle$ is the $(-\pi, \pi)$ restriction operator, critical areas may be highlighted by the presence of error propagation patterns. This can be detected by using the reconstructed phase as a *flattening* signal for the original interferogram, that is, by generating the following *residual* interferometric fringes:

$$\varphi_{\text{res}} = \langle\varphi_m - \varphi_u\rangle. \tag{8}$$

Note that, should the unwrapping be successful, *i.e.* $\varphi_u = \varphi$, the residual interferogram would be everywhere zero. It is also worth to note that, thank to the use of iterative residual unwrapping techniques, global techniques exhibit higher noise immunity with respect to local integration methods [3, 12].

A refinement of LS solution to further reduce error propagation effects is represented by the Weighted LS (WLS) PhU [3,7,11,12]. This is based on the adoption of a weighted norm in the distance definition in (6). More specifically, by having an *a priori* knowledge on the location (within the image) of critical areas, error contributions arising from these

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(²) For instance different norms may be chosen [17, 18]. In $L^0$ norm we minimize the number of occurrences (points) in which the gradient of the retrieved solution differs from the measured pseudogradient [17].

areas are attenuated (or even excluded) by proper weighting coefficients in the distance computation. Generally weighting coefficients are chosen to be binary (*i.e.* 0 or 1): therefore pixels are either considered or excluded from the integration domain. Proper pixel exclusions should eliminate as many few pixels as to render $\mathbf{s} = \nabla\varphi$, or better $\mathbf{s}$ a true and not pseudogradient, in the remaining image domain. WLS-PhU algorithms may be numerically implemented *via* the Finite Difference Method or the Finite Element Method (FEM). In both cases the unwrapped phase results by solving a linear equation system [11, 12] which corresponds, as for the unweighted case, to a discretization of a Poisson problem, but Neuman conditions must be added on all the resulting boundaries of the useful domain [3, 7]. Spectral solutions are no longer useful in terms of computational efficiency.

On the other hand, a novel PhU technique is based on the application of Region Growing (RG) strategies to the LS-PhU algorithms [13]. In this case the wrapped image is divided in regions of increasing confidence. Region partition and confidence assignment is carried out essentially by referring (as for the weighting mask generation in the WLS PhU) to the coherence and amplitude images, that are always available during the INSAR processing. It turns out that noisy regions are always associated to lower coherence(3) values, while layover is usually associated to both low coherence and high amplitude values. The basic idea of the Region Growing LS procedure is to LS unwrap higher confidence regions first and subsequently proceeding into critical areas. Regions cannot be independently unwrapped; they are connected together by appropriate junction conditions on the common region boundaries [13]. These translate in the presence of Dirichlet instead of Neumann boundary conditions on all the boundaries confining with already unwrapped regions; this can be easily accounted for with slight modifications of the WLS PHU numerical code [13].

There are two main advantages of the RG LS PhU procedure. First of all, it strongly limits possible error propagation effects from low to highly reliable areas. Second, thanks to the use of correct phase boundary values evaluated from highly reliable data, the solution within the critical areas is improved with respect to the one obtained *via* the use of traditional LS-PhU algorithms. Finally, for binary weights, the RG LS algorithm is an extension of the WLS PhU procedure; in particular the latter can be viewed as a special case involving only two regions: the weighted and unweighted ones.

## 4. – Large-scale DEM generation

The large-scale interferogram of 300 km×100 km resulting from the experiment has been obtained by processing the frames 819 and 837 of the ERS-1/ERS-2 tandem configuration relative to orbits 21159 (ERS1) and 1486 (ERS2). The data cover a large area in the southern part of Italy.

Use of tandem data, which are acquired at 1 day temporal separation (1 and 2 August 1995 for our data set), has been dictated by the need of limiting the effects of temporal scene scattering changes that may cause increase of the interferometric phase noise in the measured interferogram. The baseline distance between the two passes is of about 56 m. This corresponds, through eq. (4), to a theoretical DEM accuracy of the order of 22 m for a reasonable average coherence degree of 0.7, which is associated to $\sigma_\varphi = 52°$ [3, 4].

The four data sets corresponding to the selected frames have been separately pro-

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(3) Coherence is the correlation coefficient between the registered SLC images.

Fig. 2. – Interferogram relative to the whole area of about $300 \times 100\,\text{km}^2$. Average pixel spacing is of 66 m and 90 m in azimuth (vertical) and range (horizontal) directions.

cessed. First of all, for each of the passes, the raw data pair has been partitioned in four blocks (with an overlapping of 1000 samples) that have been focused to generate four pairs of SLC images. Subsequently, the ERS-2 SLC (slave) images have been registered to the corresponding ESR-1 (master) ones to minimize the geometric distortion effects due to the different imaging geometry: this step was carried out with 1/16 pixel accuracy. Following this step, phase difference has been extracted for each block with a multilook of 4 pixels in range and 16 pixels in azimuth. The resulting interferogram covering the whole area is shown in fig. 2: the average pixel spacing is of 66 m and 90 m in azimuth and range, respectively.

