

QUALITY ASSESSMENT OF HIGH RESOLUTION RADAR DSMs

Umut G. Sefercik^{a,*}, Karsten Jacobsen^b

^aZonguldak Karaelmas University, Department of Geodesy and Photogrammetry, ugsefercik@hotmail.com

^bLeibniz University Hannover, Institute of Photogrammetry and GeoInformation, jacobsen@ipi.uni-hannover.de

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ABSTRACT:

Radar remote sensing has a significant role in remote sensing technologies and develops rapidly. A series of new synthetic aperture radar (SAR) satellites has been launched to space having various operation modes which offer different resolutions and advantages. A very actual SAR satellite is German TerraSAR-X (TSX), launched on 15th June 2007. This satellite is a revolution for the SAR technologies at the resolution side and offers 1m ground resolution in Spotlight mode. To investigate the quality of digital surface models (DSM) which are derived from high resolution data of this satellite, a comparison has been made to a DSM based on optical space images taken by IKONOS. For the test DSMs have been generated with the SAR and the optical data covering parts of Istanbul, Turkey and are compared with a more accurate DEM of same area, based on aerial photogrammetry. This was leading to the result, that the high resolution Spotlight mode TSX model has nearly the same visual quality and absolute accuracy as the IKONOS model and has a slightly better relative accuracy.

1. INTRODUCTION

Recently, the remote sensing technologies have been improved with high acceleration. New satellites have been launched into space containing different types of operation principles and data collection configurations. They provide and present actual information about Earth to the users from different work disciplines. The remote sensing satellites and corresponding imaging systems can be separated into two main groups as satellites with optical sensors and satellites with radar sensors. Two advanced optical and radar systems are IKONOS and TSX. High resolution digital surface models generated from these satellite's data have been compared in the test area Istanbul in order to assess the quality of the generated digital height models.

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 Bosphorus. Istanbul is one of the biggest cities in the world. About 14 million people live in the city and surrounding suburbs. The city is a suitable test area for the accuracy analysis in urban areas with changing topography. In patches the terrain is flat, hilly up to steep; partially open, build up and covered by forest. The test area covers 10km×8km. It includes the Istanbul Historic Peninsula and near surroundings. The Historic Peninsula (old city) is one of the most important regions in Istanbul, located on the European side, neighbored to the Bosphorus and Marmara Sea. Figure 1 shows the 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.

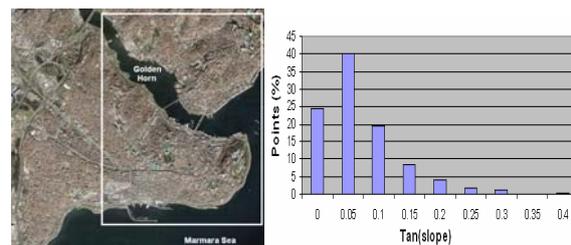


Figure 1. Test area and frequency distribution of terrain slope

2.2 Data Sets

Currently, TSX is one of the most modern SAR satellites; its data is evaluated in this study. The satellite has been launched on June 15th 2007 from oldest Russia's space launch facility, Baikonur Cosmodrome in Kazakhstan. It is built in German; the lifetime will be at least 5 years. The mission is a joint project in a public private partnership (PPP) between the German Ministry of Education and Science (BMBF), the German Aerospace Center (DLR) and the Astrium GmbH. Under DLR contract Astrium constructed and built the satellite while DLR is responsible for the development of the ground segment, instrument calibration and scientific use of satellite at its lifetime (reference URL 1).

TSX can be used in interferometric arrangement and offers the highest SAR quality 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 uses 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. TSX data can be used for interferometry allowing DSM generation.

