Capture and evaluation of airborne laser scanner data

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ABSTRACT:

The development of laser sensors for the direct measurement of the terrain surface resulted in airborne systems allowing an area covering 3D data capture which are already in commercial use. By the integration of the laser scanner with sensors for the absolute orientation of the laser scanner at the time of measurement, like the NAVSTAR Global Positioning System (GPS) for the positioning task and an Inertial System (INS) for the orientation task, a powerful sensor system for the direct acquisition of 3D terrain data from an aircraft is available. Using scanning laser sensors as the main component of the laser sensor system, the points on the the terrain surface can be measured dense and well-distributed.

The main purpose of the data evaluation is to derive an appropriate representation of the sensed (terrain) surfaces. This evaluation of the measured data consists of several single steps. Within this paper the different steps are described and results of the data evaluation are presented.

1 INTRODUCTION

Applications like the rectification and mono-plotting for remote sensing data or aerial images require the assembly of a Digital Terrain Model (DTM). Usually those DTM can be captured automatically by automated stereo image matching. Even though this method provides good results for open terrain, severe problems can occur for regions, like forest areas, wetland and coastal areas and build-up areas. To overcome this problems, Airborne laser sensor systems have been developed to permit the direct measurement of the topographical terrain surface.

The main fields of application of airborne laser sensor systems are expected to be areas, where conventional methods of topographical terrain survey (photogrammetry or tachymetry) run into problems or are too slow.

- ▷ forest areas, where tachymetry is too expensive and photogrammetry fails due to the problems seeing the ground in images in forest areas
- ▷ wetland and coastal areas, where tachymetry fails due to the tides and photogrammetry has great problems because of the bad block geometry and the low texture
- ▷ opencast areas, where results of the surveying are needed within a very short period of time
- ▷ urban areas, where image matching techniques suffer from problems due to occlusions and height discontinuities.

The development of airborne laser sensor systems at the Institute of Photogrammetry began in 1988. The main goal was the development of a sensor system for the direct three dimensional airborne measurement of the topographical terrain surface, resulting in a digital terrain model of the overflown area.

2 AIRBORNE LASER SENSOR SYSTEMS

An airborne laser sensor system mainly consists of two main sensor groups: on the one hand a laser rangefinder, which measures the distance from the aircraft to the terrain surface and on the other hand sensors for the absolute orientation of the laser rangefinder at the time of measurement.

2.1 SCANNING LASER RANGEFINDERS

The central component of the airborne laser sensor system is a laser sensor, which allows the direct measurement of the distance from the aircraft to the topographical terrain surface. In the beginning of the development a profiling laser sensor was used due to the lack of other laser sensors [Lindenberger 1993]. With those sensors the terrain surface had to be captured by a lot of parallel profiles. This resulted in a large effort of time and in high demands on the accuracy of flight navigation. Nevertheless the high performance of airborne laser sensor systems for the direct measurement of the topographical terrain surface -especially in forest areas- could be shown with the profiling laser sensor in several test flights [Ackermann, Lindenberger & Schade 1992],[Ackermann, Englich & Kilian 1994].

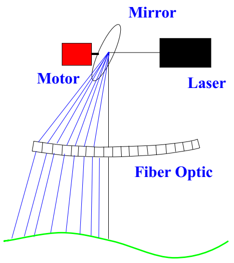


Figure 1: Principle of a laser line-scanner

The technical development in the last years made a new generation of laser sensors available. Those laser scanners permit an area covering measurement of topographical terrain surface with a high point density. To allow an area covering data capture with a laser sensor the laser beam has to be deflected periodically. Within the system used to provide our test data sets, the deflection is performed by a nutating mirror, which sends the deflected laser beam through a linear fiber-optic array. The fiber-optic array consists of different single optic channels with different viewing directions. Therefore the laser scanner virtually defines a push-broom-system, which -in combination with the movement of the system in flight direction- results in a strip-wise data acquisition. Figure 1 shows a schematic picture of a laser line scanner. Table 1 summarizes the main parameters of a laser scanner of this type [Lohr & Eibert 1995]. The main advantage of the additional use of a fiber optics, is the stability of the direction of the laser beam in a highly kinematic environment like an aircraft. The mechanical swinging mirror might be deflected additionally and uncontrolled by accelerations of the aircraft during the flight. This results in a distorted direction of the laser beam, which is corrected by the fiber optics.

sensor type	pulse modulated Laser Radar
scanning principle	fiber optic line scanner
range	< 1000 m
measurement principle	run-time measurement
scan frequency	300 Hz (adjustable)
field of view	$\pm 7°$
pixels per scan	127
swath width at 1000m flight height	250 m
accuracy of a single distance measurement	< 0.3 m
laser classification	class 1 by EN 60825 (eye-safe)

Table 1: Performance parameters of the used laser scanner

The laser rangefinder, used in an airborne laser sensor system has to meet a few physical characteristics to be suitable as sensor for the measurement of the topographical terrain surface. One important aspect is the wavelength of the laser rangefinder. To measure points on the earth surface, the laser beam should not penetrate into the ground. This can avoided by using a wavelength in the near infrared.

