A STUDY ON ACCURACY AND FIDELITY OF TERRAIN RECONSTRUCTION AFTER FILTERING DSMs PRODUCED BY AERIAL IMAGES AND AIRBORNE LiDAR SURVEYS

David Day [(b)]; Karsten Jacobsen [(c)]; Ricardo Passini [(a)]; Sean Quillen [(a)]

[(a)] Ricardo.passini@baesystems.com
[(c)] Jacobsen@ipi.uni-hannover.de
[(a)] Sean.quillen@baesystems.com
[(b)] dday@KASurveys.com

Key words: DSM, DTM, Filtering, Linear Prediction, Accuracy

ABSTRACT: Digital Surface Models (DSM) and Digital Terrain Models (DTM) were produced from digital images taken by the UltraCam Eagle of Keystone Aerial Surveys. The flight covered approximately 40 km^2 of rolling terrain with areas of dense and isolated trees, large buildings, industrial complexes, shopping malls, houses, electrical power lines, etc. (i.e., suburban / industrial zone). The image flight was acquired at 5 cm GSD with 60% end lap and 60% lateral overlap. 85 targeted ground control points were used for the bundle block adjustment, leading to root mean square differences of 2 cm and σ_o of 1.7 microns. The DSM and DTM were automatically/interactively produced by BAE SYSTEMS "NGATE" (New Generation of Automatic Terrain Extraction). The resulting DTM was checked by setting up all flight models, making sure all points of the cloud were on the ground (DTM). The same was carried out using SimActive's "Correlator3D". The resulting DSMs were automatically filtered to eliminate all points non belonging to bare ground using the same product and a different method than above software uses. The interactively produced and automatically DTMs were analyzed in details. Additionally, an airborne LiDAR mission carried out by Keystone Aerial Surveys, using an Optec Gemini scanner covered the same area. The LiDAR flight covered the area in contiguous strips with double coverage in North – South and east – west Directions providing a LiDAR point cloud with a density of about 20 to 25 ppm^2. The same above mentioned automatic filtering technique was used to produce a clean DTM from the LiDAR DSM. The resulting LiDAR DTM was then compared with the photogrammetrically derived DTMs. Detailed analysis highlights the advantages and disadvantages of the used automatic filtering method.

INTRODUCTION

Digital Surface Models (DSM) (Miller and Laflamme, 1958, Doyle, 1978) are point clouds combined with an interpolation scheme defining the visible surface (figure 1a), while Digital Terrain Models (DTM) are defining the bare ground (figure 1b). The extraction of the third dimension from stereoscopic image pairs is a well-known technique. Photogrammetry is one of the oldest methods, which has been used for 3D information generation, with developments already beginning around 1840 (Falkner, 1995). Aerial photography from air planes was a first source for creating high quality height information by manual stereo measurements. Since the early 1980s, computer technology has made it operational to acquire process and display elevation data efficiently (Förstner, 1982; Ackermann, 1984). The height models may be presented by a random point distribution or regular grids of points, usually interpolated from an irregular distribution of points.

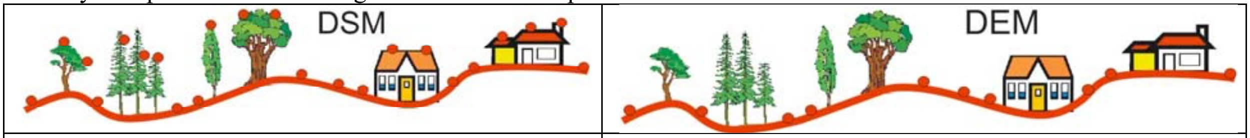


Figure 1a: Digital Surface Model (DSM) describing the visible surface

Figure 1b: Digital Elevation/Terrain Model (DEM/DTM) describing the bare ground

The data acquisition of Digital Elevation Models (DEM) by manual photogrammetric measurements has widely been replaced by automatic image matching, LiDAR and Interferometric Synthetic Aperture Radar (INSAR). All these techniques are generating digital surface models (DSM) with points located on top of buildings and dense vegetation and not on the ground, like mainly requested. Especially in urban areas and forests, a high percentage of points are not belonging to the solid ground. The manual editing of the DSM is very time consuming, limits the advantage of the new techniques and is a break within the chain of automation. Different programs have been developed which are analyzing and reducing the DSM to a DTM without human interaction. Only artificial objects, which shall not be removed, like dams, have to be specified by break lines in advance. By automatic image matching, points located on top of the visible surface are generated. Due to several reasons mismatches cannot be avoided that produces errors in the vertical component of the mismatched point. Moreover, in buildup areas all methods do have problems with shadows and viewing shadows. LiDAR can penetrate not too dense forest, but even the last pulse will not in any case be located on the ground. With the exception of some problems with the scene orientation, direct errors of LiDAR measurements can be neglected. With L- and P-band INSAR can penetrate the vegetation, but Synthetic Aperture Radar (SAR) in general has problems in build up areas with lay over. All methods are generating points located on buildings. There are some programs in use, especially by LiDAR companies, which are not fully automatically and very often there is no information about the used technique available. Another problem is the computation time, because the more often used filtering by prediction (least squares interpolation) is very time consuming. For mass production not highly qualified staff has to handle the programs for filtering of the DSM that means the required settings have to be generated automatically.