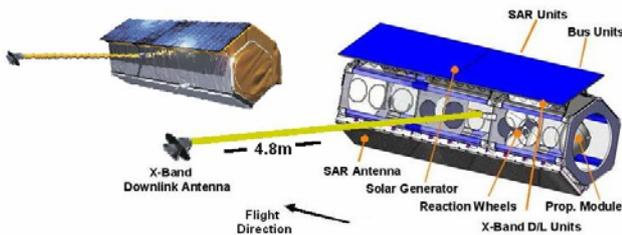


Figure 2. System components of TSX

Launch date, Lifetime	15 June 2007, at least 5 years
Launch site	Baikonur, Kazakhstan (Russia)
Carrier	Dnepr-1
Satellite mass	1230 kilogram
Satellite size	5 m height x 2,4 m diameter
Orbit characteristics	514 km altitude, 11 days repetition, 97.44° inclination
Antenna	4.8 m active array, multi-polarized, 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	Stripmap (3m), Spotlight (1-2m), and ScanSAR (16m)

Table 1. System components of TSX (URL 1)

TSX is capable to operate two types of Spotlight modes. The first type purely named as Spotlight mode is limited to a scene size of 10kmx10km (length and width) and records with 2m ground resolution. The second type limits the scenes to 5kmx10km but offers higher resolution. This type is named high resolution Spotlight mode as the scenes have 1m azimuth resolution. For these two types of Spotlight mode just the ground resolution in azimuth direction is different. During the observation of a particular ground scene the radar beam is steered like a spotlight so that the area of interest is illuminated longer and hence the synthetic aperture becomes larger. The largest azimuth steering angle range is $\pm 0.75^\circ$ (Roth, 2003).

At the investigation, for the generation of a DSM, two HRS modes TSX SAR images were used which have 1m resolution in azimuth direction and five months time interval. Figure 3 shows these images and the following table 2 presents the characteristics.

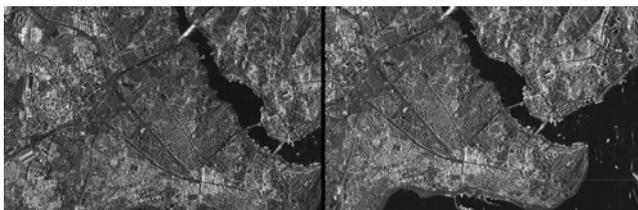


Figure 3. HRS TSX SAR images

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 high resolution TSX SL images

For the generation of TSX DSM, 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 thresholds depending upon quality and characteristics of the SAR images used for DSM generation (e.g. co-registration settings, best choice of azimuth and range looks). For 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 to obtain a DSM from TSX HRS mode SAR image-pairs (figure 4).

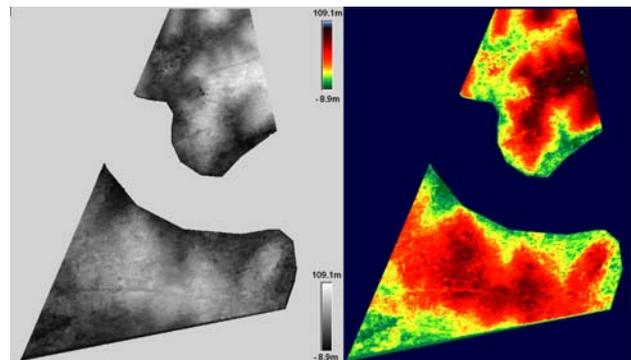


Figure 4. TSX SL DSM, grey value and color coded presentation

The world's first commercial very high resolution optical satellite IKONOS was launched to space in 1999 by Geoeye, USA. It has panchromatic and multispectral bands and is able to take images with a ground resolution of 0.82m in the panchromatic band (PAN) and 3.28m in the multispectral bands (MS) with 11.3km swath width from 681km orbit altitude. By the combination of both sensor products 0.82m pan-sharpened color images can be created, but in most cases IKONOS Geo scenes with 1m/4m ground sampling distance (GSD) are used. The more than 300 million square kilometers of imagery that IKONOS has been collected are used for national security,

military and civilian mapping, air and marine transportation, by regional and local governments and others (reference URL 2).

For this investigation a panchromatic IKONOS GEO stereo model with 1m GSD was available. The height-to-base (h/b) ratio value is 1.6, corresponding to 35° angle of convergence. The sun elevation angle is 65.5°. With this stereo model a DSM has been generated with 3m grid spacing. For the optimal handling the DEM has been shifted by adjustment to the reference DEM and blunders have been eliminated by automatic filtering. Figure 5 shows the IKONOS stereo-images and figure 6 illustrates the generated DSM along with its color coded version after the refinement process.

