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Published in:
Accuracy 2010

Publication date:
2010

Document Version
Early version, also known as pre-print

A new method for checking the planimetric accuracy of Digital Elevation Models data derived by Airborne Laser Scanning

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***Abstract*—The current state of the art in checking the planimetric accuracy of Digital Elevation Models derived from Airborne Laser Scanning is analyzed. The principle of a proposed method is presented including the mathematical equations. Special emphasis is given to the precision of derived points which are used for the comparison with true values. Least squares adjustment is applied and the influence of blunders in the observations is reduced by means of the iterative determination of weights as a function of the size of the corrections. Practical tests have been carried out with data from the new Digital Elevation Model of Denmark. The required reference values were derived by means of aerial images and photogrammetric techniques. A few ground control points were determined by GPS. The reliability and practicability of the method is then discussed on the basis of the experiences obtained from the practical usage of the method. It is concluded that the proposed method is accurate, robust against blunders and with potential for automation.**

Keywords: Digital Elevation Models; Airborne Laser Scanning; planimetric accuracy; robust adjustment; precision

I. INTRODUCTION

Digital Elevation Models (DEMs) are part of the national geospatial data infrastructure. The efficient production of DEMs and the multiple usages of DEMs are in focus of many mapping organizations today. Airborne Laser Scanning (ALS) has become an important data acquisition method for DEMs. In order to improve the economy in the data acquisition the flying height of the laser scanner may be increased provided that the required accuracy for a certain application can be achieved. The use of laser scanning data for 3D city models and risk maps for flooding requires very accurate DEMs with a high density of the laser points. The demand for accuracy concerns the vertical **and** the horizontal (planimetric) accuracy. Large planimetric errors create vertical errors in areas with slope. Buildings extracted from the point cloud will be displaced. In laser scanning the planimetric errors are much higher than the elevation errors. In the past, the assessment of the planimetric accuracy of DEMs derived by ALS has often been neglected. This contribution proposes a method for derivation of planimetric accuracy for built-up areas where high accuracy and high density is required.

II. DETERMINATION OF PLANIMETRIC ACCURACY IN GENERAL

ALS has, as any other method of data acquisition, stochastic and systematic errors. Also blunders may occur. The sources of these errors may be in the laser scanner, its geo-referencing and in the type of terrain. The post processing of data can also introduce planimetric errors. Automated processes for detection of blunders and for the classification of the ALS data in terrain and off-terrain points may introduce errors as well. Errors can also be introduced by filling of gaps and by exchange of data due to different definitions of origins.

In order to find the source of errors in the applied instrumentation the determination of the planimetric accuracy is best done using the original point cloud. The user of the data is more interested in the quality of the derived Digital Terrain Model (DTM) or the Digital Surface Model (DSM), which may have different forms (grid, TIN or contour lines). The user of the DEMs should be concerned whether the available DEM data are usable for the intended application.

In general, a method for assessment of the planimetric accuracy compares the planimetric co-ordinates of points with the accurate co-ordinates of well-defined reference points. The laser 'points' are not points but small areas called foot prints. The foot print cannot be recognized in the terrain or in the image. The planimetric accuracy has to be determined indirectly using planes derived from many laser points. Distinction has to be made between methods which determine the relative or the absolute accuracy. The relative accuracy can be determined between redundant observations, e.g. between overlapping strips. This helps to discover systematic errors without expensive measurements in the terrain. Important for the user is the absolute accuracy.

The standard accuracy measures to be derived are the Root Mean Square Error (RMSE), the mean (ME) and the error standard deviation (S). These errors are computed for each coordinate of the reference system. The planimetric error is then calculated as:

$$S_P = \sqrt{S_X^2 + S_Y^2} \quad (1)$$

These accuracy measures require a normal distribution of the errors. If normal distribution does not exist, then robust accuracy measures like the Median and the 95% quantile should be applied (Höhle&Höhle 2009). The reference points should be of superior accuracy and the size of the sample should be sufficiently large.

Previous investigations on the subject of planimetric errors are rare. In (Maas 2002) planimetric errors are derived by means of correlation between elevations of overlapping strips. Areas with differences in elevation are then required. In (Vosselman 2008) it is suggested to compare the distance between ridges of gable roofs extracted from adjacent strips. In both methods only the relative accuracy can be determined. The direction of flying may influence the results. The absolute vertical and planimetric accuracy can be determined using specially designed ground targets which can be measured in the point clouds (Ray &Graham 2008). The positioning and surveying of several of such targets in the field is expensive and not very practical. From the techniques in 3D modelling of houses and roofs various solutions are known, which automatically extract planes of roofs from ALS data, e.g. in (Overby et al. 2004).

