

Comparison of High Resolution InSAR and Optical DEMs

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Abstract. A Digital Elevation Model (DEM) alias Digital Height Model (DHM) is the digital cartographic representation of the elevation of the terrain at regularly spaced intervals in X and Y directions, using Z-values related to a common vertical datum. DEMs are required for several applications and in order to satisfy the need, various DEM generation techniques have been developed up to this time. Remote sensing is one of those techniques and contains two main methods for DEM generation as optical imagery and interferometric synthetic aperture radar (InSAR). These methods have several advantages and disadvantages against each other. For example; object recognition is easier in optical imagery but the images should be cloud-free. In contrast to optical imagery, object recognition is poor in InSAR but data collection is independent from weather conditions, clouds can be penetrated and large coverage up to global can be obtained fast at specific times.

In the study, the comparison of high resolution InSAR and optical DEMs was aimed at the same test field to determine the quality of TerraSAR-X (TSX) which is one of the most advanced InSAR satellite. TSX is German made and launched on June 15th, 2007. It offers high resolution (~1m by Spotlight mode) imagery which could not been achieved from radar technologies up to this time similar to high resolution optical imagery. The data sets provided by TSX newly obtained by scientific community and evaluations are currently being performed.

According to the aims of the study, high resolution spotlight (HRS) mode TSX and panchromatic (PAN) IKONOS DEMs were generated with 3m grid spacing in Istanbul, Turkey and evaluated using more accurate reference DEM, generated by photogrammetry. It has 1m grid spacing and 10cm up to 2m accuracy. At the evaluation processes, absolute and relative accuracy, stability, homogeneity and dependency upon various parameters are determined. After the evaluation analysis of the height models, it has been seen that HRS mode TSX model has nearly same visual quality and absolute accuracy with IKONOS model and has better relative accuracy.

Keywords. InSAR, DEM Generation, Comparison, TerraSAR-X, IKONOS

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.

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1 Test Field and Data Sets

1.1 Test Field

The test area includes the Istanbul Historic Peninsula and near surroundings, Turkey and covers 10km×8km. 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 (white frame) with the frequency distribution of terrain slope. This area has smoother topography in relation to the rest of Istanbul. The elevation reaches from sea level up to 130m.

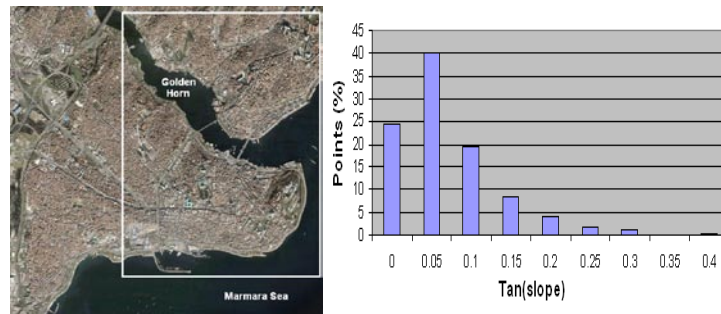


Figure 1. Test field with frequency distribution of terrain slope.

1.2 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.

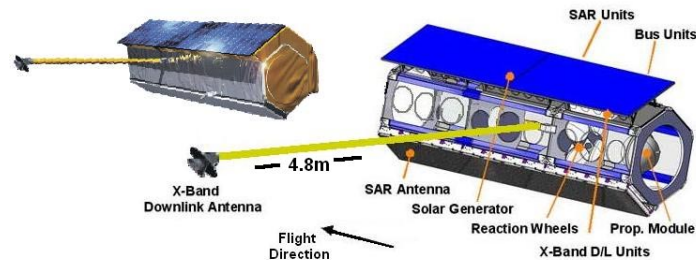


Figure 2. System components of TSX.

Table 1. System components of TSX (URL 1).