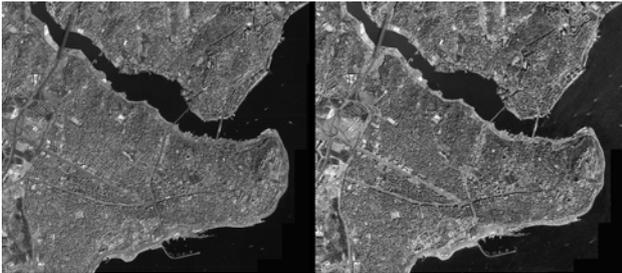


Figure 5. Used panchromatic IKONOS images

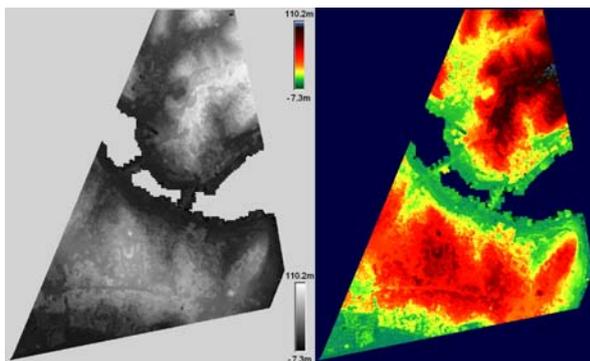


Figure 6. IKONOS DSM, grey value and color coded

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

The reference DEM was derived from 1:1000 scale digital maps including large parts of the Historical Peninsula and near surroundings, based on digital aerial images from Greater Istanbul Municipality. This DEM was generated between 2007 and 2009. The original grid spacing of the DEM is 5m but it has been resampled to 1m according to the needs of the project. Figure 8 illustrates this reference DEM along with colored version to support the visualization of the elevation levels.



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

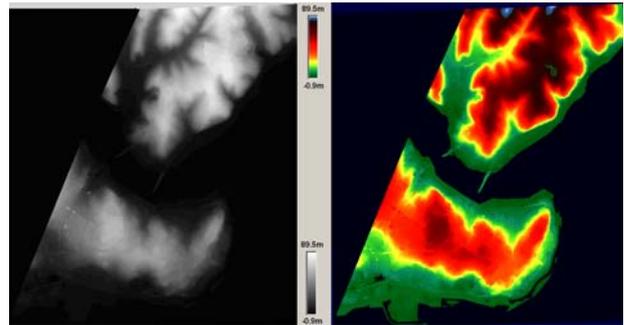


Figure 8. Grey value and color coded reference DEM

The reference DEM overlaps with the test field approximately 5km×5km and covers more than 95% built-up areas that's why the accuracy analysis was not performed for open and forest areas separately. It has 10cm up to 1m accuracy and the elevations are between sea level and 90m.

3. DEM EVALUATION STRATEGY

In the project initially the common coordinate system was defined as UTM (universal transverse Mercator) for the whole of data sets and references. That's why before the evaluation processes, the transformation of the coordinate systems of all of data sets into UTM suitable zone have been performed using program BLTRA. This program belongs to program system BLUH (Bundle Block Adjustment Leibniz University Hannover), developed by Dr. Karsten Jacobsen, Institute of Photogrammetry and Geoinformation (IPI), Leibniz University of Hannover, Germany.

After the transformation of all models into UTM, for the evaluation analysis, a number of investigations have been performed using several modules of the software package BLUH. Table 3 shows these evaluation programs and their functions.

Besides, 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, several presentations of the height model can be seen in a color scale accompanied to minimum up to maximum heights with choose able color palettes. Using the optimum palette in every process, the details can be seen clearly. All color coded versions of the height models have been created by this program.