Our method suggests the use of photogrammetry to derive reference data. The extraction of laser points belonging to roof planes can also be accomplished by photogrammetry. For the derivation of planes robust methods will be applied. The precision of the intersected planes will be monitored. Blunders will then have no influence on the results.

III. THE PROPOSED METHOD OF PLANIMETRIC ACCURACY DETERMINATION

Well-defined points are at the roofs of buildings, e.g. at hip roofs or cross gable roofs. Such roofs exist in European cities and villages. Such roof points can indirectly be determined from the laser points by derivation of planes and by intersecting them. The obtained point coordinates are compared with the values derived by photogrammetry.

Some problems have to be solved. The laser points belonging to the various roof planes have to be identified. In the first step the laser points situated within the roof polygon are extracted. This selection of points is done in 2D. An existing vector map could be used. Our approach determines the corners of the houses together with the reference points by means of photogrammetry. In the second step a selection is done in 1D using the Z-values only. The selected points, which have an elevation outside the roof, will be removed. Enough points should remain in order to derive accurate values for the parameters of the plane. The mathematical formulation uses the equation of a plane:

$$Z = a \cdot X + b \cdot Y + c$$

where a, b, and c are the coefficients to be determined from a couple of laser points with its coordinates X, Y and Z. The solution for the coefficients is found by least squares adjustment. Three planes are used to derive roof points with their spatial coordinates:

$$X = \frac{b_1 \cdot c_2 - b_1 \cdot c_3 + b_2 \cdot c_3 - b_2 \cdot c_1 + b_3 \cdot c_1 - b_3 \cdot c_2}{a_1 \cdot b_2 - a_1 \cdot b_3 + a_2 \cdot b_3 - a_2 \cdot b_1 + a_3 \cdot b_1 - a_3 \cdot b_2}$$

$$Y = \frac{a_1 \cdot c_3 - a_1 \cdot c_2 + a_2 \cdot b_3 - a_2 \cdot b_1 + a_3 \cdot b_1 - a_3 \cdot b2}{a_1 \cdot b_2 - a_1 \cdot b_3 + a_2 \cdot b_3 - a_2 \cdot b_1 + a_3 \cdot b_1 - a_3 \cdot b_2}$$

$$Z = \frac{a_1 \cdot b_2 \cdot c_3 - a_1 \cdot b_3 \cdot c_2 + a_2 \cdot b_3 \cdot c_1 - a_2 \cdot b_1 \cdot c_3 + a_3 \cdot b_1 \cdot c_2 - a_3 \cdot b_2 \cdot c_1}{a_1 \cdot b_2 - a_1 \cdot b_3 + a_2 \cdot b_3 - a_2 \cdot b_1 + a_3 \cdot b_1 - a_3 \cdot b_2}$$

where the indices 1-3 refer to the number of the plane used for the intersection. Standard deviations of the intersected co-ordinates and confidence ellipses can also be derived.

$$\sum{}_p = J \cdot \sum{}_{\Delta\Delta 1 \Delta\Delta 2 \Delta\Delta 3} \cdot J^T = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_y^2 & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_z^2 \end{bmatrix} \quad (2)$$

where

$\sum_p$ …covariance matrix for the intersected point,

$\sum_{\Delta\Delta 1 \Delta\Delta 2 \Delta\Delta 3}$ …covariance matrix for the three planes, and

J …Jacobi matrix.

More details on the precision of points computed from intersections of lines or planes are published in (Cederholm 2004).

In order to reduce the influence of points which do not belong to the roof plane (e.g. chimneys) robust adjustment is applied. This means that the residuals are used to derive weights for the spatial coordinates and the solution is found in several iterations. The principle is that large residuals receive low weight. The applied weight function is depicted in Fig. 1. This adjustment method is often called the "Danish method". The approach is effective and does not eliminate measurements. Several roof points are calculated and their precision is monitored. Blunders have to be detected and eliminated. The planimetric errors are derived by comparison with the 'true' values determined by photogrammetry. The reference values are found by means of aerial images taken over the same area. Such imagery is often available from mapping missions. The roof points do not change in the course of time. Nowadays laser scanners are often operated

