Aalborg Universitet

AALBORG UNIVERSITY

DENMARK

The Photogrammetric Derivation of Digital Terrain Models in Built-up Areas

Höhle, Joachim; Øster Pedersen, Christian; Bayer, Tomas; Frederiksen, Poul

THE PHOTOGRAMMETRIC DERIVATION OF DIGITAL TERRAIN MODELS IN BUILT-UP AREAS

Joachim Höhle[1], Christian Øster Pedersen[1], Tomas Bayer[2] and Poul Frederiksen[3]

[1]Aalborg University, Department of Development and Planning, Denmark

[2]Charles University in Prague, Department of Applied Geoinformatics and Cartography, Czech Republic

[3]National Survey and Cadastre, Denmark

jh@land.aau.dk, choepe@gmail.com, bayer.tomas@upcmail.cz, pof@kms.dk

ABSTRACT

The photogrammetric method of DTM generation in built-up areas is investigated. New filtering and classification approaches are presented. Results of practical tests with the suggested processing of the 3D point clouds are analyzed. The obtained results of two tests (16 cm and 17 cm in the standard deviation and 14 cm and 18 cm in the 68% quantile) using large format images from 1000 m altitude are considerably better than the results with the raw data. The potential of the photogrammetric method for DTM generation is summarized and a comparison with airborne laser scanning is made. Applications like the extraction of buildings from dense point clouds or the completion and updating of existing DTMs could take advantage of using the photogrammetric approach.

Key words: Digital Terrain Models, photogrammetric matching, filtering, error analysis

1. INTRODUCTION

Aerial photogrammetry can automatically determine elevations, which represent the surface of the landscape. The elevations are generated on the terrain and on top of buildings, trees and other topographic objects lying above ground. Non-topographic objects will also appear in the point cloud. Blunders and gaps may be present in the point cloud. In order to derive a digital terrain model (DTM) from the point cloud, all elevations, which do not represent the terrain (bare ground), have to be removed and all gaps have to be filled by means of new data. This 3D point cloud processing should take place automatically. Some manual editing may be necessary. Various new tools have been developed; some of them in combination with existing GIS data. The generation of accurate and complete DTMs can now be improved considerably. This article deals with new tools and techniques. Tests are carried out in order to find out how efficient these techniques are for the derivation of accurate and complete DTMs in built-up areas. Such areas are of economic interest and the requirements regarding the accuracy and completeness are high.

In the following the photogrammetric method is shortly characterized; new filtering and classification approaches are explained thereafter. Results of practical tests with the suggested processing of the 3D point clouds are presented and analyzed. Finally, the potential of the photogrammetric method for DTM generation is summarized.

2. THE PHOTOGRAMMETRIC METHOD OF DSM GENERATION

The automatic generation of DTMs is based on matching of image patches from two or more images. The methodology is depicted in Figure 1. Corresponding parts of images are matched using features and intensity values. The result is a point cloud which is transferred to a regular grid by interpolation. The accuracy and density of the generated Digital Surface Model (DSM) is improved from iteration to iteration using higher and higher resolution in the overlapping images.

Over the years a lot of research has taken place on matching image patches of a stereo pair, e.g. (Förstner 1986), (Gülch 1994), (Ackermann & Krzystek 1995) and (Wind 2008). The task is not simple because mismatches can occur when the imagery lacks texture and when the corresponding image patches have differences in scale and content. The DSM may therefore have blunders and gaps. Such areas have to be corrected and supplemented with new elevations. The automatically generated point cloud as well as the interpolated DSM can be very dense.
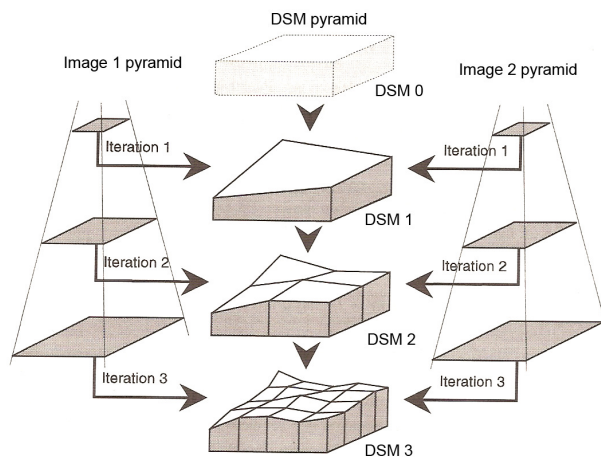

Figure 1. DSM generation by means of automated photogrammetry.

modified after (Kraus 1996)

Elevations of the DSM are determined not only in the terrain, but also on top of buildings, vegetation and other elevated objects. The elevations of temporary objects like vehicles, animals, persons, hay stacks etc. have to be removed. Classification in terrain and off-terrain points is therefore necessary. Filtering can already take place in the DSM generation.