Another important requirement is the use of a pulsed laser rangefinder, which is able to registrate the last reflected parts of the emitted pulse. Even though some pulses are completely reflected by leaves or branches of the vegetation, in many cases the reflected pulse will refer to the terrain and can therefore be used to determine the terrain surface.

2.2 DETERMINATION OF THE ABSOLUTE ORIENTATION

In order to perform the evaluation process the laser scanner data has previously to be georeferenced. In this process the exterior orientation of the laser sensor at the time of measurement is determined. The determination of the absolute orientation (position and attitude) of the laser sensor at the time of measurement is necessary to derive the ground coordinates of the laser points.

Different sensors can be used to measure directly the absolute orientation of the laser sensor at the time of measurement. Using either inertial navigation systems (INS) or a multi-antenna GPS receiver or a setup of several GPS receivers, the exterior orientation of the sensor can be obtained directly.

Either the INS or the GPS can be used as a single sensor to perform the positioning and the attitude determination of the laser sensor. But due to the error characteristics of both sensors, GPS is used to provide the positioning and an INS is used for the attitude determination.

The positions, measured with GPS, and the attitudes, measured with the INS, have to be interpolated to provide a position and attitude for each laser measurement. The GPS data are of a relatively low data rate (up to 10 Hz), in comparison to the data rate of laser scanner (1000 Hz and more). Therefore a model of the flight path of the aircraft and an interpolation of the positioning parameters is necessary. Another possibility to condense the positioning information provided by GPS, is to use additionally relative positions from the INS, which are measured with a higher data rate (e.g. 100 Hz or more).

3 EVALUATION OF LASER SCANNER DATA

Combining the GPS/INS system for the determination of the exterior orientation with an laser sensor for distance measurement, a powerful system for the direct 3D measurement of the topographical terrain surface is available. To derive a Digital Terrain Model from the measured data a lot of single evaluation steps are necessary. Roughly spoken, four main evaluation steps can be distinguished during the processing.

3.1 Preprocessing

During the preprocessing task, the ground coordinates of the laser points are derived from the raw data provided by the laser scanner and the orientation sensors. Therefore the measurements of the different sensors (GPS, INS and laser scanner) have to be synchronized, the positions and attitudes have to be determined for each single laser measurement. Then the synchronized measurements can be transformed into the ground coordinate system.Using the orientation parameters $(X_0, Y_0, Z_0, \omega, \varphi, \kappa)$ and the measured range S_L, the 3D coordinates (X_L, Y_L, Z_L) of a specific laser footprint are computed by

$$\begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + \mathbf{R}(\omega, \varphi, \kappa) \cdot \begin{bmatrix} 0 \\ 0 \\ S_L \end{bmatrix}$$

3.2 Calibration of the laser sensor system

To cover larger areas, several overlapping strips have to be measured similar to an aerial image flight. Due to uncorrected systematic errors of the single sensors, especially of the GPS and INS sensors used to provide position and orientation of the laser scanner on the installation angles of the laser sensor, the single overlapping strips do not fit to each other exactly. Therefore a calibration of the laser sensor system is necessary. The aim of the calibration procedure is to determine additional transformation parameters (calibration parameters) for the transformation of the single strips to a homogeneous exterior coordinate system.

The overlapping areas of the single strips can be used to perform the calibration task. Therefore a two step method is applied: in a first step tie- and control point information is determined and in a second step this information is used to connect the single strips to each other and transform the block to an exterior coordinate system. Figure 2 shows the principle of the procedure.

