Geometric Accuracy Evaluation of the DEM Generated by the Russian TK-350 Stereo Scenes Using the SRTM X- and C-band Interferometric DEMs

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Abstract

TK-350 stereo-scenes covering 200 km × 300 km on the ground with a base-to-height-ratio of 0.52 have been analysed on Zonguldak testfield in the northwest of Turkey. The pixel size on the ground is 10 m. Control points digitised from 1:25 000 scale topographic maps have been used in the test. The sensor orientation was executed by the PCI Geomatica® V8.2 software package. TK-350 stereo-images can yield 3D geopositioning to an accuracy of about 10 m horizontally and 17 m vertically. Based on this orientation, DEM with 40 m cell size was generated by the related module of PCI system. For the validation of extracted DEM, matched data was checked against the interferometric DEMs from SRTM X- and C-band SAR data. Based on this comparison, the RMSE of Z values was found to be in the range of 25.6 to 36.9 m and 28.7 to 38.7 m outside and inside the forest area, respectively. However, accuracy results obtained against the SRTM C-band DEM are more representative than those of X-band since the coverage of C-band DEM on the interest area is larger than the X-band. There are some systematic shifts of the TK-350 DEM against the SRTM DEMs which lie between the 3.7 m to 6.2 m which is probably due to the different sensor orientation of TK-350 and SRTM datasets. Height discrepancies are also analysed as a function of terrain slope. It was found that slope depending components were always larger in the case of C-band DEM because of its larger cell spacing. In the forest areas, more dependency upon the slope was observed against the open areas.

Introduction

Digital elevation models are basic requirements for engineering projects. They must be available with required accuracy and the resolution without gaps for the areas of interest. An alternative to the generation of such data using stereo-images from linear array pushbroom space sensors from western countries is the photographic data taken by Russian TK-350 camera. A massive global archive covering a wide geographical range is available from this system, and it offers users the ability to generate DEMs where no such data are available. Additionally, because of the historical archive (since 1981), it is also possible to consider the use of TK-350 imagery for change detection applications. Nevertheless, for a long time, images from this camera were used only by Russian organizations for mapping purposes and became available for a wide circle of users in 1991 as the result of an unexpected decision by Russian government (Petrie, 1999; Li, 2000).

The rights for the commercial distribution of TK-350 images are held by a company named "Sovinformsputnik" which is the first Russian company of its type (see **www.sovinfomsputnik.com**) and scientific investigations illustrating the potential of this imagery for mapping came from this company's engineers. In general, photographs from TK-350 system are used to produce 1:50 000 and smaller scale topographic maps in addition to the DEM generation for creating orthophotos from high resolution KVR-1000 images. Based on Sovinformsputnik's publications, "when no external ground control is used, the planimetric accuracy of these maps is typically 20 to 25 m, and the vertical accuracy is 10 m. If GPS derived control points are available, the accuracy of the maps increases to 15 to 20 m horizontally and 5 to 7 m vertically" (Chekaline and Fomtchenko, 2000; Lavrov, 1996; 2000). These results were achieved by the use of their locally-developed software packages. However, up to till now, there are no reported studies from the scientists outside the Russia on the potential of TK-350 stereo-imagery for mapping. Independent checking seems to be crucial in this case.

In this paper, the authors first report on the calibration of TK-350 images because of their extremely large format, which can cause image deformations, using reseau crosses available on them. Then, the geometric correction of these images was carried out by the PCI Geomatica® V8.2 software package. This is followed by a discussion of DEM generation process using stereo-TK-350 data. The study will be completed by the validation of extracted DEM with the interferometric DEMs derived from the SRTM X- and C-band SAR data which was collected for an 11 day period in 2000.

Russian Space System "KOMETA"

Figure 1 shows the Russian Space Mapping System "KOMETA" equipped with TK-350 and KVR-1000

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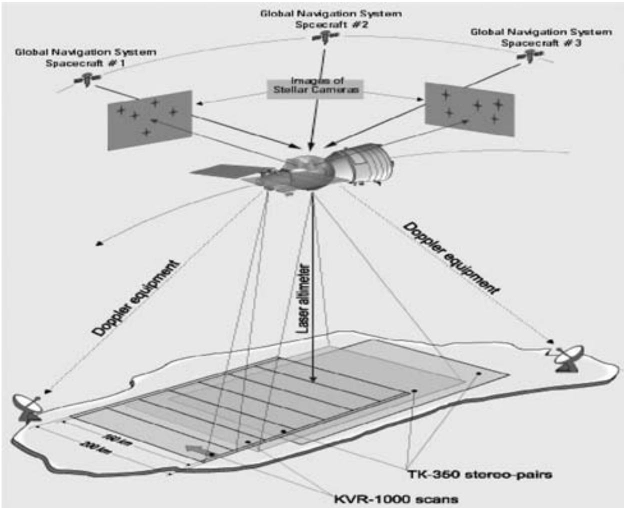

Figure 1. Russian Space System "KOMETA" equipped with TK-350 and KVR-1000 satellites.