The derivation of DSMs requires setting of various parameters. For example, the selection of the size of the search window (parallax bound), the minimum correlation coefficient, and the weights for the interpolation of the grid will influence the result. Currently there is an intense development on such programs by professional software suppliers and also by research groups. Development work on the generation of DTMs including testing was recently reported in (Zhang 2007), (Lemaire 2008), and (Haala & Wolff, 2009).

3. FILTERING AND CLASSIFICATION

The editing of the derived DSM data can be done in four ways:

-removing all grid meshes determined with low redundancy (e.g. less than five automatically

measured ground features)
-removing all points of poor accuracy (e.g. $\sigma_z > 0.1$ ‰ of the flying height)
-removing elevations within areas of elevated objects (buildings, trees, hedges, etc.)
-filtering for blunders, and
-classification into terrain points and off-terrain points.

The derived indicators for poor accuracy represent only an 'internal accuracy'. They do not correspond to the 'external accuracy' determined by accurate reference values. Existing topographic databases of urban areas can be used to find buildings and other elevated area objects. The elevations in such areas can then be removed. A buffer zone around the elevated area object may be useful if planimetric errors exist. Filtering should first of all detect and remove gross errors. A threshold for the deviations from the DTM has to be defined as a parameter. The classification into ground points and off-ground points is realized by so-called object filters. Filters for buildings use the parameters cell size, minimum area of the building, and minimum slope. The cell size is the distance between the grid points of the DTM. The boundaries of buildings are detected when the specified (minimum) slope angle is exceeded. In order to qualify as a building, all the surrounding boundaries of the building have to be present and the building must have the specified minimum area. A vegetation filter uses four parameters: Two different cell sizes and two heights. The cell size is used for the interpolation of an internal DTM, which is then used to analyze the derived DSM. The cell size is selected as twice the spacing of the DSM. The relation between the cell height and the cell size influences the degree of filtering. For a strong filtering the cell height has to be selected much smaller than the cell size. Two combinations of (cell size/cell height) are used for the vegetation filter. The meaning of the various parameters is explained by means of graphics in Table 1.

The filters can be applied separately or combined for a region or for the whole project. The described filters and editing functions are implemented in a software product of the Inpho GmbH. More details can be taken from the manual of the producer. Overviews on general methods of post processing are described in the literature, for example in (Vosselman 2009).

The final DTM should have a complete regular grid of elevations representing the terrain ('bare earth'). This means that the elevations removed by the filtering have to be replaced by new ones using the remaining terrain points as support in the interpolation. A maximum 'gap distance' has to be specified. By this completion new errors may possibly be introduced and/or gaps will remain. Until now all operations are computer-based and can be carried out automatically. Manual work should be avoided because of cost. Nevertheless, manual work may be necessary in order to complete the DTM.

4. QUALITY CONTROL

The **vertical accuracy** is derived by means of check points of superior accuracy. The standard accuracy measures are the Root Mean Square Error (RMSE), mean and standard deviation and the number of gross errors. The gross errors are defined by a threshold, for example like in this investigation by $T=|\Delta h| \geq 3 \cdot RMSE$. The derived DTMs may have gross errors (blunders) and/or a skew distribution of errors can be present. Robust accuracy measures take these phenomena into account and should therefore be used in such cases (Höhle&Höhle 2009). They are based on the median and the 68.3% quantile of the error distribution. The median is the middle of all errors (Δh) placed in a sequential order. The 68.3% quantile indicates the limit of the interval [0, $Q_{|\Delta h|}(0.683)$] in which 68.3% of the absolute errors ($|\Delta h|$) are situated.
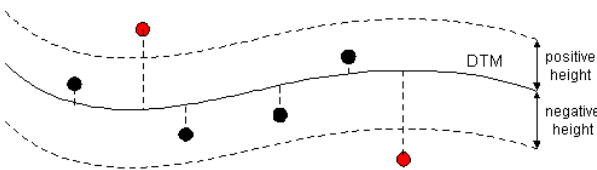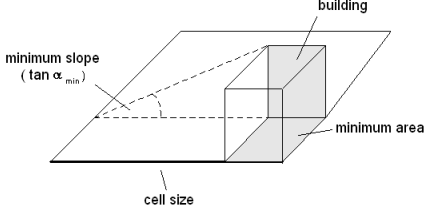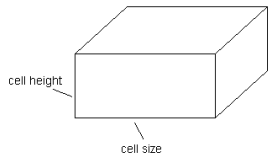
Table 1. Filters and their parameters for editing of DSMs

