Quality Assessment of Laser-Scanner-Data

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ABSTRACT

Numerous publications deal with the precision of Digital Terrain Models (DTM) which is produced by airborne laser-scanning. This precision is influenced by several factors, that have different effects.
While the height-precision can be declared to be some dm, the horizontal precision sometimes is about one meter or even better. This in turn also has an effect on the height-precision, in fact, the steeper the terrain is. In order to determine the precision, the laser-data must be compared to some reference data. The planimetric accuracy of the data, for example on the basis of building-corners, is difficult mostly, since the laser-data often have only a too low point-density. Conclusions on the horizontal precision can be found, by comparing two independent terrain-models, which have been generated with two different systems.
The quality of a Laser-DTM also is heavily influenced by the quality of filtering of the raw laser data. Diverse mathematical models as well as algorithms can be used. A specific problem is the typical asymmetric error distribution of laser measurements when compared to reference data. The data show only small negative deviations to the terrain-surface (below the terrain-surface), however, relatively big positive deviations due to vegetation or buildings (above the terrain-surface). This general problem must be taken into account. If linear prediction is used as filtering method , it must be applied iterative, because otherwise the results are influenced strongly by those height points lying far above the mid-terrain-level. In our investigations satisfying results have been obtained in forest areas, other areas however show problems.

1. INTRODUCTION

Scanning of the terrain by means of airborne lasers represents an alternative to the traditional recording-methods to derive a Digital Terrain Model (DTM). Above all, in areas (for example forest) which are difficult to access by traditional methods this method is well suited to replace the time and cost-intensive terrestrial surveys. In fact, in forests with this method, as with photogrammetry points are measured on top of the vegetation, however the number of the ground-points is large enough in order to derive terrain-co-ordinates. The precision and quality of these data plays an important role. Systematic errors can be observed and influences the error-budget of these data at present, but also processing-steps of the measured distances to the terrain-height of the DTM are not flawless.

2. FACTORS INFLUENCING THE ACCURACY

The precision of a DTM generated by laser-scanning depends from three components primarily. This is:

- the distance-measurement
- the dynamic orientation of the sensor
- the dynamic position of the sensor

The precision of the laser-sensor, i.e. the primary distance-measurement, can be given by ±6 cm [KATZENBEISSER et al., 1996].

A precise determination of position and orientation becomes possible only by the combination of INS (Inertial Navigation System) and dGPS (differential GPS). None of the two systems is yielding the necessary precision for itself alone. The precision of the orientation is in the order of approximately 0,01°, while the precision of the position for the sensor is in the order of approx. 10 cm using carrier phase measurements.
In order to expound the influence of an INS error, a local co-ordinate-system is established through the airplane having its origin within the laser-sensor. An orientation error in flight-axis , i.e. the coordinate system is turned around this axis, will result in changes of position and height of the derived DTM. The DTM strip is inclined against the terrain. The resulting differences are small in the center of the strip and become bigger across track.
If the error in orientation is perpendicular to the flight axis, all points recorded across track are dis-

placed in location. The error in height is not noteworthy.
If the aircraft is turned about the local z-axis, small displacements of few cm appears at most. The closer the points are to the flight-axis, the smaller is this displacement.
But in any way a position error induced by orientation errors, can cause an error in height. The bigger the terrain-inclination is, the stronger is this effect.

The precision of GPS is a function of the number GPS-Satellites, their uniform distribution as well as the distance to the reference station. The two first-named factors play only a minor role because of the fully established GPS satellite system. The spacing of the reference-station to the examination-area should be less than 50 km.
The determination of position using dGPS comprises numerous possible systematic error-influences. Errors can be due to the orbit of the satellite or due to signal propagation (troposphere, ionosphere). The atmospheric effects are reduced generally by differencing and the use of two-frequency-receivers. The errors introduced by tropospheric effects however are important, since this might change quickly during a laser-scanner-flight-mission.
But also the determination of the ambiguities in the phase measurement can be a cause of a systematic error. The ambiguity is a unknown for each satellite which has to be to estimated once, if the satellite signal can be tracked continuously. A loss of the satellite signal decreases the attainable precision considerably, and the ambiguities must be solved again. In order to do so a predicted and therefore a probably erroneous position is used which as a consequence results in drift-effects in the following position calculations [ACKERMANN et al., 1992].