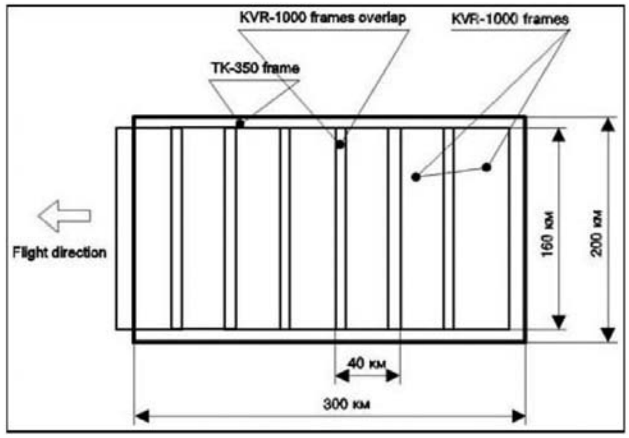

Figure 2. Imaging Configuration of TK-350 and KVR-1000 cameras.

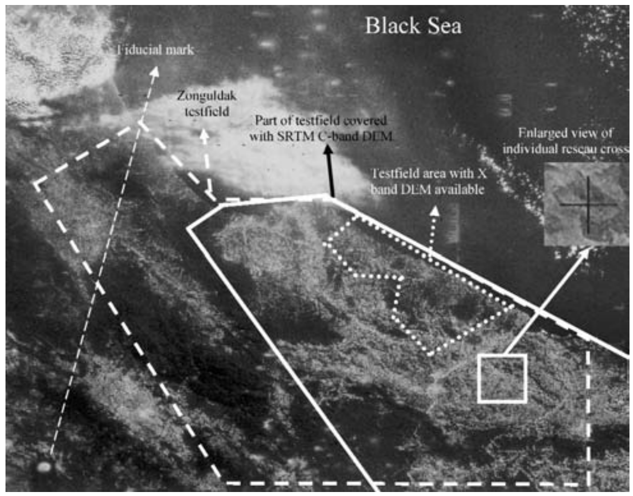

Figure 3. The portion of the TK-350 image showing the testfield with important details.

photographic film cameras and additional on-board devices including two star-trackers, a laser altimeter, and the positioning system for the determination of external parameters. A Comet Class Spacecraft with the sensor is launched periodically from the Baikonur Cosmodrome in Kazakhstan, and it orbits the Earth for about 45 days collecting up to 10 million square kilometers of imagery. The entire satellite returns to Earth for film processing.

The TK-350 camera allows for the acquisition of stereo-images during the same satellite pass with short time intervals; this procedure is in contrast to the time separations measured in days, which is normal for most medium resolution satellites, e.g., SPOT. This situation greatly enhances the possibility of extracting better quality DEMs because the overlapping images are acquired under identical atmospheric and ground conditions. There are no differences in haze, sunlight, vegetation growth, or soil moisture influencing the radiometric behavior of conjugate images. The accuracy of the DEM significantly depends on the base-to-height ratio (B/H) at the moment the overlapping images are acquired. TK-350 reaches the optimal B/H from the large film format of 300 mm × 450 mm with a 350 mm focal length. Such a film format encompasses a single image covering 200 km × 300 km of the ground. An additional photographic system in the KOMETA is the KVR-1000 camera which provides 2 m resolution panoramic imagery with an image scale of 1:220 000. Each film frame from the KVR-1000 camera can capture an image which covers 160 km by 40 km on the ground. Thus, the area recorded in a single TK-350 frame is also covered by seven KVR-1000 images. The respective coverage of the TK-350 and KVR-1000 images are shown in Figure 2. As can be seen from this figure, the KVR-1000 images are nested within the TK-350 images and provide higher resolution. Both cameras take BW images within the panchromatic band of 0.58 μm to 0.72 μm.

