DIGITAL HEIGHT MODELS BY CARTOSAT-1

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ABSTRACT:

By the Shuttle Radar Topography Mission (SRTM) a nearly world wide height model has been generated, which is available free of charge. The mayor limitation of this height model is the point spacing of 3arcsec, corresponding to approximately 92m at the equator. From the very high resolution space sensors like IKONOS, QuickBird and OrbView-3 only a limited number of stereo combinations, taken from the same orbit, are available. The stereo scenes from SPOT-5 HRS are not commercially distributed. With Cartosat-1 and ALOS/PRISM new satellite stereo sensors are available having 2.5m ground sampling distance (GSD). The very short difference in time for imaging both scenes of a stereo model guarantees optimal conditions for matching.
In the frame of the ISPRS-ISRO Cartosat-1 Scientific Assessment Programme (C-SAP) the orientation of 3 stereo scenes has been computed by bias corrected, sensor oriented RPC-solution. The generation of digital elevation models (DEMs) followed by least squares matching. An analysis of the DEMs against reference DEMs showed sub-pixel accuracy of the height values as x-parallax. By automatic image matching digital surface models (DSM), showing the visible surface like buildings and vegetation, are generated. By filtering the DSMs have been changed into DEMs, including mainly the points on the bare ground, if enough points are still located on the bare ground. After filtering for open and flat terrain a standard deviation of the generated DEM in relation to a reference DEM of up to 2.4m has been reached. This corresponds to a standard deviation of 0.7 GSD for the x-parallax. The 2.5m GSD justifies a point spacing of 7.5m for the DEM. This accuracy and morphologic information contents is sufficient for most of the space application. Of course the automatic image matching fails if the object has no contrast like in the case of snow coverage, but nevertheless very qualified height models have been generated.

1. INTRODUCTION

Digital elevation models (DEMs) are required for several purposes. If the free of charge available SRTM height models are not detailed and / or accurate enough, there is a possibility to generate DEMs by matching high resolution satellite images. From very high resolution satellites like QuickBird, IKONOS and OrbView-3 there is only a limited number of stereo combinations available, taken from the same orbit or with very short time difference. The stereo models from SPOT HRS are not distributed, only the DEMs can be bought, but with Cartosat-1 and ALOS-PRISM stereo models from stereo satellites, equipped with 2 or 3 cameras are available, allowing the generation of DEMs under own control. Cartosat-1 has a view direction of 5° ahead and 26° behind, corresponding to a height to base relation of 1.6 if the curvature of the orbit is respected.
Cartosat-1 data of the test fields Mausanne, with stereo scenes from January and February 2006, and Warsaw from February 2006 have been used. The control points of the Mausanne scenes originally came from an ADS40-orientation of the JRC, Ispra. These points could not be well identified in the 2.5m resolution images of Cartosat, so the results of the orientation have been limited by the point identification. New control points have been determined later, improving the results – only these values are shown.
The handling of the Cartosat data was made with programs developed at the Leibniz University Hannover. After control point measurement in the images with program DPLX the orientation has been made based on the RPCs and control points with program RAPORIO. The image matching followed with program DPCOR, embedded in DPLX, by least square matching leading to corresponding scene coordinates. With program RPCDEM the height models have been generated by intersection and analysed with program DEMANAL. A filtering for elements not belonging to the bare ground followed with program RASCOR. The horizontal fit of the generated DEMs with the reference DEMs has been checked with program DEMSHIFT. Partially the reference data had to be improved by geoid undulation with program UNDUL.

2. IMAGE ORIENTATION

The orientation with the Hannover program RAPORIO computes at first the object coordinates with the given height values based on the rational polynomial coefficients. After this step a horizontal transformation to the control points has to be done. For this horizontal fitting a 2D-affine transformation was required and sufficient. The used unknowns are checked for correlation and significance by Student-test. The not required unknowns can be eliminated from the adjustment. Only the Y-scale of the horizontal affine transformation in some cases was not significant. The program shows the shift of the direct sensor orientation via the RPCs against the control point frame. In the stereo model Mausanne January shift values up to 5937m occurred, the later scenes do have shift values below 360m. Of course the large shift of up to 5937m may be caused also by the satellite attitude and this may cause a not negligible influence to object points located in a different altitude than the dominating number of control points. By this reason in addition to the horizontal affine transformation an improvement of the view-direction can be introduced as unknowns, but in no case this was significant. So finally only a horizontal affine transformation followed the RPC-solution.

