DIGITAL HEIGHT MODELS IN MOUNTAINOUS REGIONS BASED ON SPACE INFORMATION

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ABSTRACT

For an extension of the water catchments areas for the Greater Istanbul Municipality, investigations in the region of Istiranca, a mountainous forest area North West of Istanbul, have been made. For the project area a Cartosat-1 stereo pair, a height model from SPOT-5 HRS, the SRTM C-band height model and a digital elevation model (DEM) for the topographic map 1:25 000 are available. In addition the SPOT-5 HRS height model has been checked in suburbs of Istanbul against a more precise reference DEM from maps 1:5000 and also the SRTM C-band height model. The automatic image matching of the Cartosat-1 stereo pair in the mountainous area, dominated by forest was astonishing successful, with exception of small areas covered by clouds and cloud shadows, the matching was with 98% successful. A comparison of the different DEMs has been made. Usually SPOT-5 HRS, not like Cartosat-1 including the infrared spectral range, has problems of matching in forest areas, but a complete DEM without gaps was delivered. In large parts the SPOT-5 HRS DEM was nearly identical to the SRTM height model, raising some questions.

INTRODUCTION

Digital elevation models are basic requirement for any geo-information system (GIS) they are required for several applications. For example for the requested planning of water catchments area height information is essential. Not in any case the required accuracy, completeness and actual height information is essential.

	RMSZ [m]	bias [m]	RMSZ F(terrain inclination) [m]
Arizona, open area (flat – smooth mountains)	3.9	1.3	$2.9 + 22.5 * \tan\alpha$
Williamsburg NJ, open area (flat)	4.7	-3.2	$4.7 + 2.4 * \tan\alpha$
Atlantic City NJ, open area (flat)	4.7	-3.6	$4.9 + 7.6 * \tan\alpha$
Bavaria, open area (rolling)	4.6	-1.1	$2.7 + 8.8 * \tan\alpha$
Bavaria, open area (steep mountain)	8.0	-2.4	$4.4 + 33.4 * \tan\alpha$
Zonguldak, open area (rough mountain)	7.0	-4.4	$5.9 + 5.6 * \tan\alpha$
West-Virginia, forest (mountainous)	11.6	-7.7	$7.3 + 7.2 * \tan\alpha$
Atlantic County, open area (flat)	4.4	-3.4	4.4
Pennsylvania, open area (flat – rolling)	5.4	-0.2	$5.3 + 9.4 * \tan\alpha$
Pennsylvania, forest (mountainous)	7.9	-4.3	$7.0 + 6.4 * \tan\alpha$
Philadelphia, city area, filtered (flat)	3.2	-1.3	3.2

Table 1: root mean square Z-discrepancies of SRTM C-band height models [m]
α = terrain inclination

Based on the C-band of Shuttle Radar Topography Mission (SRTM) in February 2000 a nearly world wide height model has been generated, covering the world from 56° southern up to 60.25° northern latitude, free available in the internet. The original resolution has been transformed into a 1arcsec grid, having a spacing of 31m at the equator, but with this resolution the data are only available for the area of the United States, outside it is reduced to 3arcsec spacing (92m spacing at equator). From the DLR on the same mission there was also the X-band SAR which was also used for the computation of DEMs. They can be bought from the DLR with a point spacing of 1 arcsec, but the X-band has not been used in the scan-SAR mode, so it covers only parts of the mentioned area. The C- and also the X-band radar cannot penetrate the vegetation, so these height models are digital surface models (DSMs), showing the height of the visible surface and not the solid ground. The accuracy of the SRTM-height models (Passini et al 2007, table 1) are sufficient for several purposes, but the point spacing causes especially in mountainous regions an additional degradation.

Nearly world wide height models are also available from the HRS-sensor from SPOT-5. The images of this sensor are not sold, only the generated height models. The high resolution stereo sensors (HRS) of SPOT-5 includes two optics viewing forward and after in the orbit direction with incidence angles of 23°, generating a stereo model with a height to base relation of 1.2. With 12000 pixels a swath width of 120km is available. In the orbit direction, the pixel size on the ground is just 5m, so a standard scene with 12 000 x 12 000 pixels is covering an area of 120km x 60km. The smaller pixel size in orbit direction has advantaged for the vertical accuracy. Like the SRTM-height model the height models from automatic image matching are DSMs. In not too much undulated area, where also points of the bare ground are included, the DSM can be filtered to a DEM. In a closed forest area such a filtering is not successful. SPOT HRS-height models have been analyzed in (Jacobsen 2003).

	RMSE [m]	bias [m]	RMSE - bias	RMSE F(slope)
DSM: all points	10.2	-5.5	8.5	8.7 + 10.6 x tan α
DSM: open areas	6.7	-3.0	5.9	6.4 + 4.9 x tan α
DSM: forest	17.0	-14.3	9.2	16.4 + 3.4 x tan α
DEM: all points	5.7	-2.0	5.1	5.0 + 5.4 x tan α
DEM:open areas	**4.4**	-1.3	4.1	**4.2 + 1.6 x tan α**
DEM: forest	12.3	-8.5	8.6	10.0 + 6.9 x tan α

Table 2: SPOT-5 HRS height model - root mean square difference DEM / DSM against reference DEM determined by laser scanner

The SPOT-5 HRS height models are only slightly better than the SRTM-height model, but it has a point spacing of 20m, showing quite more morphologic details. If such a height model is not sufficient, height models may be generated by means of other sources like by automatic matching of Cartosat-1 stereo models.