Launch date	15 June 2007
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-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
Lifetime	At least 5 years
Imaging modes	Stripmap (3m), Spotlight (1-2m), and ScanSAR (16m)

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. TSX is capable to operate two types of Spotlight modes. The first type purely named as Spotlight mode the scenes of interest area can be obtained for an area of 10kmx10km (length and width) and recorded with 2m resolution. At the second type, the lengths of the scenes are shorter by 5kmx10km but offer higher resolution. This type is named as high resolution Spotlight mode and the scenes have 1m azimuth resolution. Between these two types of Spotlight (HRS) mode just the geometric azimuth resolution is different in order to increase the azimuth scene coverage of Spotlight mode. 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 Maximum azimuth steering angle range is $\pm 0.75^\circ$ [1].

At the investigation, for the generation of a DSM, one HRS mode TSX SAR image-pair was used which has 1m resolution in azimuth direction and five months time interval. Figure 3 shows this image-pair and the following table 2 presents the characteristics of them. At the generation process, 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 3. HRS TSX SAR image-pair

Table 2. Characteristics of high resolution TSX SL InSAR images.

Characteristics	HRS TSX Image 1	HRS TSX Image 2
Sensor Id	SAR	SAR
Sensor mode	High resolution Spotlight	High resolution Spotlight
Start date	2008-05-05T15:57:33,985	2008-10-06T15:57:42,522
End date	2008-05-05T15:57:34,738	2008-10-06T15:57:43,262
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
Length and width of scene	5km×10km	5km×10km

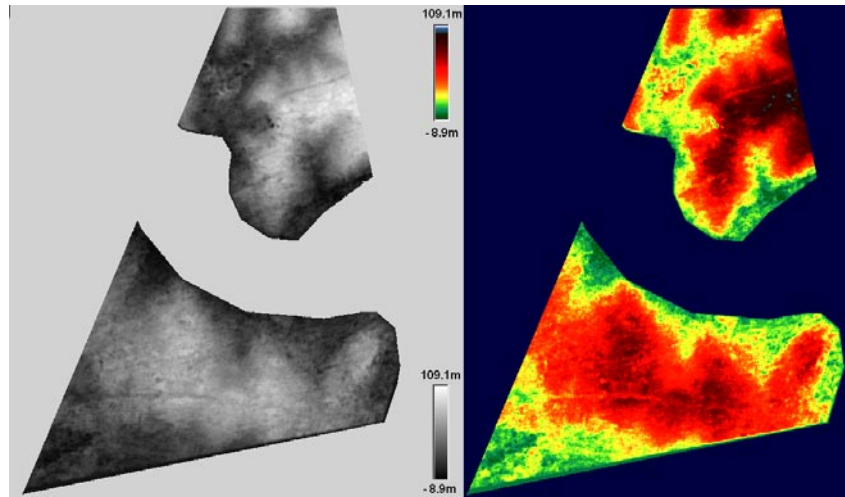


Figure 4. TSX SL DSM, grey value and color coded presentation.

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 high resolution panchromatic IKONOS images.

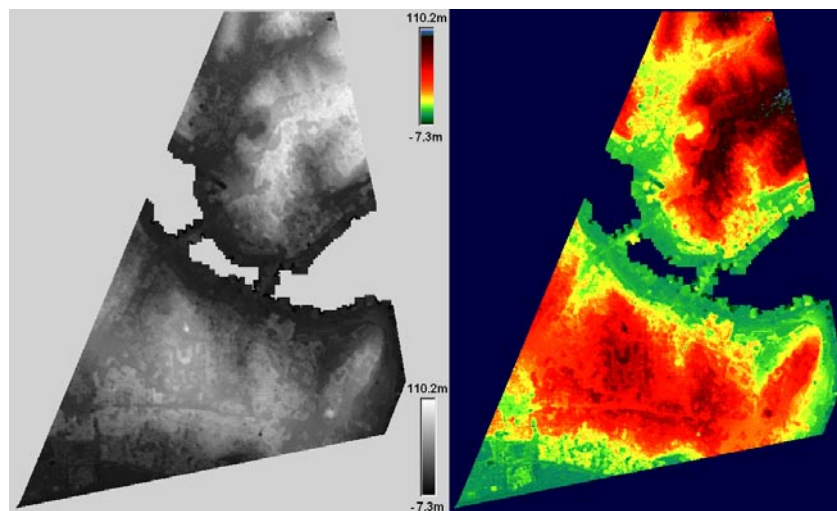


Figure 6. IKONOS DSM, grey value and color coded.

