

## OPTICAL AND RADAR DATA FUSION FOR DEM GENERATION

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### ABSTRACT

This paper presents a DEM generation procedure based on optical (SPOT stereo) and radar (InSAR, interferometric SAR) data. The first part of the paper is focused on InSAR. The second one is concerned with the integration of optical and radar data. Two levels of integration are proposed: the SPOT data can support the InSAR procedure (in particular phase unwrapping) and the SPOT and InSAR data can be fused to perform a joint estimation of the terrain surface.

### 1 INTRODUCTION

The description of the terrain surface by means of DEMs is a requisite of many engineering activities. Among the main applications of DEMs are telecommunications, defence, thematic mapping and GIS. There is an important commercial demand, which can not be served by the current offer of DEMs. This demand is stronger for high resolution DEMs (e.g. height accuracy better than 5 m), but the market for digital elevation models with lower accuracy is still significant and can be addressed by remote sensing techniques.

Since the advent of the first spaceborne sensors, DEM generation has been based mainly on electro-optical data and photogrammetric techniques.

Beside this kind of data, SAR images are recently gaining increasing importance thanks both to the development of different promising techniques to exploit them (interferometry, radargrammetry and shape from shading) and to the world-wide availability of spaceborne SAR data.

The DIIAR - Polytechnic of Milan (Polimi) is involved in an European Union Concerted-Action called ORFEAS (Optical-Radar sensor Fusion for Environmental ApplicationS), including several European research groups (University of Thessaloniki, Cartographic Institute of Catalunya, ETH Zurich, Technical University of Graz and Polytechnic of Milan).

An important part of the research activities in the frame of the ORFEAS project is concerned with the generation of DEMs. The Polimi contribution to this topic is two-fold:

- 1) comparison between the SPOT stereoscopia and interferometric SAR (InSAR) results;
- 2) synergetic use of the data coming from the two techniques.

In next paragraph, the InSAR technique and its characteristics are described. In the second part of the paper, the synergetic use of SPOT and InSAR data is addressed.

### 2 INSAR TECHNIQUE

SAR interferometry for DEM generation was proposed by Graham in 1974 [Graham 1974] and applied for the first time at JPL in 1986 using airborne data [Zebker and Goldstein 1986]. Today, SAR data from several spaceborne sensors (e.g. SIR-A/B/C, ERS-1/2, J-ERS

and Radarsat) are available and a large number of research groups are working on InSAR DEM generation.

At Polimi, an InSAR procedure for the generation of DEMs has been implemented; for a complete description of this procedure, refer to [Crippa et al. 1998].

The first stages of the processing (i.e. the image registration, the interferogram generation, flattening and filtering) are based on the public domain software ISAR-Interferogram Generator [Koskinen 1995] distributed by ESA-ESRIN. This software has been written at Electronics and Information Department of Polytechnic of Milan; it allows generating in a very effective way the filtered interferogram and the related coherence image.

All the remaining stages of the procedure (i.e. the phase unwrapping, the sensor parameter calibration and the DEM generation) are based on software written by the authors.

The phase unwrapping is the most critical stage of the entire procedure; it greatly influences the quality of the generated DEMs. In the following, the critical aspects of the unwrapping stage are presented.

#### 2.1 Phase Unwrapping

The interferometric phase shows many discontinuities, which originate the classical fringe pattern. The fringes are due to the fact that instead of the full phase value  $\phi$ , only the principal value  $\phi_p$  (with  $-\pi < \phi_p < \pi$ ) is known.

In order to derive DEMs, it is necessary to obtain the full value  $\phi$  from its principal value  $\phi_p$  (called wrapped phase); this is the task of the phase unwrapping. Many unwrapping approaches have been proposed; the unwrapping implemented at Polimi employs the so-called "ghost-line" approach [Goldstein and Zebker 1988]. It is based on the assumption that no phase differences greater than  $\pi$  occur between adjacent pixels, (i.e. it is always  $\Delta\phi < \pi$ ). The unwrapping is obtained by integration, pixel by pixel, of the phase differences along a path that does not cross lines of aliasing (called ghost-lines, where the full phase difference is greater than  $\pi$ ).