Experimental Area

In this test, a TK-350 stereo-pair taken on 09 October 1986 with a 60 percent forward overlap and B/H of 0.52 was used, acquired at a flying height of 214 km which results in an image scale of 1:610 000. Figure 3 shows a part of a TK-350 image over the Zonguldak testfield including the City of Zonguldak and its surroundings. This testfield covers a 120 km × 90 km area on the ground which represents a small part of the large format TK-350 image. The Zonguldak testfield cannot be extracted from the whole image because of the risk of losing the fiducial marks necessary for the inner orientation. In addition to the four fiducial marks, 1,073 reseau crosses are available on each TK-350 image with a spacing of 10 mm; an enlarged view of one of such reseau cross is displayed in Figure 3. For the bundle orientation, 135 uniformly distributed GCPs were digitized from the 1:25 000 scale topographic maps within the interest area. Horizontal accuracy of these GCPs is estimated with a standard deviation of approximately 7.5 m. On the TK-350 images, linear features appeared sharp enough, so GCPs are mainly selected from road crossings and bridges. Digital image coordinates for GCPs were measured manually using the GCPWORKS® module of the PCI software with a zoom factor of 4. This guarantees the sub-pixel measuring accuracy on the image. Figure 3 also shows the area where the SRTM X- and C-band DEMs are available for validating the DEM extracted from the TK-350 stereo-pair.

SRTM X- and C-band Data

SRTM is a cooperative project of the National Aeronautics and Space Administration (NASA) and the National Geospational Intelligence Agency (NGA) in the USA and the Deutches Zentrum für Luft and Raumfahrt (DLR) in Germany. The Italian space agency is cooperating with DLR by contributing flight hardware previously flown in 1994 and by participating in data processing. Two single-pass interferometers were built and operated in parallel in the mission, the USA C-band system and a German/Italian X-band system X-SAR. The master channels (transmit and receive) of both interferometers used the original components in the shuttle cargo bay. The secondary (receive-only) antennas were mounted at the tip of a 60 m long lightweight mast. During lift-off and landing, the mast was stowed away in a 3 m long canister. Once in orbit, the mast was unfolded by a smart mechanical construction; the geometry of data acquisition is shown in Figure 4.

The C-band radar with a wavelength of 5.6 cm has an electronically steerable antenna and is therefore able to operate in ScanSAR mode with a 225 km swath. Most of the mappable area was imaged two or more times from ascending and descending vantage points. However, the X-band radar system operated at a 3 cm wavelength with its passive primary antenna historically limited to a 45 km wide swath resulting in coverage holes of approximately 150 km × 150 km at the equatorial regions. X- and C-band swath widths are illustrated in Figure 5. Due to the avoidance of ScanSAR and the shorter wavelength, the quality of the X-band interferograms and DEMs is expected to be better than of those from C-band by a factor of 2 (Rabus *et al.*, 2002). However, from a topographic structure viewpoint, the X- and C-band data should contain very similar information. The X- and C-band data are therefore of quite similar quality and can be productively compared in the regions of overlap (Rosen *et al.*, 2001).

Until the availability of the DEMs from the SRTM mission, there was a lack of suitable global height information. The best elevation models showing a global coverage are provided in a 1 km raster size with varying quality. They are available as the GLOBE, GTOPO30, and DTED-0 products. As would be expected, regionally better DEMs exist. However, they were acquired with a variety of sensors and many different techniques were employed during the elevation generation process. The SRTM filled this gap, and importantly, it provides global DEM with the same sensor in one mission using one processing technique i.e., the interferometric SAR (INSAR) for the areas within the geographic latitudes of 60°N and 58°S. SRTM DEMs are provided in geographic coordinates, and WGS84 is used as horizontal and vertical datum which means that ellipsoidal heights are provided. The DEM accuracy requirements are ±16 m absolute vertical (AV) and ±6 m relative vertical (RV) accuracy. The relative accuracy describes the error in a local 200 km scale, while the absolute value stands for the error budget throughout the entire mission (Rabus *et al.*, 2002).

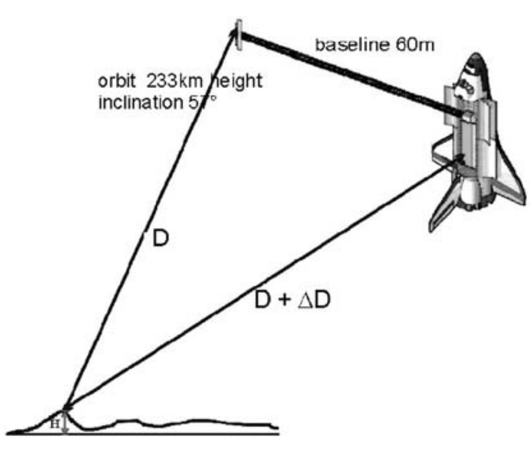

Figure 4. Principles of Interferometric SAR.

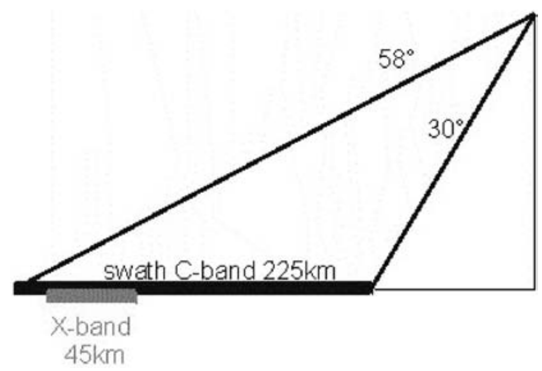

Figure 5. Swath widths of C-band and X-band SAR.