Remaining imprecisions in the GPS-positioning and in the INS-orientations may lead to different coordinate-values in neighboring overlapping flight-strips. By using appropriate methods the strips have to be adjusted to each other. With this adjustment, errors can occur in the overlap-area.

The calibration of the system components is of big importance for the precision of the overall system, i.e. for the preparation of the Digital Surface Model - as well as terrain-model. According to [LINDENBERGER, 1993] 9 components for the correction of systematic errors are computed by self-calibration, using laboratory and flight data. These are three parameters for the mounting-angles of the laser-sensor, three translation parameters to correct for constant errors in the GPS-positioning as well as three parameters of rotation to correct for systematic errors of the INS. Consideration should be given, if a correction of INS and GPS errors should be performed for the total area or if a strip-wise correction should be enforced. It could be observed that single strips can show different systematic behavior throughout. The errors induced by GPS and INS have to be determined by exterior information, by which the laser-measurements can be assigned to the terrain co-ordinate system.

2.1. Quality and precision measures

When assessing the quality and precision of a data set it is essential, that the quality and precision can be proofed, either by using an independent data set to check or independent sample measurements within the area of investigation. The surveying authorities, being one of the main contractors of laser scanner data, very often use flat football planes or GPS point measurement on streets for the checking of laser scanner data.
Sometimes photogrammetric measurements can be used, if this data is available at a time period comparable to that of the laser scanner flight. However photogrammetric measuring has some pointing difficulties in forest areas, therefore this type of measurement or check is often restricted to “open” areas.

In this case aerial photography at a scale of 1:6.000 was available and could be used to check the accuracy of the laser data. Unfortunately the images have been taken 2 years after the laser scanner flight. The area under investigation (see chapter 3.1) is suspect to terrain subsidence due to heavy mining activities. Despite this fact the accuracy of the laser scanner data with respect to the photogrammetric measurements was shown to be within ±10-30 cm. Taken into account the possible terrain subsidence the “true” accuracy is suspected to be even better.

This means, a statement about the final precision of the height-data also is always a function of the precision of the reference-data, a fact, which should not be neglected, when assessing accuracy and quality of this type of data.

3. COMPARISON OF TWO DIFFERENT LASER-SCANNER-SYSTEMS

In the west of Germany, a few kilometers north of the city Recklinghausen, an area has been surveyed by two different laser-scanner-systems. The company "TopScan Ltd." used the Canadian OPTECH instrument "Airborne Laser Terrain Mapping System ALTM 1020". The flight has been carried out in December 1996. The same area was covered by the company "TopoSys Topographische Systemdaten GmbH" in March as well as April 1998, therefore approximately 15 months later, using their laser-scanner-system [LOHR et al., 1995].

Both systems differ in functioning principle and imaging-geometry. Through comparison of both Digital Terrain Models conclusions can be made with respect to the relative horizontal and vertical precision.

3.1. Area of Investigation

The examination-area is in the west of Germany in the state North Rhine-Westphalia a few kilometers north of Recklinghausen. This is an area which is heavily influenced by coal mining and which suspect to terrain subsidence. Under the responsibility of the "Deutsche Steinkohle AG" (DSK) the company TopoSys was contracted to perform a laser scanner survey. The data set from the company TopScan originates from the surveying authority of North Rhine-Westphalia, who supplied the data for this study.