CARTOSAT-1 HEIGHT MODEL GENERATION

Cartosat-1 has two panchromatic cameras, looking 26° forward and 5° backward and so creating in any case a stereoscopic coverage of the imaged area. The satellite can be rotated around the flight axis to cover also areas not located below the orbit. The ground sampling distance (GSD) for scenes, not rotated around the flight axis, is 2.5m. With 12000 pixels in the joint CCD-line, a swath of 30km is covered.

With a Cartosat-1 stereo pair a height model in the mountainous forest region Istiranca (figure 8) has been generated by automatic matching with the Hannover program DPCOR. For the orientation of the Cartosat-1 images control points from the topographic map 1:25 000 have been used, leading in the average to RMSX=6.78m, RMSY=7.11m and RMSZ=6.08m. This accuracy is dominated by the limited control point quality, but with the 14 well distributed control points a satisfying orientation can be guaranteed. The automatic matching by least squares resulted in a nearly complete coverage of the area by matched points. The matching failed only in small sub-areas, covered by clouds. In the forest, not influenced by clouds, more than 98% of the possible object points have been matched successfully with correlation coefficients above 0.5 and with a maximum of the correlation coefficients in the range of 0.85 (figure 3). For mountainous forest areas this is an unusual good result and it is caused by the spectral range of Cartosat-1 from 0.50 up to 0.85µm, including the near infrared having good contrast in forest regions. The matching was made for every third pixel, leading to a point spacing of approximately 7.5m. This results in more detailed morphologic information like based on the SPOT-5 HRS DSM having 20m spacing and the SRTM C-band DSM with 92m x 80m spacing.

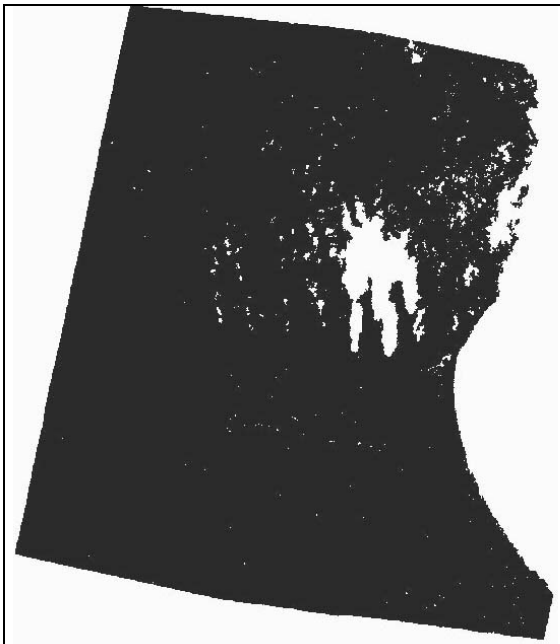


Figure 1: object points determined by matching of Cartosat-1 stereo pair Istiranca (black), not covered area mainly influenced by clouds

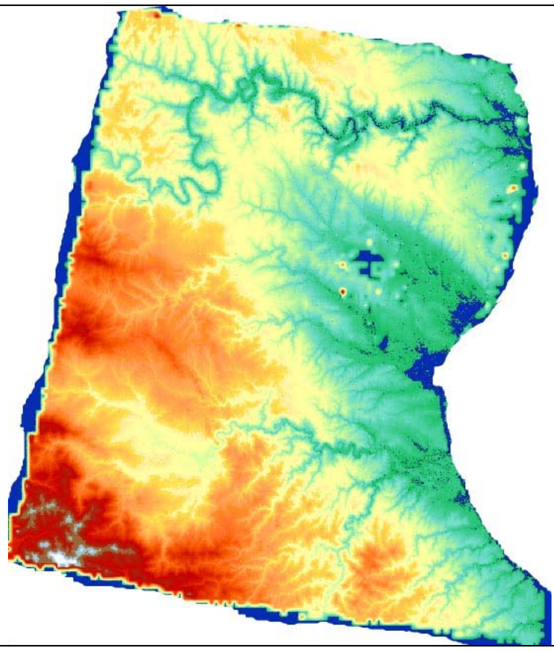


Figure 2: colour coded Cartosat-1height model

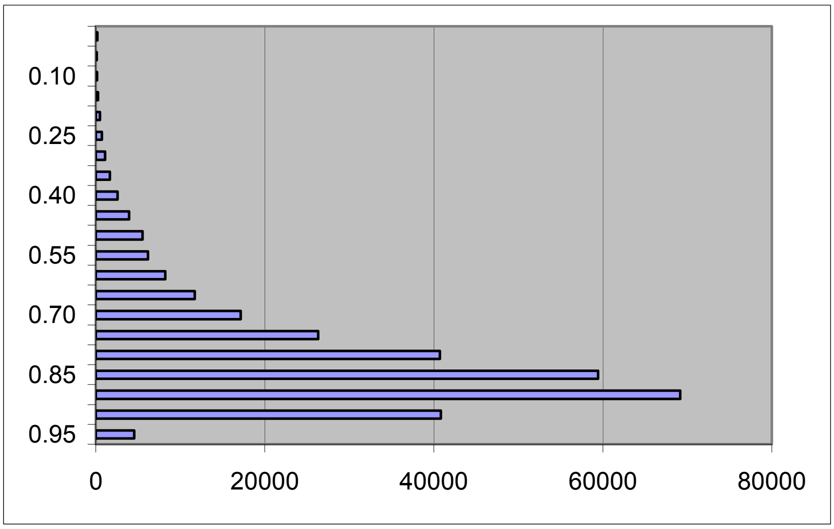


Figure 3: frequency distribution of least squares matching correlation coefficient – sub-area of Cartosat-1 Istiranca
Acceptance limit =0.5