A complete description of the X-band component of the SRTM mission was provided by the German Remote Sensing Data Center (DFD) of DLR. The coverage of the acquired X-band data at one arc-second (approximately 30 m) spatial resolution can be accessed at DFD's web gate Eoweb (**http://www.eoweb.dlr.de**). For the C-band, three arc-seconds (approximately 90 m) data can be downloaded from the web at **ftp://edcsgsg.cr.usgs.gov/pub/data/srtm/Eurasia**, while one arc-second data is only freely available over the USA. The quality assessment and validation of DEM from SRTM X-SAR was carried out by Koch *et al.* (2002) based on the reference data (trigonometric points and reference DTM) of a test site situated in south of Hanover, Germany. The maximum height difference in this area is about 450 m. The standard deviation of SRTM DTED-2 was found to be ±3.3 m in open landscape using spatial similarity transformation. Rosen *et al.* (2001) reported the RMS height error of DEM from SRTM C-band data on the order of 3 m using six fully mosaiced cells for the NGA test sites.

Calibration of TK-350 Frames

Since TK-350 images are hardcopy photographic materials, they have first to be converted into digital form by a scanning procedure. However, because of their extremely large format size of 45 cm × 30 cm, these frames cannot be scanned using a standard photogrammetric scanner. Therefore, they were scanned with a pixel resolution of 1,500 dpi (16.93 μm) by the EskoScan 3648 scanner from Danish Company Purup-Eskofot, which can scan a material up to an A0 format. Such a scanning pixel size fits with the resolving power of TK-350 given as 35 line pairs/mm in the center

Table 1. Accuracy Results Derived from the Calibration of TK-350 Image Pairs

Type of Analysis	Root Mean Square Errors (RMSE) x-RMSE (μm)	y-RMSE (μm)	Systematic part of RMSE Systematic x-RMSE (μm)	Systematic y-RMSE (μm)	RMSE Without Systematic Part x'-RMSE (μm)	y'-RMSE (μm)
Planicomp P1 measurements against the nominal values of reseau crosses on TK-350 image 324 (largest discrepancy)	8.0 (29.8)	8.3 (37.3)	5.2 (16.0)	5.0 (16.1)	6.1 (22.4)	6.6 (32.1)
Digital image coordinates against the Planicomp P1 measurements for TK-350 image 324 (largest discrepancy)	10.7 (36.2)	9.7 (38.9)	7.3 (21.8)	6.4 (22.3)	7.8 (28.1)	7.2 (30.8)
Planicomp P1 measurements against the nominal values of reseau crosses on TK-350 image 326 (largest discrepancy)	7.5 (22.0)	7.8 (26.5)	3.7 (11.4)	4.6 (14.8)	6.5 (19.6)	6.3 (19.7)
Digital image coordinates against the Planicomp P1 measurements for TK-350 image 326 (largest discrepancy)	6.2 (18.7)	7.7 (24.1)	2.4 (10.0)	4.1 (11.1)	5.7 (19.3)	6.5 (20.5)

and 30 line pairs/mm towards the edge of the image (Lavrov, 1996). This resolution, combined with the image scale, corresponds to a ground resolution of approximately 10 m. In this case, a single digital TK-350 image has a size of 27,508 × 18,497 pixels occupying approximately 0.5 GB of image storage.

Due to the extreme large format of TK-350 photographs, image deformations can be expected, and so image accuracy had to be validated by means of the reseau crosses at known locations. For this purpose, two different coordinate sets were generated. The "First Set" includes the image coordinates of crosses measured in pixels. The "Second Set" consists of coordinates measured using the Zeiss Planicomp P1 analytical plotter. An analysis of the reseau crosses was made initially by comparing the P1 measurements with the nominal grid coordinates. Then, the digital pixel values of the crosses were compared with the P1 measurements to separate different error sources, and the acquired results from these analyses are represented in Table 1. In this table, RMSE values were computed from the residuals calculated after an affine transformation between the measured and nominal reseau coordinates of the crosses. However, to determine the unknown systematic effects available in the measurements, they were further corrected by 15 additional parameters. The systematic aspect of the RMSE shows the influence of these parameters. Then, the last column in the table showing the RMSE without systematic part was simply obtained by taking out the systematic influence from the RMSE values.

