GENERATION AND ANALYSIS OF DEMs BASED ON SPACE-BORNE REMOTE SENSING

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KEY WORDS: InSAR, Optical Imagery, TerraSAR-X, IKONOS, DEM, Generation, Comparison

ABSTRACT:

The extraction of the third dimension from stereoscopic image pairs is a well known technique. However, in a number of countries aerial images and laser scanner data are unavailable, expensive, or cannot be operated in national coverage. Because of these problems, space-borne remote sensing techniques provide a viable alternative to digital elevation model (DEM) generation for many applications.

The automatic extraction of accurate DEMs especially in urban areas is still a very complicate task due to occlusions, large differences in height and the variety of objects and surface types. Space-borne Remote Sensing provides two main methods for DEM generation based on optical imagery and interferometric synthetic aperture radar (InSAR). These methods have advantages and disadvantages against each other. For example, object recognition is easier in optical imagery, but the imaging depends upon weather conditions. On the other side object recognition is hard in radar images, but clouds can be penetrated by radar.

InSAR is a technique to derive a DEM from at least two complex SAR images taken from slightly different orbits that provide an across-track baseline of suitable length. The data are either taken simultaneously (single-pass mode) or sequentially (repeat-pass mode) from air or space. One of the most advanced SAR sensors is TerraSAR-X (TSX), a German system launched on June 15^{th}, 2007. It offers high resolution imagery (~1m by Spotlight mode) which could not been achieved from civilian available radar technology up to then.

Alike InSAR technique, for 3D-data aquisition by optical imagery, at least two optical images of the same area taken from different directions are required and image orientation has to be known in the specified object coordinate system. The number of optical space sensors and the ground resolution recently improved strongly. The break through of very high resolution imaging came with IKONOS, launched in 1999 by Geoeye, USA. For nadir view IKONOS enables imaging with 0.82m ground sampling distance (GSD) in the panchromatic band (PAN) and 3.68m in the multispectral bands (MS).

The aim of this investigation is the generation of DEMs by TSX InSAR and IKONOS optical images. DEMs have been generated with 3m grid spacing in Istanbul, Turkey by high resolution spotlight (HRS) mode of TSX and IKONOS PAN images. A reference DEM, generated by aerial photogrammetry, is available with 1m grid spacing and 10cm up to 1m vertical accuracy.

1. INTRODUCTION

Radar remote sensing plays a significant role in remote sensing and develops rapidly. The number of civilian available SAR (synthetic aperture radar) satellites grows fast. One of the most actual SAR satellites is German TerraSAR-X, launched on 15^{th} of June 2007. It provides up to 1m GSD in Spotlight mode. With InSAR as well as with optical images digital surface models (DSM), with points on top of the visual surface are generated. The DSMs from InSAR and from IKONOS images have been compared with a more accurate reference DEM.. Under optimal conditions DSMs can be filtered to DEMs containing only points located on bare ground. But in the densely build up area of Istanbul not enough points located on the bare ground are included in the DSMs, by this reason the DSMs have not been filtered. Only blunders have been eliminated applying smoothing filters.

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2. TEST FIELD AND DATA SETS

2.1 Test Field

Istanbul is located in north-west area of Turkey. The Greater Municipality Area has a coast line to the Black Sea and the Marmara Sea connected by the Bosporus. Istanbul is one of the biggest cities in the world with a population of about 14 million.. The city is a suitable test area for the investigation because its different types of terrain. In patches, terrain is open-flat, hilly-steep and woody. The test area covers 10km×8km. It includes the historical peninsula and near surroundings. Historical Peninsula (Old City) is one of the most important regions in Istanbul, located on the European side, neighbored to the Bosporus and Marmara Sea. Figure 1 shows the high resolution satellite image of the test field with the frequency distribution of terrain inclination. This area has smoother topography in relation to the rest of Istanbul. The elevation reaches from sea level up to 130m.