vertical axis: correlation coefficient

horizontal axis: number of matched points

Close to the centre of the images cloud bands disturb the image matching (figure 4 and 5). The clouds have different location in both scenes, enlarging the area where a three-dimensional point determination is not possible. The successfully matched points, having a correlation coefficient exceeding the used threshold of 0.5 are laid over a Cartosat-1 scene in figure 4. In the quality image (figure 5), the matched points are laid over a Cartosat-1 scene with a grey value corresponding to the value of the correlation coefficient – points with r=1.0 (optimal) are shown in white, while points with a correlation coefficient r=0.5 are shown with the grey value 123. This quality image looks like an image because it is showing the valleys, roads and costal area, where the contrast is better, in white, while the forest areas are darker.

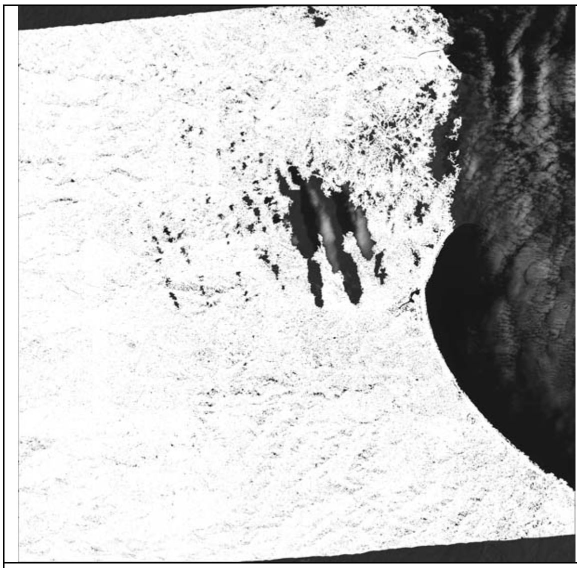


Figure 4: matched points overlaid to image – matched points = white

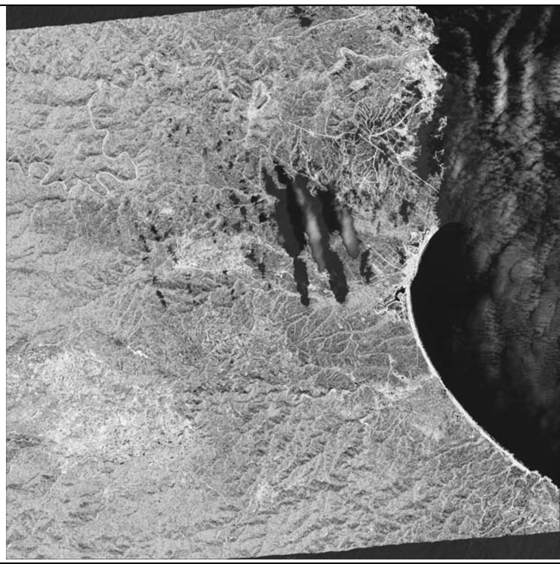


Figure 5: quality image overlaid to image the grey value corresponds to the correlation coefficient r=1.0 = grey value 255 (white) r=0.5 = grey value 123 (grey)

In the frame of the ISPRS-ISRO Cartosat-1 Scientific Assessment Programme (C-SAP) Cartosat stereo pairs have been generated and analysed against very accurate reference data leading to the results listed in tables 3 and 4 (Jacobsen 2006). Of course this cannot be compared directly with the matching in the area Istiranca because of the mountainous forest area, but it indicates the quality in areas with good contrast.

	SZ	bias	SZ as F(inclination)
open areas	4.13	-1.16	3.96 + 3.06∗tan α
forest	3.59	0.58	2.82 + 1.70∗tan α
open areas filtered	3.39	-0.58	3.22 + 1.97∗tan α
forest filtered	3.42	1.43	2.69 + 1.97∗tan α

Table 3: analysis of the Mausanne February DSM [m]

	SZ	bias	SZ as F(inclination)
open areas	3.23	-0.54	3.16 + 1.19∗tan α
forest	4.37	0.64	4.11 + 0.34∗tan α
open areas filtered	2.43	0.44	2.39 + 8.80∗tan α
forest filtered	3.13	0.81	3.11 + 6.50∗tan α

Table 4: analysis of the Warsaw DSM [m]

In the comparable area Zonguldak, Turkey, an automatic image matching has been made with panchromatic SPOT-5 images (Büyüksalih, Jacobsen 2005). They have for the panchromatic band the same spectral range like the SPOT-5 HRS sensor with a wavelength of 0.48 and 0.70µm and not including the infrared range and causing an unfavourable grey value distribution (figure 6b) (Jacobsen 2003). This leads to matching problems in the forest areas, which are dominating dark in this spectral range, like shown in figure 6a, where the darker forest areas could not be matched. It is a little astonishing, that the height model distributed as SPOT-4 HRS DEM for the Istiranca area has no gaps – this is only possible, if the unavoidable gaps of the HRS height model have been filled with other information.