		SX [m]	SY [m]	SZ [m]
Mausanne January, new control	after	2.36	2.13	
	forward	2.04	2.06	
	3D solution	2.10	2.70	3.37
Warsaw	after	1.41	1.50	
	forward	1.35	1.27	
	3D solution	1.33	1.14	1.76

table 1: root mean square discrepancies at control points of the Cartosat-1 orientation by bias corrected sensor oriented RPCs

The orientation accuracy of the Warsaw scenes is in the range of 0.5 up to 0.6 GSD, for the vertical component in the case of the 3D-solution the height to base relation of 1.6 has to be respected, that means, the standard deviation of the x-parallax is in the range of 0.45 GSD. With the new control points the accuracy determined at the control points in the Mausanne area are 0.8 up to 0.9 GSD, the standard deviation of the x-parallax is 0.8 GSD. This sub-pixel accuracy of course includes the influence of the control point identification and accuracy, so the scene accuracy and orientation itself is better because of the approximately 30 control points.

2. DEM GENERATION

The automatic image matching of the 3 Cartosat-1 scenes was made with the program DPCOR based on least squares matching using region growing by the Otto Chau algorithm.

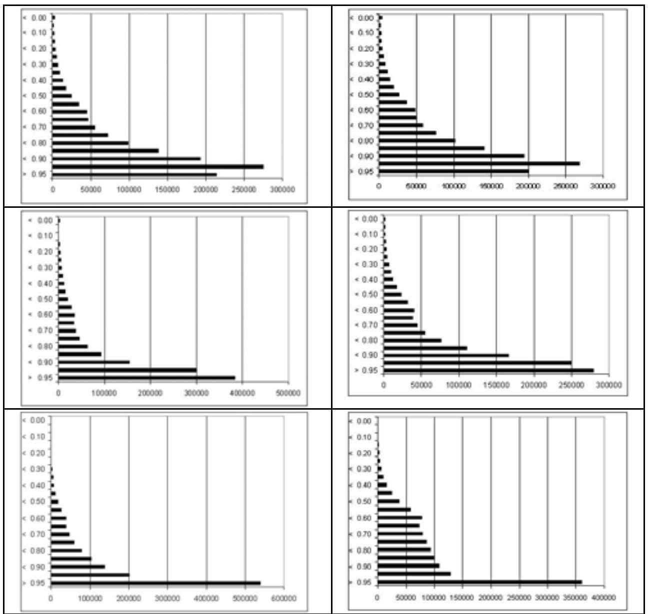

Fig. 1: frequency distribution of correlation coefficients
horizontal: number of points in the correlation group
vertical: correlation groups (step width 0.05), above 0., below 1.0 8 lower lines > r=0.6 = accepted
(– lowest bar = correlation coefficient > 0.95, second lowest bar = 0.90 – 0.95, other bars corresponding with steps 0.05)
first row: 2 sub-sets of Mausanne, January 84% accepted
second row: 2 sub-sets of Mausanne, February 93% accepted
third row: 2 sub-sets of Warsaw 94% accepted

For the matching the size of the used sub-matrix of matching can be changed – as standard 10x10 pixels are used, a smaller sub-area can fit better to local height variations, but is more sensitive to noise. In addition the tolerance limit for the correlation coefficient has an influence to the result – as default a threshold of 0.6 is used, but in some cases even a smaller value can lead to better results. If all pixel centres are used for matching, neighboured height values are strongly correlated, by this reason as default every third pixel centre in the x- and y-direction is used as default to avoid unnecessary computation time.