The Planicomp P1 was calibrated on two occasions and proved precise with a measuring accuracy of 1 μm. Systematic discrepancies between the Planicomp P1 measurements and the nominal reseau positions reflected the general image deformations. The random element refers to the local image deformations, which are also limited, in this case. The comparison of the positions of the reseau crosses in the digital images against the photographic locations measured by the Planicomp P1 shows the accuracy of the point determination on the digital imagery and the accuracy of the image scanner used in this test. Systematic differences of 7.3 μm and 6.4 μm for image 324, and 2.4 μm and 4.1 μm for image 326 confirms the accuracy of the EskoScan 3648 scanner. The random errors which are in the range of 0.3 to 0.4 pixels verify that no general geometric problems exist and equal to the accuracy of manual measurements on digital image.

Bundle Orientation by PCI Geomatica® v8.2 Software Package

Since the TK-350 images were obtained under perspective geometry, simple mathematical models based on well-known collinearity equations can be implemented for geometric accuracy testing. For this purpose, Airphoto Edition (AE) module of PCI Geomatica® v8.2 system was used. This module treats TK-350 imagery like an aerial image and employs the parametric modeling method based on the collinearity equations (Toutin, 1995). This method reflects the physical reality of the complete viewing geometry and compensates for distortions that may occur during image formation (further details may be found at **http://www.pcigeomatics.com**).

Table 2. The Accuracy Values Resulted from Different GCPs/ICPs Configurations from TK-350 Stereo Scenes Using the PCI System

# GCPs/ICPs	GCPs X-RMSE (m)	Y-RMSE (m)	Z-RMSE (m)	ICPs X-RMSE (m)	Y-RMSE (m)	Z-RMSE (m)
119/0	10.0	11.1	17.3	—	—	—
12/107	7.1	12.4	15.0	11.7	12.5	18.4
6/113	7.1	12.1	12.5	11.8	15.7	22.9

Table 2 provides the accuracy results obtained by PCI system. In this test, 14 of the 135 GCPs were found to be erroneous and removed automatically. Using all remaining 119 points, RMSE values were found to be about 10 m in X, 11 m in Y, and 17 m in Z. When only 12 points were used as GCPs at the remaining independent check points (ICPs) accuracy values of 11.7 m, 12.5 m, and 18.4 m are acquired in X, Y, and Z components, respectively. Figure 6 shows the resulted error vectors at ICPs. As can be seen from this figure, the overall representation of error vectors displays a random pattern but with groups of points showing locally systematic trends. When the number of GCPs was decreased to six and the RMSE values at ICPs compared to those acquired with 12 GCPs: while the accuracy value in X stayed almost same with 11.8 m, it increased to 15.7 m in Y, and 22.9 m in Z.

DEM Generation

The image quality of the TK350 photography is limited. As can be seen from Figure 7, many scratches can be seen, and the contrast is low. In addition, the film grain can be detected because the scanning pixel size corresponds to a photographic resolution of 31 line pairs per millimeter. Automatic image matching was first tried with the original image data using the related module of PCI software

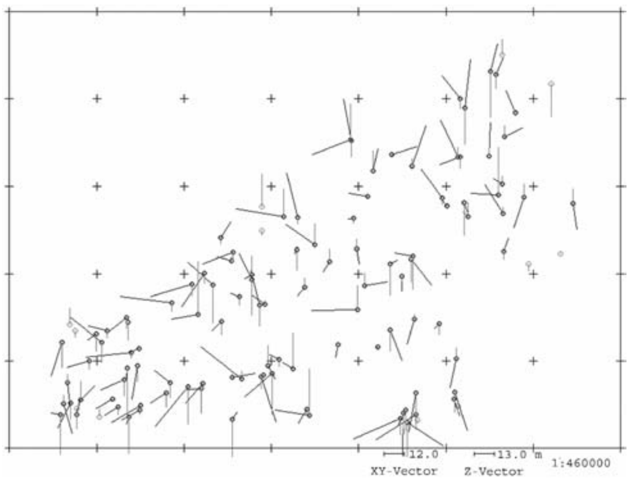

Figure 6. Vector plot of residual errors obtained from the PCI processing.

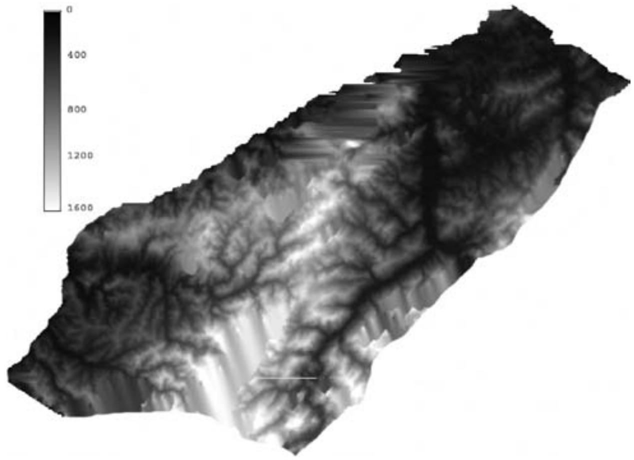

Figure 8. Greyscale-coded representation of TK-350 DEM.