filter	parameters	graphics
gross error	positive height negative height	DTM positive height negative height
building	cell size minimum slope minimum area	building minimum slope ($\tan \alpha_{min}$) minimum area cell size
vegetation	cell size 1 cell height 1 cell size 2 cell height 2	cell height cell size

Table 2. Accuracy measures for the vertical accuracy of DTMs

Vertical error	$\Delta h = h_{DTM} - \text{reference elevation}$
Root Mean Square Error	$\hat{RMSE} = \sqrt{\dfrac{1}{n}\sum_{i=1}^{n}\Delta h_i^2}$
Mean error	$\hat{\mu} = \dfrac{1}{n}\sum_{i=1}^{n}\Delta h_i$
Standard deviation	$\hat{\sigma} = \sqrt{\dfrac{1}{(n-1)}\sum_{i=1}^{n}(\Delta h_i - \hat{\mu})^2}$
Threshold for gross errors	$|\Delta h| \geq 3 \cdot RMSE$
Number of gross errors	N
Median	$m_{\Delta h}$
68.3% Quantile	$\hat{Q}_{|\Delta h|}(0.683)$

The checking of the **horizontal (planimetric) accuracy** is also necessary. Planimetric errors will produce vertical errors if the terrain has slopes and height differences, for example at buildings. A few check points of superior accuracy have to be used. Their spatial co-ordinates may be determined by aero-triangulation or geodetic measurements on the ground. These reference values are then compared with the values derived from the point cloud. The roofs of hip houses, for example, have planes which can be intersected to points. The planes are determined by robust adjustment. The planimetric error (RMSE$_P$) is then calculated from the errors in the co-ordinates (E, N) by

$$RMSE_P = \sqrt{RMSE_E^2 + RMSE_N^2}$$

In general, the planimetric errors in the photogrammetric method of DTM generation are small.

5. TESTS AND RESULTS

In order to evaluate the proposed methodology and the obtainable results two practical tests have been carried out. They are named in the following as "Test 1" and "Test 2". Some data are the same in both tests, some data differ and are then written in parenthesis or marked by the number of the test, for example "Test 2".

5.1 Description of the test area

The test area has a size of 1.5 km^2. About half of the area is covered by houses; most of them have heights of 4-6 m. It is a typically Danish residential area including backyards with hedges, bushes and trees. The coverage with such elevated vegetation is about 20%. The differences in elevations are less than 20 m.

5.2 Data

The used data are aerial images, reference data and existing maps. The images were taken with a large-format frame camera (Intergraph DMC) from an altitude of 1000 m above ground. The ground sampling distance (GSD) was 10 cm. Four images with a forward overlap of 60% were used for the DTM generation. Reference data are needed for the orientation of images and for the checking of the DTMs. All of these points were determined by field measurements using GPS/RTK. All ground control points were measured twice within a few hours between the measurements. The precision derived from double measurements were σ $_{E,N}$ = 1.2 cm and σ $_Z$ = 1.9 cm. 146 check points in the built-up area were determined. Maps in vector form were used to extract houses, hedges and single trees. The map data have a (specified) planimetric accuracy of σ$_P$=0.1 m. In addition, a zone around the object was created ("Test 2").