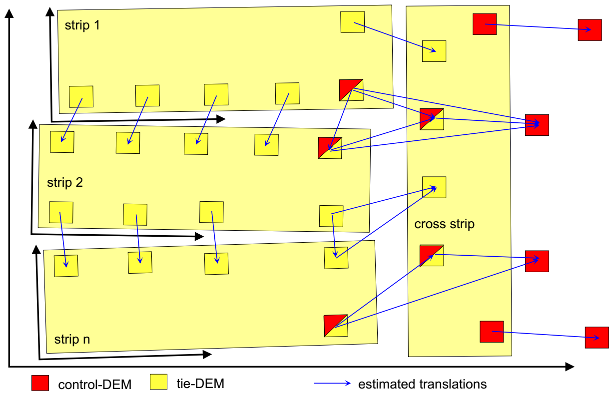


Figure 2: Tie and control points for DEM matching

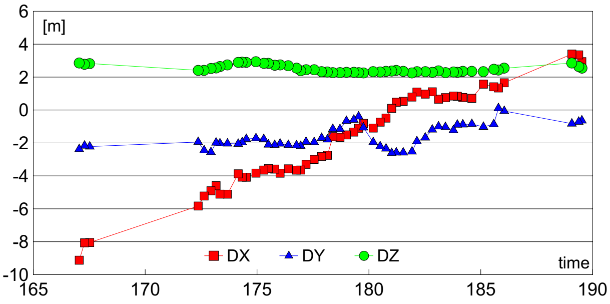
Determination of tie- and control point information

Due to uncorrected systematic errors two neighboring laser strips do not fit together exactly or the single strips do not fit to the exterior coordinate system, i.e. the single strips do not refer to the same (exterior) coordinate system. The aim of the calibration procedure is to determine transformation parameters for each strip to allow the transformation of each measured laser point to an exterior coordinate system.

In the first step of the calibration procedure tie- and control point information is determined. Therefore a matching process is applied to estimate translation parameters between corresponding areas of two different digital elevation models. The translation parameters between two identical windows of different laser strips are used as tie point information, the translations between windows of laser strips with external information, covering the corresponding area, are used as control point information. To provide external information for the position control, e.g. ground plans of buildings can be used by measuring corners of buildings in the ground plans and the corresponding corner coordinates in the laser data. Points in flat areas, e.g. street crossings, can be used for height control. The matching of laser data with external digital elevation models is another possibility to provide control point information.

For each pair of windows in the overlapping areas three translation parameters dX, dY, dZ are determined. Therefore an algorithm, originally developed for intensity based image matching [Haralick & Shapiro 1993] was adapted for matching height data. The original algorithm, using intensity images (grey values in matrix form) was modified to handle irregular distributed height data. The matching process is a three step procedure, determining approximate values of the unknowns in a first step, translations in X and Y between two corresponding windows in the second step and the height offset (Z translation) in the last step. In the second step occlusions resulting from the different view points of the scanner are eliminated to get a better matching result. The height offsets are exclusively estimated in flat areas. Even though a affine transformation (7 unknowns) is assumed for the matching process, only the 3 translation parameters were used for the second step of the calibration process.

Figure 3 shows the results of a matching process for the overlapping area of two different strips. The data set was measured with a prototype version of the sensor described in table 1. This prototype uses 64 pixels per scan. The flight height was 300 m and the measurement frequency was 300 Hz. This resulted in a point distance of about 30 cm in flight direction and about 3 m perpendicular the flight direction. For this test the positioning and attitude determination of the laser rangefinder was only performed with an Inertial Navigation System, which resulted in rather large offsets and drifts in the estimated translation parameters between two different strips as shown in figure 3. Each point in this figure, consisting of dX, dY, dZ, can be considered as a tie point information.



Distance between two windows: 10m
windowsize: ~40m * 40m

Figure 3: Matching results before calibration

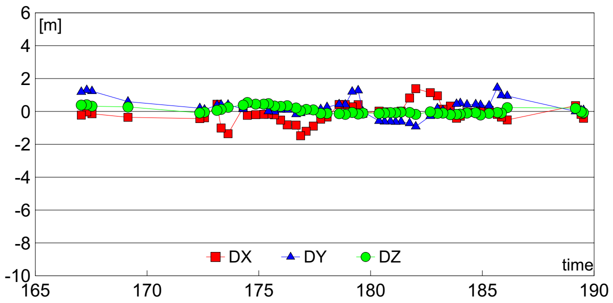
Estimation of transformation parameters

Using the tie and control point information a strip adjustment is performed. The result of this step is a set of transformation parameters for each single strip. This transformation parameters allow a transformation of each measured laser point to the exterior coordinate system. The laser sensor system can be calibrated using these transformation parameters.