The critical point of this method is the reconstruction of the ghost-lines. Dealing with wrapped phases, is only possible to detect the endpoints of these lines (called ghost-lines because are not visible in the interferogram!). This is done by integration of the phase differences, along a closed path, taking into account that phase differences greater than  $\pi$  can not occur:

if  $\Delta\phi_{\text{wrapped}_{12}} = \Delta_{12} > \pi$ , it is assumed:  
 $\Delta\phi_{\text{unwrapped}_{12}} = \Delta_{12} - 2\pi$   
 if  $\Delta\phi_{\text{wrapped}_{12}} = \Delta_{12} < \pi$ , it is assumed:  
 $\Delta\phi_{\text{unwrapped}_{12}} = \Delta_{12} + 2\pi$

The integration is performed along the shortest closed path, i.e. along four adjacent pixels. If no ghost-lines are crossed (or if they are crossed an even number of times) during the integration, the circular integral equals zero. On the contrary, if the ghost-lines are crossed an odd number of times, the circular integral equals an integer number of  $2\pi$ . In the latter case, aliasing occurs in one of the four pixels (such a point is called residual). This point is considered to be the endpoint of a ghost-line.

In the current unwrapping implementation, the reconstruction of the ghost-lines is realised connecting all the "residuals" with a "Minimum Spanning Tree" of ghost-lines, i.e. the ghost-lines are drawn using only a geometric criterion. Assumed there are no large errors (e.g.  $2\pi$  errors due to aliasing propagated along the integration path) after unwrapping, many local errors in the phases are caused only by the approximate location of the ghost-lines.

It is possible to take advantage of the information coming from an existing DEM (e.g. a SPOT-derived DEM) in order to locate more precisely the ghost-lines and hence to reduce the unwrapping related errors in the generated DEM. This kind of improved phase unwrapping is presented in the second part of the paper.

During the phase difference integration, aliasing can occur due to the incomplete location of all the ghost-lines. The major problem of this kind of unwrapping is the propagation of the aliasing errors along the entire integration path. Due to this propagation, in the same integration zone can exist different portions of unwrapped phases characterised by relative phase shifts multiple of  $2\pi$  (called  $2\pi$  jumps). The unwrapped phases have to be checked and corrected for this kind of jumps (manual editing); otherwise the quality of the generated DEM is strongly degraded.

As discussed in the second part of this paper, the SPOT-derived DEMs used to support the unwrapping can be of help to reduce the need of human operator editing, that represents a very time-consuming stage of the InSAR procedure.

## 2.2 Characteristics of InSAR DEMs

The DEMs generated by SAR interferometry are characterised by a very high spatial resolution. Using a 4 times compressed interferogram (i.e. using a complex average every 4 lines in azimuth), the generated irregular grid has a mesh size of about 20 m.

The InSAR DEMs have also a quite good accuracy (e.g. RMS error of about 10 m) assumed at least a medium-high coherence (e.g. bigger than 0.5) over the entire interferogram and gentle terrain variations within the covered area.

Many problems arise dealing with more complex topography or low coherence. The atmospheric artefacts represent another important limitation.

### Complex Topography

The slant range nature of the SAR data implies big distortion effects (foreshortening, layover and shadowing) when mountainous and hilly terrain is imaged.

Where foreshortening and layover occur, the interferometric phase signal is under-sampled, producing aliased phase differences between adjacent pixels. If in the phase unwrapping the lines of aliasing (ghost-lines) are not properly detected, the unwrapping generates aliasing errors (multiple of  $2\pi$ ). These errors degrade the DEM quality (e.g. with a baseline of 150 m, an aliasing of  $2\pi$  in the phase results in about 50 m height error in the generated DEM).

### Low Coherence

Changes in the terrain surface during the two image acquisitions can cause low coherence in the interferometric pair; low coherence (e.g. less than 0.1) means bad phase quality and can engender many problems for the phase unwrapping. In such areas the DEM quality is degraded.

### Atmospheric Artefacts

Between the two image acquisitions of the interferometric pair, changes in the refractive index may occur. These changes are mainly due to tropospheric disturbances [Hanssen and Feijt 1996] and can result in very big phase shifts (shifts up to 3 cycles are reported). Their consequences in the generated DEMs can be very impressive: artefacts (e.g. depressions) interpreted as relief can appear. Their magnitude depends on the baseline length and can reach 100÷200 m. The atmospheric effects are not treated in this paper.

In order to overcome the above-described InSAR limits, the integration with other data (e.g. optical) seems to offer a good solution. In the following, two different levels of optical radar data integration are presented.

## 3 SYNERGETIC USE OF SPOT AND INSAR DATA

The quality of the DEMs generated by InSAR and SPOT stereoscopy is often affected by the intrinsic limitations of the remote sensing systems. For instance, optical images can be corrupted if fog or clouds cover the imaged scenes; SAR images are affected by strong geometric distortions in rugged areas.