5.3 DSM generation

The DSM was generated by the program "Match-T DSM" of Inpho GmbH (version 5.1.3). Elevations are calculated from a block of images. This so-called sequential multi-image matching is an improvement with regard to previous versions of the program. A high number of surface points are extracted and filtered by robust algorithms. From the dense point clouds a grid of elevations is derived by means of robust finite elements interpolation. The DSM is seamless. Some parameters have to be set. In the tests the settings were the following:

Generation type: DTM
Grid width: 3 m (2.6 m)
Number of DEM levels: 9
Type of terrain: Undulating
Parallax bound: 16 pixels (8 pixels)
Epipolar line distance: 1 pixel (2pixel)
Threshold for the correlation coefficient: 0.8
Window size for correlation coefficient: 5 x 5 [pixel^2]
Resampling: on
Adaptive matching: on

The weighting of the finite elements interpolation used default values. The size of the area was specified by the given overlap area. Borderline correction was chosen with 'on'. The values in parenthesis regard "Test 2". The results of the DSM generation are named in the following as raw data.

5.4 Filtering and classification

The objective of this post processing is to remove all elevations above and below the terrain. Such filtering occurs already when proper parameters in Match-T DSM are set. Data can be eliminated by means of precision codes, which are derived in Match-T DSM for each elevation. "Test 1" used Inpho's 3D editor program "DTMaster" in addition. The filtering of the DSM can automatically be carried out for large areas. The parameters of filters may be found by some manual operations using the "brush" function of DTMaster. Filters for gross errors, buildings and vegetation can be applied separately or combined in a "strategy".

In "Test 1" the strategy "Hoe 1" and in "Test 2" the strategy "Chr 1" was applied.

Filter strategy "Hoe 1"
Gross error filter: The positive and a negative threshold value were set to 1.5 m, which is based on the result with the raw data.

Building filter: In this filter the following parameters have been applied: Cell size=6 m, minimum area = (20 m)^2, minimum slope = 0.6. Two other building filters with similar parameters were used in this strategy.

Vegetation filter: The four parameters of this filter type were selected with: Cell size 1 = 12 m, cell size 2 = 6 m, cell height 1 = 1 m, cell height 2 = 0.3 m. Two other vegetation filters with similar parameters were used in this strategy.

Filter strategy ("Chr 1")
The gross error filter used 0.5 m as the positive and negative threshold. The value is based on the expected RMS error. Such a small value for the threshold means that strong filtering is carried out. Two vegetation filters were applied. The first one removed small houses and low vegetation, the second one the large buildings and vegetation.

In addition, buildings, hedges and trees were extracted from a map data base. Buffer zones around these objects were generated. All points in the generated areas could then be removed from the DSM . Such *"Editing based on GIS data"* removes all elevations in areas where map data of elevated objects are available.

5.5   Completion of the DTM

The DTM should have a complete regular grid. The removed elevations in the filtering have to be replaced by new ones using interpolation with the adjacent terrain points. The maximum 'gap distance' was set to 9 m ("Test 1"). Another possibility is to derive a TIN model. The method is described in (Bayer et al. 2009) and was applied in "Test 2".

5.6   Accuracy assessment

DTMs derived by digital photogrammetry and automatic filtering may have gross errors and a non-normality in the distribution of errors. The standard accuracy measures **and** the robust accuracy measures were therefore derived (cf. Table 2). Altogether, 146 check points were used for the built-up area. The selection of check points was close to buildings (cf. Figure 2).

5.7   Results

The assessment of the vertical accuracy is done by comparing the reference values with the interpolated values. If the output is a gridded DTM then bilinear interpolation is used. In case of gaps two approaches are then used. In "Test 1" a threshold for the maximum distance to the next grid point was specified. If this tolerated "gap distance" was exceeded, this check point was not used. The amount of check points is then variable. In "Test 2" a linear interpolation is used after a Triangulated Area Network (TIN) is computed (cf. Figure 3). In both tests the distribution of errors is monitored if a normal distribution is present. Histograms of the error distributions give an answer. In the case of non-normal distribution, it is more adequate to use the robust accuracy measures.

The horizontal (planimetric) accuracy has been derived by means of 39 points on hip houses. The reference points had an accuracy of $RMSE_P$=6 cm. The comparison between the co-ordinate sets revealed a planimetric accuracy of $RMSE_P$=47 cm. The accuracy is sufficient. The test area is rather flat and the assessment of the vertical accuracy will, therefore, not be affected.

In the following the assessment of the vertical accuracy is done separately for the two tests.