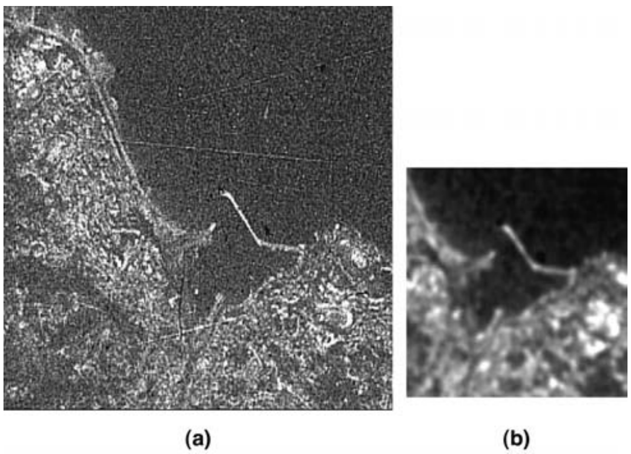

Figure 7. (a) part of the TK-350 digital image showing the influence of scratches and film grain, (b) results following the filtering process.

employing an area-based image correlation technique (see Al-Rousan, 1998 for details). This attempt totally failed and produced too many areas where false matching was evident. A low-pass filter was applied to the raw TK-350 images using Photoshop® in an attempt to remove the effects of the scratches. This process was more successful and a DEM was generated with 40 m cell size. A greyscale-coded form of the matched DEM is provided in Figure 8.

DEM Analysis

During DEM extraction, the PCI system provides a DEM report file which includes: elapsed time required for extraction, maximum and minimum elevations, cell spacing, height residuals at GCPs with average, maximum residuals, RMSE values for height, and DEM correlation success rate. According to this report file, the RMSE in height was found to be 17.0 m derived using the standard formula $\sqrt{(\Sigma(\text{GCP elevation} - \text{extracted elevation})^2/n)}$. The maximum error was 53,7 m. In relation to the matching quality, PCI only gives "DEM correlation success rate" in the DEM report file and it was 55 percent for this experiment. This value is simply the percentage of pixels that successfully correlated and returned an elevation value for DEM.

Apart from the accuracy result obtained based on the GCPs used at the phase of sensor orientation, an additional test has been carried out using three GPS profiles measured along the main roads of the Zonguldak testfield. In total, 55 points have been collected by differential GPS, and their height values were compared with those of TK-350 DEM. As a result, the RMSE-Z value was found to be 14.78 m. This result confirms the RMSE-Z values given in Table 2.

For detailed analysis, the matched DEM was checked against the interferometric DEMs produced by the SRTM X- and C-band SAR data. It should be mentioned that in the computation phase, all the pixels of SRTM DEMs which cover the same area with the generated TK-350 DEM have been considered. Figure 9 shows the greyscale representations of the X- and C-band DEMs over the interest area of Zonguldak testfield. A close inspection of these figures shows somewhat similarity between the interferometric DEMs and the matched DEM, but the TK-350 DEM includes several mismatches (as white areas) and gaps which were filled with the grey values obtained by the interpolation of neighboring pixels. As discussed later, these represent the areas covered mainly by forests and their influence on the accuracy analysis can be excluded in a computational way. The accuracy of X- and C-SAR DEMs were previously assessed based on the GPS-surveyed GCPs. In this case, the RMSE-Z values for X- and C-band DEMs were found to be in the range of 9 m.

In order to separate the forest areas from the DEM, image classification (see Figure 10) methods were employed using a Landsat TM scene of the experimental area. Points within the forest layer were included in the analysis program DEMANAL which has been developed for comparing the TK-350 based DEM with the SRTM DEMs. By means of this program, DEM analysis was achieved for forest-covered areas and also for the areas without forest. Furthermore, analysis of the DEM could be achieved for different heights relative to the terrain surface, and so the frequency distributions derived from the resultant