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 7 illustrates this reference DEM along with colored version to support the visualization of the elevation levels.

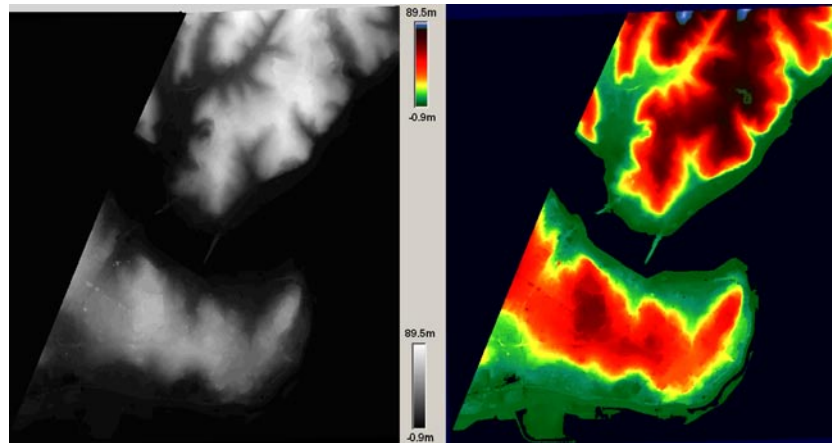


Figure 7. Grey value and color coded reference DEM.

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 were not performed for open and forest areas separately. It has 10cm up to 1m accuracy and the elevations are between sea level and 90m.

2 Methodology of DEM Evaluation

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.

Table 3. 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 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	Enterpolation using window function, Analysis of a DEM
ZPROF	Plot profiles
UNDUL	Calculation of Geoid Undulation
HPSHOW	Visualization of aspects

3 Results and Discussion

3.1 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 8 shows a selected point with the corresponding locations for the pre-correction.

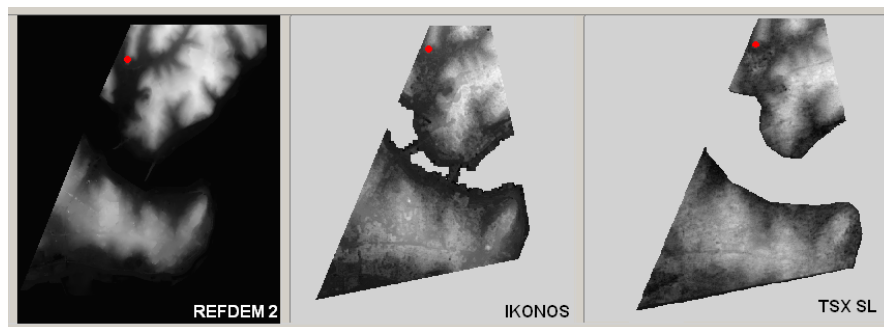
**Figure 8.** Corresponding point in DEM for pre-correction of shifts in red

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.

Table 4. Influence of DEM-shifts to RMSZ against reference, manual shifts in the range of 200m

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	+21.44	8.25

3.2 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.

Table 5. Accuracy of DSMs for test field

DSM	General	
	SZ [m]	Not accepted points[%]
IKONOS (3m)	$7.04+1.03 \times \tan(\alpha)$	0.00
TSX SL (3m)	$7.09+11.22 \times \tan(\alpha)$	0.00

The frequency distribution of height differences against the reference is shown in figure 9. 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 10 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.

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 11 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.