"Test 1"
The distribution of the vertical errors is depicted in Figure 4 and 5. The distribution in the test with raw data is not normal. This can already be judged by the number of blunders. After the processing the large blunders are removed and the MEAN error (systematic shift of reference) is considerably reduced. The results of "Test 1" are summarized in Figures 6 (standard accuracy measures) and 7 (robust accuracy measures). The accuracy of the raw data (σ=44 cm, Q(0.683)=34 cm) improves by 18% and 24% respectively with the "Filter based on precision" and by 70% and 62% respectively with the "Filter for gross error, buildings and vegetation" ("hoe 1"). The accuracy is slightly reduced when the gaps are closed by means of interpolation. The achieved accuracy (using 146 check points) is relatively high (σ=16 cm, Q(0.683)=14 cm).
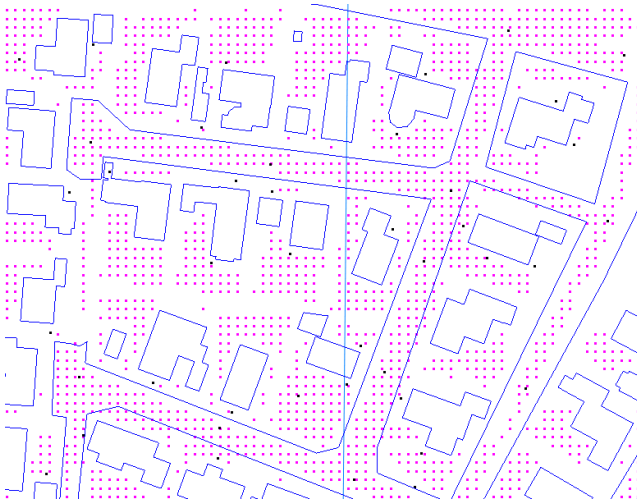
Figure 2. Result of the filtering and erasing of points within the outlines of buildings.
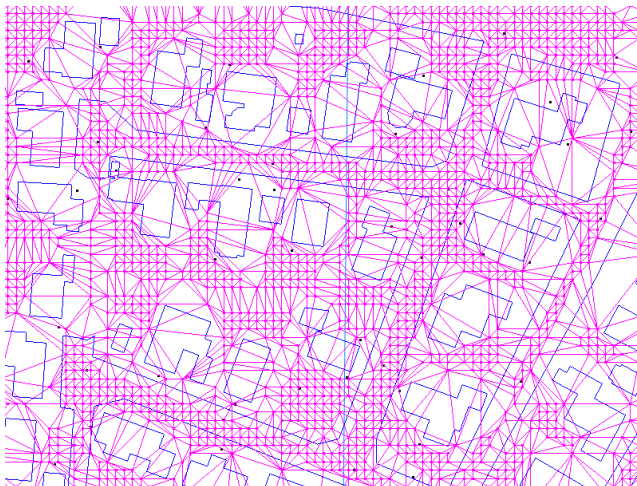*It means: Remaining elevation points (pink), check points (black), buildings (blue).*

Figure 3. Generation of a TIN and determination of errors at check points by linear interpolation.
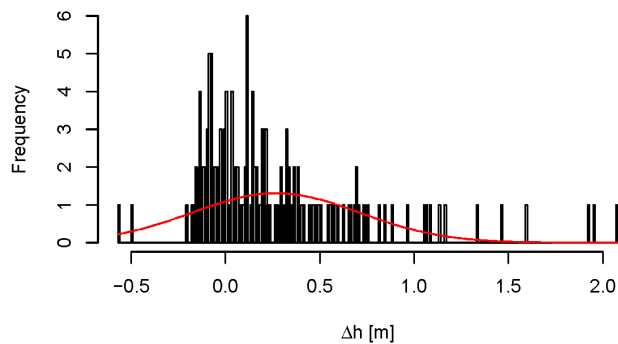

Figure 4. Distribution of errors in "Test 1" / raw data. Superimposed is the curve of normal distribution.
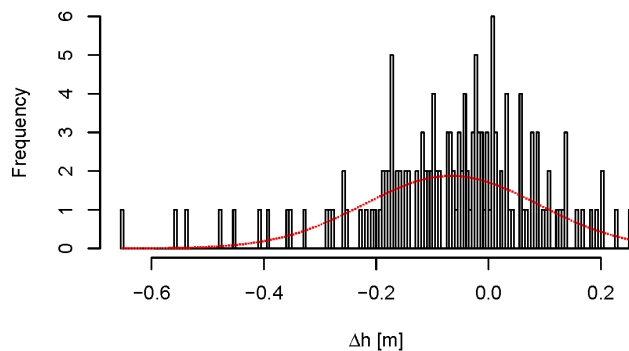