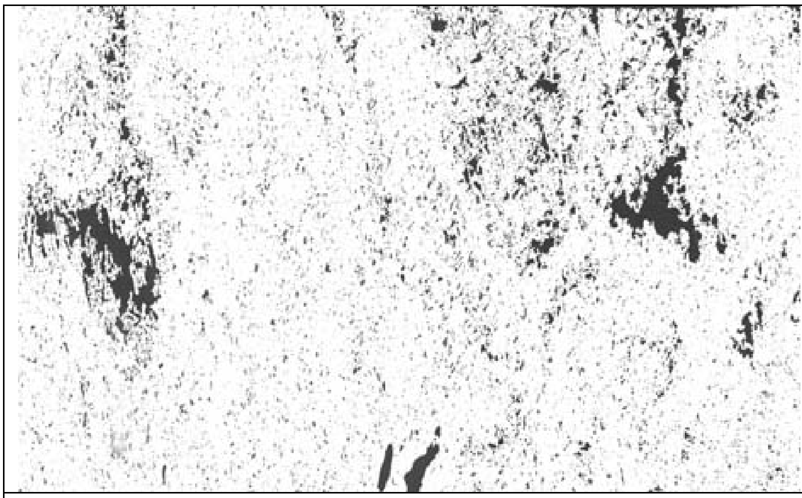


Figure 6a: matching of SPOT-5 HRS-images in test area Bavaria – white = matched points, dark = matching failed, gaps caused by forest

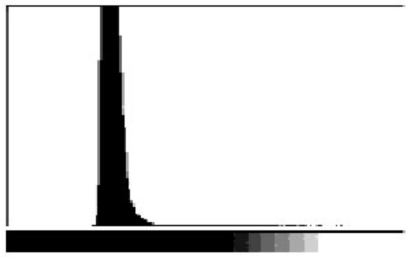


Figure 6b: grey value distribution of SPOT-5 HRS images in forest regions

From the HRS-stereo sensor of SPOT-5 usually only the generated height models are available. They are distributed with a spacing of 20m, based on the GSD of 5m in flight direction and 10m GSD across flight direction. Within an ISPRS test, HRS images have been available and height models could be generated by automatic image matching. Depending upon the area, for flat up to rolling parts standard deviations of the height up to RMSZ=4.3m + 1.0m $*$ tan α for open areas after filtering of objects not belonging to the bare ground and in the forest RMSZ=11.0m + 6.2m $*$ tan α where achieved. The lower accuracy in the forest was caused by poor contrast of the forest (Jacobsen2003).

The SRTM C-band height models are available free of charge in the internet with a point spacing of 3arcsec, corresponding to 92m in north-south direction and in the investigated area in east west direction 82m. The accuracy of SRTM C-band height models depends upon the topography and the location – see table 1.

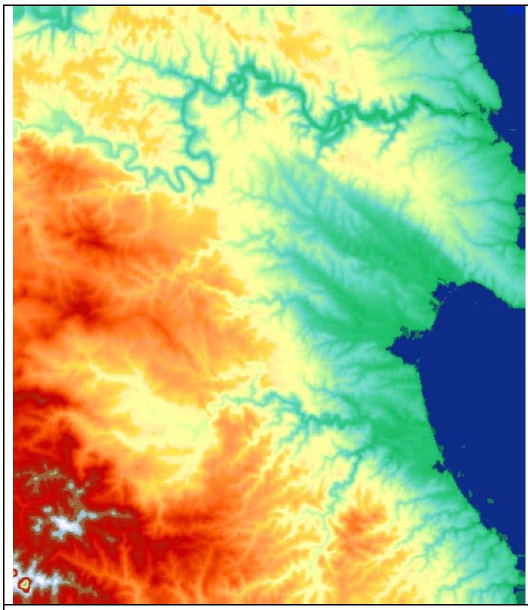


Fig. 7: SRTM C-band height model Istiranca

Fig. 8: Virtual Earth image Istiranca area

Up to now for the Istiranca area no reference height model is available which can be used as close to error free in relation to the above mentioned data, so the height models have been compared to each other. For the comparison a 10km x 10km sub-area has been used to avoid the influence of the clouds in the Cartosat-1 scene.

Compared height models	RMSZ [m]	Bias [m]	RMSZ - bias	RMSZ as function of terrain inclination
Cartosat – SRTM	7.97	0.75	7.95	7.28 + 1.19∗tan α
Cartosat - HRS	6.68	1.91	6.40	6.34 + 0.97∗tan α
Cartosat – DEM 25 000	10.92	-5.80	9.25	9.09 + 7.68∗tan α
Filtered Cartosat –DEM 25 000	9.86	-4.12	8.91	7.86 + 8.20∗tan α
HRS - SRTM	3.13	-1.23	2.88	1.73 + 6.76∗tan α
HRS – DEM 25 000	8.68	-4.14	7.63	6.80 + 7.33∗tan α
SRTM – DEM 25 000	10.23	-5.36	8.71	7.98 + 8.57∗tan α
Filtered Cartosat - SRTM	7.94	-1.15	7.85	6.41 + 4.85∗tan α

