3D Mapping Potential of COSMO-SkyMed Sensor: Definition of an Image Matching Strategy

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Abstract. The topic of this paper is the presentation of an image matching technique suited to generate Digital Surface Models (DSMs) following a radargrammetric approach applied to Spot-Light Synthetic Aperture Radar (SAR) stereo pairs collected by the new high amplitude resolution radar sensors COSMO-SkyMed (Italian) and TerraSAR-X (German). At present, thanks to this kind of imagery (GSD up to 1 m), the traditional radargrammetric stereo-mapping approach is likely to become a serious alternative to interferometry for the Digital Surface Models (DSMs) generation from Synthetic Aperture Radar (SAR) imagery. Nonetheless, DSMs accuracy level is strictly related to image orientation and matching strategy. A crucial issue is the definition of an image matching strategy to perform 3D surface reconstruction. Generally we can distinguish two classic techniques to carry out the matching process, the Area Base Matching (ABM) and the Feature Base Matching (FBM): these techniques do not appear suited to manage the strong geometrical deformation and the complex and noisy radiometry of SAR imagery, if separately used. Therefore, here we propose an advanced matching method based on a coarse-to-fine hierarchical solution with an effective combination of geometrical constrains and an Area Base Matching (ABM) algorithm. The suite for radargrammetric approach has been implemented in SISAR (Software per Immagini Satellitari ad Alta Risoluzione), a scientific software developed at the Geodesy and Geomatic Institute of the University of Rome "La Sapienza". In order to investigate the 3D mapping potential of SpotLight imagery, the implemented radargrammetric tool was applied to a COSMO-SkyMed stereo pair acquired over the area of Merano (Northern Italy), where a quite good LiDAR Digital Elevation Model is available as ground truth. The results are quite encouraging, with an accuracy of about 2 meters over open areas and a quite dense points cloud even over forested areas, where it is possible to estimate the average canopy height with a mean error of about 4 meters.

Keywords. SAR, COSMO-SkyMed, DSMs, RPC model, image matching algorithms

Introduction

Today, images of our planet from space are acquired continuously; a large number of spaceborne sensors devoted to the Earth observation are available and also various kinds of sensors are on orbit.

As regards the Synthetic Aperture Radar (SAR) satellites for Earth observation, a possible geomatics application can be the topographic mapping, in particular the generation of Digital Surface and Terrain Models (DSM/DTM).

DSMs extraction from satellite stereo pair offers some advantages, among which low cost, speed of data acquisition and processing, availability of several commercial software and algorithms for data processing. Moreover, advantages of radar include the capability to penetrate clouds, haze, rain and others atmospheric particles and to operate during night and day.

The goal of this investigation is the DSM generation from very high resolution SAR sensors. Two different methods may be adopted for DSM generation from SAR data,: interferometry and radargrammetry, both using at least a stereo pair. The interferometry uses the phase differences information between the SAR images to lead the terrain elevation, in this case the baseline is usually short; unlike radargrammetric technique analyzes the signal amplitude and exploits the stereoscopy similarity to optical methods and the baseline have to be much longer [1].

Due to the low resolution of SAR imagery available until now, the radargrammetry did not find common employ in respect to interferometric technique, which was widely used up to now. After the launches of Italian COSMO-SkyMed and German TerraSAR-X missions new possibilities of SAR application are incoming, due to the high resolution of the new SAR sensors, up to 1 m in SpotLight mode. DSM extraction procedure consists of two basic steps: the stereo pair orientation and the image matching for the detection of corresponding (homologous) points. A suite for radargrammetric approach has been implemented in SISAR (Software per Immagini Satellitari ad Alta Risoluzione), a scientific software developed at the Geodesy and Geomatic Institute of the University of Rome “La Sapienza".

The radargrammetry orientation model technique performs a 3-D reconstruction based on the determination of the sensor-object stereo model, in which the object position is calculated by the intersection of two radar rays with two different look angles. The SISAR model is based on the classical Range-Doppler equations proposed in the book of Leberl [2]; moreover a refinement of the orbital model have to be taken into account to comply with and to exploit the potentialities of the novel high resolution (both in azimuth and in range). Corrections of three parameters (the so called *acquisition start-time, Pulse Repetition Frequency* (PRF) and *near range*) are estimated; consequently a 3D orientation based on two range and two zero-Doppler equations allows to determine the ground coordinates of tie-points [3].