Program	Function
RASCOR	Filtering, analysis, correction and plot of a DEM
DEMSHIFT	Shifting of a DEM to another in X, Y, Z and 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 the points
BLCON	Conversion of ground coordinates window function, reduction to equal distributed points, change of spacing
DEMINT	Computation of Z-value for points with given X and Y by interpolation of a raster-digital elevation model
ZANAL	Analysis of a DEM
ZPROF	Plot profiles
UNDUL	Calculation of Geoid Undulation
HPSHOW	Visualization of aspects

Table 3. Evaluation programs and their functions

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. Shifts against the reference DEMs are determined and respected. In this operation, the respected height difference against the reference DEM was limited to 50m to avoid an effect caused by blunders. As result of this first determination, large shift values caused large incorrect root mean square Z-differences (RMSZ) with values up to 14m because exceeding the radius of convergence for the shift adjustment. Accordingly, for the elimination of large shifts the DEMs were pre-corrected by manual shift via manually identified corresponding points in the height models. Figure 9 shows a selected point with the corresponding locations for the pre-correction.

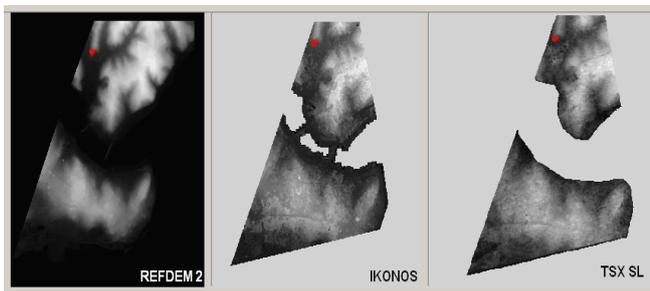


Figure 9. Corresponding point in DEM for pre-correction of shifts shown in red

Table 4 presents the RMSZ-values before and after pre-correction of shifts in the range of 200m, adjusted shift values after pre-correction by DEMSHIFT and the final RMSZ values.

DEM	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 DEM-shifts to RMSZ against reference, manual shifts in the range of 200m

4.2 Accuracy Analysis of DSMs

After shifting the height models, their accuracies have been analyzed in detail 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 to eliminate effects of blunders. In the second iteration, shift and vertical scale were respected. These settings were made depending upon the characteristic of the test field.

Following tables and figures show the results of accuracy analysis for IKONOS and TSX SL DSMs against REFDEM. Nearly the whole area is built-up with just small forest coverage not justifying a separate analysis.

DSM	SZ [m]	Not accepted points [%]
IKONOS	$7.04+1.03 \times \tan(\alpha)$	0.00
TSX SL	$7.09+11.22 \times \tan(\alpha)$	0.00

Table 5. Standard deviation of height models depending upon terrain inclination α

The frequency distribution of height differences against the reference is shown in figure 10. The main point which should be analyzed in this presentation is the symmetry of the distribution. If the frequency distribution is symmetric, no influence of elements not belonging to the bare ground, as buildings and vegetation, exist, what is not the case here.

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 REFDEM. The excluded points are represented by the dark spots.

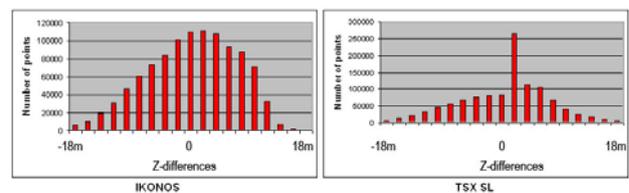


Figure 10. Frequency distribution of height differences between IKONOS and TSX SL DSMs and reference DEM

