Improvement of InSAR DEM Accuracy
Using Data and Sensor Fusion

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ABSTRACT

During the recent years, SAR interferometry (InSAR) developed to a powerful technique to derive high precision digital elevation models (DEMs) from SAR image pairs. All weather and daylight independence, along with an abundance of data coming from different SAR sensors, enable SAR interferometry to compete with stereoscopy, the classic, optical approach for DEM generation.
This paper addresses the error of the InSAR DEM in those areas, where the received radar signals are corrupted by ground properties. Because these errors result from SAR properties themselves, the only way to resolve them, is a fusion with data from other sources. For that purpose, the error of the InSAR DEM in these areas will be evaluated and compared to the error of the DEM from complementary sources, before a final data fusion.

KURZFASSUNG

In den letzten Jahren hat sich die SAR Interferometrie zu einem maechtigen Werkzeug zur Generierung digitaler Hoehenmodelle entwickelt. Die Unabhaengigkeit von Wetter und Tageszeit, zusammen mit der grossen anfallenden Datenmenge verschiedener Sensoren, ermoeglichen es der SAR Interferometrie mit der klassischen, optischen Methode zur Hoehenmodellgenerierung, der Stereoskopie, zu konkurrieren.
Dieses Paper handelt von den Auswirkungen der Gegebenheiten des Terrains auf das rueckgestreute Radarsignal und in wieweit sich diese auf den Fehler des Hoehenmodells auswirken. Da diese Fehler durch die SAR Signaleigenschaften bedingt werden, koennen sie nur unter Zuhilfenahme von Daten anderer Sensoren beseitigt werden. Hierzu wird der InSAR Hoehenfehler in problematischen Gebieten ausgewertet und dem komplementaerer Quellen gegenuebergestellt, bevor in einem letzten Schritt die Daten vereinigt werden.

1. INTRODUCTION

Travel time of a radar signal between sending and receiving is closely related to the topography and can be used as a measure of the local elevation. The travel time difference of two radar signals can be detected very precisely through phase measurement. Using the phase differences of two SAR images, taken from almost the same position, as an estimate of the local elevation is the key process in interferometry, which is now the major technique for DEM generation from SAR images.

The main problem within the interferometric processing chain is the so-called phase unwrapping. Since the phase differences are only known modulo 2π, the correct multiple of 2π has to be added to each phase value of the interferogram, in order to obtain the real travel path difference. The algorithms usually applied for phase unwrapping assume that there is no phase jump above π (i.e. gentle changing terrain) between two adjacent pixels of the interferogram. Also, high signal to noise ratio (SNR) and little temporal decorrelations between the images are required to obtain reliable DEM results after phase unwrapping (Werner, 1992).

This paper deals with those regions, where the terrain properties do not match the assumptions made above due to layover, shadowing and temporal decorrelation. Layover occurs in very steep terrain, leading to phase jumps of more than π between two pixels of the interferogram. Shadowing, another source of SAR signal corruption will yield a bad SNR. Temporal decorrelations between two SAR images occur mostly due to vegetation, especially in areas of intensive land use.

Using an ERS-1 image pair with ascending orbits, the resulting InSAR DEM error of those areas will be measured and compared to the error of the DEMs, generated from SAR image pair with descending orbits and a SPOT stereo image pair. The results may be the basis for further multiple source data fusion.

2. AREAS OF INTEREST

This section addresses the conditions under which layover, shadowing and decorrelation occur and which effect they have on the error of the InSAR DEM. Some ways, how to extract those areas from the SAR images, are presented and what sources of data might be superior in those areas. It is far beyond the scope of this paper to give a detailed description of SAR properties and its interference through terrain in detail, like it is given in (Olmsted, 1993).

2.1 Layover

As mentioned above, layover is a terrain induced distortion of the SAR image and occurs in very steep terrain on the sensor facing side of the mountain, where the condition

$$\alpha > \varphi \tag{1}$$

α: terrain slope angle
φ: incidence angle

is fulfilled.

The received signal in such an area is not only superimposed with signals coming from other ground cells because of almost same travel time due to terrain elevation. Additionally, signal responses from the peak of a mountain will be mapped before the responses of lower parts. The phase signal will be disturbed by superposition with responses from other ground resolution cells. Phase differences between two adjacent pixels may exceed π, because of signal superposition due to terrain slope, indicating an error for the phase unwrapping process and therefore yielding height errors or blunders in the DEM.

Regions of layover can easily be computed with (1) from a given DEM and the SAR sensor data. If no DEM is available, they can be extracted by inspection of SAR images, as they appear very brightly due to superposition of response signal energies (Fig. 1).

Depending on the viewing angle, layover areas may be better resolved by SAR sensors with another view angle or an opposed viewing position. As layover is a typical SAR distortion, optical sensors may be of better use in those areas, provided the terrain is not too steep for stereo matching.