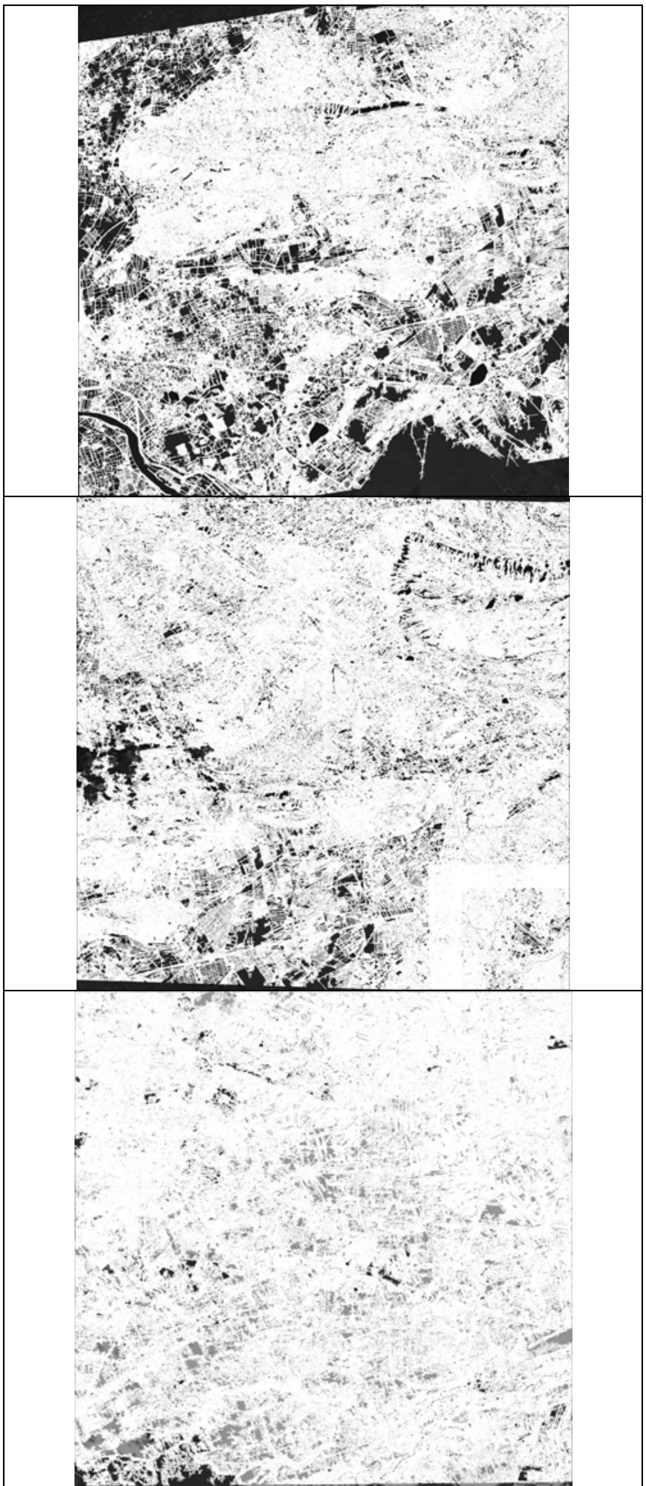

Fig. 2: overlay of matched points (white) to after scenes
above: Mausanne January, centre: Mausanne February
below: Warsaw

As mentioned in explanation to figure 1 and visible in figure 2, not all points have been accepted, the correlation coefficient was below the threshold or even the basic requirements for the least squares matching have not been accepted.

Fig. 3: matched points (white) overlaid to image – sub-area of Warsaw scene

The reason for not accepted points is obvious in figure 3, in some areas there is no contrast. In the Warsaw scene there is a low snow coverage, making the matching impossible in larger fields, but most of the fields are small and have clear contrasts at the boundaries. A similar problem exists in the Mausanne area, where the empty fields show no contrast - this can be seen especially in the lower right corner in the upper image of figure 2. In figure 2 the not white areas are showing the original image, in Mausanne the not accepted areas are dominating dark, in the Warsaw area dominating lighter grey.

The matching of the Mausanne January scene was not so good like the others. The highest number of matched points is in the correlation coefficient group from 0.90 up to 0.95 while for both other models the highest number of matched points are in the group 0.95 – 1.0. In the Warsaw scene this group is dominating (figure 1). In addition in the Mausanne January scene only 84% of the possible points have been accepted while it was 93% for the February scene and even 94% for the Warsaw scene. This can be seen also very well at the overlay of the matched points to the after scenes (figure 2). In the Mausanne January model the contrast in the fields is very low, not allowing a matching. The field boundaries always have been matched. The forest in the northern centre part did not cause any problem. In the Mausanne February scene (figure 2, centre) the situation was better, but also some fields are disturbed. In the left centre side some small clouds did not allow the matching. In the north-east corner dark shadows of the mountain caused some problems. The matching in the Warsaw scene was better than expected – the snow coverage on the fields still included some contrast, nevertheless also some fields covered by snow could not be matched. The failure in the fields did not cause large problems in the DEM generation because the fields are dominating flat, allowing interpolation between the surrounding points without loss of accuracy.