Figure 5. Distribution of errors in "Test 1" / with filtering and completion. Superimposed is the curve of normal distribution.
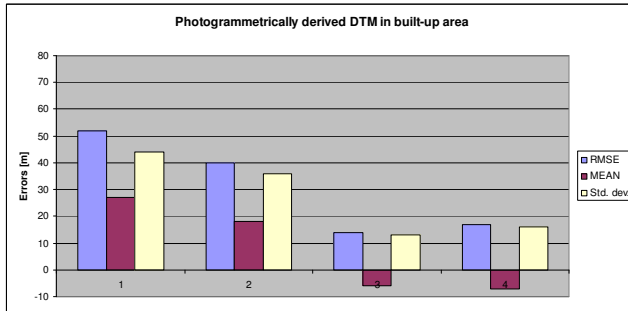
Figure 6. Results of DTM derivation by photogrammetry (standard accuracy measures) – "Test 1".

It means: 1…raw data (n=146, N=4), 2…editing based on precision (107, 3), 3…with filtering (56, 1), 4…filtering and completion (146, 3).
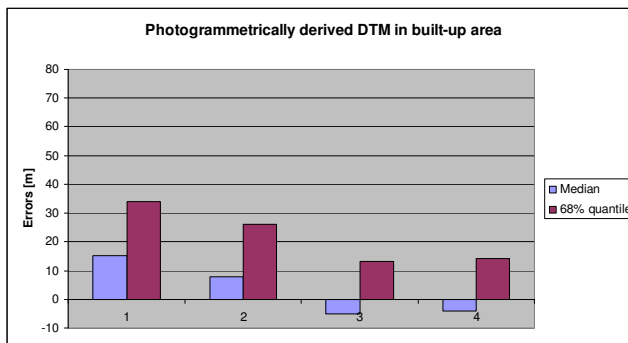

Figure 7. Results of DTM derivation by photogrammetry (robust accuracy measures) – "Test 1".

It means: 1…raw data (n=146, N=4), 2…editing based on precision (107, 3), 3…with filtering (56,1), 4…filtering and completion (146,3).

"Test 2"

The results of "Test 2" are displayed in Figures 8-11. The errors derived from the raw data have blunders up to 3 m and the distribution is not normal (cf. Figure 8). The accuracy measures of the raw data (σ=58 cm, Q(0.683)=37cm) decrease with the "Editing based on GIS data" by 29% and 22%, respectively; with the "Filter for gross error, buildings and vegetation" by 69% and 35% respectively. The accuracies are further improved when editing and filtering are combined. The achieved accuracy using 146 check points is relatively high (σ=17 cm, Q(0.683)=18 cm). The distribution of the errors is normal (cf. Figure 9), there are no blunders anymore and both accuracy measures have small values.
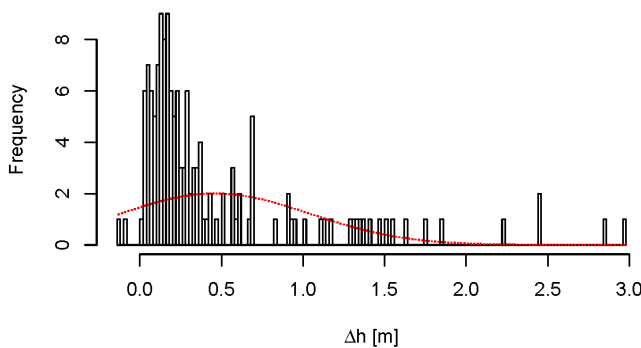

Figure 8. Histogram of the error distribution in "Test 2" / raw data. Superimposed is the normal distribution curve.
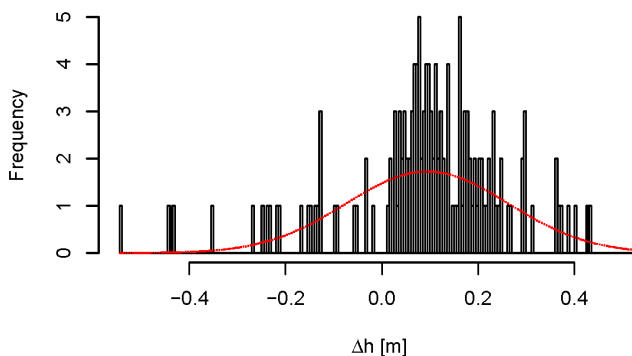