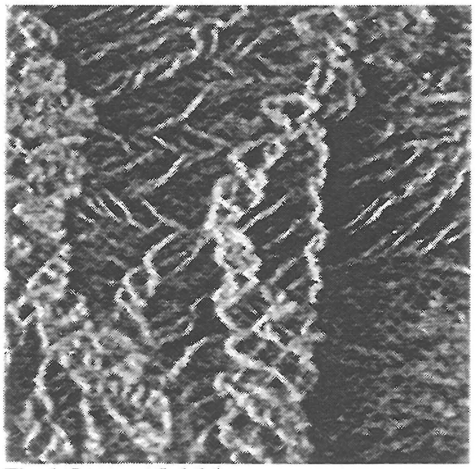

Fig. 1: Layover (bright)

2.2 Shadowing

Much like solar illumination, SAR microwaves may not detect the backside of a mountain in case of

$$\alpha \leq \varphi - 90° \tag{2}$$

The sensor will receive no or only few weak response signals from the shadowed region (Fig. 2). Since the energy of a SAR response signal depends directly on the terrain slope, only signals of low energy from the backside of mountains will be received, bearing a low SNR. Any available phase signal of such a region will therefore be strongly noise corrupted, resulting in inaccurate DEM height results. Lacking any reliable data in shadowed areas, large blunders within the DEM may occur.

Shadow areas may also be computed from a given DEM, using (2). Detecting shadowing by inspection, by looking for areas with no signal response, may be more demanding, since there are different reasons, why no signal can be received (e.g. reflection of microwaves from water, streets).

The most intuitive way to fill the DEM gaps, caused by shadowing, is the application of a DEM, generated from images of the opposing side of the shadowed area. The problem of this application is, that foreshortening or layover effects may then occur in that region.
The use of optical data is restricted to the same bounds as in case of layover.

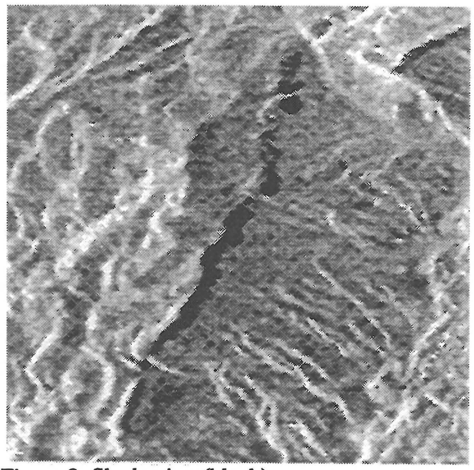

Figure 2: Shadowing (black)

2.3 Temporal decorrelation

Repeat pass, single antenna SAR interferometry suffers mainly from the decorrelations of the ground resolution elements between the two passes. These decorrelations derive from the surface and backscatter properties. A DEM can only be generated with SAR interferometry under the conditions that changes between successive images are limited and radar scattering characteristics, especially the position of the scatterers, remain almost constant. If the second condition is not met, this state is called temporal decorrelation.

Both restrictions may be offended by the surface properties of agricultural areas. Not only harvested fields, but also crop movement in presence of wind make it impossible to recover topography. Even if the conditions are met to a certain extend, highstanding crop cause a height offset, since the SAR signal is scattered from the top of the plants. In forested areas, also multiple scattering may occur. The correct signal from these responses can not be reconstructed due to phase jumps of the reflected signal and signal interference.

Agricultural areas in SAR images are most easily detected with help of land use maps, where location and kind of use are mapped. The coherence map of two SAR images may also be of good use to find these areas (Fig. 3), although coherence is not only affected by temporal decorrelation.

For topographic mapping of agricultural areas with interferometry, single pass interferometry would be the appropriate means. The one day repeat pass ERS-1/2 tandem mission may also have good results, provided the conditions mentioned above are met. Highstanding crops or forests may also add a height offset to an optical stereo DEM.

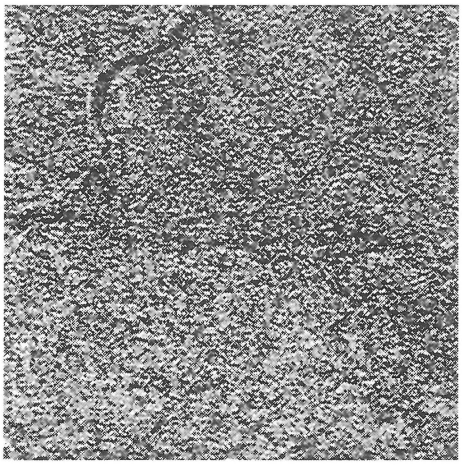

Fig. 3: Temporal decorrelation in coherence map (dark)

3. TEST SITE

Our test site is an area of 50x60 km^2 west of Tarragona/Spain. The terrain varies from plain Ebro delta at the Mediterranean coast to the mountains of the Catalonian coastal chain with heights up to 1200m. Intensive land use takes place along the Ebro depression.