Interferogram corresponding to the first block has been unwrapped *via* both the WLS and the RGLS PhU algorithms. In this latter case we have selected six different regions

Fig. 3. – Interferogram relative to block #1 (left image), rewrapped unwrapped phase of the WLS (center image) and the RGLS (right image) PhU. Azimuth is horizontal, range is vertical.

by using both amplitude and coherence images. To compare the results of the two PhU algorithms on this block, we show in fig. 3 the *rewrapped* WLS (center) and RGLS (right) unwrapped phases together with the original fringes (left). A much better qualitative measure is represented by the residual fringes; these are obtained by subtracting the unwrapped phases of the WLS and RG LS PhU algorithms from the original interferogram and rewrapping the result. These are presented on left and right side of fig. 4, respectively. Recalling once again that successful unwrapping algorithms should zero the residual fringes, it is evident that the RG LS PhU achieved superior performances.

Fig. 4. – Residual fringes obtained by subtracting the rewrapped unwrapped fringes of fig. 3 from the starting interferogram. Left image is the residue of the WLS PhU; right image is relative to the RGLS PhU. Image orientation is as that of fig. 3.

Fig. 5. – Same as fig. 3 but for block #2.

Concerning block #2, PhU has been carried out in a similar way: the achieved results corresponding to figs. 3 and 4 for the first block are presented in fig. 5 and 6, respectively. Again we note that the RG LS algorithm attained better results with respect to those of the WLS procedure.

Block 4 has been unwrapped by only using the WLS procedure because it already produced high-quality results: see fig. 7 for the interferometric phase and the WLS residual fringes. Moreover, in this block the starting raw data were characterized by the presence of a large number of missing lines. These are highlighted by a vertical strip in the amplitude image, in the coherence map (center image in fig. 7) and in the fringe

Fig. 6. – Same as fig. 4 but for block #2.

Fig. 7. – Interferogram relative to block 4 (left image), coherence (center) image and residual fringes (right image) of the WLS PhU. Image orientation is as that of fig. 3. The coherence image graylevel scale ranges from 0 (black) to 1 (white).

pattern (left side image in fig. 7) that may complicate the region partition step peculiar to the RG LS PhU.

Let us finally come to the third block which includes a much more complicated pattern with reference to the PhU problem due to the presence of both very steep topography and large noisy areas that create aliasing effects extending all over the image. This is a typical problem of ERS data and is recognized by looking at the interferometric phase and coherence images, presented on the left side and in the middle of fig. 8, respectively.

To overcome these problems we decided to aid the PhU by partially subtracting (flattening) "some" topographic information. Flattening can be carried out starting from the knowledge of a rough reference DEM, synthesizing the corresponding phase pattern(4) and using this as an "equivalent flat earth surface" similarly to what done in the processing step 3. Following this (roughly) known phase pattern subtraction, the fringes should only be sensitive to the high-frequency signal components of the topography that characterize the higher resolution of the SAR DEM with respect to the one used in the flattening.

The rough DEM we tried to use is a DTED0 digital elevation map that can be network downloaded (http://www.nima.mil/geospatial/geospatial.html#products) in patches. The latitude and longitude spacing is of 30 arcsec corresponding to a cartographic pixel spacing of 800–900 meters in both Easting (E) and Northing (N) directions. Due to the large coverage of the SAR DEM, this operation required to download nine patches that have been subsequently joined together as described in the header information. The available DEM is referenced to the latitude and longitude coordinates (*i.e.* a geographic system) whereas the phase pattern to be flattened is with respect to SAR azimuth and range coordinates. Application of an inverse geocoding step allowed to translate the DEM in terms of phase difference at the SAR antennas of the interferomet-

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(4) Once that orbital information is known.

Fig. 8. – Interferogram relative to block 3 (left image); coherence (center) image and flattened fringes by using the downloaded DTED0 DEM (right image). Image orientation is as that of fig. 3. The coherence image graylevel scale ranges from 0 (black) to 1 (white).

ric system in the SAR reference system; these are usually referred to as synthetic fringes. The flattened interferogam is shown on the right-hand side of fig. 8. A deep investigation of this image shows that, indeed, in some regions the flattening procedure was successful in reducing phase variation (see the upper left part of the image on the right-hand side of fig. 8) but locally some phase variations have been even increased. This effect is even more pronounced in the remaining part of the image.