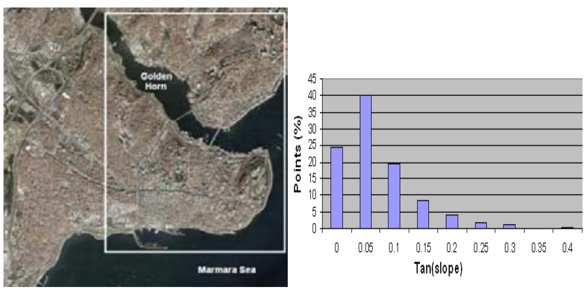

Figure 1. Test area and frequency distribution of terrain inclination

2.2 Data Sets

Just now TSX is one of the most modern SAR satellites. The satellite has been launched on June 15th 2007 from Russia's space launch facility, Baikonur Cosmodrome in Kazakhstan. It was built in German; the lifetime will be at least 5 years on the space (http://www.dlr.de).

TSX offers the highest quality spatial data that were not available from space before for civilian application using high frequency X-band SAR sensor which can be operated in different imaging and polarization modes. Figure 2 and Table 1 present the system components of the satellite.

As it can be seen from Table 1, TSX offers 3 different operation modes as Stripmap, Spotlight, and ScanSAR. These modes provide high resolution images for detailed analysis as well as wide swath data whenever a larger coverage is required. Imaging is possible in single, dual and quad-polarization (experimental). Besides, TSX data of suitable baseline can be used for interferometry to generate a DSM.

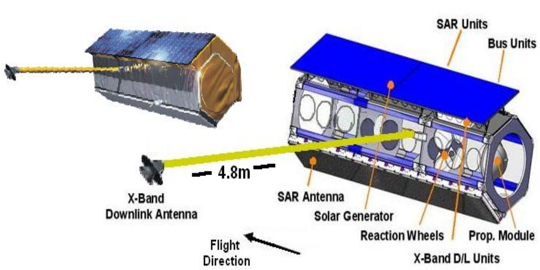

Figure 2. System components of TSX

Launch date, Life	June 15th 2007, at least 5 years
Launch site	Baikonur, Kazakhstan
Carrier	Dnepr-1
Satellite mass	1230 kilogram
Satellite size	5 m x 2.4 m
Orbit characteristics	514 km altitute, 11 days repetition, 97.44º inclination
Antenna	4.8 m active array, multi-pol, steerable in elevation and azimuth
Radar frequency	9.65 GHz
Power consumption	800 W in average
Data reception, Mission operation	DLR, Neustrelitz, Oberpfaffenhofen, Weilheim
Bandwidth	150 MHz (300 MHz experimental)
Memory	256 Gbit (end of life)
Downlink	300 Mbit/s
Imaging modes (GSD)	Stripmap (3m), Spotlight (1-2m), and ScanSAR (16m)

Table 1. System components of TSX (http://www.dlr.de)

TSX is capable to operate two types of Spotlight modes. The range resolution is the same in both cases (it depends on the pulse bandwidth), but the scene coverage and the azimuth resolution are different. The azimuth resolution depends on the integration time that is the synthetic aperture. In the standard SAR Stripmap mode the oblique antenna beam permanently points on the ground perpendicular to the sensor track. In such manner very long image stripes of constant range and azimuth resolution can be obtained. In contrast, the Spotlight modes focus on smaller areas of interest, which are illuminated longer by steering the antenna accordingly. The Maximum azimuth steering angle range is ±0.75º (Roth, 2003). Both Spotlight modes differ in terms of azimuth resolution and therefore scene coverage.

The first type, named as Spotlight mode covers areas of 10km x 10km with about 2m GSD. The second type, called high resolution Spotlight mode, features a reduced coverage of 5km x 10km, but offers higher resolution.

For the generation of the investigated DSM, two HRS mode TSX SAR images were used which have 1m azimuth resolution and five months time interval. Figure 2 shows these images and the following Table 2 presents the characteristics.