These limitations in the original data can influence both the accuracy and the completeness of the generated DEMs (e.g. cloudy areas in the optical image result in holes in the generated DEM grid). This influence is particularly evident in the case of the InSAR derived DEMs: they are quite accurate in flat and gently undulating areas but, on the contrary, dealing with mountainous areas their quality decreases dramatically. The use of InSAR and SPOT data and their integration (data fusion) can offer a solution to overcome the above-mentioned limitations.

Two levels of data integration have been individuated:

- 1) the SPOT-derived DEMs can support the most critical stage of the InSAR procedure, i.e. the phase unwrapping;
- 2) the height data coming from InSAR and SPOT can be fused in order to perform the joint estimation of the terrain surface.

In the frame of the ORFEAS project, an interesting data set, covering south Catalunya - Spain (ascending and descending ERS-1 SAR images, SPOT stereo images, precise orbital data, ground control points, orthophotos,

reference DTM, land-use map, etc.), is available for the participants.

The data fusion procedures are presented in the following paragraphs along with the experimental results obtained with the ORFEAS data set.

### 3.1 Use of SPOT DEMs in Phase Unwrapping

Phase unwrapping represents the most complex stage of the InSAR procedure and a large number of research groups are working on it. The purpose of the phase unwrapping is the calculation of the full phase values starting from the principal ones (wrapped phases). This operation is made difficult by noise and by under-sampling of the terrain that causes aliasing effects. If a DEM (in our case a SPOT-derived DEM) already exists for the imaged area, the a-priori knowledge about the terrain topography can be exploited in order to support the unwrapping.

The exploitation of an existing DEM is two-fold:

- 1) the interferogram flattening can be refined reducing the effects of the aliasing errors in the unwrapped phases;
- 2) the ghost-line detection can be supported reducing both the errors due to aliasing and the ones due to ghost-line mislocations.

#### 3.1.1 Refined Interferometric Flattening

The phase unwrapping implemented at Polimi is performed on a filtered and flattened interferogram. The original interferogram (as it is generated from the SAR image pair) shows many fringes that are mainly due to the InSAR geometry and, in particular, to the relative positions of the two satellites. These fringes are called systematic fringes. In order to simplify the phase unwrapping, the systematic fringes are removed (flattening) leaving only the non-systematic ones mainly caused by relief variations. An interferogram covering a flat area shows a linear trend in the phases along the range direction. The ISAR software performs the flattening estimating this linear term by spectral analysis and subtracting it from the original interferogram. The estimation of the linear phase term performed by ISAR is very coarse; in fact, it always assumes the interferogram covering a flat area. It is important to underline that the flattening is only temporarily applied to the interferogram to simplify the unwrapping. Once unwrapped, the interferogram is "unflattened" (i.e. the phases subtracted are re-added) and then used to generate the DEM.

The interferogram flattening can be refined if a DEM of the covered area is available. Using the existing DEM, beside the systematic fringes also the fringes related to the terrain relief can be simulated and subtracted to the original interferogram. Assuming ideal conditions, in the resulting interferogram appear no more fringes and the unwrapping can be even avoided. Actually, after flattening still remain residual fringes due to three main sources: errors in the existing DEM, errors in the geometric sensor parameters (e.g. orbits, etc.) and changes in the atmospheric and terrain conditions between the two image acquisitions. However, the flattened interferogram can be unwrapped much more reliably because the effect of the aliasing errors is reduced. In figure 1 the original unflattened, the ISAR flattened and the refined flattened interferograms are shown. In the interferogram flattened with the refined

procedure, the number of fringes is drastically reduced, although residual fringes still appear.

The flattening procedure is quite simple. It requires as input a DEM and the same orbital and sensor parameters used to generate the InSAR 3D grid. The input DEM, coming for instance from a SPOT stereo pair, can be a regular or irregular grid of 3D points known in the same coordinate system of the orbits.

The simulation of a synthetic interferogram based on a priori known DEM involves a transformation from the object space (the DEM) to the image space (azimuth and slant range coordinates) that represents the inverse of the phase to height conversion applied in the InSAR DEM generation. The transformation algorithm works point wise for the entire input DEM grid. As in the DEM generation, the accuracy of the transformation from object to image space critically depends on the sensor parameters; they are usually refined by self-calibration using GCPs (Ground Control Points).

#### 3.1.2 Ghost-line Refinement

The major problem of the phase unwrapping based on the ghost-line approach is the detection of the lines of aliasing (ghost-lines, where the full phase difference between adjacent pixels is greater than  $\pi$ ).