MOTIVATIONS OF THIS RESEARCH

Two software packages that extract automatically/interactively a DSM and the corresponding DTM (DEM) using correlation and other techniques (not yet published) from oriented imagery have been used. They are BAE SYSTEM's **"NGATE"** and SimActive's **"Correlator3D"**. Both are quite successful during the extraction of the initial DSM and the conversion to DTM. Although in a reasonable amount, both products require manual editing, whose amount depends mainly on the setting parameters of the programs, in the complexity of the terrain and on the land cover/use. In the Institute for Photogrammetry and Geoinformation of the Leibnitz Hannover University the program RASCOR has been developed to automatically reduce a DSM (extracted/collected from any source) to a DTM (Passini et al. 2002). Its fundamentals will be detailed further on.

The main motivations of this research are:

1. Within the study area and using check points to test the accuracy of the generated DTMs by the two programs mentioned above (NGATE and Correlator3D)
2. The same in relation with the automatically reduced DSMs to DTMs with the Hannover program RASCOR
3. To analyze the accuracy and accuracy characteristics of the filtered DTMs (by RASCOR) against the reference DTMs produced by NGATE and Correlator3D
4. To test the effectiveness of RASCOR with LiDAR data by converting the cloud of points into bare Earth (DTM)
5. Using check points, to test the accuracy of the LiDAR DTM
6. To analyze the accuracy and accuracy characteristics of the LiDAR DTM (produced by RASCOR) against the reference DTMs produced by NGATE and Correlator3D

DESCRIPTION OF USED DATA

The digital aerial photographs that have been used for the production of the height models were flown by Keystone Aerial Surveys with its digital camera UltraCam Eagle. The photo flight was done at a GSD of 5 cm in the East – West direction with 60% end and lateral overlaps. The area has 85 targeted points, been measured with a RMSE of about 1 cm. The resulting Bundle Block Adjustment (using self-calibration) has a standard deviation of unit weight σ_o= 1.0 microns and root mean square Z-differences of 5.6 cm at check points. Using the oriented images and BAE SYSTEMS Socet Set – NGATE, height models with 50 cm spacing were extracted as well as with the Correlator 3D software.

Additionally a LiDAR mission was flown over the area by Keystone Aerial Surveys using its Optec Gemini Lidar Instrument. Lidar lines, covering the area in contiguous strips with double coverage in North – South and South – North directions providing a LiDAR point cloud with a density of about 20 to 25 ppm^2. The flying altitude was approximately 600 m above ground.

Figure 2 and Figure 3 show characteristics of the used area. It is a rolling terrain, with big shopping malls, industrial building complexes, parking lots, residential areas, high ways, bushes, isolated trees, poles, electrical power lines.

Figure 2: UC Eagle image

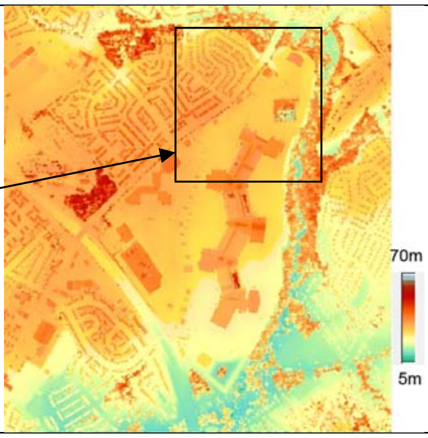


Figure 3: DSM extracted by Correlator3D

PROGRAM RASCOR FOR FILTERING DSM TO DTM

The automatic reduction of a DSM to a DTM (bare Earth) is based on the relation of the neighbored height values. In the Hannover program RASCOR (Passini et al. 2002) the following methods are combined: check for minimal and maximal height, height difference of a point in relation to the neighbored points in X- and Y-direction, linear or polynomial regression in X- and Y-direction, and height difference against a moving rotated plane or polynomial surface and height difference against the surface of a prediction. The linear or polynomial regression and also the rotated plane or polynomial surfaces are combined with data snooping – it is necessary to use the redundancy numbers for isolated points. In addition, for the identification of buildings sudden changes of the heights in the same profile with back changes are used.