The quality images (figure 4) show the distribution of the correlation coefficients, presented as grey values. The correlation coefficient 1.0 corresponds to the grey value 255, while the correlation coefficient 0.6 is shown with grey value 51. The not accepted points ($r < 0.6$) are black.

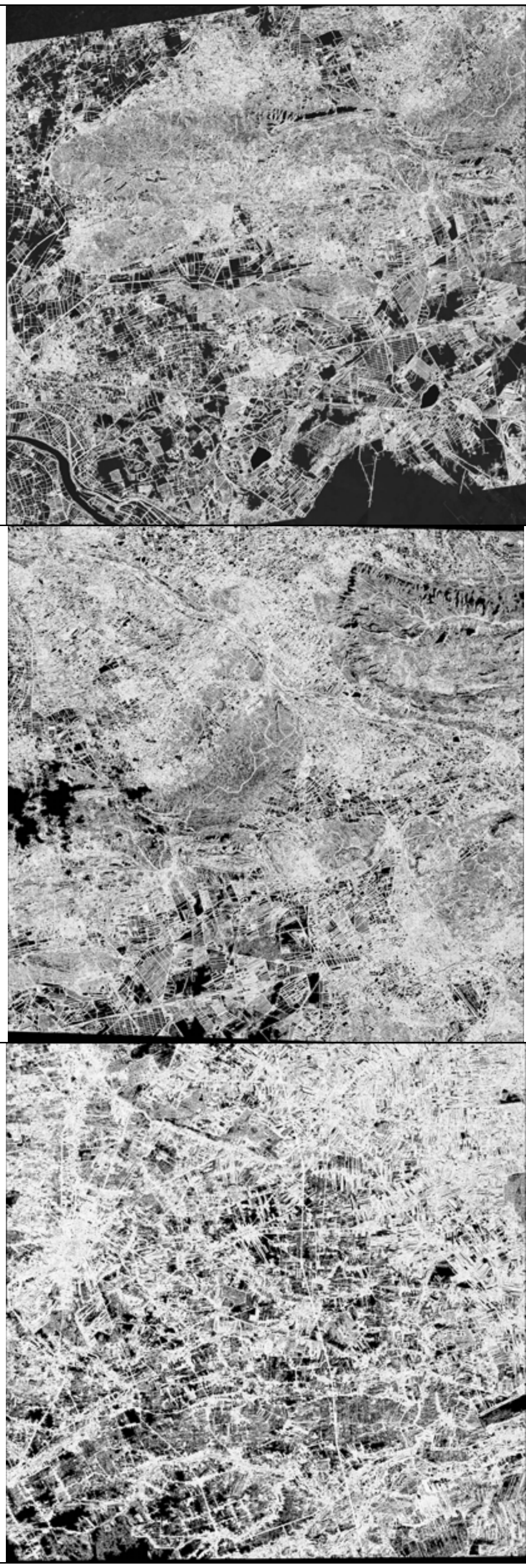

Fig. 4: quality of matching - correlation coefficient shown as grey value $r=1.0$ = grey value 255 $r=0.6$ = grey value 51 $r<0.6$ = black
above: Mausanne January, centre: Mausanne February
below: Warsaw

In the Mausanne January scene the matched forest in the above centre location shows lower correlation coefficients (figure 4 above), while the urban areas, roads and field boundaries do have larger values. Also the Mausanne February model shows lower correlation values in the forest areas as well as in some fields with low contrast. In the build up areas the good contrast resulted in large correlation values. The same can be seen in the Warsaw model, here in addition some snow covered fields caused problems.

3. DEM ANALYSIS

The reference DEM in the Mausanne test field is presenting ellipsoidal heights while the control points and corresponding to this also the generated height models having orthometric heights. This required a correction of the Mausanne reference DEM by geoid undulations with a vertical shift by approximately 50.0m. The precise EGG97 with spacing of 0.025° times 0.017° was used. A check against the free of charge available EGM96 having 0.25° spacing showed only 10cm root mean square difference to this.

Often the generated height models, based with the horizontal location on the control points, are shifted against the reference height models. By adjustment of the shift with the Hannover program DEMSHIFT only negligible differences in the horizontal location have been determined for all 3 data sets. The negligible shifts did not influence the root mean square height differences.