There are various physical phenomena, which poison interferometric data. Their effects on the phase can be grouped in two kinds of perturbations:

- 1) the disappearance of the geometric phase, either when fringes are totally hidden by the noise because of the decorrelation between the original SAR images, or when there is no geometric phase because of non-responding surfaces or shadow areas;
- 2) the discontinuities of the fringe pattern when the phase signal is under-sampled because of the foreshortening and layover effects on mountain fore-slope, producing aliased phase differences between adjacent pixels.

It is possible to detect (partially) the latter perturbations, taking advantage of a priori known DEMs (e.g. derived from a SPOT stereo pair).

Once the synthetic interferogram is calculated (simulated from the DEM), the discontinuities of the fringe pattern due to foreshortening and layover effects are detected by a simple test over the phase differences between adjacent pixels. Another way to find the discontinuities is to perform the test over the SPOT DEM slopes (the SAR geometry known, the slopes affected by foreshortening and layover are easily detected) and then project the foreshortening and layover slopes in the image space.

The detected discontinuities can be directly integrated in the ghost-line reconstruction algorithm before starting the phase integration.

This kind of the improved ghost-line reconstruction gives much better unwrapping results than the one based only on the "Minimum Spanning Tree" connection of the residuals.

#### 3.1.3 Analysis of an Example

The InSAR classical procedure (based only on SAR data) has been compared to the one supported by a SPOT-derived DEM.

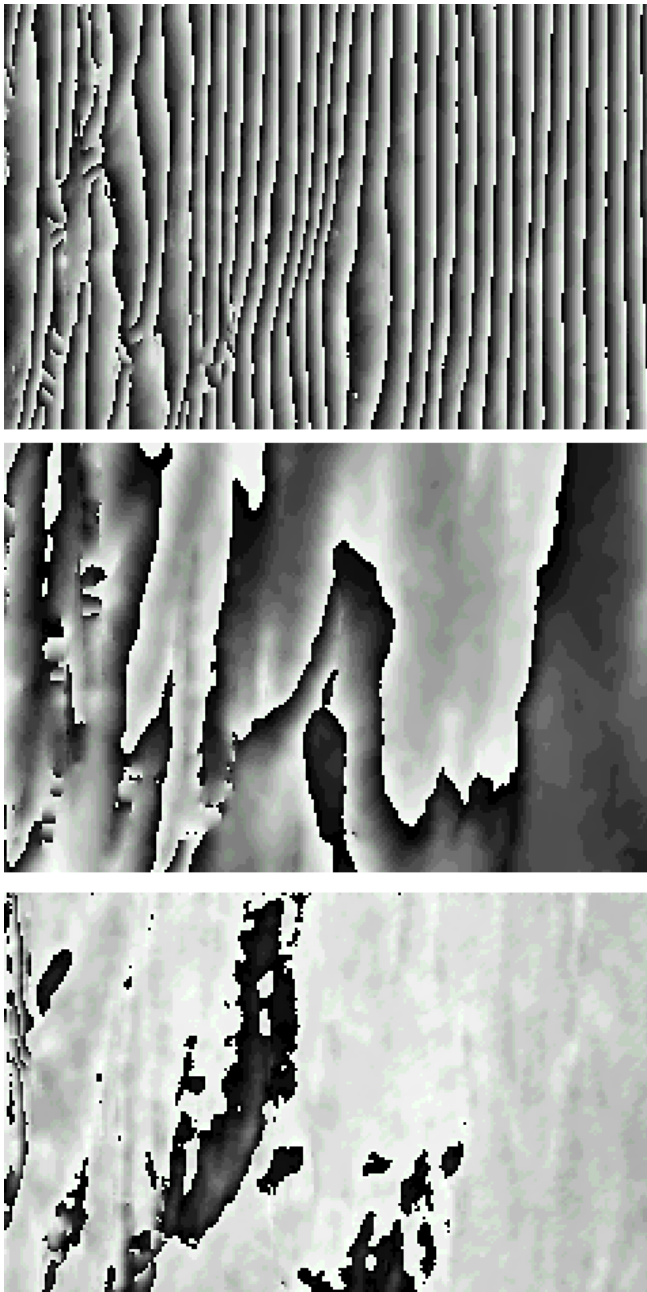


Figure 1: Interferogram Flattening:

- Original (unflattened) Interferogram (above);
- ISAR flattened Interferogram (centre);
- Refined flattened Interferogram (below).