The use of a linear regression in the X- and Y-direction and a rotated plane is based on a general classification of the area as flat, rolling or mountainous. The fine tuning of the thresholds will be done automatically by data analysis. The required parameters for the filtering are identified by the program. The model analysis has to be done step by step. If the area has not been identified as being not homogeneous, the height distribution is analyzed. After the elimination of the points located outside the tolerated Z-interval, the height differences of neighbored points are analyzed. Based on the histogram a limit for the accepted height difference of neighbored points is determined by the programs and the data set is thus reduced, based on this specification. In this way the program continues also for the next criteria. For the linear or polynomial regression and also the moving rotated plane or polynomial surface and the prediction, in addition the number of respected points in the neighborhood is determined automatically. Break lines can be included to avoid the elimination of sudden height changes in such areas.

If contour lines shall be generated, the DEM should be filtered more strongly. This can be reached by a second iteration – after finishing the sequence of filtering, the program starts again from the beginning. In the second iteration the tolerance limits determined by the program will be smaller caused by the effect of the first filtering and so the final result will be a smoother model. Figure 4 shows on the left hand side the contour lines based on the original data set from image matching, it includes the buildings and is influenced by the vegetation and small errors of matching. The contour lines of the right hand side of figure 4 are generated after filtering with 2 iterations without any manual editing.

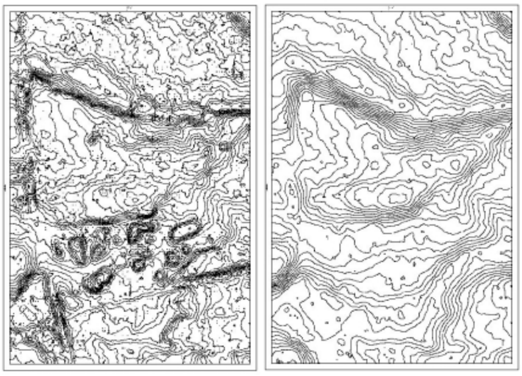
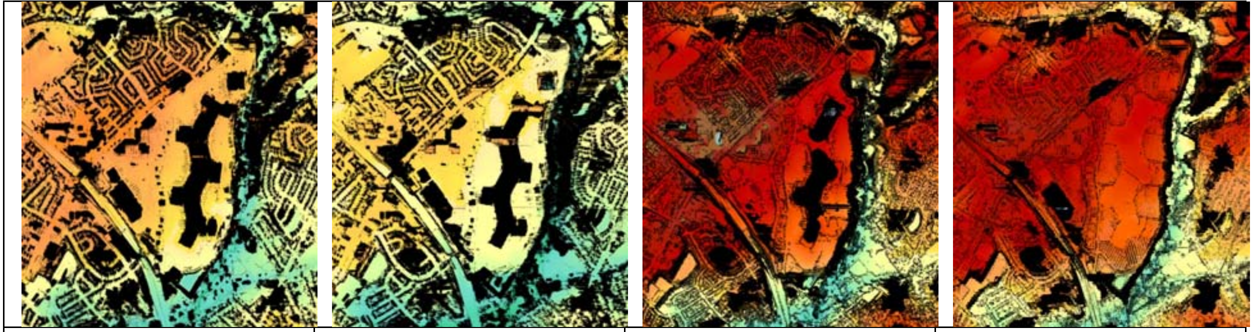


Figure 4

The comparison of overlapping LiDAR-strips showed large discrepancies in the vegetation areas where the last return is not always on the ground, so for a correct comparison a special vegetation filter has been generated, eliminating the height values in areas with strong height variation. So just the vegetation points can be eliminated, keeping all other height values unchanged.

The big mall in the project area could not be eliminated with the existing filter methods, so for this a special building filter was introduced, which could eliminate together with the other filtering steps the buildings and vegetation (figure 5) as well parking cars at the mall.