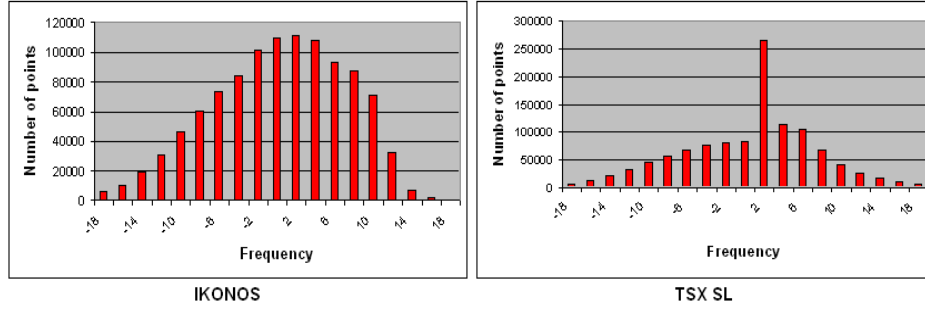


Figure 9. Frequency distribution of height differences between IKONOS and TSX SL DSMs and REFDEM.

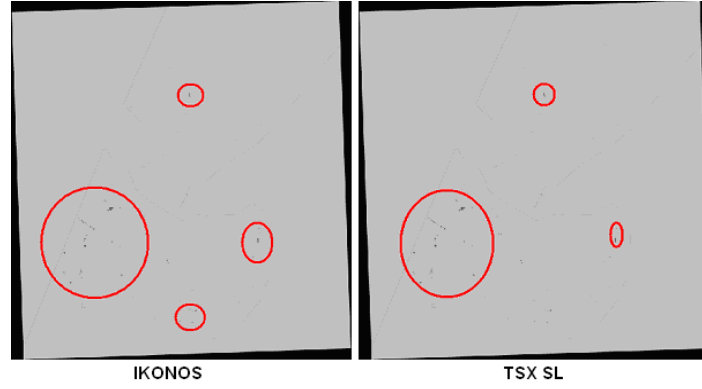


Figure 10. Excluded points of IKONOS and TSX SL DSMs.

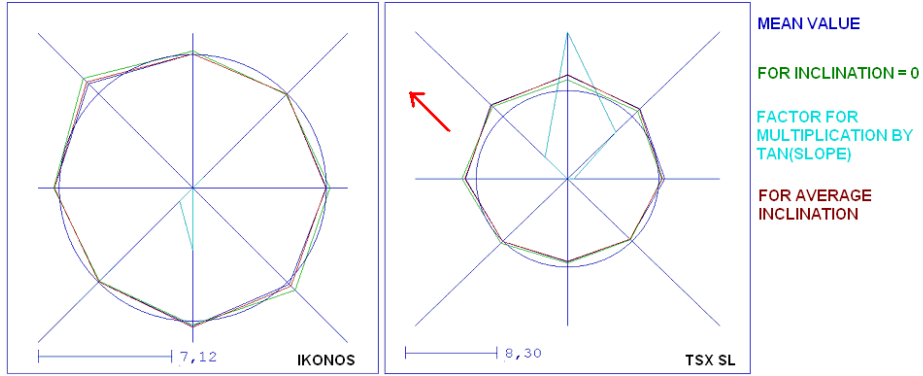


Figure 11. Height accuracy depending upon aspects (IKONOS and TSX SL DSMs).

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.

$$RSX = \sqrt{\sum (dxi - dxj)^2 / (2 \times nx)} \quad (1)$$

Formula 1. Relative standard deviation RSZ, d = distance between points, $d_l < d < d_u$ = distance groups, d_l = lower distance limit d_u = 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.

Table 6. Relative accuracies of IKONOS and TSX SL DSMs

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

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.