Moreover, a tool for the Rational Polynomial Coefficients (RPCs) generation has been implemented in SISAR software. The possibility to generate RPCs starting from a rigorous model sounds of particular interest since, at present, the most part of SAR imagery is not supplied with RPCs, although the Rational Polynomial Functions (RPFs) model is available in several commercial software.

As regard the image matching the critical issue is the definition of a strategy to search the corresponding points. Generally we can distinguish two classical techniques to carry out the matching process, the Area Base Matching (ABM) and the Feature Base Matching (FBM): each of these strategies does not appear suited to manage the strong geometrical deformation and the complex and noisy radiometry of SAR imagery if employed on its own.

Therefore, here we propose an advanced matching method based on a coarse-to-fine hierarchical solution with an effective combination of geometrical constrains and an Area Base Matching (ABM) algorithm.

The proposed matching strategy was tested to generate a DSM starting from a COSMO-SkyMed same side stereo pair acquired in SpotLight mode over the area of Merano (Northern Italy).

1. Data-set and orientation results

The available data for the experimentation is a COSMO-SkyMed SpotLight stereo pair acquired over the area of Merano (North Italy). The images belongs to the Level 1A (SCS) category products, that is focused data in complex format, in slant range and zero-Doppler projection. The area is heterogeneous, representing a urban zone, the town of Merano, and a mountainous one; the heights range about from 300 m to 2500 m (Fig. 1 left).

Table 1. Merano stereo-pair data

Area	Acquisition data	Coverage (Km^2)	Incidence Angle (°)	Orbit	Look side	B/H
Merano	30/11/2009	10 x 10	25.9	Descending	Right	0.4
	2/11/2009	10 x 10	42.3	Descending	Right	

The stereo pair orientation was performed with SISAR and its accuracy was evaluated on the basis of 20 Ground Points (GPs) (Fig. 1 right), used all as CPs [4]; their horizontal coordinates were derived from cartography (scale 1:5000) whereas the heights came from the LiDAR Digital Terrain Model (mean elevation accuracy of 0.25 m and horizontal spacing 2.5 m), used also for the DSMs assessment; both these data are available for free on the website of the Provincia Autonoma di Bolzano (http://www.provincia.bz.it/urbanistica/cartografia/cartografia.asp). It has to be underlined that the accuracy of the stereo pairs orientation was around 2.5 m in the height but the results obtained in the orientation step are just representative of the geometric potentialities as regards 3D surface reconstruction, whereas the accuracy of the final product is dependent on the quality of the subsequent matching procedure (**Table 2**).

Table 2. Merano stereo-pair RPCs orientation

	East (m)	**North (m)**	**Up(m)**
Average	2.35	-1.12	0.83
St. Dev.	3.26	2.37	2.16
RMSE	4.02	2.62	2.31

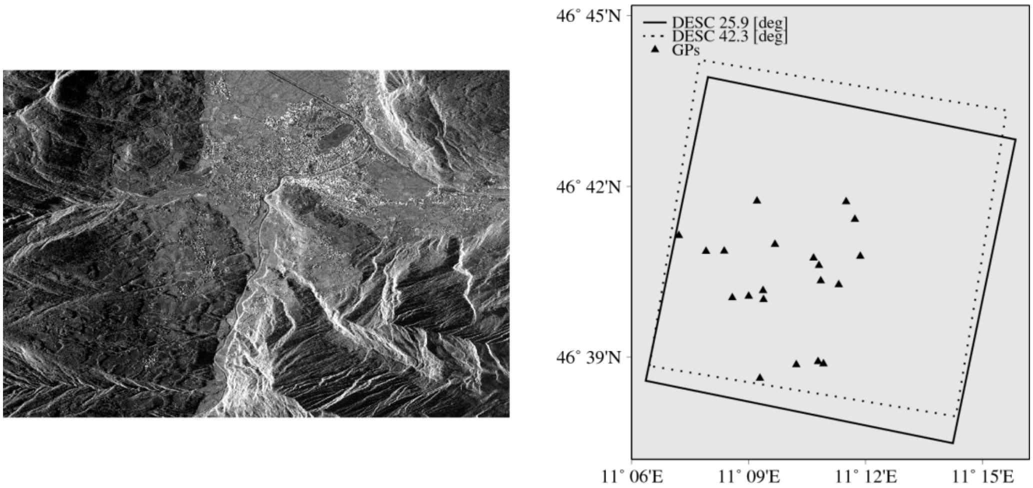

Figure 1: Merano COSMO-SkyMed SpotLight and Ground Points data set

2. Image denoising

The imagery produced by SAR systems is affected by a high level of noise due to the inherent nature of radar backscatter. The largest source of noise in a SAR image is the speckle noise.