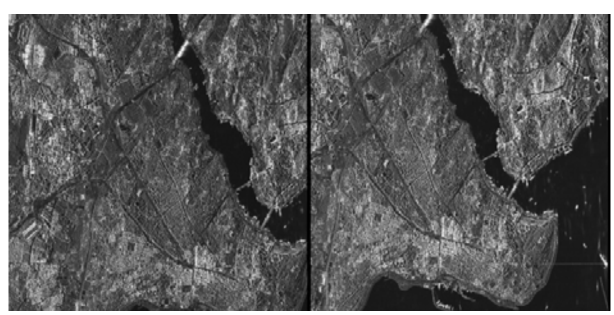

Figure 3. HRS TSX SAR images of the test area

Characteristics	HRS TSX Image 1	HRS TSX Image 2
Sensor Id	SAR	SAR
Sensor mode	High resolution Spotlight	High resolution Spotlight
Start date	2008-05-05T15:57:33,98	2008-10-06T15:57:42,52
End date	2008-05-05T15:57:34,73	2008-10-06T15:57:43,26
Polarization mode	Single polarization	Single polarization
Polarization channel	HH	HH
Looking direction	Right looking	Right looking
Pass direction	Ascending pass	Ascending pass
Centre incidence angle	40.9752891207°	41.0898290780°
scene size	5km×10km	5km×10km

Table 2. Characteristics of used high resolution TSX SL images

For the generation of TSX DSM, the interferometric processing steps of SARScape module of program ENVI Version 4.6 have been used. Interferometric processing steps of DSM generation are not as simple as DSM generation with optical imagery. The operator has to apply several complex steps and to assign threshold application values depending upon quality and characteristics of the used SAR images (e.g. co-registration settings, best choice of azimuth and range looks etc.). At the interferometric processing, after registration of images, baseline estimation, interferogram generation along with co-registered single look complex (SLC) generation, flattening, filtering and coherence generation, phase unwrapping, orbital refinement, phase to height conversion and geocoding steps have been performed step by step, leading to the DSM of TSX HRS mode SAR image-pairs (Figure 4).

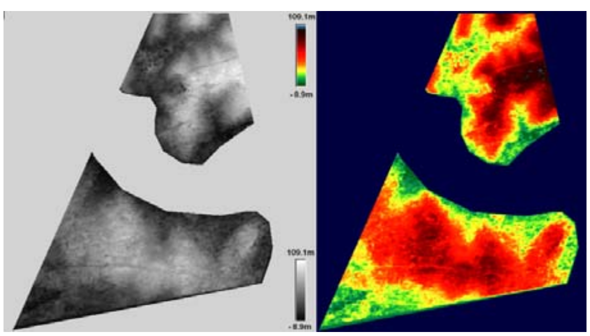

Figure 4. Generated TSX SL DSM, grey value and color coded presentation

The world's first commercial very high resolution optical satellite IKONOS was in 1999 by Geoeye, USA. It has panchromatic and multispectral bands and is able to take images with a ground resolution of 0.82m (PAN) and 3.68m GSD (MS) with 11.3km swath width from 681km altitude. .

In this investigation, for the Istanbul test field, a panchromatic IKONOS GEO stereo model with 1m GSD was available. The height-to-base (h/b) ratio value is 1.6 (angle of convergence 35°), the sun elevation angle is 65.5°. With this stereo model a DSM has been generated in 3m grid spacing. Figure 5 shows the IKONOS stereo-images and figure 6 illustrates the DSM generated by least squares matching as color coded version after refinement (Alobeid et. al., 2009).