Table 4: root mean square differences between height models, Istiranca, sub-area 10km x 10km

Corresponding to the above mentioned results of other investigations, the accuracy of the Cartosat-1 height model against the SRTM-DSM and the SPOT-5 HRS DSM is within the expectation. The discrepancies against the DEM from the topographic map 1:25 000 is dominated by the influence of the vegetation; the large value of the bias shows this. Of course the DSMs can be filtered for objects not belonging to the bare ground, but in a closed forest area the filtering is limited because no points are located on the ground, nevertheless the filtered Cartosat DSM fits better to The discrepancies of the SPOT-5 height model against the SRTM height model are a little strange – they are quite below the accuracies from the references (tables 1 and 2) shown above and cannot be explained by similarities of the height determination. The differences of both height models are even smaller in areas with more dense forest, where under usual conditions the SPOT-5 HRS height models fails (figure 10, lower left). On the other hand in the quite more open area of Istanbul, larger discrepancies are available like in this difficult area (table 6). The only possible explanation is, that the gaps in the SPOT-5 HRS-height model have been filled with SRTM data.

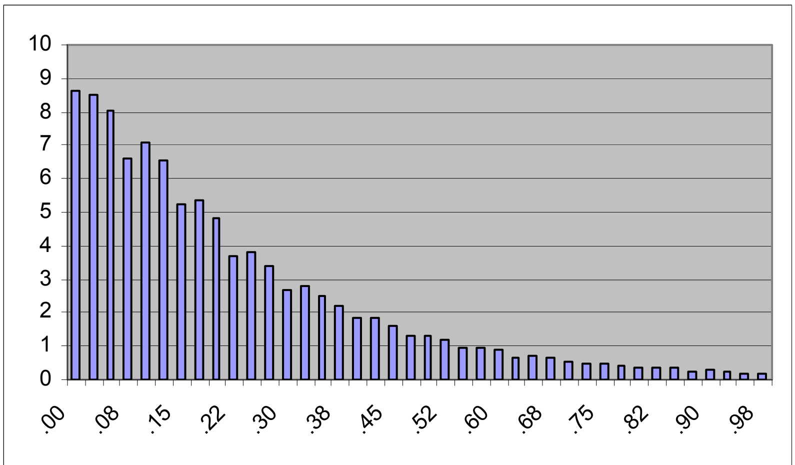
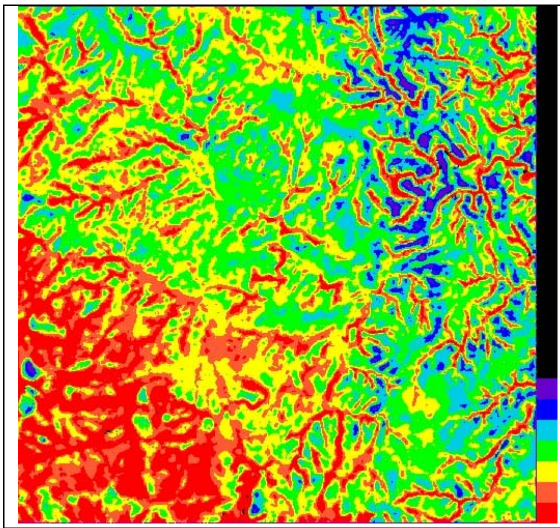


Figure 9: frequency distribution of terrain inclination in the Istiranca sub-area

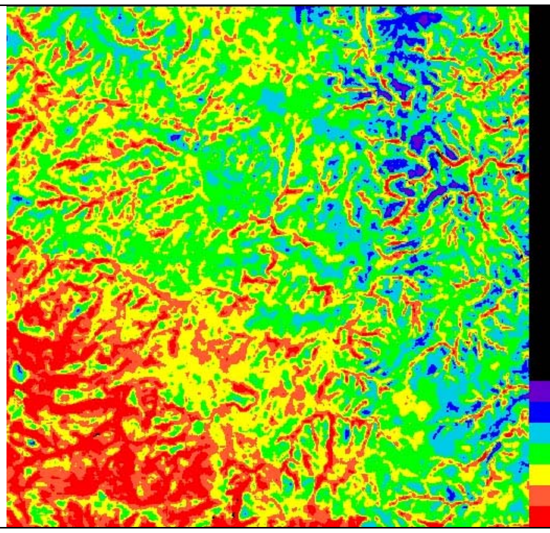
Vertical: % of area

Horizontal: tangent of terrain inclination

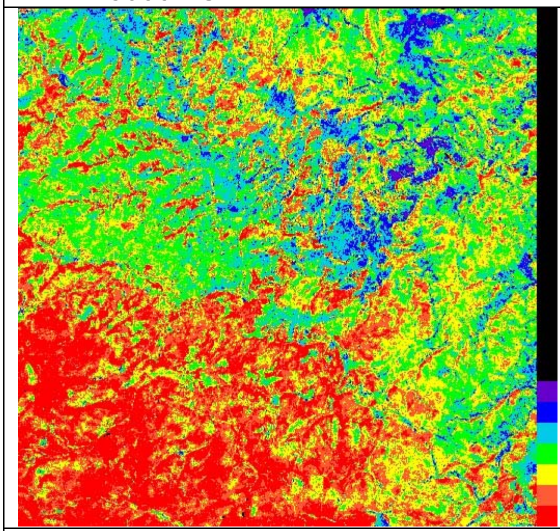
Figure 9 shows the characteristics of the investigated terrain – this is a typical mountainous area, where even a terrain inclination of 45° (tangent = 1.0) is available for 0.2% of the area. In such an area even just by the interpolation from 3arcsec point spacing of SRTM data to 20m point spacing a similar loss of accuracy may occur. For testing, the SPOT-5 HRS-data have been reduced to a point spacing of 80m and after this interpolated again to the full resolution. The interpolated data set has been compared with the original data, leading to root mean square discrepancies in the range of the differences between SPOT-5 HRS and SRTM (table 5), (figure 11).