Two ascending ERS-1 images of the ORFEAS data set have been chosen for the processing; these are their main characteristics:

SLC 1: acquisition date: 15-9-1991      Frame: 819  
 SLC 2: acquisition date: 12-9-1991      Frame: 819

The component of the baseline perpendicular to the slant range is 168 m. This is a quite good baseline for DEM generation. From the original SLC images (2500 samples in range, about 15000 lines in azimuth) two sub-images of 1500 [range] times 5000 [azimuth] have been extracted. The sub-images cover an area of about 35x25 Km<sup>2</sup>. The mean coherence over the entire interferogram equals 0.57 after filtering.

Before performing the phase unwrapping, the interferogram has been compressed 4 times in azimuth (complex average). This operation reduces the phase noise. The average is justified by the fact that after interferogram filtering the phases of adjacent pixels are strongly correlated.

The unwrapping generated 4 major zones of integration (the bigger one covers approx. 85.4% of the interferogram). The unwrapped phases have been checked and corrected for aliasing errors and the zones have been "welded". The manual editing of the aliasing errors inside the main integration zone has been very complex. All the editing operations have been very time-consuming (about 20 hours).

Using 9 GCPs the InSAR DEM has been generated and compared with the reference one (coming from aerial photogrammetry with a RMS error of about 1 m) giving:

Mean error	= 1.4 m
Standard deviation	= 21.0 m

The error map (difference between InSAR and reference DEMs) is shown in figure 2.

Looking at the error map, one may notice areas affected by large errors: these are rugged zones where the unwrapping procedure generates big errors (due to aliasing and ghost-line mislocations).

The same interferogram has been processed integrating the SPOT data in the unwrapping stage. Using a SPOT-derived DEM (its characteristics are described in paragraph 3.2.1) the refined flattening of the interferogram has been performed.

Performing a test over the SPOT DEM slopes, the foreshortening and layover areas have been masked. These areas have been projected to the image space and integrated in the ghost-line reconstruction procedure.

The SPOT supported unwrapping generated one main zone of integration (covering approx. 83.8% of the interferogram). The manual editing on the unwrapped phases has been very fast (half an hour) and limited to the correction of few aliasing errors inside the integration zone (minor integration zones have been discarded for the DEM generation). Comparing the editing times of the two processing one may notice a dramatic improvement due to the SPOT data support.

Using the unwrapped phases, an InSAR DEM has been generated. The comparison with the reference gives:

Mean error	= 0.7 m
Standard deviation	= 18.4 m

The error map is shown in figure 3 (compared with figure 2, the covered area is smaller because minor integration zones have been discarded).

Looking at the error map, one may notice a reduction of the areas affected by large error: as expected, the typical unwrapping errors generated in rugged areas are reduced using the a priori knowledge about the terrain topography. In conclusion, the integration of SPOT DEMs in the InSAR procedure improves both the productivity (reduction of the manual editing time) and the accuracy of the generated DEMs.

Similar benefits can be expected using other kinds of existing DEMs. The effectiveness of their integration critically depends on their quality. More experiments have to be carried out to establish the DEM requirements necessary to obtain an effective support for the unwrapping.