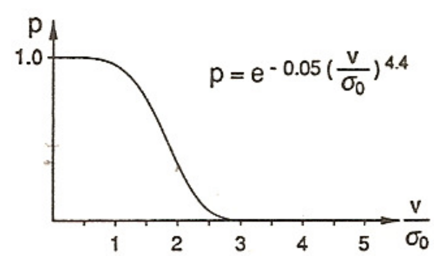

Figure 1. Iterative determination of weights (p) as a function of the size of the corrections (v). It means: σ_0 standard deviation of the unit weight. Source: (Albertz&Kreiling 1989)

together with a medium-format digital camera. The used images must be georeferenced. This is normally achieved by adjustment of the photogrammetric bundles of rays. Some ground control is necessary which can be taken from existing map data or determined by ground surveying. In the process of the bundle adjustment roof points can be determined. They should be well-defined and their accuracy should be at least three times better than the points derived from the laser points. These check points should be distributed over the whole DEM area.

The realisation of the proposed methodology was carried out by means of the programming tool "MatLab". The professional software "ArcGIS" was used to measure image coordinates and the photogrammetric point determination was carried out by means of the bundle adjustment program "DGAP" (IFP 2009). The flow chart for the calculations of the planimetric accuracy is depicted in Fig. 2. The graphical output of confidence ellipses and error vectors enables monitoring of blunders and systematic errors.

IV. PRACTICAL TESTS

The proposed method has been tested by means of the original point cloud from the new Danish DEM. Reference data and other roof points are derived from an existing photo flight with the large format digital frame camera DMC of Intergraph. Ground control and check points have been measured by means of GPS/RTK. The photogrammetric determination of **reference data** used four images with a ground sampling distance of 10 cm. A few ground control points were measured on the ground. The exterior orientation of the aerial images was determined by bundle adjustment. The reference system was UTM with the coordinates Easting (E) and Northing (N).

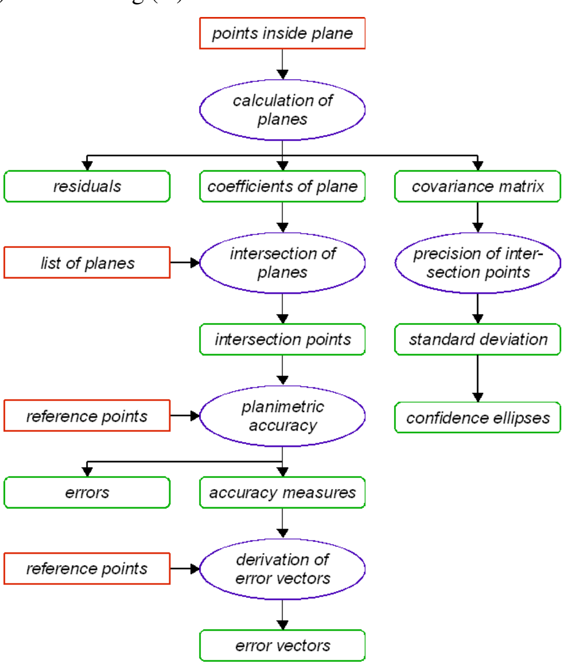

Figure 2. Flow chart for the derivation of the planimetric accuracy of DEMs. The used symbols mean: Ellipse (process), square (input), square with rounded corners (output).

The used **ALS data** are collected by a Lite Mapper 5600 scanner produced by Riegel/IGI mbH. The average density of the point cloud is 0.45 points/m^2. The overlap between strips is at least 5% of the swath width. The Inertial Measuring Unit (IMU) determined the attitude of the laser scanner with a nominal accuracy of 0.004° for roll and pitch angles. At the used flying height of 1000 m such an error corresponds to 0.125 m. The foot print of the laser beam was 0.5 m.

The measuring of the **image coordinates** occurs on the screen of a desktop computer. The same point has to be measured in two or more images. The georeferencing of the large format images proved to be very accurate. The standard deviation of the unit weight was 4.0 µm in the image only. The quality of the orientation was tested by independent check points. A RMSE of 4.2 cm has been found for each of the two planimetric co-ordinates. It is assumed that the upper roof points when measured manually by photogrammetry have the same accuracy. Having such a high accuracy these points are qualified as reference data. Together with the reference points also the roof corners have been determined. They are used for the extraction of laser points which are used for the calculation of planes.