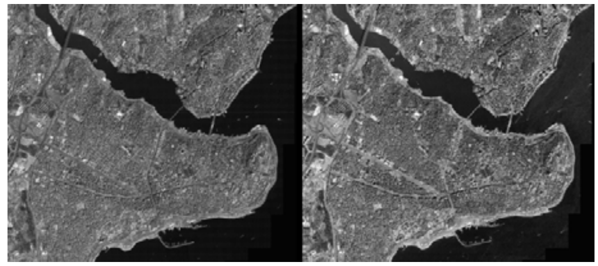

Figure 5. High resolution IKONOS PAN images

Against optical images, SAR images have some speckle effects which can be reduced by filtering, but this causes also a loss of information. On the other hand some special objects like railroads with metallic rails can be seen clearer as in optical images. The information contents of SAR images can be improved by multi polarization as shown in Figure 7. By the combination of HH and VV polarization the image interpretation is improved (Jacobsen, 2008).

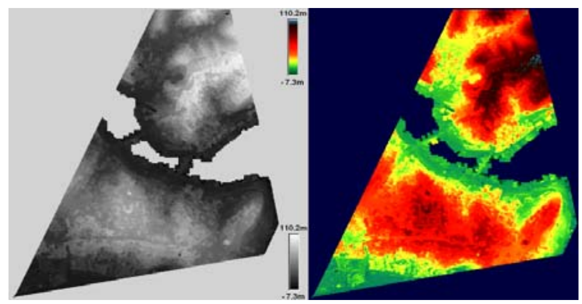

Figure 6. IKONOS DSM, grey value and colour coded

Figure 7. Multi-polarization (HH/VV) TSX SL image from the city of Dresden

The reference DEM was derived from 1:1000 scale digital aerial photogrammetric maps by Greater Istanbul Municipality and covers a large part of Historical Peninsula and near surroundings. This DEM was generated between 2007 and 2009. The original grid spacing of the DEM is 5m but it has been resampled into 1m according to the needs of the project. Figure 8 illustrates this reference DEM grey value and colored.

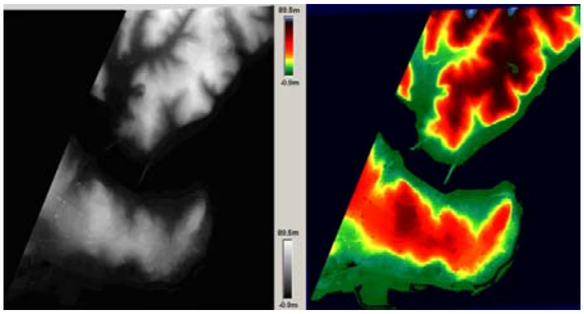

Figure 8. reference DEM

This DEM covers approximately 5km×5km of the test area. 95% is built-up that's why accuracy analysis were not performed for open and forest areas separately. The accuracy is in the range of 0.1m up to 1m.

3. DEM EVALUATION STRATEGY

The height models have been handled in UTM (universal transverse Mercator). That's why before the evaluation processes, a transformation of the coordinate systems of all of data sets into UTM has been performed using program BLTRA, belonging to program system BLUH.

After the transformation of all control points and partially height models into UTM a number of investigations have been performed using several modules of the software package BLUH (Dr. Karsten Jacobsen, Leibniz University Hannover). Table 3 shows these evaluation programs and their functions.

Program	Function
RASCOR	Filtering, analysis, correction and plot of a DEM
DEMSHIFT	Shifting of a DEM to another in X, Y, Z and possible scaling in Z
DEMANAL	Accuracy Analysis of DEM against a reference DEM
MANI	Manipulation of object coordinates, image orientations, IMU-data and pixel addresses, numbering of points
BLCON	Conversion of ground coordinates window function, reduction to equal distributed points, change of spacing
DEMINT	Computation of Z-values for points with given X and Y by interpolation of a digital elevation model
ZANAL	Analysis of a DEM
ZPROF	Plot profiles
UNDUL	Calculation of Geoid Undulation

Table 3. Evaluation programs and their functions

For the visualization, interpolation (by triangulation, moving surfaces etc.) and regular gridding of DSMs and DEMs, program LISA has been used. This program has been generated by Dr. Wilfred Linder. In program LISA, a height model and its height levels can be visualized in a color scale accompanied minimum up to maximum heights at the same screen using different color palettes All shown color coded versions of the height models have been created by this program.