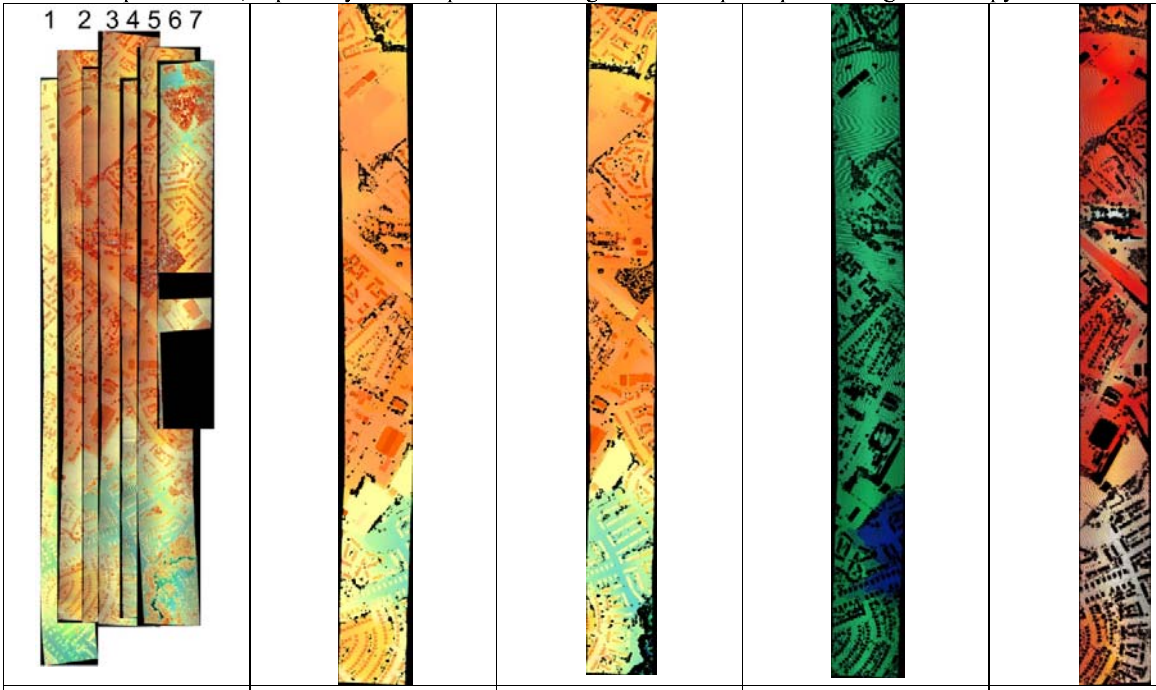
NGATE DSM | Correlator3D DSM | Correlator3D DTM | NGATE DTM

Figure 5: effect of filtering different height models, black = points eliminated by filtering with RASCOR

Figure 5 shows the effect of filtering together with the new developed building filter. The amount of filtering the DSM from NGATE and Correlator 3D for the buildings is very similar, but it shows clear differences in the vegetated parts caused by different handling of the height models by the used matching programs. In the DTM generated by Correlator 3D also a high number of points have been eliminated, indicating that the generation of a DTM was not optimal. In the case of the NGATE DTM quite less points from buildings have been eliminated, but several points from vegetated parts, indicating that the filtering in vegetated parts was not optimal. In the NGATE DSM only one large building (lower left from the mall) has been overseen, so it also was automatically eliminated by the building filter.

LiDAR DATA

The characteristics of LiDAR data with regards to their spatial distribution is such that it is much different than the photogrammetric correlated points of a DSM. This is more like a continuous surface, whereas the LiDAR data are more of a point cloud, especially with respect to the vegetation and point penetrating the canopy.



Overlay of 7 investigated strips | Strip 2, vegetation filter | Strip 3, vegetation filter | Strip 2, building filter | Strip 3, building filter

Figure 6: LiDAR-strips, width ~ 280m, length ~ 2800m, black parts of the filtered data = excluded points

The seven investigated LiDAR strips (figure 6) have 60% to 65% overlap. As mentioned before, the direct comparison of the LiDAR-strips showed large discrepancies in the vegetation because of dependency of the penetration upon the view angle. By this reason a filtering just in the area of the vegetation was required (figure 6, second and third from left). For the comparison with the photogrammetric determined height models a filtering of all objects not belonging to the bare ground was made (figure 6, fourth and fifth from left).

data	RMSZ	bias	SZ	NMAD	LE90	LE95	SZ F(slope)	Tilt X	Tilt Y
Strip 1-2	0.09	0.00	0.09	0.06	0.18	0.21	0.05+0.07*tan(a)	-0.015	-0.100
Strip 2-3	0.09	-0.01	0.09	0.04	0.18	0.20	0.06+0.15*tan(a)	-0.041	0.092
Strip 3-4	0.09	-0.01	0.09	0.04	0.18	0.21	0.04+0.06*tan(a)	-0.019	-0.035
Strip 4-5	0.10	-0.01	0.10	0.04	0.21	0.24	0.03+0.10*tan(a)	-0.040	-0.010
Strip 5-6	0.10	-0.01	0.10	0.04	0.20	0.23	0.04+0.90*tan(a)	-0.040	0.031
Strip 6-7	0.11	-0.03	0.10	0.05	0.22	0.25	0.06+0.08*tan(a)	-0.067	-0.139
Average vegetation filter	**0.10**	**-0.01**	**0.09**	**0.05**	**0.20**	**0.22**	**0.04+ 0.2*tan(a)**	**-0.02**	~
Average building filter	**0.11**	**-0.01**	**0.10**	**0.05**	**0.21**	**0.25**	**0.04+0.1*tan(a)**	**-0.03**	~
Average against block adj.	**0.15**	**0.01**	**0.15**	**0.08**	**0.23**	**0.29**	**0.05+0.4*tan(a)**	**0.02**	~