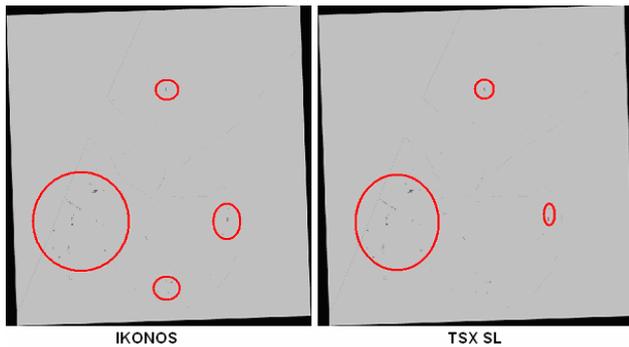
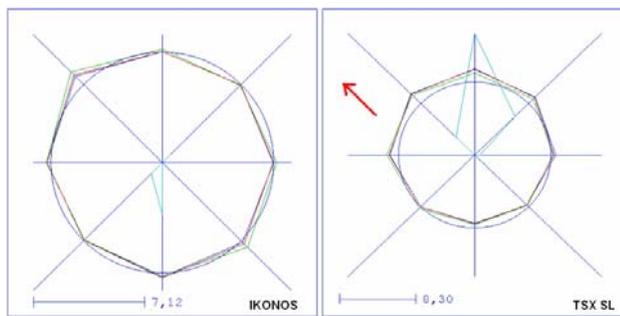


Figure 11. Excluded points of IKONOS and TSX SL DSMs

In addition the RMSZ of the evaluated models against reference models as a function of the terrain inclination direction (aspects) is computed. Especially, in height models based on SAR the accuracy shows a dependency upon the aspects caused by foreshortening. Especially the error component dependent upon the terrain inclination depends also upon the north-direction of the inclination. Figure 12 shows the accuracies as function of the aspects for IKONOS and TSX SL height models in relation to the reference with clear enlarged standard deviations in the view direction of TSX. As expected, the IKONOS DSM shows no dependency upon the aspects.



MEAN VALUE FACTOR FOR MULTIPLICATION BY TAN(SLOPE) FOR INCLINATION = 0 FOR AVERAGE INCLINATION

Figure 12. Height accuracy depending upon aspects

Besides the absolute accuracy assessments the relative accuracies (relative standard deviations) of evaluated DEMs have been analyzed. As distinct from absolute accuracies, relative accuracies indicate the interior accuracy of a model that means for a point in relation to the neighbored points.

$$RSZ = \sqrt{\sum(DZ_i - DZ_j)^2 / (2 \cdot nx)}$$

Formula 1. Relative standard deviation RSZ, d = distance between points, dl < d < du = distance groups, dl = lower distance limit du = upper distance limit of the distance

The relative accuracy is important especially for the morphologic details. The morphologic details for example, are not influenced by an error of phase unwrapping, leading to a local absolute error of the DSM, but not to a relative error of closely neighbored points. In this study, for the evaluation of relative accuracy, the accuracy of each point to the neighbored points was calculated for both evaluated DSM. For example, for a DSM with 3m grid spacing the relative accuracies were calculated for neighborhood distances between 3m and 30m for 3m distance groups. The relative accuracies of the evaluated DSMs can be seen in table 6. Depending upon the reference

model spacing, the relative accuracies have been calculated for distance groups from 1m to 10m.

Distance [m]	IKONOS [m]	TSX SL [m]
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 accuracies of IKONOS and TSX SL DSMs

It can be seen in table 6, TSX SL DSM has a better relative accuracy as the IKONOS DSM, which is more depending upon building structures. That means the interior integrity of TSX model is powerful, also caused by the flattening effect of the InSAR height model. A limitation of TSX SL DSM may be caused by phase unwrapping.