The applied method is similar to the photogrammetric strip adjustment. The used mathematical model is a linear drift model for positions and attitudes. Therefore for each strip 12 unknown transformation parameters are estimated. These are 6 offset parameters with $\Delta X(t_0)$, $\Delta Y(t_0)$, $\Delta Z(t_0)$ representing an offset for the translation parameters, $\Delta\omega(t_0)$, $\Delta\varphi(t_0)$, $\Delta\kappa(t_0)$ representing an offset for roll, pitch and heading of the sensor system and 6 parameters v_X, v_Y, v_Z, v_ω, v_φ, v_κ representing a time–dependent drift for each of the 12 parameters. With the variable t representing the time of measurement, each estimated translation results in the following three observation equations for the unknown calibration parameters.

$$\begin{aligned}
dX(t) &= \Delta X(t_0) + v_X(t) + \\
&\quad f((\Delta\omega(t_0) + v_\omega(t)), (\Delta\varphi(t_0) + v_\varphi(t)), (\Delta\kappa(t_0) + v_\kappa(t))) \\
dY(t) &= \Delta Y(t_0) + v_Y(t) + \\
&\quad f((\Delta\omega(t_0) + v_\omega(t)), (\Delta\varphi(t_0) + v_\varphi(t)), (\Delta\kappa(t_0) + v_\kappa(t))) \\
dZ(t) &= \Delta Z(t_0) + v_Z(t) + \\
&\quad f((\Delta\omega(t_0) + v_\omega(t)), (\Delta\varphi(t_0) + v_\varphi(t)), (\Delta\kappa(t_0) + v_\kappa(t)))
\end{aligned}$$

After the calibration of the airborne laser sensor system, all measured laser points are defined in the same exterior coordinate system.



Distance between two windows: 10m
windowsize: 40m * 40m

Figure 4: Matching results after matching

The results of the matching procedure shown in figure 3, to calibrate the laser data by performing a strip adjustmenr. In order to evaluate and control the calibration process a second matching process was applied afterwards. The results are shown in figure 4. The drifts and offsets, as seen in figure 3 are eliminated. The RMS of the remaining X,Y translations is about 0.7m (0.8 m in X and 0.5 m in Y). Considering a laser point as a pixel with point size 3 m * 0.3 m (point distance), this value is better than 1/3 of a pixel. This corresponds with the accuracy of the intensity based image matching, which is given with 1/3 of a pixel. The RMS of the remaining height translations is 0.3 cm. This value corresponds to the given accuracy of the laser distance measurement.

By the use of GPS for the positioning task and an high precision INS for the attitude determination of an airborne laser sensor system, which is state of the art in the present system, the offsets and drifts could be reduced considerably, compared to the results shown in figure 3. Especially the X,Y offsets are small (< 2 m). Nevertheless especially for high precision applications the calibration of the laser sensor system described in this section still has to be performed to eliminate remaining error influences –especially the height offsets– and control the system.

3.3 Filtering of the measured laser points

Especially in forest and in build-up areas airborne laser sensor systems are superior to conventional methods for 3D data capture. In areas covered with vegetation it is advantageous to use a pulsed laser sensor, which is able to measure the reflected part of a laser at different points of time instead of a continuous wave laser sensor. For a pulsed laser a certain amount of the emitted laser beam is reflected at the tree canopy, while other parts penetrate the canopy through gaps in the foliage and therefore reach the ground. Therefore the last reflected laser pulse, i.e. the part which is received at last, will refer to the ground surface. Nevertheless the laser beam is frequently reflected completely by the foliage, i.e. some measurements do not reach the ground surface at all. The penetration rate, i.e. the number of measurements reaching the ground surface, that can be achieved for laser measurements in forest areas depends on the season. In summer time, which is the worst season due to the full foliage, still penetration rates of about 25% in deciduous areas and of about 30% in coniferous areas are reached. Especially in deciduous areas these rates can be improved by flying in winter time [Ackermann et al. 1994]. Nevertheless it can be shown that for all seasons there is always a sufficient number of measurements reaching the ground surface in forest areas which makes it feasible to determine the topographical terrain surface by the registration of the last reflected signal of the laser beam, followed by further filtering and processing of the measured laser points.