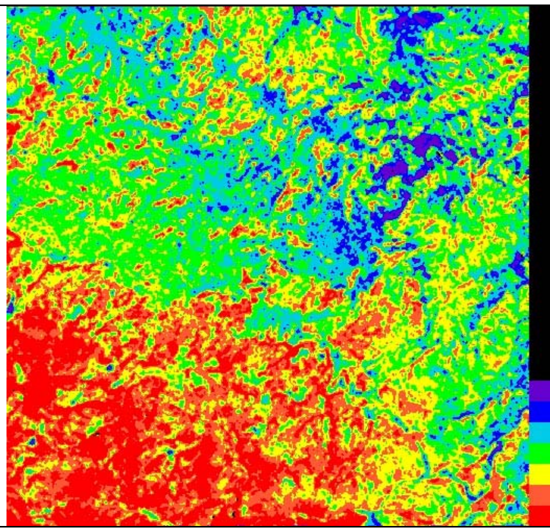
DEM 25000 - SRTM



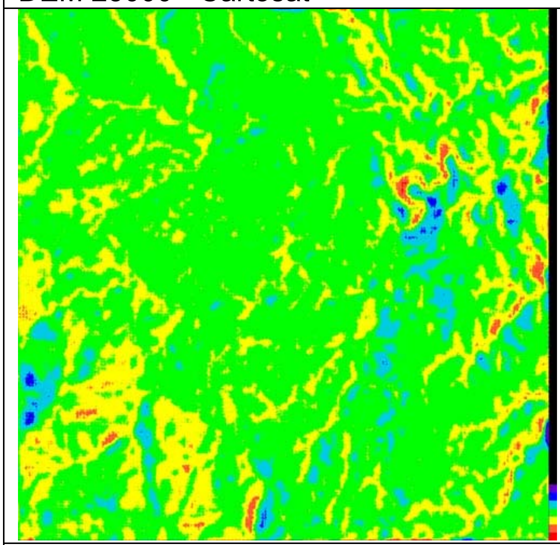
DEM 25000 - HRS



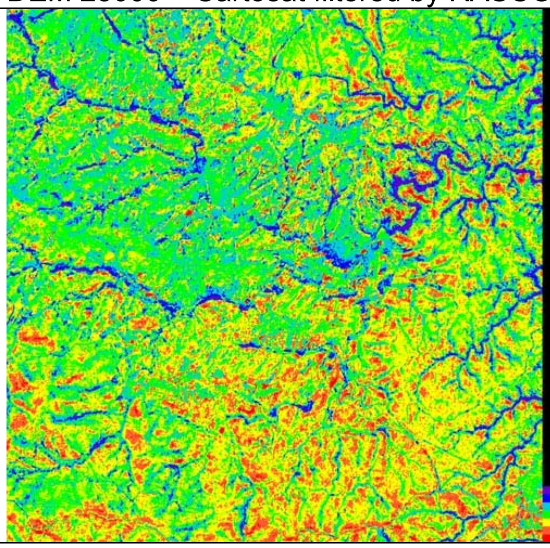
DEM 25000 - Cartosat



DEM 25000 – Cartosat filtered by RASCOR



HRS - SRTM



HRS - Cartosat

Figure 10: colour coded differences of height models

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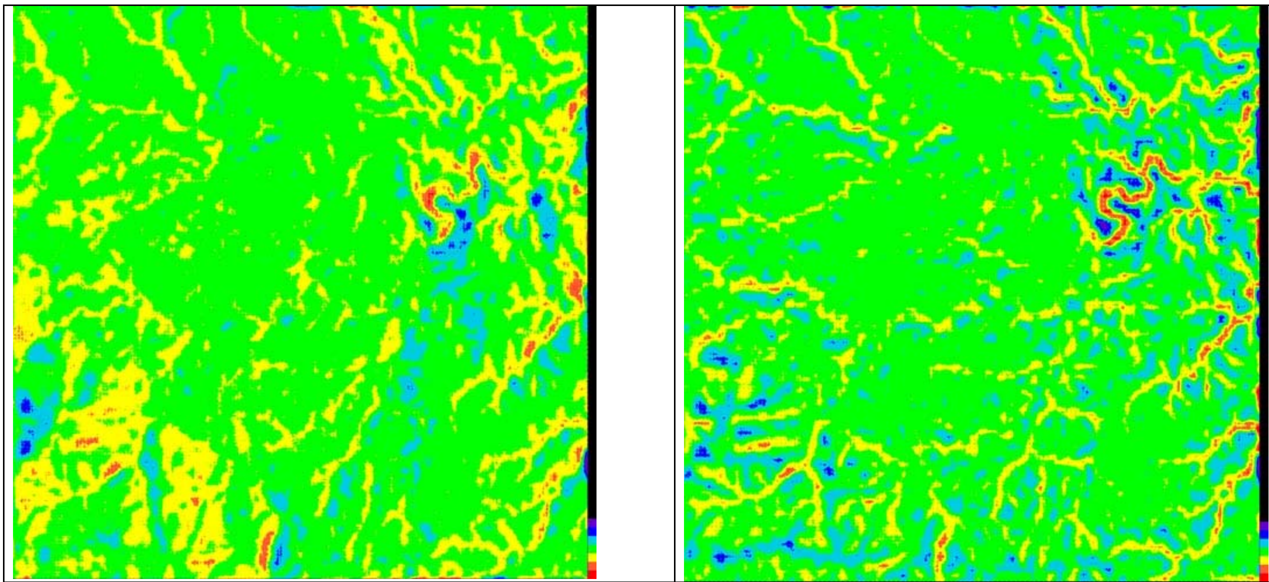
GROUPING OF COLOUR-CODING:
DZ-RANGE
-21.00-15.00 RED
-15.00 -9.00 BROWN
 -9.00 -3.00 YELLOW
 -3.00  3.00 GREEN
  3.00  9.00 GREEN-BLUE
  9.00 15.00 BLUE
 15.00 21.00 VIOLETT
```

The differential height models (figure 10) indicate the characteristics of the height models in the chosen 10km x 10km window. The characteristics of the DSMs against the reference DEM from the map 1:25 000 can be seen in the height differences shown by red colour – this indicates forest with high trees. The strange similarity between SRTM and HRS is obvioius in the corresponding differential height model – only in the open parts remarkable differences exist. The Cartosat DSM shows quite more details like the other.

Compared height models	RMSZ [m]	Bias [m]	RMSZ - bias	RMSZ as function of terrain inclination
HRS - SRTM	3.13	-1.23	2.88	$1.73 + 6.76 * \tan \alpha$
HRS 80m interpolated – HRS original	3.32	0.00	3.32	$2.50 + 4.18 * \tan \alpha$

Table 5: influence of the interpolation over 80m spacing in comparison to the discrepancies HRS - SRTM



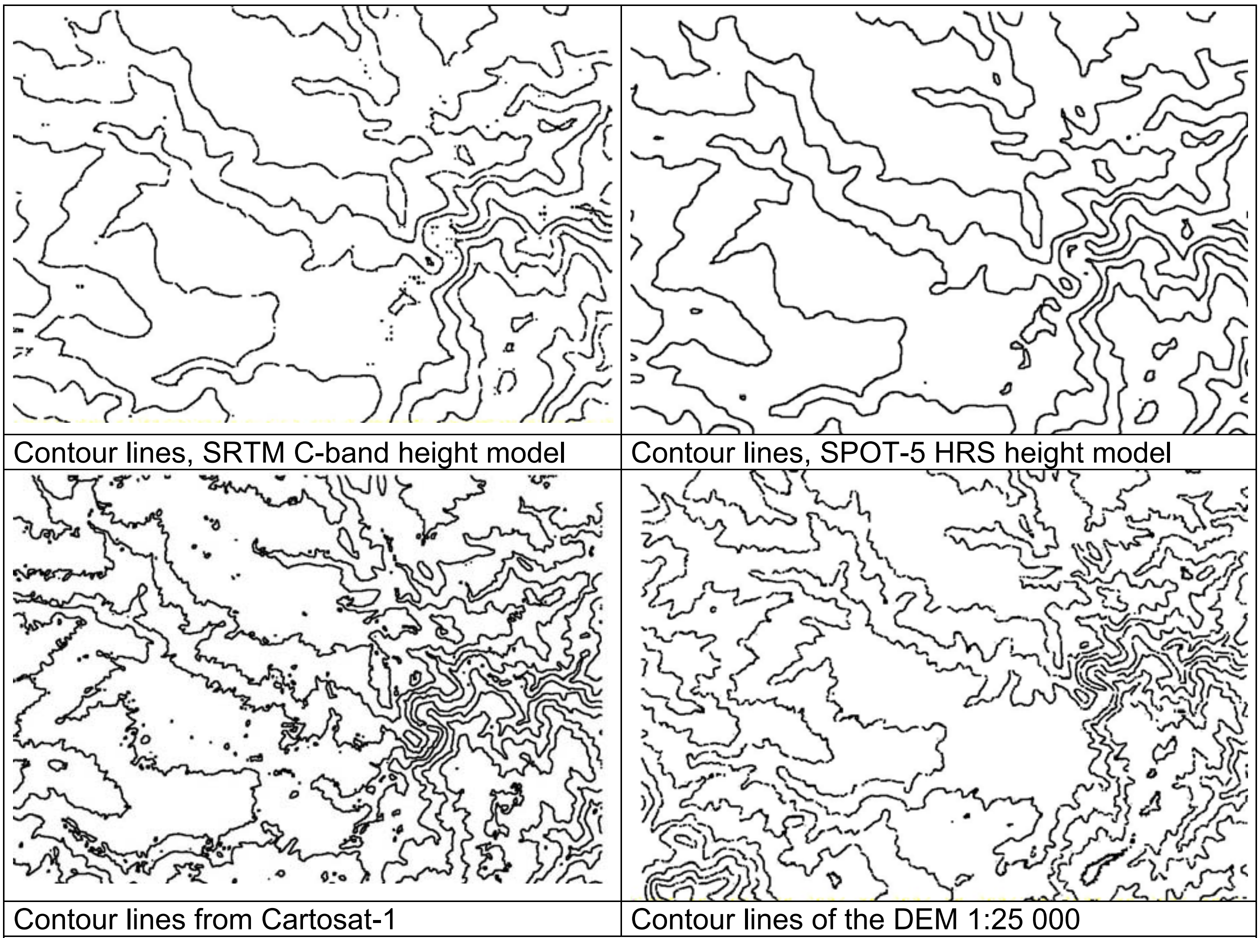
Colour coded height differences HRS - SRTM

Colour coded height differences of the influence of interpolation over 80m spacing

Figure 11: height differences of the HRS DSM against SRTM DSM compared with the influence of interpolation over 80m

The RMS height differences of the SPOT-5 HRS DSM against the SRTM C-band DSM are nearly identical to the influence of the interpolation over 80m distance raising some doubts at the origin of the "SPOT-5 HRS DSM" like mentioned before.