4. RESULTS AND DISCUSSION

4.1 Shift of DSMs and Preparations

In order to perform the correct accuracy analysis, the DSM which will be evaluated must have the same location as the reference DEM. For this the determination of shifts to the reference height model has to be determined. Initially, using program DEMSHIFT shifts against the reference DEMs are determined. Large shift values causing large incorrect RMSZ values up to 14m occured and even the radius of convergence for the shift adjustment was exceeded. Accordingly, for the elimination of large shifts the DEMs were pre-corrected by manual shift via point matching using program MANI. The points of corresponding location and their planimetric coordinates (X and Y) were selected from evaluated DSMs and the reference DEM. The coordinate differences were calculated and used for the rough shifts. Figures 9 shows the selected points at the corresponding locations for the pre-correction of the evaluated DSMs and reference DEMs in the test field.

Figure 9. corresponding point (marked red) in used height models

The Table 4 shows the RMSZ values before and after pre-correction and adjustment of shift values by DEMSHIFT and the final RMSZ values.

height model	Original RMSZ (m)	RMSZ after manual shift(m)	Shift by DEMSHIFT (m)		Final RMSZ (m)
			ΔX	ΔY	
IKONOS	13.67	7.44	-11.38	+8.03	7.32
TSX SL	13.78	8.44	-7.93	+21.4	8.25

Table 4. Influence of shifts to RMSZ

4.2 Accuracy Analysis of DSMs

After shifting the DEMs, their accuracy have been analyzed in relation to the reference DEMs using program DEMANAL. For the analysis by DEMANAL, the maximal accepted DZ was limited to 50m and the maximal accepted tangent of terrain inclination was selected as 1.00. These settings were made depending upon the characteristic of the test fields.

Following Tables and Figures show the results of accuracy analysis for IKONOS and TSX SL DSMs against the reference.

DSM	General	
	SZ [m]	RMSZ
IKONOS (3m)	7.04+1.03×tan(α)	7.32 m
TSX SL (3m)	7.09+11.22×tan(α)	8.25 m

Table 5. Root mean square height differences of DSMs against reference DEM as function of terrain inclination and absolute value

The frequency distribution of DZ values against the reference DEM is shown in Figure 10. The components of this graphic are achieved from the list file of program DEMANAL after the analysis and generated by Microsoft Excel. The height differences and the corresponding number of points can be seen in this graphic presentation. The main point which should be analyzed in this graphic is the symmetric distribution. If the frequency distribution is symmetric, no influence of the buildings and vegetation exist. In this project, these graphic visualizations have been prepared between all evaluated models and reference models to form an opinion about the frequency distribution of DZ values. Figure 10 shows the frequency distribution of DZ values between IKONOS and TSX SL DSMs and the reference height model.

As mentioned before, at the accuracy analysis of heights, for the elimination of blunders, the maximal accepted DZ value is selected to 50m in program DEMANAL and the points which exceed this threshold value are automatically excluded by the program. If the image of this exception process is generated, the parts which are constituted by eliminated points can be seen clearly. By this way, these parts which have problems can be excluded when the models will be used for the precise applications. Using program DEMANAL, images have been created containing the excluded points. Figure 11 illustrates the image which contains the excluded points for IKONOS and TSX SL DSMs against the reference DEM. The excluded points are represented by the dark spots.