3.3 Morphology

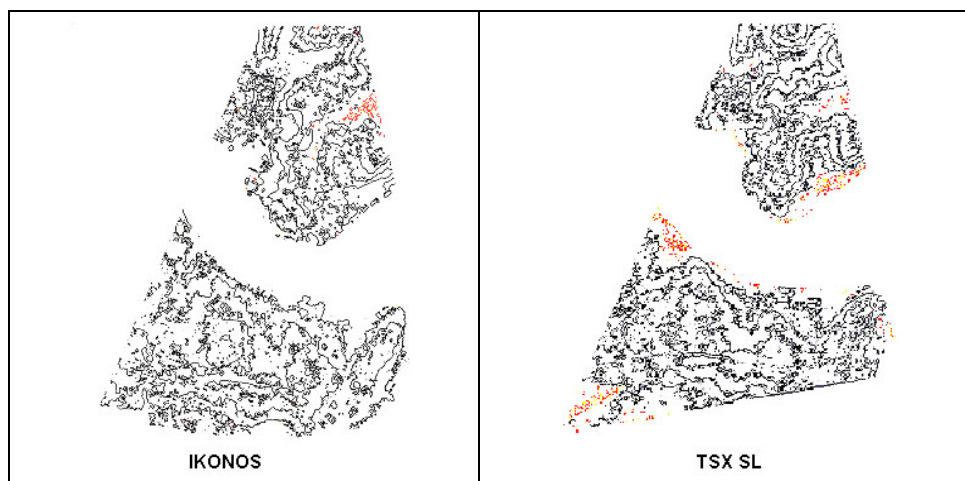


Figure 12. Contour lines of IKONOS and TSX SL DSMs with 20m contour interval.

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 12 shows the contour lines, generated from IKONOS and TSX SL DSMs.

As a summary of Figure 12, 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 not included in the case of larger point spacing.

3.4 Differential DEMs

A differential height model of the IKONOS DSM minus the TSX SL DSM has been created for visualization (figure 13). For the visualization an exaggeration factor of 5 was used to make the height differences clearer.

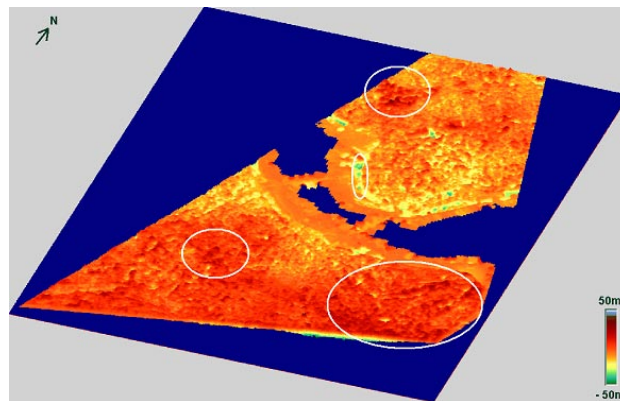


Figure 13. Differential height model of IKONOS DSM minus TSX SL DSM

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.

3.5 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 14 and 15 illustrate the results of shadings.

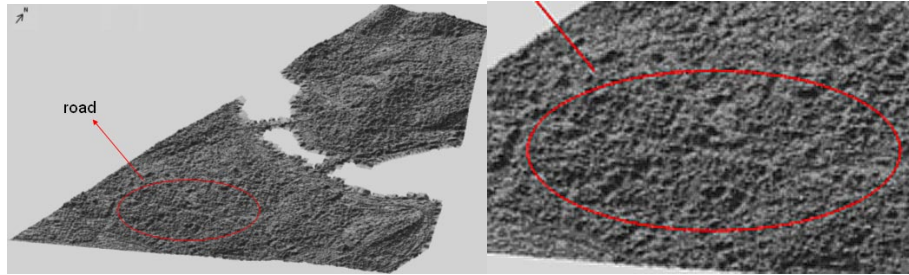


Figure 14. Shaded DSM (IKONOS, 3m), overview and detail

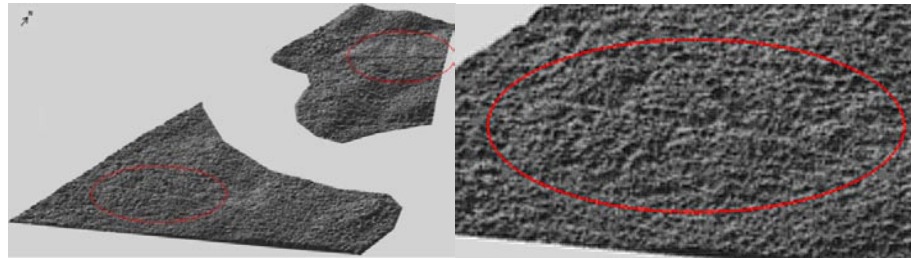


Figure 15. Shaded DSM (TSX SL, 3m), overview and detail

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.

4 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.

5 Acknowledgements

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