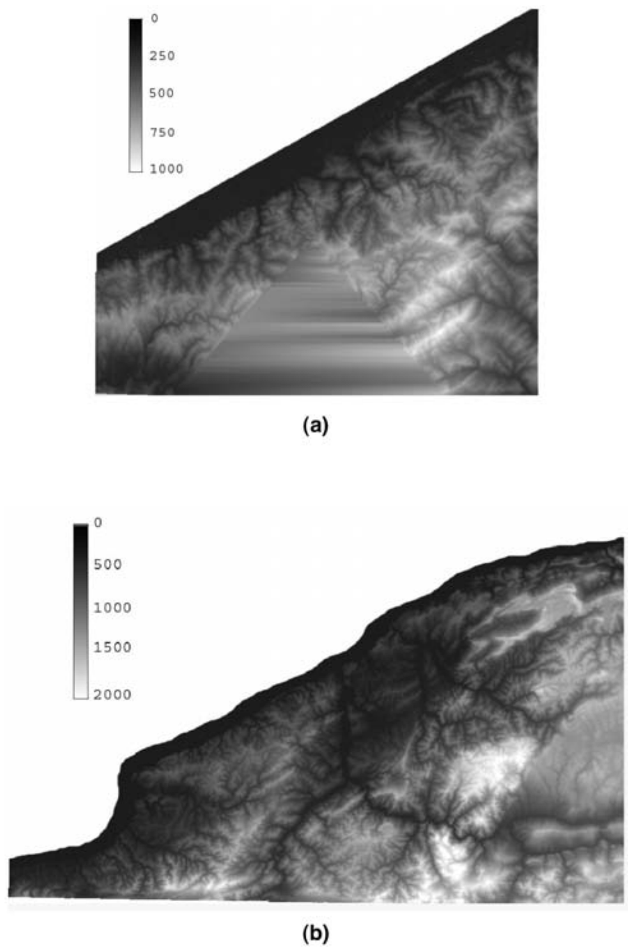

Figure 9. SRTM X- and C-band SAR DEMs available for the Zonguldak testfield.

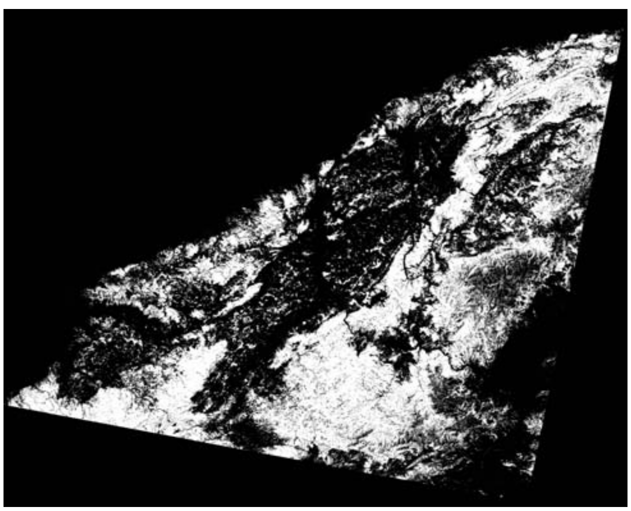

Figure 10. Forest layer (white areas) of the experimental site showing the same coverage with the SRTM C-band DEM.

discrepancies were used to identify specific problems caused by vegetation height. This is important since the generated DEM relates to the visible surface of the vegetation and building roofs.

Based on the comparison of TK-350 DEM and the SRTM DEMs, the RMSE values for open and forest areas are computed using different limits for height discrepancies (DZ) and are given in Table 3. Once bias is removed, accuracy values are in the range of 25.6 to 36.9 m and 28.7 to 38.7 m for the open and forested areas, respectively. The results achieved in the forest area are not up to expectations, and are due to the low contrast of the panchromatic image within the forested areas. The range of the grey values available is not conducive to image matching, as perhaps demonstrated by the difficulty that a human operator has in finding tie points in such areas. For the open areas, accuracy is also rather large compared to the RMSE values in height obtained in the phase of bundle orientation. Such a difference is undoubtedly due to the nature of normal matched features, which are not as well-defined features as GCPs. These points are always selected at locations with good contrast and matching in such areas will always be more accurate.

There are some systematic shifts of the matched DEM against the SRTM DEMs which peaked at 6.2 m. These shift values may originate from different sensor orientation of TK-350 and SRTM datasets. However, accuracy results acquired from the comparison against the SRTM-X and C-band DEMs are not changing each other prominently, especially when the smaller DZ-limit and the forest type were selected for the computation. According to theory, the shorter wavelength of the X-band should be more accurate, but this is compensated by the multiple coverage of the C-band often solving the problems of layover and shadow. When compared with the coverage of C-band DEM and the matched DEM, X-band DEM covers only a sub-region; in this case only that part of the TK-350 DEM could be checked against the SRTM X-band DEM. This situation makes the C-band results more representative than those of X-band. Another point which should be mentioned that the interferometric phase center is not located at the same height for C- and X-band over forest areas: C-band penetrates the canopy deeper than the X-band does (Treuhaft and Siqueira, 2000). This is not clearly observed from the values given in Table 3, maybe due to the small coverage of X-band DEM against the C-band DEM.