An important task while evaluating laser data is the separation of points on the topographical terrain surface from topographical non relevant points, i.e. points reflected by objects like trees or buildings. Figure 5 shows a Digital Height Model computed using all measured laser points, the surface represents a combination of the topographic surface with objects rising from the terrain. To eliminate these objects a process has to be applied, which can be partitioned into the two essential parts:

- acquisition of approximate values for the ground surface
- filtering of measured points and modeling the ground surface

The acquisition of approximate values to model the ground surface is the first and essential part of the algorithm. Therefore it is necessary to use a procedure, which provides reliable approximate values for the ground surface out of the data set of laser measurements. Due to the large amount of laser measurements, this procedure should work simple and consequently fast. Using the morphological operator *Opening* for the processing of laser profiles, good results could be achieved in the past. For this reason this procedure was expanded to a 2D version to deal with the scanner data. To perform the morphological opening, first the deepest point inside a window of a certain size is detected. Each point inside a band width above this deepest

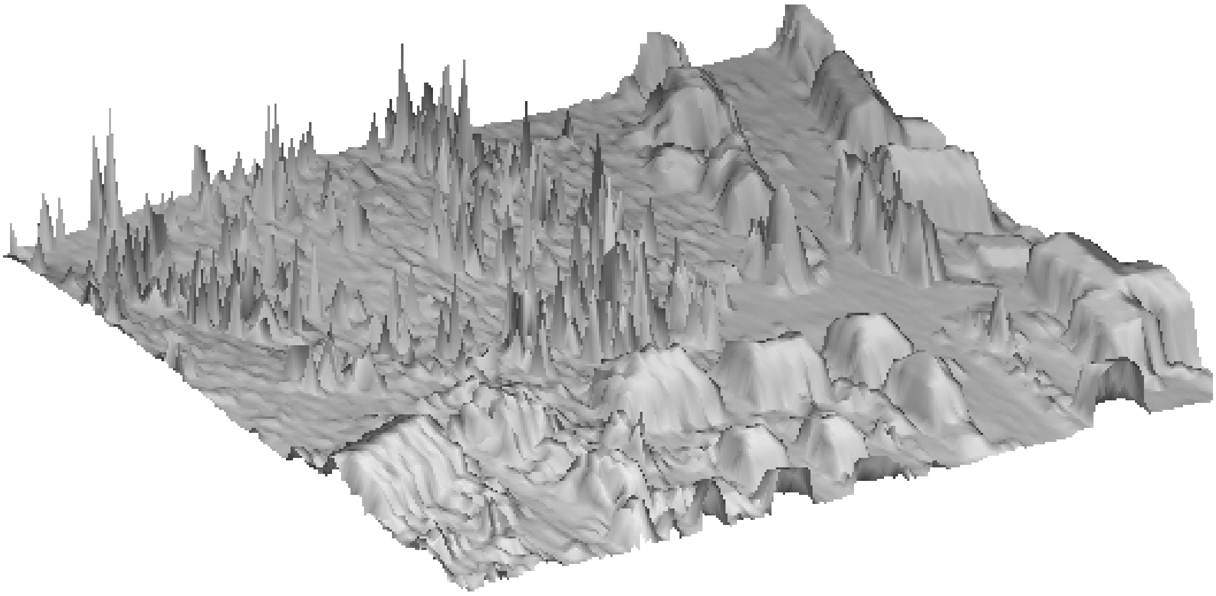


Figure 5: 3D-View of unfiltered laser data

point is defined as a approximated ground point. The used band width corresponds to the measuring accuracy of the used laser sensor. In this way the window is moved by a certain step size over the whole data set.

The main problem using this morphological operator is to define the optimal operator size, i.e. the size of the window that has to be examined. By the morphological processing not only vegetation, but also - especially in urban areas – large buildings have to be eliminated from the height data. Using a window entirely contained in a building's outlines results in "roof-points" which are falsely set as "ground points". On the other hand the operator should be small enough to preserve smaller forms of the topographic surface. Using a too large window size raises the probability, that e.g. in areas of a rounded hilltops over a greater distance no ground point can be found. Then it can happen, that in the preceding filtering and modeling step the rounded hilltop cannot be reconstructed, because there is a too large area with no approximation value in it, so that the hilltop could be cut off. In summary, the window size of the operator should be large enough to prevent the operator from running into roofs or into the foliage, and on the other side the window should be small enough to preserve also smaller forms of the topographic ground surface.