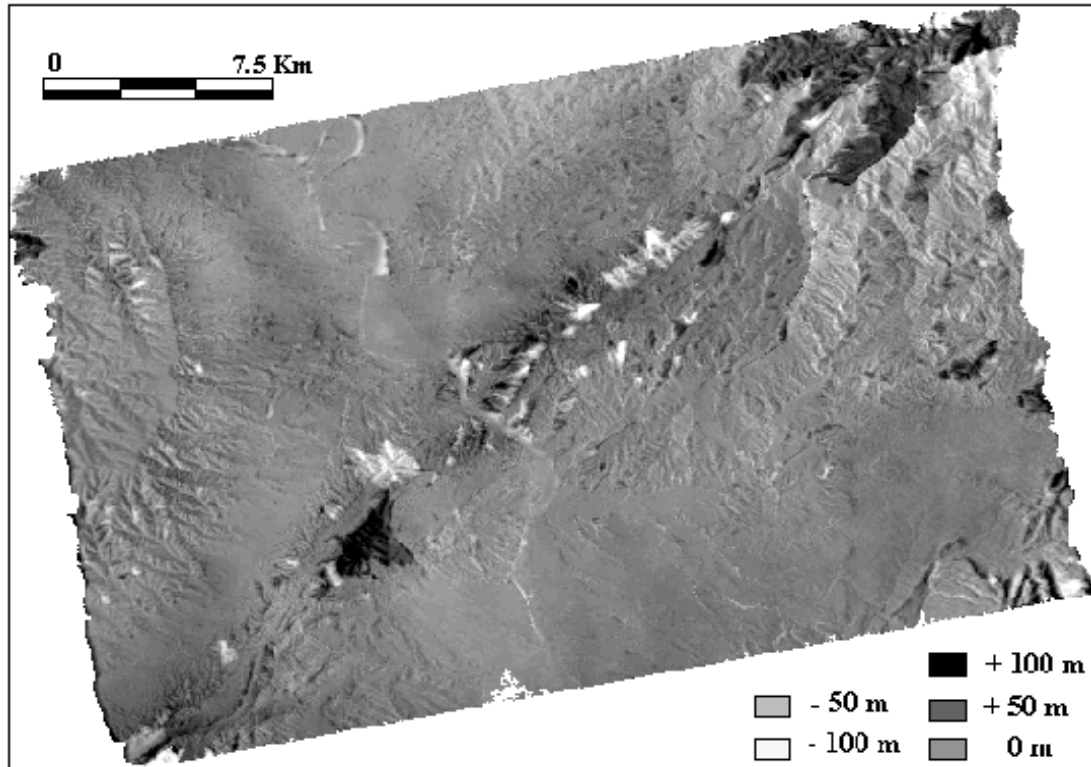


Figure 2: InSAR DEM (classical procedure) versus reference DEM: map of the height differences.

### 3.2 Fusion of SAR and SPOT Derived Height Data

As described in paragraph 2.2, the quality of the InSAR DEMs is usually low in rugged and low coherence areas. The quality of the SPOT DEMs is degraded in presence of clouds or low contrast areas (the low contrast affects the image matching).

The integration of SPOT and InSAR derived height data for DEM generation can offer a solution to overcome the limitations of the two techniques. In fact, SAR and SPOT data seem to be quite complementary: in rugged areas stereo SPOT can deliver quite good height data; InSAR can work good in areas where SPOT images can be corrupted by clouds or by low contrast areas.

The InSAR procedure implemented at Polimi is quite flexible to allow the integration (fusion) with SPOT-derived height data. Each source of data (e.g. ascending SAR pair, descending SAR pair and SPOT stereo pair) is separately processed to generate different sets of 3D points. The points are given in the same reference system (the GCPs used for SPOT and for InSAR have to be in the same system). A weight is assigned to each point. The weight can be a function of the local coherence for the InSAR points and a function of the local image correlation for the SPOT points. All the points, with their relative weights, are used to estimate the final DEM grid (with an interpolation procedure that takes into account the point weights). The joint estimation improves both the completeness (e.g. the "holes" of the cloudy areas in the SPOT image are filled up by InSAR data) and the quality of the generated DEM.

For the grid interpolation, the terrain is modelled with bilinear splines (with a constraint on the surface gradient in order to avoid oscillations). The splines are estimated by least squares adjustment so that to each estimated

height its theoretical standard deviation can be associated.

The effectiveness of the data fusion has been proved using the ORFEAS data set. The results are presented in the following paragraph.

#### 3.2.1 Results of the Data Fusion

##### SPOT Data

A SPOT-derived DEM generated at the Institute of Geodesy and Photogrammetry - Zurich Institute of Technology (Switzerland) has been processed.

The original data coming from Zurich consist of a regular grid of 3D points generated with the Helava Digital Photogrammetric Workstation (DPW) 770. To each point the DWP 770 assigns a quality factor. According to this factor, the unreliable points have been eliminated. Using the same interpolator and the same grid of InSAR (see paragraph 3.1.3), the generated SPOT grid has been compared with the reference one:

Mean error	= 1.0 m
Standard deviation	= 12.2 m

The DEM is not biased. The error distribution does not present systematic errors.

With the exception of very steep terrain (where problems for stereo matching occur), the obtained accuracy is very high. This is probably due to the well-textured images (that means good image quality for the point matching) and to the absence of cloudy zones in the imaged scene. In fact, the presence of not well textured areas or cloudy zones in the imaged scene represent the major degradation factor for the SPOT DEMs.