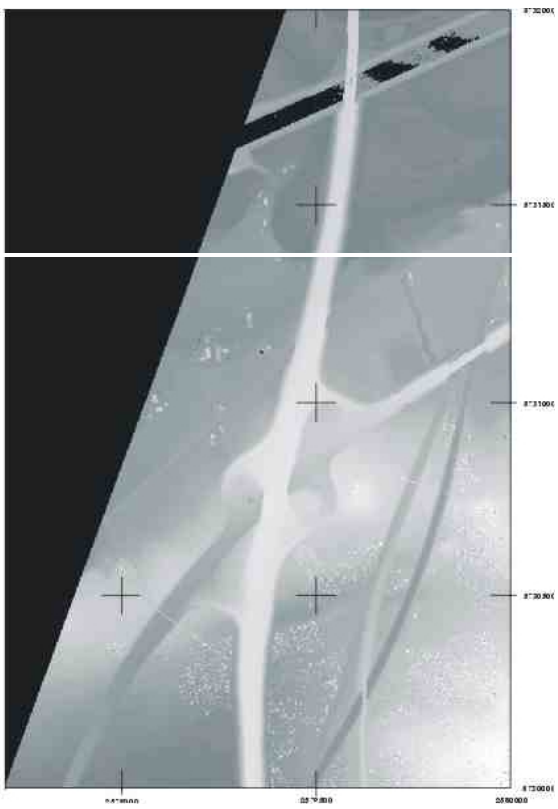

Figure 1: Area of investigation

Two highways, the A43 and the A52, lead through the area. In the center, the highway-cross is Marl-Nord, which connects both highways together. The Wesel-Datteln-Channel flows in the north. The channel is bordered by dikes (Figure 1).
Two railroad-lines, that proceed approximately from the north to the south, lie in the South-east area. The southern area is characterized mainly by forest.

The laser-scanner-data of TopoSys consists of sorted 1m-grid which has been generated by weighting the original measurements. The data of the raw measurements unfortunately was not available. In contrary the TopScan data consisted as original measurements however in irregular form. In order to compare both data sets only those measurements were compared whose position difference was smaller than 40 cm.

3.2. ALTM 1020 versus TopoSys-Laser-Sensor – A Comparison

The system ALTM 1020 of the company TopScan works with an oscillating mirror, that deflects the laser-beam across track. The mirror sweeps with a frequency of up to 50 Hz and a uses an active scan-angle of up to ±20° [REICHE et al., 1997].

Up to 2.000 distance-measurements per second can be carried out. This means, by combining the movements of mirror and airplane, a z-shaped line of points is projected to the ground. Figure 2 shows the imaging-geometry at the ground.

The width of the flight strips at an altitude of 900 m and at a scanangle of ±20° is approximately 655 m. If the mirror is operated with a frequency of 8 Hz, the point spacing becomes 3,60 m to 4,10 m, with one line holding approximately 170 points. In flight direction, the spacing can amount to up to 10 m. From this data an average point-density of 1 point per 26 m² follows.

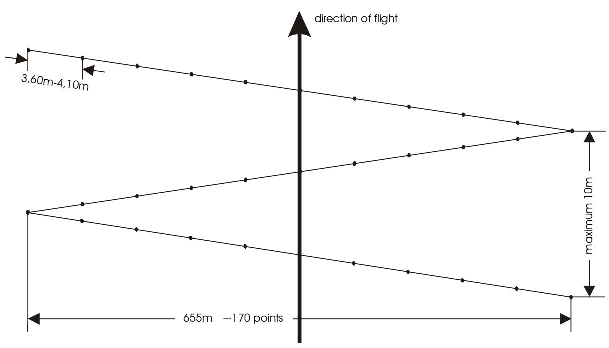

Figure 2: Imaging geometry of ALTM 1020

The TopoSys-Sensor works with help of a fiber glass bundle. The across-track resolution at a Field of View of ±7° is 127 points within each scan (Figure 3). This means, the spacing between two fibers amounts to 0,11°, which corresponds to a point-spacing of 1,73 m at a cruising altitude of 900 m. In flight direction, a spacing between two scans ranges from 0,11 to 0,13 m at a speed of 70-80 m/s. A point density of 4 to 5 samples per m² is thus achieved [LOHR et al., 1995].