4.3 Morphology

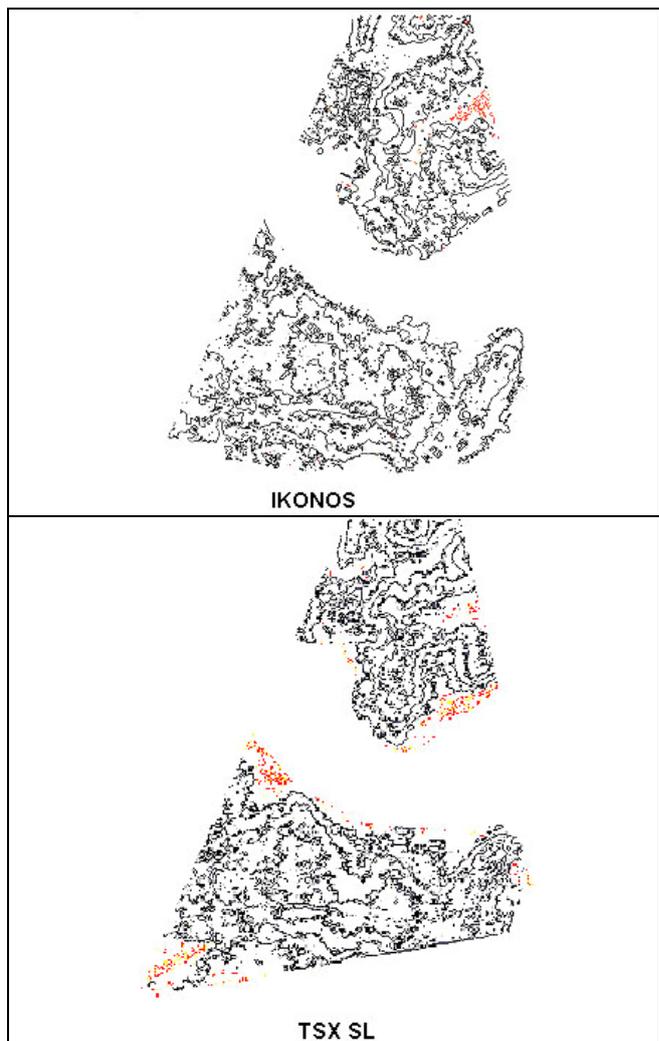


Fig. 13: Contour lines of IKONOS and TSX SL DSMs with 20m contour interval

The morphologic detail information analysis is one of the main steps of the evaluation of a height model. This analysis with the shape of the contour lines is another way to understand the relative accuracy of a height model. Several factors have a strong influence on the morphologic analysis; an important factor is the grid spacing. If the grid spacing of a height model is larger, fewer points can be used for the generation of contour lines, causing more smooth lines. Another important factor is the noise of the height model. If the inspected elevation models are noisy, small contour-line islands can be seen and the morphologic details are disturbed, but in urban areas, such islands may be caused by large buildings or building complexes. An equidistance of 20m was used for the evaluated models. Figure 13 shows the contour lines, generated from IKONOS and TSX SL DSMs.

As a summary of Figure 13, contour lines are very detailed but also noisy for IKONOS and TSX SL DSMs because of 3m grid spacing. Beside included details and noisy structure of contour lines the DSMs have several small contour islands, what may be caused by buildings, which are no be included in the case of larger point spacing.

4.4 Differential DEMs

A differential height model of the IKONOS DSM minus the TSX SL DSM has been created for visualization (figure 14). For the visualization an exaggeration factor of 5 was used to make the height differences clearer.

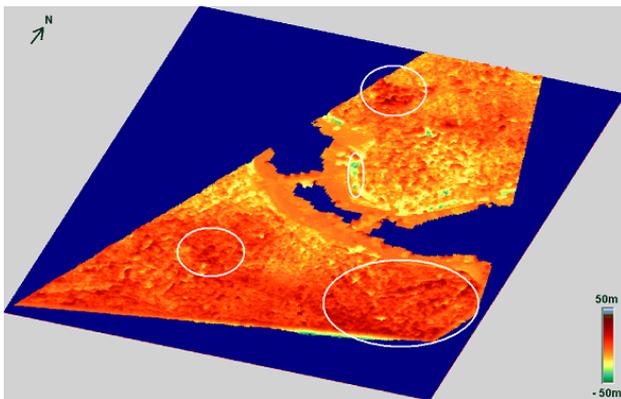


Figure 14. Differential height model of IKONOS DSM minus TSX SL DSM

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 between 0-5m. X-band SAR leads to height models which may have a height level up to a third of the tree height below the crown level, while optical DSMs show the crown level.

4.5 Shading

The shading is one of the best possibilities of visualizing a DSM. All buildings, vegetation and forest coverage in a DSM can be seen clearly. By this method, the shadings of IKONOS and TSX SL DSMs which have the same grid spacing of 3m have been generated and compared. Figure 15 and 16 illustrate the results of shadings.