The source of this noise is due to random interference between the coherent returns issued from the numerous scatterers present on a surface, on the scale of a wavelength of the incident radar.

Speckle noise gives the SAR image a grainy appearance and prevents target recognition and texture analysis efficiently. Before starting the matching procedure, an image preprocessing step to reduce speckle noise is required. In order to determine which adaptive image filters allow to get the best results in terms of DSMs accuracy, a series of tests were performed varying filter type and window size. In details, the applied filters were: Lee, Gamma Map, Frost, Median; the correlation window size has been changed from a (5 x 5) size to a (11 x 11), considering odd sizes only. Also the same filter has been passed several times (up to three) over the images. The tests performed show that Gamma Map and Lee filters gives approximately the same results in term of RMSE values, and the best are those for a (7 x 7) correlation window.

Future investigations will be necessary to assess the potential of more sophisticated image denoising techniques, such as those based on wavelet or frequency domain transforms [5].

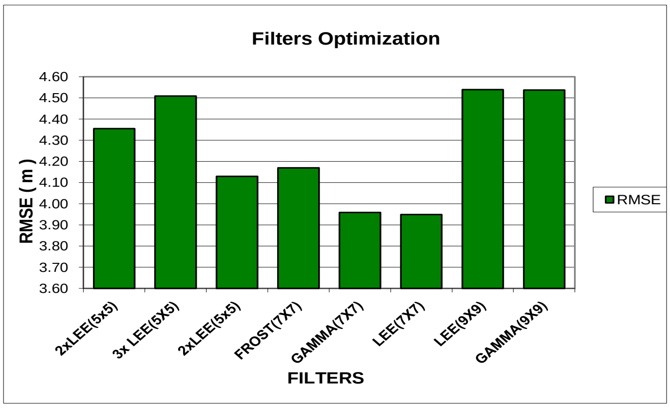

Figure 2: Filters Optimization results

3. Image matching strategy

As already mentioned, the DSM accuracy is strictly related both to the image orientation and to the matching process. In order to obtain good stereo geometry, the optimum configuration for the radargrammetric application is when the target is observed in opposite-side view; however it causes large geometric and radiometric disparities hindering image matching. A good compromise is to use a same-side configuration stereo pair with a base to height ratio ranging from 0.25 to 2 [5] in order to increase the efficiency in the matching procedure.

Many different approaches to image matching have been developed in recent years. The main step of image matching process is to define the matching entity, that is a primitive compared with a primitive in other images, in order to identify correspondences among different images. According to the kind of matching primitives, we can distinguish two basic techniques as previously recalled, the ABM and the FBM [7] [8].

In ABM method, a small image window, composed of grey values, represents the matching primitive and the principal methods to assess similarity are cross correlation and Least Squares Matching (LSM), whereas FBM uses, as main class of matching, basic features that are typically the easily distinguishable primitives in the input images, like corners, edges, lines, etc. These kind of strategies do not appear suited to manage the strong geometrical deformation (like foreshortening and layover) and the complex and noisy radiometry (speckle) of SAR imagery. Therefore, an original matching procedure has been developed. This matching method is based on a coarse-to-fine hierarchical solution with an effective combination of geometrical constrains and an Area Base Matching (ABM) algorithm [9].

After image preprocessing, the two images are resampled reducing at each pyramid level the original resolution. The correspondences between points in the two resampled images are computed by correlation function and finally a least-squares matching refinement is performed to obtain more precise results. In this way the surface model is successively refined step by step, until the last step (corresponding to the original image resolution) and a final dense and accurate DSM is reconstructed. The advantage of this technique is that at lower resolution it is possible to detect larger structures, whereas at higher resolutions small details are progressively added to the coarse surface.