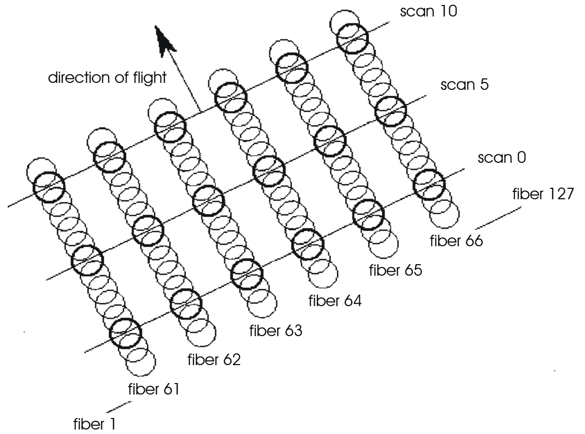

Figure 3: Imaging geometry of TopoSys-Sensor

The most important difference between both systems is the attainable point-density, being for the TopoSys-Sensor more than an order of magnitude larger than that of the ALTM.

3.3. Comparison of two DTM generated by Laser-Scanning

The comparison of two terrain-models produced through laser-measurements is based on a subset of 44.550 points. The TopoSys DTM is a sorted 1m-grid. The TopScan terrain-model is available in irregular form.

The DTM-differences were formed from the heights of these comparative points. The squared average in the sense of a standard-deviation could be calculated. This amounts to ±40,1 cm. This is however the standard-deviation of the differences only, since no one of the two terrain-models is assumed as reference. The compared heights are "true" ground-points exclusively, i.e. interpolated height-values were excluded before.

The mean value of the height-differences amounts to -1,9 cm, so that no considerable systematic effect can be recognized in the overall area. The dynamic range of the determined height-differences was divided into 5 cm wide intervals. The frequencies in the intervals were determined and are represented as histogram (Figure 4).

The interval +0,2 m marks the range between >+0,175 m and <+0,225 m. The total interval ±2,0 m contains in addition all differences, that exceed 2 m.

A first analysis shows, that the height-differences are normal-distributed. The maximum is at zero. However the frequencies represent a relatively flat bell-curve, since very many differences deviate strongly from zero.

By referring the observed differences to the locality, it was found, that these appear mainly in areas with higher terrain-inclinations (Figure 5). At objects, which have an inclinations in North-South direction, for example at dams as well as dikes, it can be demonstrated, that in the north positive and in the south negative height-differences appear. This can be observed at the dikes of the Wesel-Datteln-Channel and is observed also at the highway A52 to the east