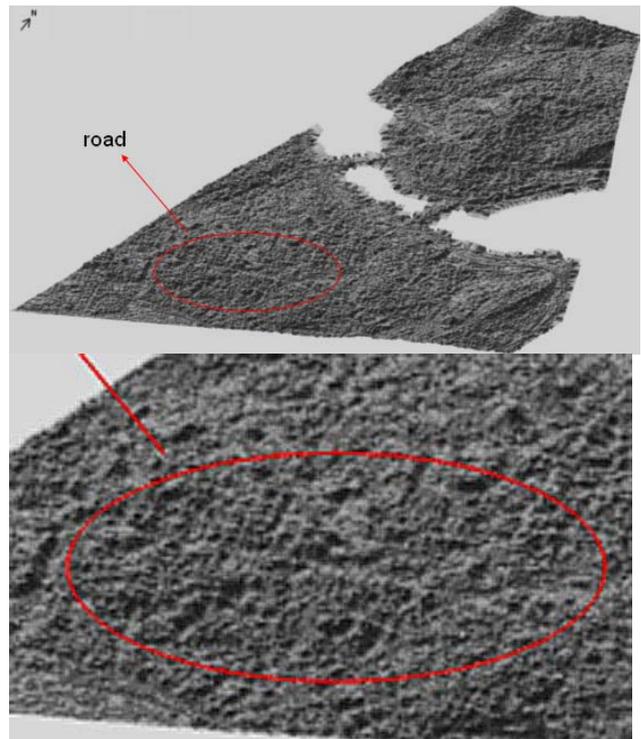


Figure 15. Shaded DSM (IKONOS, 3m), overview and detail

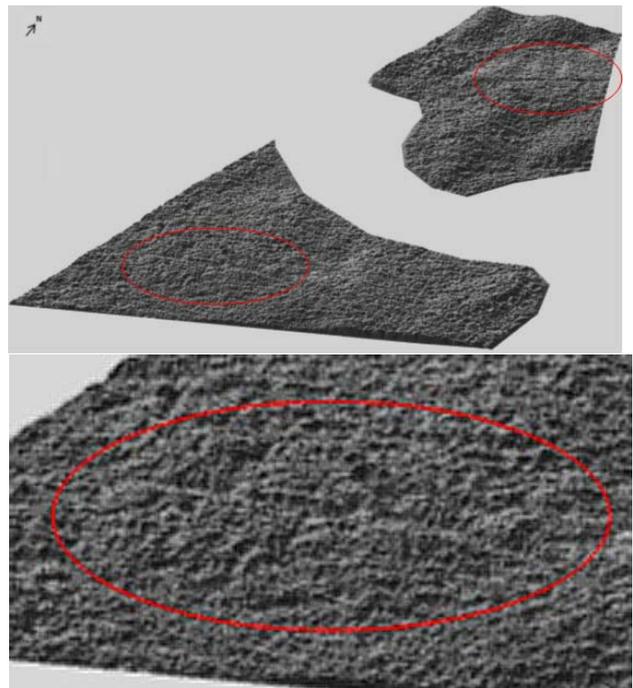


Figure 16. Shaded DSM (TSX SL, 3m), overview and detail

A visual inspection of the shaded height models shows more building details in the IKONOS DSM as in the TSX SL DSM. It shows objects like roads (in red circles), buildings, vegetation and forest.

5. CONCLUSION AND FUTURE TARGETS

In this investigation, DSMs with 3m grid spacing have been generated from TSX SL and IKONOS Pan image-pairs in the area of Istanbul, where a reference height model from aerial photos was available.

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 cannot be filtered totally because of a not satisfying number of points on the ground.

InSAR height models have a clear dependency upon the aspects. TSX SL DSM have a better relative accuracy as absolute accuracy, which may be explained by the influence of phase unwrapping, but also the case that DSMs are compared with reference elevation model containing the height of the bare ground.

Morphologic details are available in both digital surface models with more details from IKONOS imagery.

It can be mentioned that the used TSX SL image-pair, which has suitable baseline length (135m), leads to an absolute accuracy competitive to the height model based on the very high resolution optical images. A limiting effect of the accuracy are vegetation and buildings.

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

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