Table 1: Analysis of LiDAR-data [m]

Table 1 shows the analysis results of the LiDAR-data. The definition of the accuracy is not so simple. If the discrepancies are normal distributed, the standard deviation SZ (based on square sum) and the normalized mean absolute deviation (NMAD) (based on linear mean of absolute differences) should have the same size – both represent the expectation value of 68%, while LE90 and LE95 correspond to the expectation value of 90% respectively 95%. In the case of normal distributed values LE90 is SZ * 1.65 and LE95 is SZ * 1.96. With real data LE90 and LE95 are determined by the thresholds for 90% respectively 95% of the discrepancies and in most cases larger discrepancies are available with a higher percentage as corresponding to the normal distribution. This fact also leads to SZ larger as NMAD as visible in table 1. The averaged results in table 1 have in the average a LE90 relation of 1.95 to SZ and 2.29 in relation to LE95, being larger as the theoretical relations 1.65 respectively 1.95.

The listed figures are based on a threshold for blunders of 0.7m. This limit is justified by the frequency distribution of the discrepancies and the accuracy figures. Discrepancies exceeding 0.7m are not caused by not accurate point determination; they are caused by elements not belonging to the bare earth which have not been excluded by filtering. Approximately 10% of the points have been handled as blunders.

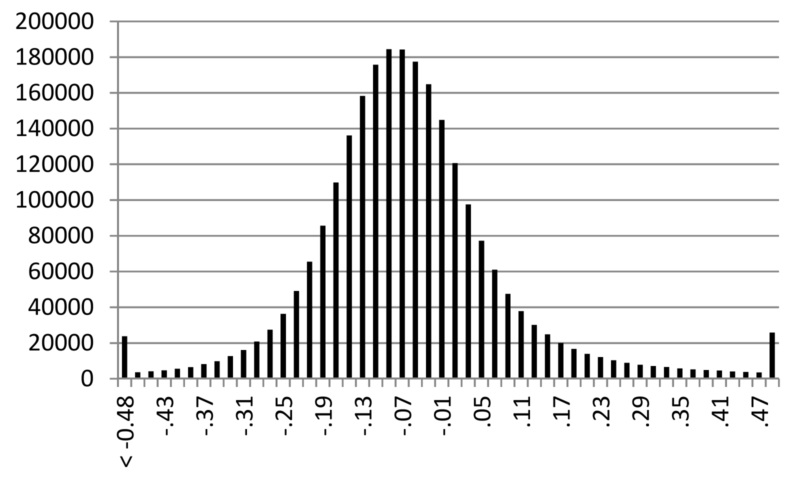


Figure 7: frequency distribution of the differences between laser strip 1 and NGATE DSM, both after filtering with building filter