In addition to the accuracy the morphologic details have to be respected. The morphologic details are important for the identification of the terrain characteristics; it is obvious with the contour lines (figure 12). The more precise morphologic information of the Cartosat-1 height model is obvious; it is based on the point spacing of just 7.5m, while SPOT-5 HRS has 20m and SRTM 92m/80m spacing. The correspondence between the SPOT-5 HRS and the SRTM C-band contour lines can be seen, supporting also the question of the original source of the HRS DSM. The Cartosat-1 height model fits better than the other to the DEM 1:25 000, but it has to be respected, that only the DEM 1:25 000 presents the bare ground, while the other represent the visible surface, that means the top level of the trees in the forest.



Contour lines, SRTM C-band height model	Contour lines, SPOT-5 HRS height model
Contour lines from Cartosat-1	Contour lines of the DEM 1:25 000

Fig. 12: contour lines from a sub-area of the window in the Istiranca area

The root mean square height differences of the different height models are in most cases within the expectation for the mountainous area, nearly completely covered by forest. The bias of the DSMs against the reference DEM from the map 1:25 000 indicates the average tree height. Elements not belonging to the bare ground can be filtered from a DSM if enough points belonging to the bare ground are included, but in the forest area the influence of filtering is limited, so the filtered Cartosat data are fitting only 10% better to the reference DEM like the original matched data. A filtering of the SPOT-5 HRS DSM has nearly no effect. The influence of the vegetation to the DSMs can be seen also at the asymmetric frequency distribution of the height differences of the DSMs against the reference DEM.

In suburbs of Istanbul the SPOT-5 HRS height model and the SRTM C-band DSM have been analysed against a more precise reference DEM from the maps 1:5000. Only 42% of this area is covered by forest. In this area no similarity between the SPOT-5 HRS DSM and the SRTM DSM can be seen. The accuracy estimation for SPOT-5 HRS and SRTM in the forest area of this location may be used as reference for the analysis of the height models in the region shown at first.

Compared height models	RMSZ [m]	Bias [m]	RMSZ - bias	RMSZ as function of terrain inclination
HRS – DEM 1:5000	6.02	0.84	5.96	$5.14 + 10.57 * \tan \alpha$
HRS – SRTM C-band	4.62	-1.33	4.43	$3.72 + 3.29 * \tan \alpha$
SRTM – DEM 1:5000	5.70	-2.29	5.22	$4.51 + 5.81 * \tan \alpha$