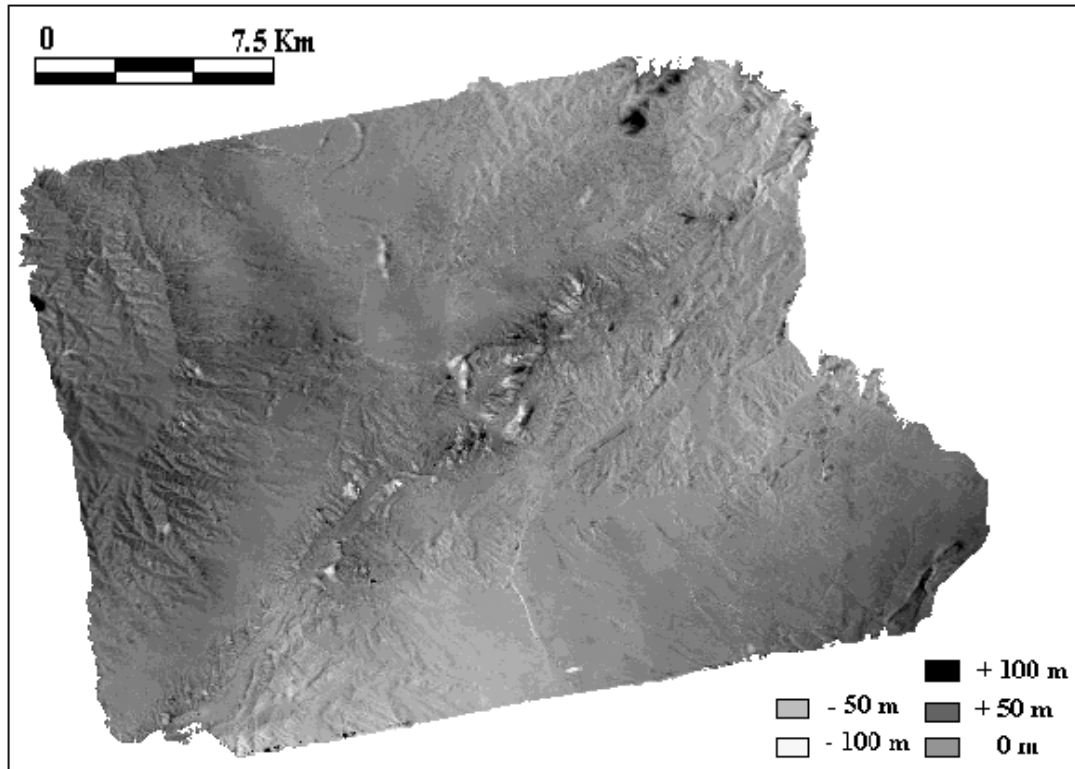


Figure 3: InSAR DEM (supported with SPOT data) versus reference DEM: map of the height differences.

Dealing, for instance, with SPOT images corrupted by clouds, in the corresponding DEM appear “holes” that deteriorate its quality. In this case, the fusion with other kinds of height data can be very effective.

### InSAR Data

The data fusion has been performed using the InSAR height data described in paragraph 3.1.3 coming from the classical InSAR procedure (unwrapping not supported by SPOT data).

The DEM accuracy is characterised by:

Mean error	= 1.4 m
Standard deviation	= 21.0 m

Looking at the error distribution of this DEM (see figure 2), important systematic effects appear. The procedure employed to geocode the DEM is not optimal: the sensor parameter and the phase shift (coming from the unwrapping) are adjusted separately. Implementing a 3D self-calibration to estimate all the parameters together will make the geocoding more precise and reliable. Another important factor that can be related to the systematic effects are the atmospheric effects. Further investigation has to be carried out in order to analyse more deeply this kind of effects.

The systematic errors that affect the InSAR DEM make the direct fusion with SPOT data not possible. They have to be removed exploiting the SPOT data. The systematic effects have been modelled with a 3<sup>rd</sup> order polynomial. The polynomial coefficients have been estimated using the InSAR and SPOT generated grids (60 m mesh size). Subtracting the estimated systematic effect to each point of the original irregular InSAR grid and estimating a new InSAR regular grid (30 m mesh size), the comparison with the reference one gives:

Mean error	= 0.9 m
Standard deviation	= 18.8 m

These values give an estimation of the actual InSAR DEM accuracy, provided the 3D self-calibration procedure and the atmospheric effects do not bias the DEM. Further investigation have to be carried out in order to better understand the systematic of effects in the InSAR generated grid.

The weight assigned to the (SPOT and InSAR) 3D points employed in the joint estimation of the DEM depends on different factors.

For the SPOT points, a linear function of the quality factor assigned by the DPW Helava has been chosen. The standard deviation ranges from 4 m to 20 m.

In order to weight the InSAR points, the areas affected by big unwrapping related errors have been treated separately: subtracting the SPOT DEM to the InSAR one the major areas affected by large height errors (bigger than 30 m) have been detected. The points that belong to these areas have not been used in the data fusion.

Masking the mentioned difficult areas, the InSAR DEM precision improves to:

Mean error	= 1.8 m
Standard deviation	= 14.5 m

These values are comparable to the one of SPOT, making reasonable the data fusion outside the difficult areas.