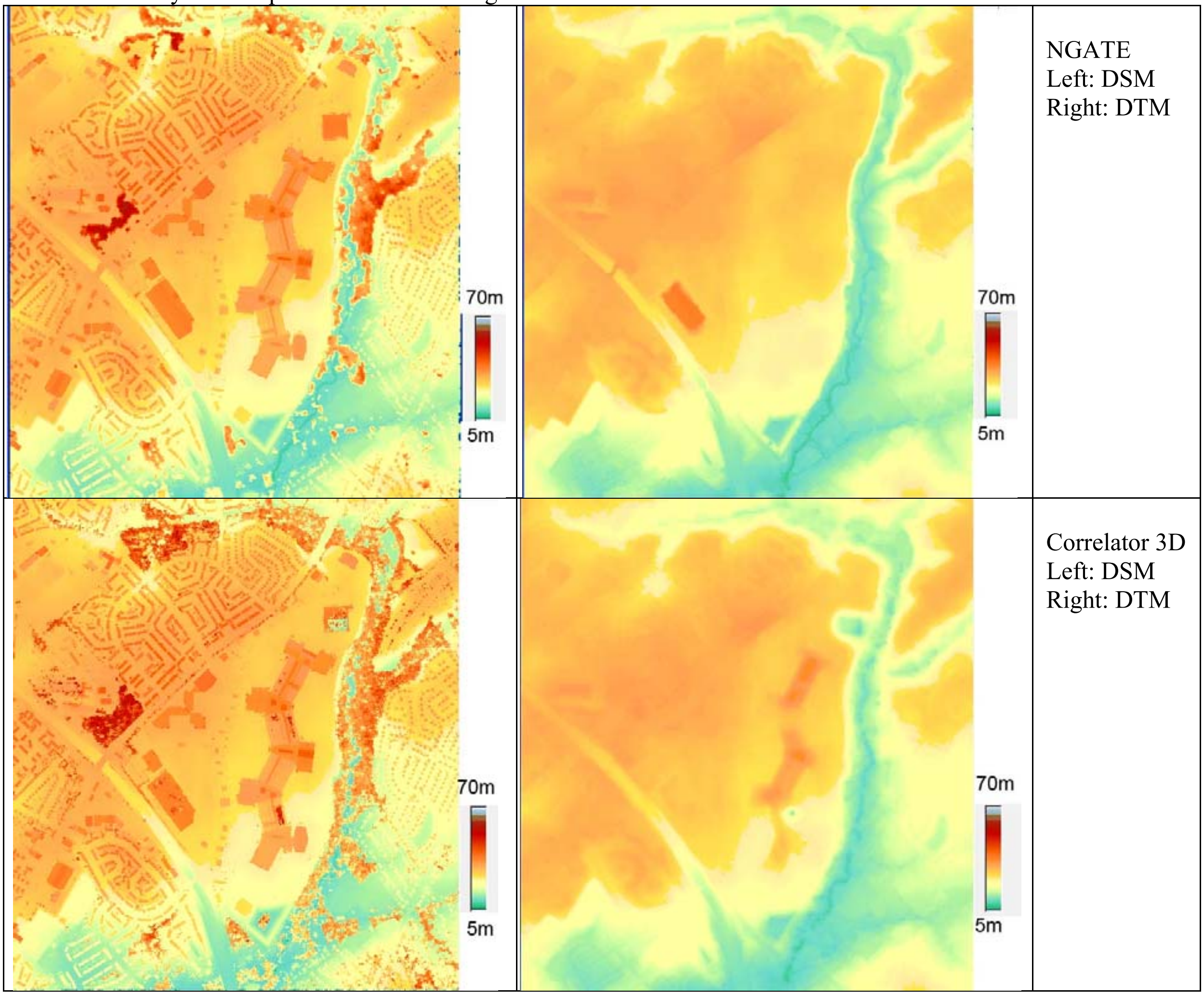
As the frequency distribution of the differences between laser strip 1 and NGATE DSM after building filter (figure 7) shows, must the frequency distribution not being symmetric and may have a higher percentage of larger discrepancies as corresponding to the normal distribution. This is exactly causing the preceding mentioned variation of the accuracy figures. LE90 and LE95 are more depending upon the random distribution of larger discrepancies while the standard deviation is based on the whole amount of the discrepancies. By this reason the standard deviation or the root mean square differences can better express the statistical nature of the observations.

The root mean square differences of the overlapping LiDAR strips in the range of 10cm are caused by both compared data sets, so the individual data sets should have a standard deviation of $10cm/\sqrt{2}$ = 7cm. This is still depending upon remaining obstacles of the terrain, indicated by the standard deviation for flat parts (tangent of slope = 0) of 0.04m. If the LiDAR-data are compared with tie point coordinates of the block adjustment with the UC Eagle data (table 1, last line), the discrepancies are slightly larger as for the comparison of the overlapping LiDAR-data. This may be explained by the different object point specification.

Some tilt of the LiDAR-strips, especially across flight direction, can be seen. The tilt goes up to 6.7cm or from the strip center 3.3cm to both sides. The value is not so large, but it is significant. In flight direction also significant not constant differences can be seen, but they are not as linear as across the flight lines. The differences in flight direction can be explained by unavoidable position orientation errors, while across flight direction it is caused by remaining attitude errors.

PHOTOGRAMMETRIC DETERMINED HEIGHT MODELS

As mentioned above, the first objective of this investigation consists to test the fidelity of the reconstruction of the bare Earth while using the program systems of BAE SYSTEMS NGATE and Correlator3D. No satisfying reference data set was available, but a comparison with the tie points determined by bundle block adjustment with the UC Eagle with 5cm GSD is possible. In addition the matched points can be compared with the LiDAR-data and against each other. Only the comparison of filtered height models makes sense.