V. RESULTS

The precision of the intersected points derived after equation (2) is calculated for each point. An average of all standard deviations is σ_{E_av}=16 cm and σ_{N_av}=13 cm. The confidence ellipses depict the quality of the determination. Circular ellipses indicate that the points are determined with high precision. The precision of the derived points differs, but the majority of the points have a high precision (cf. Fig. 3). The comparison with the 53 reference points reveals the absolute errors. The absolute coordinate errors are S_E=26 cm in Easting and S_N=18 cm in Northing. There is a systematic

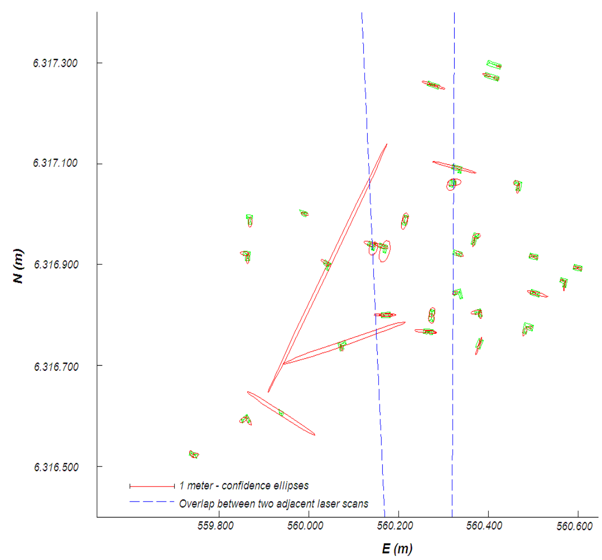

Figure 3. Confidence ellipses for the roof points derived by intersecting three roof planes.

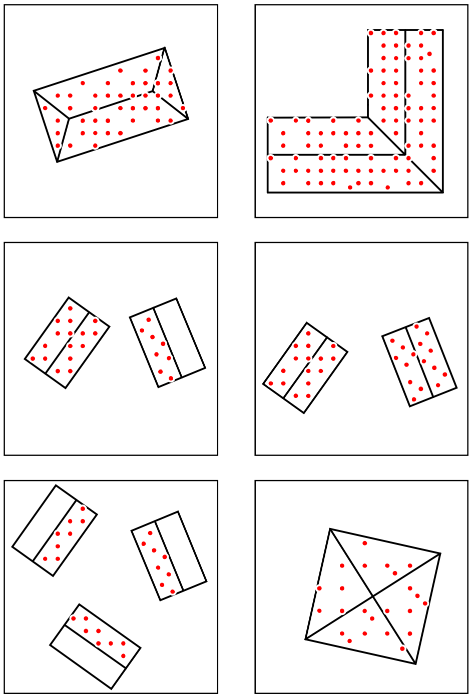

Figure 4. Building roofs for the derivation of check points. Upper row: Hip house (left) and cross gable house (right), middle row: Combinations of gable roofs, lower row: Combinations of gable roofs (left) and pyramid hip roof (right).

error (bias) of ME_E=+8 cm and ME_N=+16 cm, which made the RMSE values somewhat higher than the standard deviation ($RMSE_E$=27 cm, $RMSE_N$=24 cm). The absolute planimetric error after equation (1) is S_P=32 cm.

VI. DISCUSSION

The precision in the determination of the roof points by the proposed method was relatively high. The use of weighting of residuals in the determination of planes was necessary in order to reduce the influence of blunders. Roofs with small slopes should not be used. The confidence ellipses will display a weak determination. The number of laser points per plane should exceed four points. Houses with black roof material could not be used because the laser beam is absorbed.

Hip houses with three tilted roof planes are not always available. Cross gable roofs or roofs of two or three different gable houses can also be used provided that they have different expositions. Fig. 4 shows some of the many possibilities to derive the check points from laser points hitting roof planes.

VII. CONCLUSION

Roof points of buildings are well defined and stable. The indirect determination of points from point clouds gives the possibility to determine the planimetric accuracy of DEMs. Photogrammetry can be used for the derivation of reference points and for the selection of laser points belonging to a plane. It can be concluded that the proposed method is accurate, robust against blunders and with a potential for automation. The method can be used for the original point cloud, but also for derived DTMs or DSMs. Also the vertical accuracy can be determined by means of roof points.

ACKNOWLEDGEMENT

The authors thank the Danish Survey and Cadastre (KMS) for providing data.

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