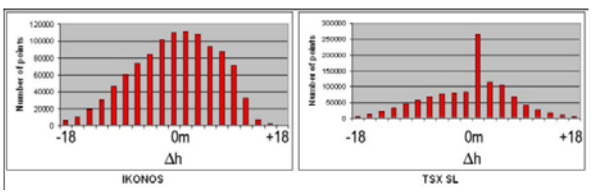

Figure 10. Frequency distribution of height differences of IKONOS and TSX SL DSMs against reference

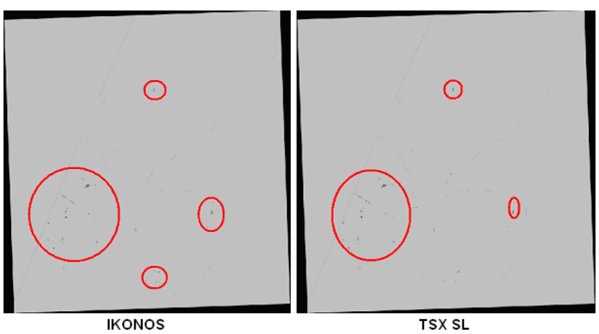

Figure 11. Excluded points of IKONOS and TSX SL (Δh > 50m)

In addition the root mean square height differences depending upon terrain inclination and inclination direction (aspects) is generated by program DEMANAL. Especially in InSAR height models the accuracy shows a dependency upon the aspects. Figure 12 shows the aspects of the accuracy analysis between IKONOS and TSX SL models against the reference.

As expected, the IKONOS DSM shows no dependency upon the aspects but TSX SL DSM has a clear dependency in relation to red arrow's direction and differences from mean value are obvious.

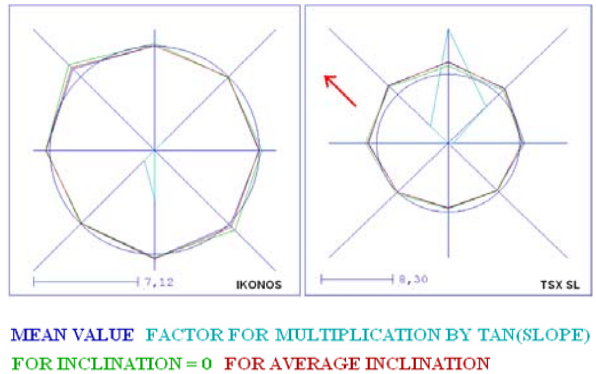

Figure 12. Aspects of the IKONOS and TSX height models

Beside the absolute accuracy assessments the relative standard deviations of evaluated DEMs have been identified. As distinct from absolute accuracies, relative accuracies indicate the interior accuracy of a model that means the accuracy of a point in relation to the neighbored points as function of the distance.

$$RSX = \sqrt{\sum (dxi - dxj)^2 / (2 \times nx)}$$

RSX = relative standard deviation, d = distance between points
dl < d < du   dl = lower distance limit   du = upper distance limit of the distance

The relative accuracy is important especially for the morphologic details. The morphologic details, are not influenced by an error of phase unwrapping, leading to a local constant error of the DSM, but not to a relative error of closely neighbored points. For example, for a DSM having 3m grid spacing the relative accuracies were calculated between 3m and 30m at the 3m distance interval. The relative accuracies of the evaluated DSMs can be seen on the Table 6. Depending upon the reference model's grid spacing, the relative standard deviations have been calculated from 1m to 10m.

Distance [m]	IKONOS	TSX SL
1	.98	.69
2	1.63	.98
3	2.14	1.31
4	2.57	1.57
5	2.92	1.82
6	3.23	2.04
7	3.48	2.21
8	3.70	2.37
9	3.89	2.52
10	4.05	2.65

Table 6. Relative standard deviations of IKONOS and TSX SL DSM as function of point distance in relation to reference DEM

It can be seen in Table 6, TSX SL DSM has a better relative accuracy than IKONOS DSM generated by least squares matching. Of course it should be mentioned, that least squares matching without filtering is not the optimal solution in densely built up areas, with semiglobal matching quite better and more detailed results can be achieved with optical images (Alobeid et al 2010). The interior integrity of TSX model is powerful, limitations may be caused by phase unwrapping.

4.3 Differential DEMs

Differences between height models have been created for visualization. Figure 13 shows the differential height model between IKONOS and TSX SL DSMs.