The heights from automatic image matching are presenting the height of the visible surface; that means they are digital surface models (DSM) and not DEMs with the height values of the bare ground. If in addition to the height values on top of vegetation – especially trees, but also buildings - points of the bare ground are available; such a DSM can be filtered to a DEM. This filtering was made with the Hannover program RASCOR (Passini et al 2002). The filtering is limited in dense forest areas where no point may be located on the bare ground and in very rough areas, where the influence of the vegetation is in the range of the height variation of neighboured points. The influence of the filtering can be seen at the frequency distribution of the discrepancies against the reference DEM. Without filtering the frequency distribution is quite more asymmetric (figure 5, left) than after filtering (figure 5, right) – the number of points not belonging to the bare ground, has been reduced. The negative values (lower part) shown in figure 5 are located above the reference DEM.

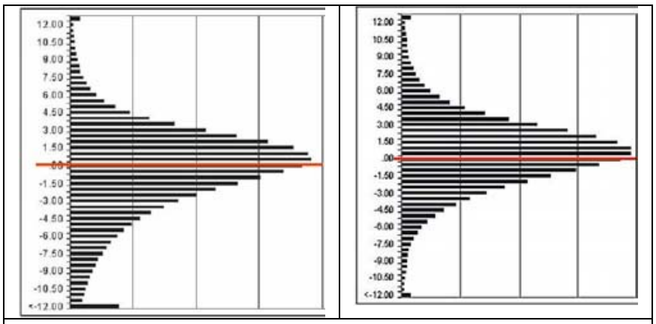

Fig. 5: frequency distribution of Z-differences against reference Mausanne, January
DEM – left: original matched DSM, right: filtered DSM
negative values: matched DSM is located above reference DEM

By the filtering especially the negative height values (points located above the reference height model) are influenced. The higher number of points with negative height values are reduced and the frequency distribution is more symmetric as it should be.

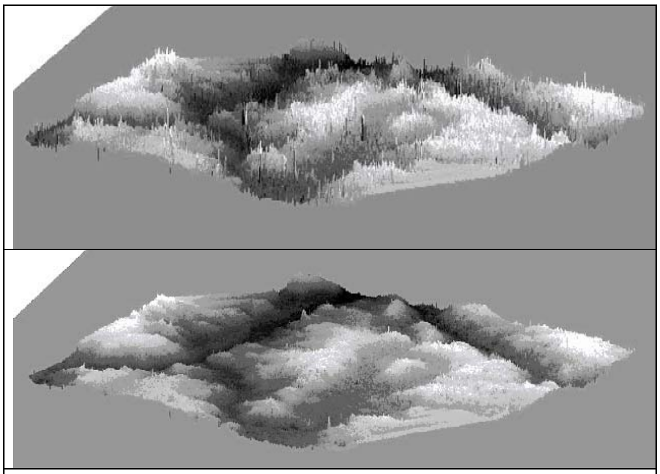

Fig. 6: 3D-view to Warsaw height model
Above: original DSM
Below: DEM after filtering

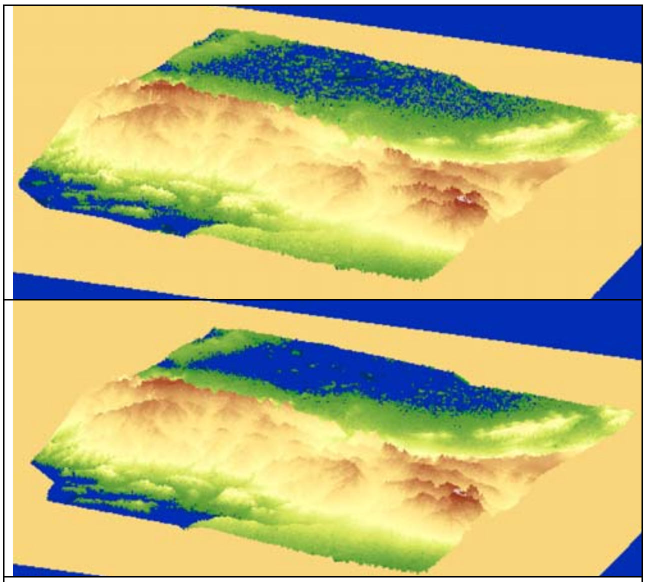

Fig. 7: 3D-view to Mausanne January scene height model
Above: original DSM
Below: DEM after filtering

The 3D-view to the Warsaw height model (figure 6) demonstrates the influence of the filtering. The original DSM shows several obstacles, which are not only caused by vegetation, partially also by mismatching; in the filtered DEM these obstacles are eliminated. This is also influencing the accuracy of the height model. In the Mausanne area (figure 7) it is similar, but because of the larger height variation it is not so obvious in figure 7, only in the flat part (shown in blue) the filtered height model looks quite more smooth.