Failure in the flattening procedure is explainable considering two major points. First of all a geometric mismatch between the synthesized and the real fringes may exist. Cross correlation measures carried out on the synthesized and SAR interferogram have confirmed the presence of geometric mismatch all over the image (but for the upper left image portion) within an upper bound of 20 pixels. The mismatch was due to problems in joining four of the nine downloaded patches of the reference DEM that are pertinent to the current block. These were confirmed by the presence of errors in redundant information of the downloaded DEM that allows joining the patches. Secondly, due to the very low resolution of the DTED0 DEM, even where a correct alignment exists, phase variations may be somewhere increased, thus creating additional layover features due to the extreme rough knowledge of the flattening DEM. In other words, being the flattening carried out by a severe interpolation of the phase values of the rough DEM sparse grid onto the finer SAR grid, layover may appears even in areas of relatively large but non-aliased phase variations. On the other hand, the rough DEM information turns out to be too sparse to locally follow and reduce the number of aliasing features in the measured phase.

At the end we used the DTED0 DEM to adjust the two absolute phase constants for the unwrapped phases in the adjacent blocks #2 #4. The block-adjacent uwrapped phases were used to carry out a boundary constrained LS PhU on block #3, thus eliminating the unwrapped phase discontinuities between blocks 2, 3 and 4. This operation fits very well the nature of the RGLS PhU and can be easily carried out by introducing

Fig. 9. – Reconstructed DEM. Horizontal direction is Easting, vertical direction is Northing. The image graylevel scale ranges from 0 m (black) to 2800 m (white).

additional Dirichlet conditions on the block #3 image border. However, due to the extreme low quality of the starting fringes (see the image on the left-hand side of fig. 8), unwrapped phase still suffers, in this block, of low-frequency errors due error propagation effects and mismatches of boundary constraints, which were indeed evaluated by the rough DEM and may significantly differ by the true ones.

The unwrapped phases pertinent to the four blocks were joined together, image pixels were geo-located and geo-coded in a UTM cartographic reference system. The reconstructed DEM is presented in fig. 9.

To carry out some quantitative quality measurement of the reconstructed DEM, we use an available DEM of the Military Geographic Institute (IGM) which has an accuracy of 5–10 m in height, a longitude and latitude spacing of 1 arcsec. The latter corresponds in UTM to 25 m pixel spacing in E and N directions; it only covers a limited region of $70 \times 55\,\text{km}^2$ located at the lower part of the image in fig. 9. In these area a mean coherence value of 0.65 has been measured: the corresponding expected height error standard deviation is 24 m [3].

Horizontal and vertical cuts of the two DEMs are presented in fig. 10; noisy high-frequency contents appear in the reconstructed DEM. The difference between the two DEM is shown in fig. 11: the large difference features are typical of atmospheric influence affecting the received phase signal that introduces significant errors. This thesis was supported by an analysis of the meteorological conditions variations between the two SAR system acquisitions. At variance of the 1 August acquisition, the data on the 2 August

Fig. 10. – Horizontal (upper image) and vertical (lower image) cuts of the reconstructed (continuous lines) and the IGM (dotted lines) DEMs.

were collected when thunderstorms were present on the investigated area. This certainly induces instabilities of the scene scattering properties, thus generating the already discussed decorrelation phenomena especially on block #3. Moreover, even where high coherence is present, presumably changes in the humidity content have generated the detected phase artifacts. Despite these artifacts, the mean and the standard deviation of the difference were assessed to be of 10 m and 33 m, respectively.

Fig. 11. – Difference between the SAR and the IGM DEMs. A gray level cycle corresponds to 150 meters. Image orientation is as that of fig. 9. Image size is approximately $70 \times 55\,\text{km}^2$.

## 5. – Conclusions

This paper has presented the description of a large-scale Digital Elevation Model generation experiment carried out by using a large ERS-1/ERS-2 tandem data. This is a challenging test due to complication arising, particularly, in phase unwrapping operation applied to the data sets in which the overall data takes have been partitioned. As a matter of fact, problems were present on a particular data set due to the effects of both pronounced layover phenomena (typical of ERS satellite interferometric data due to the very low look angle) and large decorrelated areas. Use of sophisticated unwrapping techniques has allowed avoiding the presence of phase discontinuities on the reconstructed DEM in between the blocks.

The experiment has also addressed the integration of low-resolution DEM for reducing interferogram variations (flattening). This has shown that interferogram flattening, when carried out with rather sparse information, may even be deleterious for reducing the effects of layover areas due to involved severe interpolations. Future research on the correct use of these rough information could be considered: for instance they could be integrated in the norm minimization problem, typical of PhU LS procedures, thus eliminating the need of large data interpolation.

The reconstructed DEM has been compared with a precise reference DEM on a smaller area of $70 \times 55\,\text{km}^2$ showing, despite the presence of atmospheric phase artifacts on the starting raw data, relatively small differences. The produced DEM can be used for the generation of a more precise one based on the use of ascending and descending tandem acquisitions with large baselines [19]. In this case the already computed DEM can be used to generate a reliable synthetic interferogram to be used for flattening the real ones and to avoid discontinuities between adjacent blocks.

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