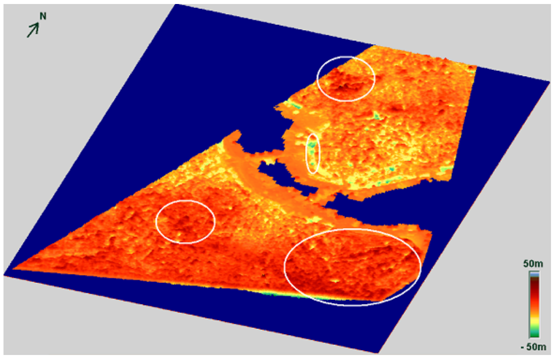

Figure 13. differential height model between IKONOS and TSX SL

Height differences are obvious in patches especially in forest areas (dark parts). Except forest regions TSX SL and IKONOS DSMs are coherent and the height differences are in between 0-5m.

4.4 Shading

Shading is one of the best possibilities of visualizing a DSM. All buildings, vegetation and forest coverage in a DSM can be seen clearly. The shadings of IKONOS and TSX SL DSMs with the same grid spacing (3m) have been generated and compared. Figure 14 and 15 illustrate the results of shadings.

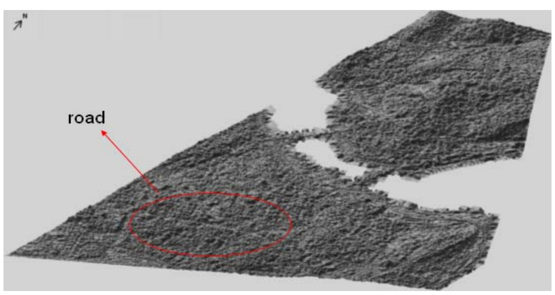

Figure 14. Shading of IKONOS height model

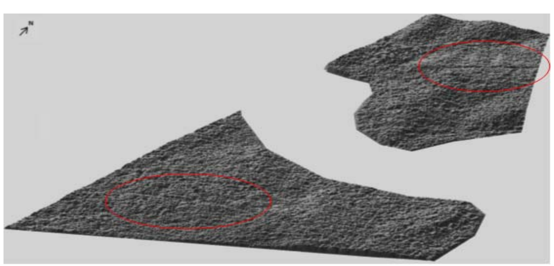

Figure 15. Shading of TSX SL height model

The visual inspection illustrates the ground objects like roads (in red circles), buildings, vegetation and forest.

5. CONCLUSION AND FUTURE TARGETS

DSMs with 3m grid spacing have been generated from TSX SL and from IKONOS panchromatic image-pairs by least squares matching. These height models have been compared in Istanbul test field, Turkey using a reference DEM, derived from 1:1000 scale aerial photos and has 10cm up to 1m accuracy.

In the densely build up area of Istanbul DSMs are strongly influenced by buildings, partly also by trees and forest. The influence of the buildings and the vegetation can not be filtered totally because of missing satisfying number of points on the ground. With optical images by semiglobal matching (Alobeid et al 2010), which is not shown here, building details and quite better information about the ground height can be determined.

InSAR height models have a dependency upon the aspects. TSX SL DSM has a better relative accuracy as absolute accuracy, which may be explained by the influence of phase unwrapping, but also the fact that DSMs are compared with reference elevation model containing the height of the bare ground.
It can be mentioned that TSX SL image-pair which has a suitable baseline (135m) presents an absolute accuracy which is useful for several topics. A dominating effect to the accuracy is still the vegetation and buildings. With the successful launch of TanDEM-X, a satellite identical to TerraSAR-X is in orbit, which shall be used in a tandem configuration for generating worldwide height models with 2m accuracy for flat terrain.

Future investigations and development will be DSM fusion with optical DEMs based on space and/or aerial images and support high resolution optical images for generation of maps 1/5000 scale and below.

ACKNOWLEDGEMENTS

Thanks are going to TUBITAK, Turkey and DLR, Germany for their supports to this research.

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