Table 2 shows the influence of the matching parameters to the height model as well as the influence of the filtering. The result of the matching with the small sub-matrix of 5 x 5 pixels cannot be accepted, it is too much influenced by the image noise. The larger tolerance limit of r=0.8 instead of r=0.6 seems to improve the results, but after filtering it has no more advantage and in addition longer distances have to be interpolated to fill the gaps, reducing the final accuracy below the result based on the tolerance limit 0.6. The step width for matching of one pixel gives an advantage of the DSM, but after filtering this advantage does not exist any more.

Matching parameters	before filtering	after filtering
r=0.6, 10x10, step 3	2.92 m	2.22 m
r=0.6, 5x5, step 3	3.84 m	3.34 m
r=0.6, 10x10, step 1	2.71 m	2.17 m
r=0.8, 10x10, step 3	2.75 m	2.20 m

Table 2: accuracy of Warsaw height model depending upon matching parameters and filtering
Matching parameters: tolerance limit of correlation coefficient, size of sub-matrix for matching [pixels], step width of matching [pixels]

The accuracy of a DEM cannot be expressed just with one figure; at least the dependency of the accuracy upon the terrain inclination has to be investigated. Figure 8 shows the root mean square discrepancies of the generated and filtered height model of the Mausanne, January as a function of the terrain inclination. A clear linear dependency to the tangent of the terrain inclination exists, by this reason the DEM accuracy has to be expressed by the function: $SZ = A + B * \tan\alpha$ with α as terrain inclination. Of course in the dominating flat area of Warsaw, a dependency upon the terrain inclination cannot be seen for all point groups.

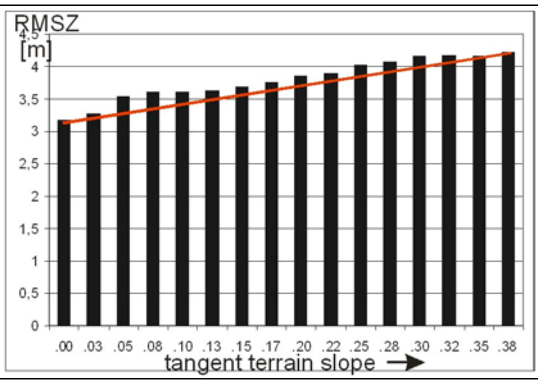

Fig. 8: root mean square discrepancies of generated DSM against reference DEM as function of the terrain inclination; Mausanne, January after filtering $SZ = 3.15m + 1.9 * \tan\alpha$

In addition to the dependency upon the terrain inclination we have to expect different results depending upon the type of terrain. Usually forest areas are showing different results like other parts, by this reason the forest areas have been analysed separately. Forest layers and in the case of Warsaw also a layer for the build up areas have been generated which can be used by the analysis program DEMANAL for the separation of the specified areas.
After matching, the object points are computed by intersection. For the intersection a tolerance limit of 3m for the y-parallax has been used. A reduction of the tolerance limit to unrealistic 1.5m caused a loss of 30% of the points but did not improve the final height model.

	SZ	bias	SZ as F(inclination)
open areas	4.02	-0.51	$3.91 + 1.64*\tan\alpha$
forest	3.55	0.92	$3.33 + 0.33*\tan\alpha$
open areas filtered	3.30	0.48	$3.17 + 3.14*\tan\alpha$
forest filtered	3.47	1,49	$2.93 + 1.81*\tan\alpha$

table 3: analysis of the Mausanne January height model [m]

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

table 4: analysis of the Mausanne February height model [m]