The height discrepancies are also dependent upon the terrain inclination as can be seen in Table 3. For both open and forested areas, constant values and slope depending components of derived equations were found to be larger in the C-band than the X-band as happened also with the RMSE-Z values. This result is perhaps due to the larger spatial resolution of interferometric DEM from C-band. Inside the forest area, there is a higher dependency on the slope.

Conclusions

For scene orientation and restitution of TK-350 stereo-images, control points were taken from a topographic map at a scale of 1:25 000. The horizontal accuracy achieved was within the range of 1 pixel or 10 m, which is appropriate and adequate for small-scale mapping. Required map accuracy is generally 0.05 to 0.1 mm (Jacobsen *et al.*, 1998). With accuracies of 10 m achieved on the object, this implies that maps of a scale of 1:100 000 can be created from this imagery. If the desired mapping accuracy is relaxed to 0.2 mm, a horizontal object accuracy of just 20 m is required, which is certainly achieved from the TK-350 imagery. With a

Table 3. Discrepancies Between the Matched DEM and the SRTM DEMs

DEM	Area Type	DZ-limit = 100 m RMSE-Z [m]	Shift [m]	RMSE-Z Without Shift [m]	Standard Deviation of Height Depending upon the Slope	DZ-limit = 150 m RMSE-Z [m]	Shift [m]	RMSE-Z Without Shift [m]	Standard Deviation of Height Depending upon the Slope
SRTM-X	All	28.19	−4.47	27.83	$22.44 + 24.55 \times \tan\alpha$	34.83	−5.37	34.42	$27.16 + 33.90 \times \tan\alpha$
	Open	25.98	−4.53	25.58	$20.17 + 21.57 \times \tan\alpha$	30.74	−4.79	30.37	$22.97 + 28.87 \times \tan\alpha$
	Forest	29.08	−4.50	28.72	$21.33 + 31.69 \times \tan\alpha$	37.07	−6.19	36.55	$26.24 + 45.12 \times \tan\alpha$
SRTM-C	All	29.49	−3.69	29.26	$18.23 + 59.74 \times \tan\alpha$	38.05	−5.31	37.68	$22.32 + 79.42 \times \tan\alpha$
	Open	28.96	−3.71	28.72	$17.30 + 61.40 \times \tan\alpha$	37.24	−5.24	36.87	$20.86 + 82.36 \times \tan\alpha$
	Forest	29.83	−4.09	29.55	$17.17 + 65.94 \times \tan\alpha$	39.14	−6.11	38.66	$21.17 + 90.23 \times \tan\alpha$

base-to-height-ratio of 0.52, a RMSE value in height of 17 m should theoretically be possible, and such a level of accuracy was achieved by bundle adjustment.

A DEM was generated using the PCI system and area-based image matching methods. In relation to the matching quality, PCI only gives "the DEM correlation success rate," which shows the percentage of successfully matched points and it was found to be 55 percent for this experiment. However, visual inspection of TK-350 DEM shows several mismatches and gaps especially in the forest areas. Such problems are probably due to a combination of film scratches, visible film grain, and lack of image contrast.

In order to analyse the accuracy of matched DEM in detail, it was checked against the SRTM X- and C-band interferometric DEMs. This analysis was carried out separately for forest covered areas and the open areas using the results from the image classification of Landsat TM scene of the testfield. Comparison with SRTM X-band produced RMSE-Z values of 26.6 to 30.4 m and of 28.7 to 36.6 m for the open and forest areas, respectively. With C-band DEM, RMSE values degraded to 28.7 to 36.9 m in the open areas and to 29.6 to 38.7 m in the forest areas. However, it should be noted that the C-band results are more representative than the X-band because the larger coverage of C-band DEM over the TK-350 DEM. There are some systematic shifts of the TK-350 DEM against the SRTM DEMs which lie between the 3.7 to 6.2 m. These are perhaps due to the different sensor orientation of TK-350 and SRTM datasets. Height discrepancies are also analysed as a function of terrain slope. It was found that slope depending components were always larger in the case of C-band DEM because of its larger cell spacing. In the forest areas, more dependency upon the slope was observed against the open areas.

As mentioned previously, large global image archive is available from Russian TK-350 camera since 1980s. With its large image format and perspective geometry, such an archive allows users to use TK-350 imagery for change detection applications and map production where none are available. Nevertheless, as was experienced in this study, TK-350 data is available as hardcopy film material which, therefore, has to be converted first into digital form for further processing. With low image quality, scanning procedure brings problems which will reduce the potential of image matching phase especially in the forest region where not many greyscale values are available. However, validation of large area TK-350 DEM can be done by SRTM interferometric DEMs which exist for most part of the world. This procedure is especially useful for the areas with no better reference DEM available for the user.

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