NGATE
Left: DSM
Right: DTM

Correlator 3D
Left: DSM
Right: DTM

Figure 8: height models generated by NGATE and Correlator 3D

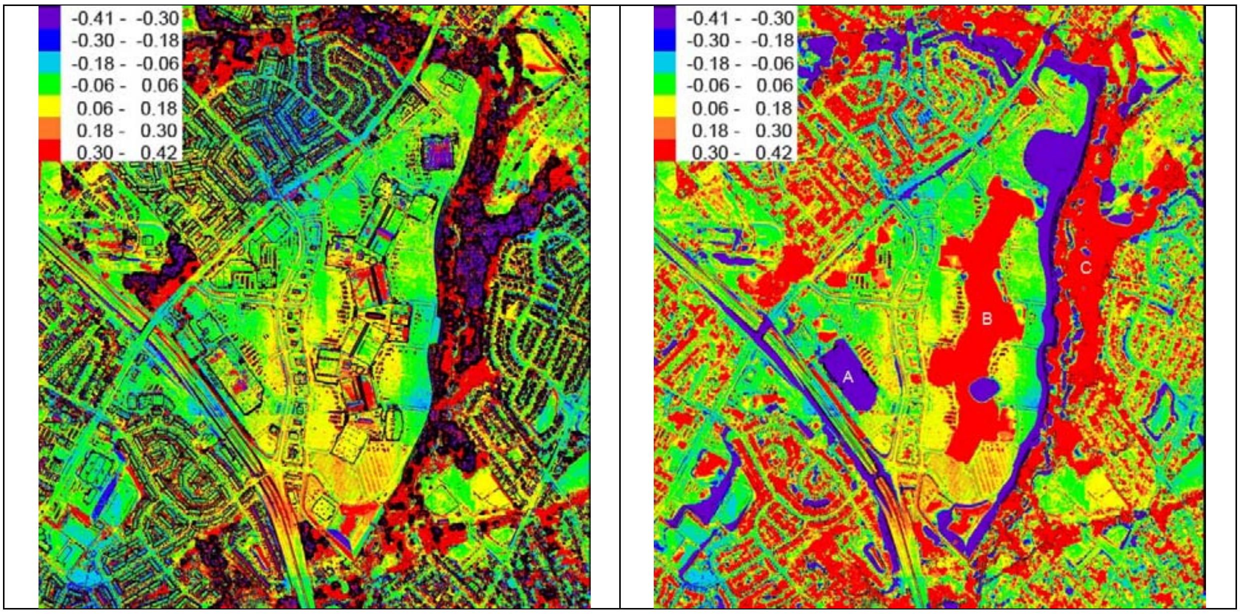


Figure 9: color coded height differences NGATE – Correlator 3D: left differential DSM, right: differential DTM [m]

data	RMSZ	bias	SZ	NMAD	LE90	LE95	SZ F(slope)	>0.7m
Comparison with tie point coordinates from UC Eagle bundle block adjustment (5cm GSD) (388 – 521 points)								
NGATE DSM	0.17	-0.02	0.16	0.11	0.24	0.35	0.10+0.86*tan(slope)	1.9%
NGATE DTM	0.14	-0.05	0.13	0.09	0.21	0.27	0.12+0.56*tan(slope)	14.7%
Correl.3D DSM	0.13	0.02	0.13	0.09	0.20	0.27	0.11+0.85*tan(slope)	1.3%
Correl.3D DTM	0.12	0.01	0.12	0.08	0.20	0.26	0.10+1.25*tan(slope)	34.0%
Comparison with LiDAR data improved by building filter								
NGATE DSM	0.17	-0.06	0.16	0.11	0.34	0.40	0.12+0.65*tan(slope)	4.2%
NGATE DTM	0.18	-0.09	0.15	0.11	0.34	0.41	0.14+0.69*tan(slope)	5.2%
Correl.3D DSM	0.17	-0.03	0.16	0.11	0.34	0.40	0.11+1.04*tan(slope)	3.1%
Correl.3D DTM	0.14	-0.06	0.13	0.1	0.27	0.32	0.12+0.66*tan(slope)	3.3%
Comparison of NGATE with Correlator 3D – both improved by building filter								
DSM	0.15	0.04	0.15	0.11	0.22	0.29	0.09+1.65*tan(slope)	1.4%
DTM	0.21	0.11	0.18	0.14	0.25	0.40	0.16+3.30*tan(slope)	8.3%

Table 2: Analysis of the height models determined by image matching, improved by building filter in RASCOR [m]

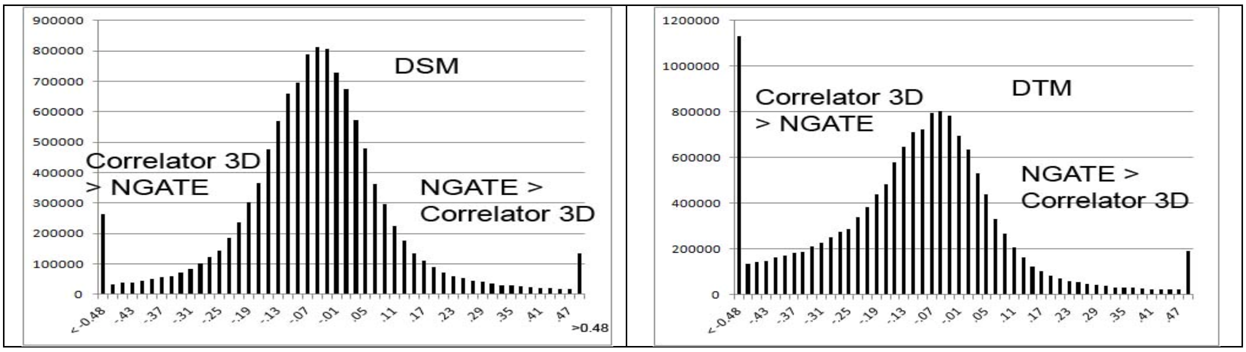


Figure 10: Frequency distribution NGATE – Correlator 3D after filtering by RASCOR, left DSM, right DTM