Figure 9. Histogram of the error distribution in "Test 2" / editing based on GIS data and filtering. Superimposed is the normal distribution curve.
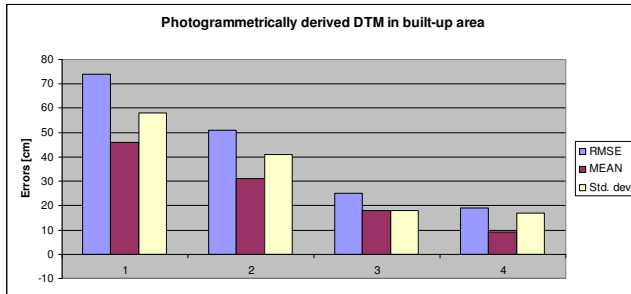
Figure 10. Results of DTM derivation by photogrammetry (standard accuracy measures) - "Test 2".

It means: 1…raw data (n=146, N=5), 2…editing based on GIS data (146, 3), 3…with filtering (146, 2), 4… editing based on GIS data+filtering (146, 0).
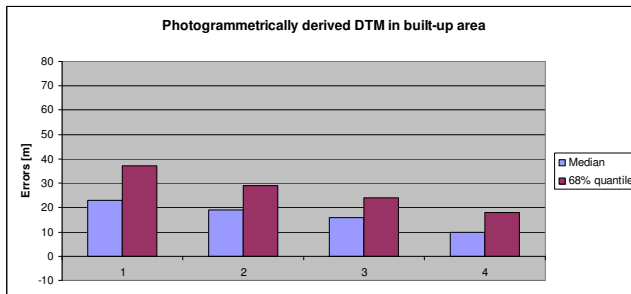

Figure 11. Results of DTM derivation by photogrammetry -"Test 2" (robust accuracy measures).
It means: 1…raw data (n=146, N=5), 2…editing based on GIS data (146, 3), 3…with filtering (146, 2),4… editing based on GIS data + filtering (146, 0).

The results of the two different processings, "Test 1" and "Test 2", are about the same (16 cm and 17 cm in the standard deviation and 14 cm and 18 cm in the 68% quantile). Both filtering approaches have improved the raw data considerably. Which set of the filter parameters is the better one is hard to answer. Strong filtering will produce large gaps, which thereafter have to be filled by interpolation. Errors are then introduced when the gap distance is becoming too big.

6.   COMPARISON WITH AIRBORNE LASER SCANNING

DTMs can be produced by different methods. Airborne laser scanning was recently used for the generation of DTMs for large areas. It is mainly the possibility to measure the terrain in areas with vegetation that makes laser scanning attractive. The measurement is done from one position only and the laser beam penetrates to the ground if the vegetation is not too dense. Photogrammetry needs at least two images to derive elevations. The imaging rays have a rather big inclination which makes measurements in forests difficult or impossible. The wide-angle photography allows for large coverage and requires therefore less flying. Its accuracy depends on the flying height. A detailed comparison between the two methods, airborne laser scanning and aerial photogrammetry, was published in (Baltsavias 1999). In the meantime many new innovations became known for both methodologies.

Actuality of the data is important for most of the DTM applications. The updating has only to be done for those areas where changes in the terrain occurred. It will be relatively small areas which have to be measured. Nation-wide photography is done in short intervals and used for updating of vector data and renewal of the orthoimages. Images are therefore available at no cost. A detailed study on the task of updating of DTMs by means of photogrammetry was recently published in (Höhle 2009). Photogrammetry is a universal method which combines the mapping of planimetric features like break lines, dikes, ditches, etc. with the mapping of elevations. High accuracy in elevations **and** planimetry is achieved. In the investigations of the authors using images with standard overlap, accuracies were achieved which approach those from laser

scanning. The density of the original data can be very high, for example 17 elevations per m^2 for images of GSD=7cm and with 80% lateral overlap and 60% side lap (Haala & Wolff 2009). At such overlap even higher accuracies can be achieved.

There are advantages and disadvantages for both methods. Laser scanning has problems with the completeness in wet areas and areas of black colour. Such gaps have to be completed and photogrammetry can fulfil this task economically when images exist. From a technical point of view, it would therefore be best to combine photogrammetry with laser scanning already in the data acquistion. Whether such a combined use is cost-effective has to be tested when hardware and software is developed. In the meantime both methods will exist side by side. Photogrammetry can meet the requirements of the majority of DTM applications.