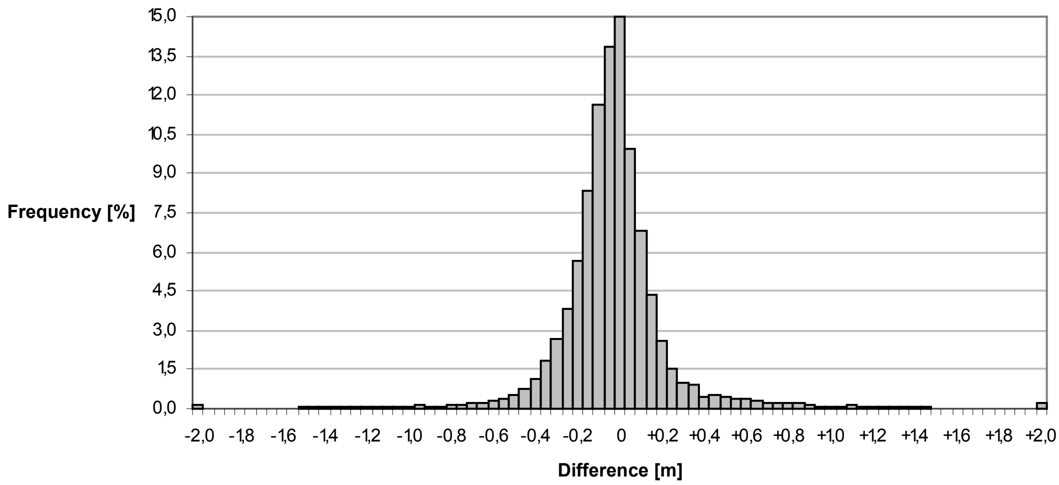

Figure 4: Histogram of Height Differences

of the highway-cross. All these objects are located above the mean terrain-level. At ditches, i.e. at objects below the mean terrain-level, the opposite sign was found. Examples for this are the railway tracks in the south-east area as well as the western part of the A52. This simultaneous appearance of positive and negative differences explains the low total-systematic behavior.
The highway-dam of the A43 in the examined area runs from the north to the south. Here, tendencies are hardly to be determined. In fact big height-differences also appear here, however, no considerable displacements can be observed by an analysis of the differences in this direction.

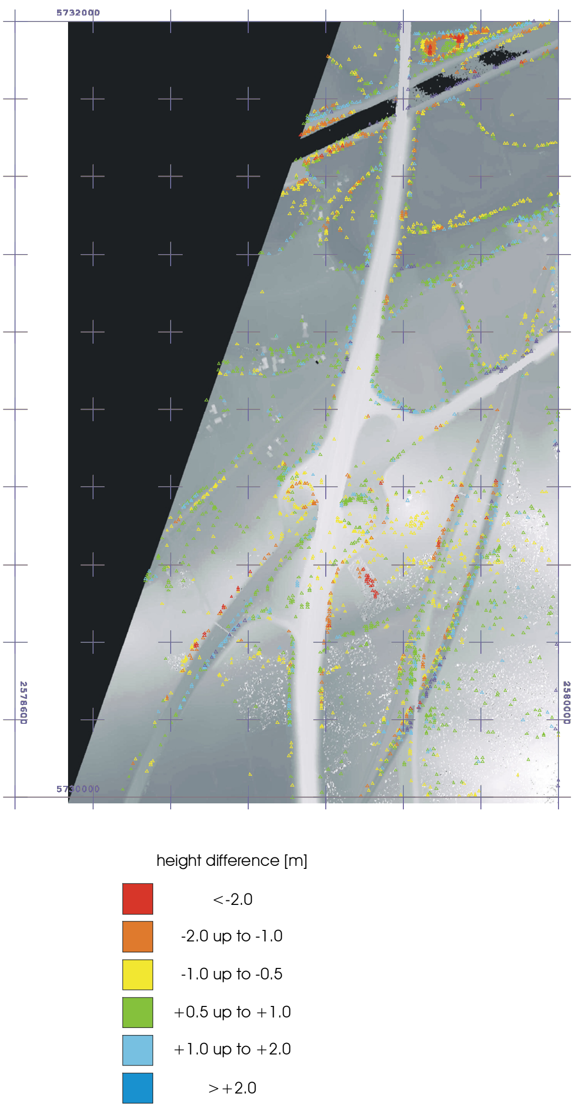

Figure 5: Observed differences

These observations are presumably due to a horizontal displacement between both DTM approximately in North-South-direction. Figure 6 shows the theoretical arrangement of the differences at objects above and below the mean terrain-level.

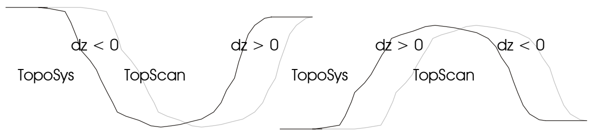

Figure 6: Theoretical arrangement of the differences

Through examination of several North south profiles distributed over the area an amount of 4 to 5 meters could be determined.
A possible cause of this horizontal displacement as well as the bad horizontal precision of a terrain-model produced through laser-measurements might be the bad precision of the reference-data used, while processing the raw data.
TopoSys has used digitized DGK5 (scanned base maps 1:5.000) for the horizontal-control. These show only a horizontal-precision of 1 to 3 meters, so that the imprecision of these reference-data propagates. The way horizontal-control is being done by the company TopScan is not known. However a possible discrepancy based on the above is easy to be explained without further analyzing the models. The experience of other projects has shown, that the horizontal-precision of a terrain-model produced through lasers is better than one meter [HOSS, 1997].
After exclusion of the areas influenced by bigger terrain-inclinations (steep slopes), the squared-mean of the height-differences reduced to approximately 2 dm, which meets the requirements of the desired height-precision of a Laser-DTM [AXELSSON et al., 1999].
The examined area is an area, that is exposed to subsidence by mining. Local systematic height differences can be explained according to the existing model of the DSK and therefore as a consequence of the temporal difference between the surveys.