On the first view the DSM generated by NGATE and by Correlator 3D are very similar (figure 8, left hand side), but the DSM in the area of the vegetation is quite different (brown in figure 8 left hand side). The differential DSM (figure 9, left) shows also in other areas clear differences. The black lines around building may be explained by differences in view direction and also different handling of buildings, but in addition to the vegetated areas there are quite more differences including systematic effects south of the mall (area B in figure 9 right hand side). In general 15.7% of the height differences exceed 0.7m and the root mean square height differences (RMSZ) of the other are 0.18m, clearly more as the estimated height accuracy. Also the DSM are far from same results – the Correlator 3D DSM still shows the buildings as obvious at the mall and at the effect of filtering (figure 5, third from left). Also in the NGATE DSM a large building was not filtered (A in figure 9, right). The color coded height differences (figure 9 right) show higher ground elevations for parts of the vegetated area for the NGATE DSM and higher ground elevation for the dominating part of the vegetation and nearly all buildings for the Correlator 3D DSM. 17.7% of the height differences of the DSM exceed 0.7m and the root mean square reaches 0.25m. If the DSM are compared after filtering by program RASCOR, the DSM show RMSZ differences of 0.15m with just 1.4% of the differences exceeding 0.7m and the DTM 0.21m with 8.3% of the differences exceeding 0.7m. The not so good results for the DTM can be explained by fewer elements excluded by the filtering because of not so clear object structures as for the DSM. The problems of the filtered DTM against the DSM can be seen also in the frequency distribution of the height differences (figure 10). The not totally filtered buildings in the Correlator 3D DTM are causing a not symmetric frequency distribution of the height differences. By the frequency distribution a standard deviation of the height of 0.14m for the differences of both independent computations or 0.10m for the individual methods can be estimated. The larger discrepancies are caused by remaining filtering effects.

Because of the larger discrepancies the filtered height models should be compared with the LiDAR-data and the tie points from block adjustment (table 2). Against the tie points the Correlator 3D data show with RMSZ = 0.13m for the comparison of the filtered DSM and 0.12m for the DTM slightly better results as NGATE with 0.17m respectively 0.14m, but 34% of the Correlator 3D DTM-data are exceeding 0.7m while only 14.7% of the NGATE data are beyond this limit (table 2). More homogenous results are in relation to the LiDAR-data. The NGATE differences and the Correlator 3D differences for the DTM have a RMSZ = 0.17m and 0.18m, only for the NGATE DTM RMSZ is with 0.14m slightly smaller. Between 3.3% and 5.2% of the discrepancies against the LiDAR-data exceed 0.7m. In general the discrepancies for flat terrain are smaller as for all points. The root mean square differences for flat terrain against the tie points are 0.10m up to 0.12m and against the LiDAR-data between 0.11m and 0.14m. This can be explained by the fact, that the flat areas are not influenced by neighbored objects causing problems.

CONCLUSION

With the high image quality of digital cameras digital height models can be generated without problems by automatic image matching. The estimated standard deviation of the heights is in the range of 0.10m for the digital stereo models with 5cm GSD and 0.07m for the LiDAR data. Such height models are DSM with points of the visible surface, they have to be filtered for objects not belonging to the bare ground to get a DTM. Also LiDAR-data with the last pulse are not DTM, in vegetated areas the last pulse must not be located on the bare ground and in the case of buildings the points are located on top of the buildings. So in any case a filtering for getting DTM is required. If LiDAR data are compared with each other, discrepancies in the vegetated areas occur – this required a new developed vegetation filter which just takes out the vegetated areas based on the local strong height variation. The very large mall building could not be handled with the existing filter, so a special building filter was developed, successfully eliminating all buildings and also the vegetation areas. It is simpler to filter the original DSM as height models always filtered by other methods because of smoothing effects by such filters, leading to a higher percentage of larger discrepancies caused by not complete filtering of elements not belonging to the bare ground. It is always a question of optimizing the filter process; a too strong filter may eliminate also objects belonging to the bare ground. This only can be avoided by break lines which have not been used in this investigation. The filtered height models from NGATE and Correlator 3D included a higher percentage of points not belonging to the bare earth, especially Correlator 3D did not eliminate the buildings totally, so both DTM required an additional filtering which was made totally automatic by program RASCOR.

REFERENCES

Passini, R., Betzner, D., Jacobsen, K., (2002): Filtering of Digital Elevation Models, ASPRS annual convention, Washington 2002