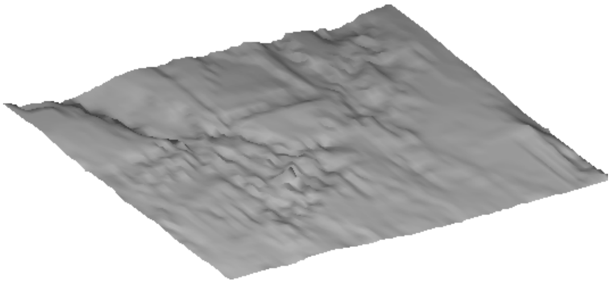


Figure 6: 3D-View of filtered laser data

This motivated the application of a multi-level procedure. The morphological operator *Opening* is applied several times with different window sizes starting with the smallest window size. Points which meet the condition to be within the band width higher than the deepest point in the applied window, get a certain weight depending on the window size; the larger the window size of the operator, the higher the weight for a laser point. After this step points which are likely to define the topographic surface posses a high, points which are likely to refer to object like buildings or trees posses a low weight. All measured laser points with their certain weight are used in the last step of the process to compute the terrain surface. As filter algorithm is used a smoothing (filtering) by means of approximating cubic splines subject to given constraints. The constraints contribute directly to the smoothness by consideration of the standard deviation (measuring accuracy of the laser sensor) of the data to be smoothed [Fritsch 1991]. The result of this process is shown in figure 6.

3.4 Derivation of further products

An important application for airborne laser scanner systems is the acquisition of three-dimensional databases for urban areas. Urban models consisting of a DTM and three-dimensional descriptions of buildings are e.g. required for tasks like 3D visualizations of urban scenes or for simulations like the propagation of electro-magnetic waves to plan optimal locations for transmitter stations.

Utilizing the classification of laser points, described in the previous section, different descriptions of the surface of the sensed object surfaces can be derived. If all measured points are included a Digital Surface Model (DSM) can be calculated which represents the terrain surface including the surface of objects rising from the terrain like buildings.

Besides the determination of laser points, which are likely to refer to the topographic terrain surface, the morphological processing which is described in the previous section can also be used to detect regions of the sensed surface, which are likely to define buildings. In order to reconstruct a 3D description of a building using the laser scanner data, DSM break-lines are extracted within regions, where buildings are expected, and matched against a parameterized building model [Haala 1995]. Figures 7 to 9 give an example of the executed 3D building reconstruction. Using the DSM shown in figure 7 a perspective view of the Digital Surface Model used for break-line extraction, the resulting CAD–like description of the reconstructed buildings is given in figure 8. For better visualization of the results, the roofs of the reconstructed buildings were additionally projected to the corresponding section of an aerial image (figure 9).

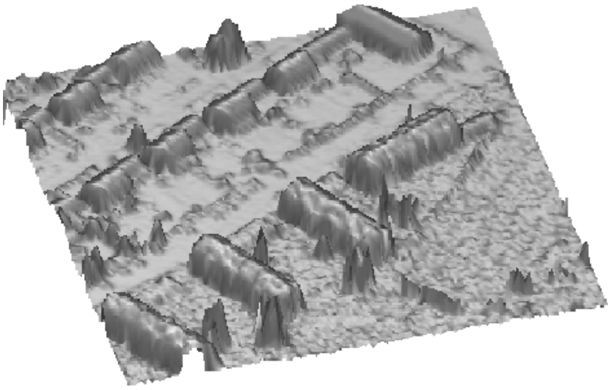


Figure 7: 3D view of used laser data

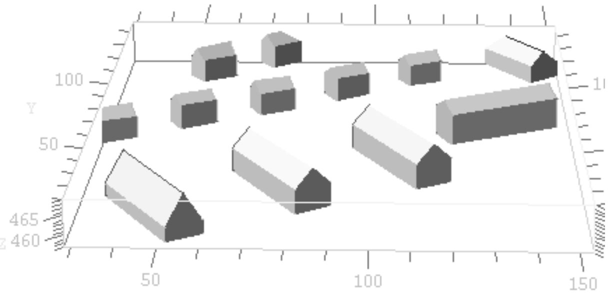


Figure 8: 3D view of reconstructed buildings

Figure 9: Houses projected to image

4 CONCLUSIONS

Using airborne laser scanning systems an direct 3D measurement of the terrain surface is possible. The derivation of different area covering 3D descriptions of the terrain surface, like Digital Terrain Modell or a Digital Surface Model can be performed by using different filtering processes on the laser data. Especially in regions, like forest areas or coastal areas, where photogrammetric data is difficult the presented system provides an excellent tool for fast and efficient 3D data capture. Fusing the distance information with other data sources, like intensity information for the 3D reconstruction of buildings shows additionally the enormous potential of this kind of information.

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