4. DATA SET

The test data set consisted of two ERS-1 SAR image pairs with ascending and descending orbit passes. The images with ascending orbits were acquired in a three-day interval. A 35 days interval laid between the other image pair, which resulted in a decreased mean coherence of about 0.5 compared to 0.57 of the ascending pass. Both image pairs have a baseline of about 160m, which enables height resolution even in steeper terrain.

A SPOT stereo image pair, which overlaps most part of the SAR images, was used for stereo DEM generation.
The data set was completed by a reference DEM, which has been obtained from a 1:5000 topographic map, and a land use map, both in 30m grid.

5. RESULTS

A DEM has been computed from each SAR interferogram with weighted least squares unwrapping. The coherence between the images has been used as weight for the unwrapping process. Since the time interval between the ascending passes has been shorter, the pair showed a relative high coherence and hence was expected to yield higher accuracy. The DEM maps topography in an accuracy, that is comparable to the SPOT stereo DEM, provided a relatively flat terrain. The absolute mean and root mean square errors (RMSE) in that area have been 4.8m and 12m in the SAR DEM and 6.3m and 8.5m in the SPOT DEM. Other research groups achieved similar results with the same data set (Crippa, 1998) (Carrasco, 1997).

In presence of layover, shadowing or temporal decorrelation, the height error of the InSAR DEMs increased significantly. Therefore, regions showing these disturbances have been identified in the ascending images and the resulting DEM respectively, in order to fill them with data from the other sources.

The layover and shadowing zones have been identified with help of the reference DEM using (1) and (2). Since these phenomena are restricted to limited areas, none of them has been larger than some square kilometres.
An area of intensive land use has been identified with the land use map and the coherence map of the SAR images. This area stretched over 10km^2 approximately.

Table 1 shows the resulting absolute mean and RMS errors of the descending pass and SPOT stereo DEM in the layover, shadowing and agricultural areas.

Effect	SAR descending	SPOT
Layover	Mean: 9.7m RMSE: 32m	Mean: 7.9m RMSE: 9m
Shadowing	Mean: 54.1m RMSE:73.5m	Mean: 16.1m RMSE:22.8m
Temporal decorrelation	Mean: 88m RMSE: 90.2m	Mean: 8.9m RMSE:10.7m

Table 1: Height errors of SAR and optical DEM in specific areas

The accuracy of the DEM from the SAR descending orbit images suffered from the long time interval between the images leading to a low coherence due to backscatter changes, which resulted in an increased RMSE. In the layover area of the ascending pass DEM, it showed its ability to serve with complementary data. In the shadowed region, foreshortening and layover occurred in the descending pass images, yielding a high error. As expected, temporal decorrelation could not be resolved with the descending pass images having the same systematic problem.

The SPOT stereo DEM showed significant higher accuracy than the SAR DEM in all areas. Only in the shadowing area, the error increased remarkably due to matching problems. It has to be mentioned, that no clouds covered the well-textured areas, which resulted in effect in that high accuracy.

The erroneous areas have been masked in the ascending image

DEM and filled with height values from the other sources. Values from the descending image DEM were only applied in case of coherence higher than 0.7, which occurred in very limited areas. The most heights have been replaced by SPOT DEM data. The absolute mean and RMS error before and after this operation are presented in Table 2.

DEM	Error
SAR ascending	Mean: 58.4m RMSE: 75.5m
DEM after data fusion	Mean: 24.3m RMSE: 41.9m

Table 2: DEM accuracy before and after fusion

For an interpretation of the results, the characteristics of the examined scene have to be taken into account. More than 70% of the scene were covered by mountainous terrain, leading to errors in the InSAR DEM for reasons stated above. The remaining flatter part of the scene consisted mostly of agricultural areas and water bodies, mainly the river Ebro. In combination, these effects cause the low accuracy of the original DEM from the ascending orbit images.

Both, absolute mean and RMS error of the DEM, decreased about 50% after replacing the height values with data from other sources. The accuracy suffered from some remaining extreme errors (0.37%), which laid between 200m and 300m, but obviously affected mean and RMSE very much. More than 68% of the heights showed an error of less than 20m. Since only shadowing, layover areas have been identified and replaced, but foreshortening effects have been replaced only with help of the coherence map, a certain error left in mountainous terrain. Also, normal vegetation changes within the whole scene, contributing to the final error, could not be assessed by this kind of data replacement.

6. CONCLUSION

It has been shown that the use of data from different sources improves the accuracy of InSAR DEMs in those areas, which can not be resolved by a single SAR image pair. The reasons for the failure of the interferometric process in those areas have been presented along with some techniques to identify the areas. The height error of different sensors in such areas has been compared and evaluated. The results have been used for enhancement of an InSAR DEM.

The identification and the substitution of the problematic zones with help of this method is a semi-automated approach to improve InSAR DEMs. Its potential is only limited as long as only the mentioned reasons of errors are considered. Therefore, future research activities will concentrate on a full-automated, multisource data fusion process for DEM generation, which heeds the sources of errors and the synergy between the different data.

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