4. Results

In order to evaluate the potentiality of the described matching strategy, two different tiles with extension of 2-3 Km^2 were considered, which were selected in order to test the potentialities of the radargrammetric approach in different morphological situations and in some difficult cases for automatic image matching. The extracted DSMs have been compared with the reference LiDAR DTM through DEMANAL software, developed by Prof. K. Jacobsen - Leibniz University Hannover, allowing for a full 3D comparison to remove possible horizontal biases too.

The height differences are computed interpolating (with a bilinear method) the analyzed DSM over the reference LiDAR DTM (the value is negative when the extracted DSM is above the reference DTM). In the evaluation of DSMs accuracy, an important aspect must be taken in account is that we compared DSMs with a reference DTM, which do not include vegetation, buildings and any other features which is elevated above the ground. For this reason, a part of the differences between the two compared surfaces is due to these features, included in the generated DSM but not in the reference DTM; this turns of particular interest over forested areas, where the differences are mainly due to the forest then representative of the canopy height.

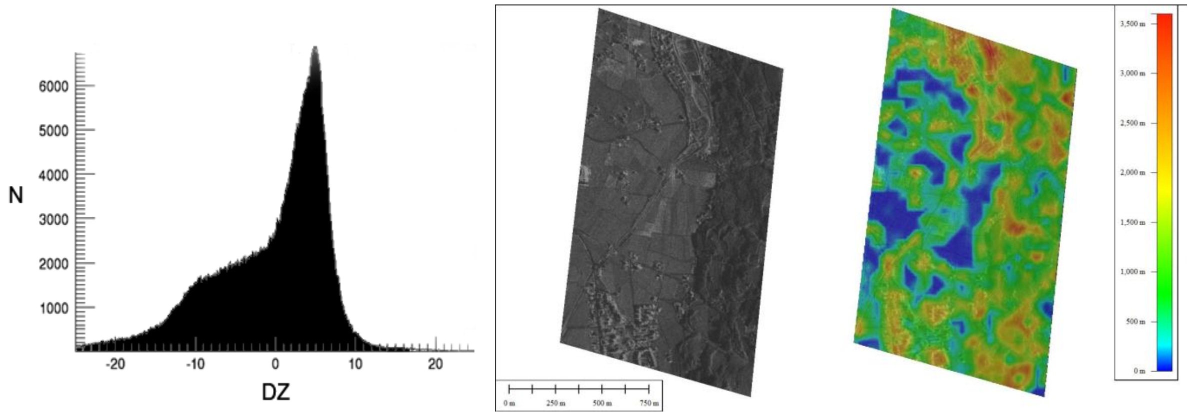

Figure 3**:** Tile 1: Histogram of height differences (left); tile screenshot and homologous points density map (right)

The area represented in tile 1 (Fig. 1, right), is characterized by a steep rather forested area which slopes down to a flatter ground where we can find open areas with poor texture and a small built up zone. During the matching process the highest density of points has been found over forested and build-up area (red zone in the homologous point density map).

An histogram of the height differences is showed in Fig. 3 (left), indicating a numerical range between -40 and +25 meters; the clearly asymmetric error distribution is due to differences between the reference DTM and the extracted DSM.

Validation analysis was made with respect to two selected areas over flat and forested terrain, respectively, the cloud of points was interpolated on a regular grid (1.6 x 1.6 m, in order to preserve the mean points cloud interdistance) to allow a full comparison.

A sample cut-off at the 95% probability level was considered, so that the LE95 was evaluated, in order to leave out the outliers from the statistical evaluation (**Table 3**).

The achieved mean accuracy is better than 3 meters over flat area and appears quite consistent with the results of orientation; over the forested terrain the standard deviation goes up to 4 meters and it is present a large negative bias, amenable to the tree coverage (mean height canopy about 15 meters) [10].

Table 3. Results for Tile 1

Absolute Error Tile 1[m]					
Terrain	**BIAS**	**ST.DEV.**	**RMSE LE95**	**LE95**	**# Points**
Flat	-2.03	1.94	2.80	4.54	48787
Forested	-14.40	4.28	15.02	9.89	17745

Also a deeper investigation was carried out through a visual inspection of the entire error map (Fig. 4 right); yellow error areas are matching failures, probably caused by zone with poor texture; large positive height differences values (blue areas) are mainly due to the presence of narrow gorges, not correctly reconstructed.