For the weighting of the InSAR points, a function of the coherence and of the distance from the ghost-lines has been chosen: the standard deviation ranges from 5 m to 40 m for the points far from the ghost-lines and equals 60 m for the points near to the ghost-lines. The low weight given to the latter points takes into account the local (big) aliasing errors due to the ghost-line mislocation.

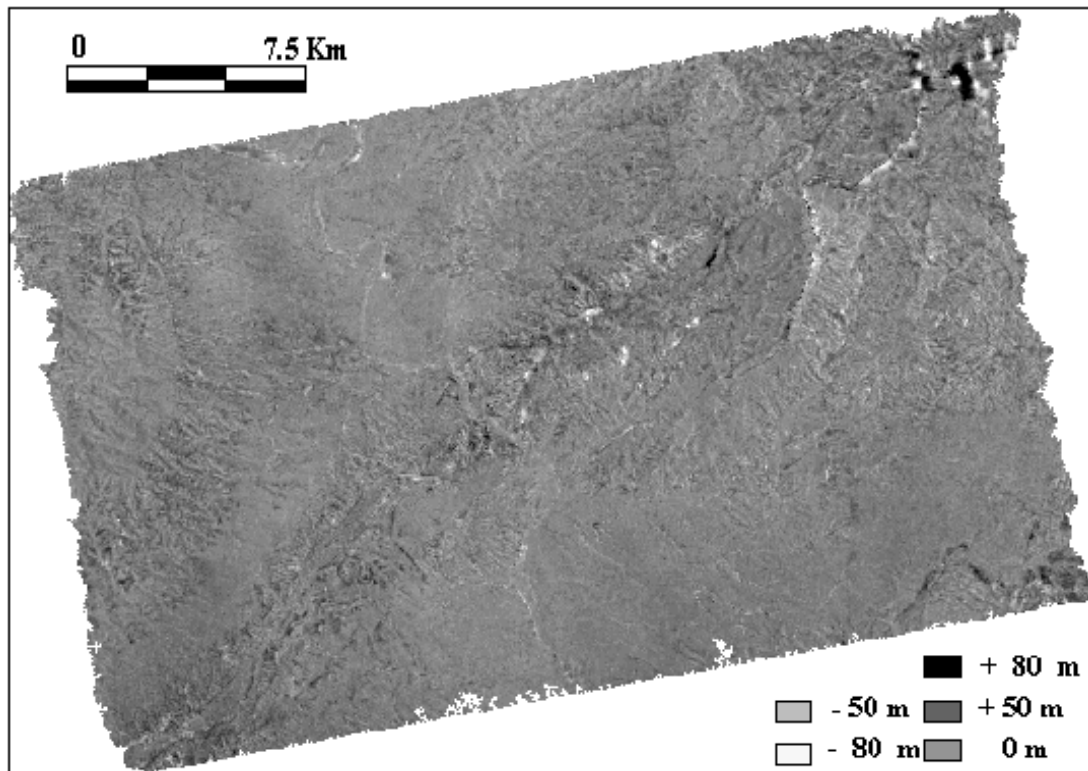


Figure 4: DEM (InSAR and SPOT data fusion) versus reference DEM: map of the height differences.

Performing the joint estimation (InSAR and SPOT data fusion) of the 30 m spacing grid, and comparing with the reference grid gives:

Mean error = 1.2 m  
Standard deviation = 12.3 m

The error map is shown in figure 4. The DEM is not biased and the error distribution does not present systematic effects. The accuracy of this DEM is much better than the one of the InSAR DEM but very similar to the one of the SPOT DEM. It is important to notice that only a portion of the SPOT stereo frame has been analysed, Other portions are covered by clouds or are not well-textured: for these areas the data fusion would be actually effective to improve the completeness of the generated DEM.

If the data integration seems to be effective for the SPOT only in presence of cloudy or not well textured areas, for the InSAR data improves very much the DEM quality.

#### 4 CONCLUSIONS

In this paper the synergetic use of SPOT and InSAR data for DEM generation is addressed. The integration of these two kinds of data allows improving significantly the quality of the generated DEMs. Two levels of integration have been individuated.

The first one consists of the exploitation of SPOT-derived DEMs in order to support the phase unwrapping. It improves the accuracy of the generated InSAR DEMs and reduces the need of human operator editing of the unwrapped phases.

The second level of data integration regards the estimation of the terrain surface using a rigorous data fusion procedure. The procedure is very flexible and allows fusing different kinds of height data taking into account their

quality. It allows improving both the completeness and the accuracy of the generated DEMs.

#### 5 ACKNOWLEDGEMENTS

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