7.   Conclusions

The photogrammetric method for derivation of digital terrain models in built-up areas can be considerably improved by applying filtering and editing using map data and GIS functions. This post processing can be carried out automatically. The obtained results of the two tests (16 cm and 17 cm in the standard deviation and 14 cm and 18 cm in the 68% quantile) using large format images from 1000 m altitude are considerably better than the results with the raw data. Gross errors are removed. Better results can be obtained by manual editing using stereo vision. The potential of the photogrammetric method can further be increased when the flying altitude is reduced and imagery with higher forward and side overlap is applied so that the elevations are determined by more than two rays. The planimetric accuracy of the DTM can easily be checked and is usually high. The DTM can also be very dense. A high density and high planimetric accuracy are required when buildings and other topographic objects are extracted from the point cloud. Such applications will be carried out in the near future. The completion and updating of DTMs is another application where photogrammetry can be used with advantage.

References

Ackermann, F. & Krzystek, P., 1995. New investigations into the technical performance of automatic DEM Generation, proceedings of the ACSM/ASPRS Annual convention, Charlotte, NC/U.S.A., vol. 2, pp. 488-500

Bayer, T., Potuckova, M., Höhle, J., 2009. Automated checking methods of the Digital Terrain Models based on TIN, proceedings of the 29th conference on Geometry and Computer Graphics (JCMF 2009), Doubice/Czech Republik, pp. 69-81, ISBN 80-86195-61-9

Baltsavias, E.P., 1999. A comparison between photogrammetry and laser scanning. ISPRS Journal of Photogrammetry and Remote Sensing 54, pp. 83-94

Förstner, W., 1986. A feature based correspondence algorithm for image matching, Proceedings of the symposium "From analytical to digital", ISPRS Commission III, Rovaniemi/Finland, International Archives of Photogrammetry and Remote Sensing, Vol. 26, Part 3/3, pp. 150-166

Gülch, E., 1994. Erzeugung digitaler Geländemodelle durch automatische Bildzuordnung, Deutsche Geodätische Kommission, Reihe C, Heft Nr. 418, ISBN 3 76969462 7

Haala, N., Wolff K., 2009. Digitale photogrammetrische Luftbildkamerasysteme – Evaluation der automatischen Generierung von Höhenmodellen, Proceedings of the annual meeting of the German Society of Photogrammetry and Remote Sensing, Jena/Germany, Vol. 18, pp. 23-40

Höhle, J., 2009. Updating the Danish Digital Elevation Model by means of photogrammetric methods, Technical Report Series of the Survey and Cadastre-Denmark, No. 3, ISBN 87-92107-25-7, 64 p., http://www.kms.dk/NR/rdonlyres/1C10C559-6CC9-4520-85C5-DE8659CB38A9/0/kmsrep_3.pdf (25.102009)

Höhle, J. and Höhle, M., 2009. Accuracy assessment of digital elevation models by means of robust statistical methods, ISPRS Journal of Photogrammetry and Remote Sensing, 64, pp. 398-406.

Kraus, K., 1996. Photogrammetrie, Vol. 2, F. Dümmlers Verlag, Bonn, 488 p., ISBN 3-427-78653-6

Lemaire, C., 2008. Aspects of the DSM production with high resolution images, Proceedings of the ISPRS Congress, Commission IV, WG IV/9, Beijing/China, International Archives of Photogrammetry and Remote Sensing, Vol. XXXVII, Part B4, pp. 1143-1146, ISSN 1682-1750

Vosselman, G., 2009. Advanced Point Cloud Processing, Proceedings of the Photogrammetric Week (PhoWo09), pp. 137-145

Wind, M., 2008. Automatic generation of elevation data over Danish landscape, dissertation at Aalborg University, 331p., http://www.kms.dk/NR/rdonlyres/AA6C65D3-4692-4432-8A4B-09B8004C6419/0/Automaticgeneration.pdf, (last accessed 10.2.2010)

Zhang, B., S. Miller, S. Walker, and K. Devenecia, 2007. Next generation automatic terrain extraction using Microsoft UltraCam imagery, *Proceedings of the ASPRS 2007 Annual Conference*, Tampa, Florida (American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland), unpaginated CDROM

Acknowledgements