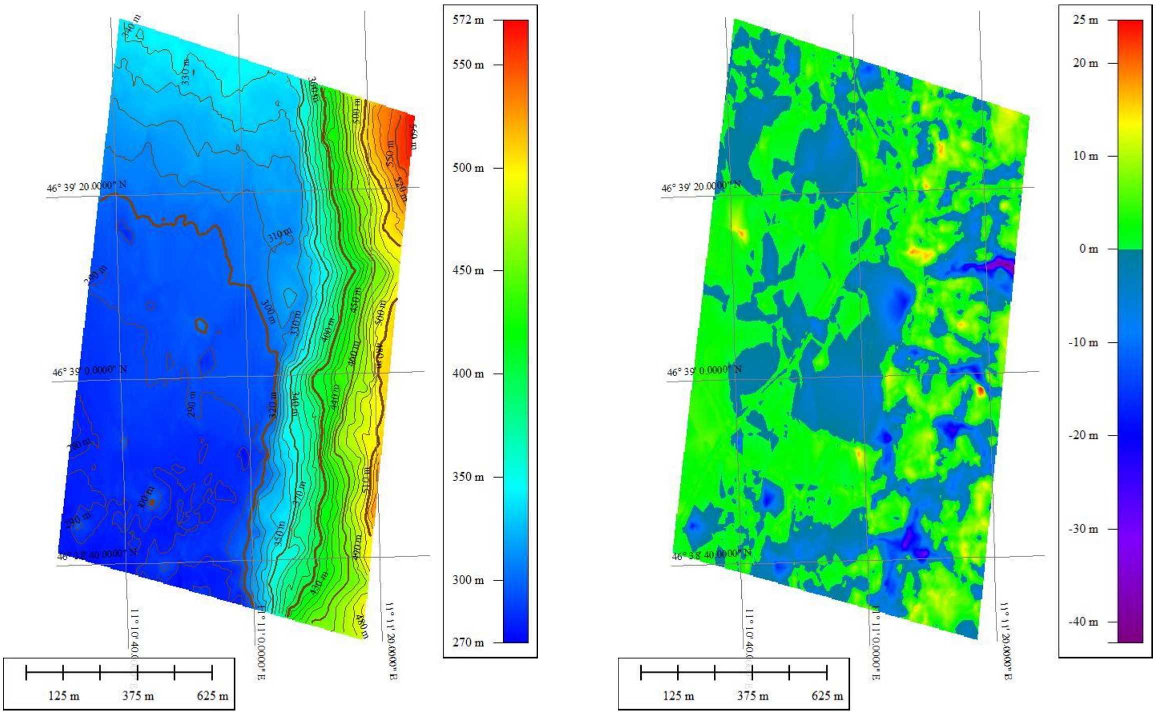

Figure 4: Tile 1: DSM extracted (left) and error map (right)

The urban area represented in tile 2 (see Fig. 5 left) has been chosen because it also contains some of the most common geometric distortions that characterize radar image. In fact, we have here a relief affected by foreshortening and layover; foreshortening compresses features which are tilted toward the radar, furthermore, because of the layover, the top of the feature is displaced towards the radar from its true position on the ground, and ”lays over” the base of the feature.

Two urban areas not affected by distortions have been selected, in order to evaluate the accuracy of the extracted DSM (Fig. 5 right); the results are shown in **Table 4**. The accuracy in term of RMSE is about 6 meters for both areas; anyway, in these cases, unlike the trees over tile 1 forested area, the buildings are not correctly reconstructed; in fact the bias is only 5 meters and it is not representative of the average building heights. Certainly, to model the complicated urban morphology, specific algorithms, considering also remarkable features as double bounces, must be developed.

Table 4. Results of Tile 2

Absolute Error Tile 2[m]					
Terrain	**BIAS**	**ST.DEV.**	**RMSE LE95**	**LE95**	**# Points**
Urban 1	-4.34	3.59	5.63	8.63	159094
Urban 2	-4.92	3.40	5.98	9.11	159789

Also to see the effect of radar distortions, an image of tile 2 has been orthorectificated using the extracted DSM (see Fig. 5. left); during orthorectification process, layover and foreshortening situations are stretched back to their correct positions and pixels are stretched or smeared, creating areas in which the matching algorithm cannot find homologous points because of lack of radiometric information.

These areas are easily recognizable in the error map (Fig. 6 right, red zone) because they are characterized by the highest values of height discrepancies (about 30 m) between the DSM extracted and the reference one. Also, we can see the blue error zone, that are caused by the shadow of the Passirio river high banks.