	SZ	bias	SZ as F(inclination)
open areas	3.23	-0.54	$3.16 + 1.19*\tan\alpha$
build up area	2.63	-0.26	2.63
forest	4.37	0.64	$4.11 + 0.34*\tan\alpha$
open areas filtered	2.43	0.44	$2.39 + 8.80*\tan\alpha$
build up filtered	1.97	0.74	1.97
forest filtered	3.13	0.81	$3.11 + 6.50*\tan\alpha$

table 5: analysis of the Warsaw height model [m]

The filtering for elements not belonging to the bare ground in any case improved the results. Like shown in figure 5, the original frequency distribution always is a little asymmetric, caused by elements located above the bare ground. After filtering, all frequency distributions are nearly symmetric. The constant part of the accuracy as function of the inclination has been improved in the open areas 21%, in the forest areas 14% and in the build up areas of the Warsaw scene 25%. In most cases the improvement in the forest is larger than the improvement in the open areas.
In both Mausanne test sites the forest areas show better results than the open areas. This may be caused by the imaging in January and February. At this time of the year the trees in these areas do not have leafs, allowing to see at least partially the bare ground. The shadows and the different structures in the forest areas are improving the contrast, finally leading to better results. This is not the case for the Warsaw test site where the best results have been achieved in the build up areas.
The systematic difference between the height models, named bias, is influenced by the objects located above the terrain. It is strongly influenced by the filtering because mainly points identified by the filter process as not belonging to the bare ground are dominating located above the DEM. By filtering the bias is getting a positive correction.
The vertical accuracy can be expressed like following:

$$SZ = \frac{h}{b} * Spx$$ Formula 1: standard deviation of Z

h=height b=base
Spx = standard deviation of x-parallax [GSD]

For Cartosat 1 the height to base relation is 1.6. With this relation and formula 1, the achieved results can be transformed into the standard deviations of the x-parallax, allowing a comparison with other sensors (table 6).

	matched DSM		filtered	
	open	forest	open	forest
Mausanne, January	0.98	0.83	0.79	0.73
Mausanne, February	0.99	0.70	0.80	0.67
Warsaw	0.79	1.02	0.60	0.78
Warsaw build up area	0.66		0.49	

table 6: accuracy of x-parallax (computed from constant value of function depending upon inclination) [GSD]

The results achieved in the open areas of the Warsaw test area are better than in the Mausanne test areas. This is mainly caused by the better contrast in the Warsaw images. The best results have been achieved in the build up areas of Warsaw having good contrast. The influence of the not very densely located buildings can be reduced by filtering. In general the imaging conditions in the northern latitude of 44° (Mausanne) and 51° (Warsaw) in January and February are not optimal – the sun elevation in the Mausanne area was just 28.8° respectively 31.1° and in the Warsaw area 30.3°. With higher sun elevation and also with vegetation on the fields the object contrast will be better. Nevertheless under operational conditions usually no better results can be expected.

5. CONCLUSION

The geometric conditions of Cartosat-1 oriented by bias corrected sensor oriented RPC-solution are not causing any problems. A sub-pixel accuracy has been reached.

The stereo models of Cartosat-1 have optimal conditions for the generation of digital height models by automatic image matching. The short time interval between both images avoids a change of the object and shadows between imaging. The height to base relation of 1.6 is a good compromise for open and not too dense build up areas. A larger angle of convergence often causes problems in matching especially in mountainous and city areas, so the percentage of accepted matched points may be smaller than the reached 84% up to 94%. On the other side a smaller angle of convergence has a negative influence to the accuracy but advantages for city areas.

With a standard deviation of the x-parallax between 0.49 and 0.80 GSD similar x-parallax accuracies like with the comparable SPOT HRS have been reached (Jacobsen 2004). Of course with the different GSD and different height to base relation the absolute vertical accuracy based on SPOT HRS cannot be as good like for Cartosat-1.

Of course the matching results depend upon the used area. In general open areas with sufficient contrast are optimal, but also under the not so optimal conditions of forest the achieved results are satisfying.

REFERENCES

Fryskowska, A., 2007: Determination, Filtering and Analysis of Digital Elevation Models, Diploma thesis Leibniz University Hannover, 2007

Jacobsen, K., 2004: DEM Generation by SPOT HRS, ISPRS Congress, Istanbul 2004, Int. Archive of the ISPRS, Vol. XXXV, B1, Com1, pp 439-444

Passini, R., Betzner, D., Jacobsen, K., 2003: Filtering of Digital Elevation Models, ASPRS annual convention, Washington 2002, on CD