Table 6: root mean square differences between height models, Istanbul, sub-area 20km x 20km

The differential height model between the SPOT-5 HRS DSM and the DEM 1:5000 in the Istanbul area shows larger buildings and forest areas. Also small valleys can be identified caused by the smoothening effect of the SPOT-5 HRS data set with 20m spacing, while the valleys are shown clearer in the DEM 1:5000.

CONCLUSIONS

Digital height models based on Cartosat-1 images, SPOT-5 HRS and SRTM C-band have been investigated in a mountainous forest area in Turkey. The automatic image matching of Cartosat-1 images was very successful and includes quite more details like the free of charge available SRTM C-band height models. Astonishing is the SPOT-5 HRS DSM in relation to the SRTM height model. The matching in forest areas with HRS images is usually difficult because of the limited spectral range of the HRS sensor between 0.48 and 0.70µm wavelength, not including the near infrared, which leads to sufficient contrast in the forest; so gaps have to be expected in the HRS DSM, but they are not available. It seems, the SPOT-5 HRS height model has been completed by the SRTM C-band data without mentioning this fact. For detailed analysis the HRS DSM has been reduced to 80m spacing and compared with the original HRS heights having 20m spacing. The resulting effect of the interpolation is with the size and distribution nearly identical to the discrepancies between the SPOT-5 DSM and the SRTM DSM, supporting the mentioned hypothesis.

All height models based on space information are digital surface models, showing the visible surface of the vegetation and artificial objects. A filtering of the DSMs in the closed forest area has limited effect because only few object points are really located on the bare earth. Nevertheless the morphologic details in the Cartosat-1 height model are at least on the level of the existing DEM of the topographic map 1 : 25 000. The SRTM C-band height model of course cannot show the same level of detail, but it can be used for several applications. The bought SPOT-5 HRS height model is disappointing in this area because it seems to be mainly a copy of the SRTM height model.

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