The use of at least two stereopairs acquired under different look side seems to be an effective strategy to overcome these kinds of problems, in order to model the terrain surface also in presence of occlusions, distortions and shadows.

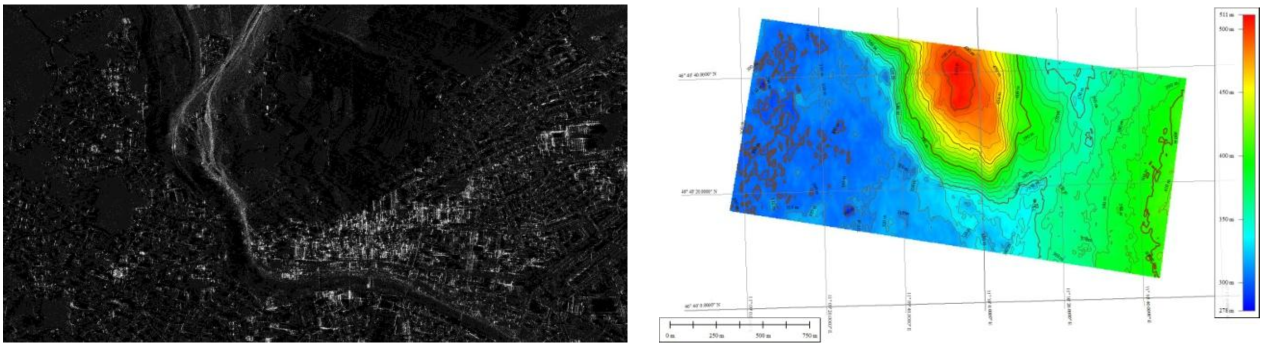

Figure 5: Tile 2: Screenshot (left) and DSM extracted (right)

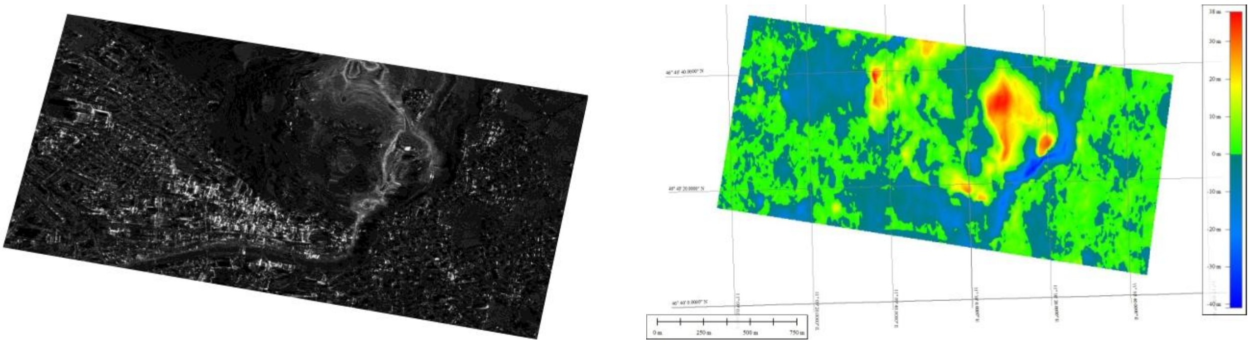

Figure 6: Tile 2: Orthofoto (left) and error map (right)

5. Conclusions and future work

A new model for radargrammetric processing (orientation and DSM generation) of SAR stereo pairs collected in SpotLight mode was defined and implemented in the scientific software SISAR.

An experiment was carried out with a stereo pair collected over the test site of Merano (Northern Italy).

The DSM assessment showed that achievable accuracy is strictly related to the terrain morphology: over a flat area the RMSE is better than 3 m; moreover, quite dense points cloud were generated even over forested areas, where it was possible to estimate the average canopy height with a mean error of about 4 meters over; on the contrary, building areas were not correctly reconstructed.

These results show that radargrammetric and the interferometric techniques could be integrated in order to exploit at best SAR data, particularly to fill the gaps due to the lack of coherence in the interferometric DSMs [1]. Although results are encouraging, further tests and researches are needed, especially to improve the potentialities of the automatic matching procedure for DSMs generation in urban areas or in with more complex morphologies.

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