4. DTM-FILTERING

Removing of the height-values, which are characterized as vegetation or building points, is called filtering. There are diverse methods and procedures for the implementation of filters [ECKSTEIN et al., 1995], [LOHMANN et al., 1998], like:

- Morphological Filters [REICHE et al., 1997]

- Linear Prediction [KRAUS, 1997]
- Spline-Approximation [BORKOWSKI et al., 1997]
- Shift invariant filters

Frequently morphological filtering is used. But also the method of linear prediction serves as a robust tool to the filtering of digital-surface-models.

4.1. Linear Prediction

The linear prediction is a statistical interpolation-method. It is applied, where functions are present, that can not be represented in analytical form, like a DSM (Digital Surface Model), which is a continuum. Therefore linear prediction for the interpolation and filtering is useful for this task.
The elaborate algorithm has been published many times, so that only a short overview is presented [KRAUS, 1997].

The interpolated surface in the point P_i is given by:

$$u_i = \underline{c}^T \underline{C}^{-1} \underline{z} \tag{1}$$

$$\underline{c}^T = \left[C(P_iP_1) \quad C(P_iP_2) \quad \cdots \quad C(P_iP_n)\right]$$

$$\underline{C} = \begin{bmatrix} \underline{V_{zz}} & C(P_1P_2) & \cdots & C(P_1P_n) \\ C(P_2P_1) & \underline{V_{zz}} & \cdots & C(P_2P_n) \\ \vdots & & \ddots & \vdots \\ C(P_nP_1) & C(P_nP_2) & \cdots & \underline{V_{zz}} \end{bmatrix}$$

$$\underline{z} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix}$$

u_i predicted value
$\underline{c}$ covariances between point to be interpolated and measurements
$\underline{C}$ covariance matrix
$\underline{z}$ vector of centered measurements

$C(P_iP_k)$ is the covariance function and has the general form:

$$C(P_iP_k) = A \cdot e^{-\left(\frac{\overline{P_iP_k}}{B}\right)^2} \tag{2}$$

The covariance between two points P_i and P_k is dependent on their reciprocal spacing. If the points are close to each other, the covariance is high. With growing distance, the covariance tends against zero. A is the vertex-value, therefore the covariance for the spacing zero. B describes the slope of the covariance function.
The parameters of the covariance function are either known, or they are determined empirically.
The prerequisites for the application of a covariance function are given only, if a trend function is separated beforehand. The separation of the trend can take place by means of a polynomial of very low degree or a moving plane. The result is the vector $\underline{z}$, which contains the centered points of measurement z_i. These values describe the deviations of the sample points from the polynomial or the moving plane. The matrix $\underline{C}$ contains the covariances between the points of measurement. Interpolation with filtering is applied, if the main-diagonal contains the variances V_{zz} of the centered points of measurement. Residuals appear at these points. The height-measurements are thus corrected for the noise.

4.2. The program DTMCOR

By means of DTMCOR a Digital Terrain Model could be analyzed. The search for blunders is done by input of minimum and maximum height and a local linear prediction [JACOBSEN, 1999].
Trend separation within DTMCOR is performed by the calculation of a moving plane, which is defined by three unknown coefficients a_0, a_1, a_2:

$$Z_i = a_0 + a_1 X_i + a_2 Y_i \tag{3}$$

The area of investigation is divided into meshes of equal size (Figure 7). While processing the points of one mesh (processing unit = 1 mesh) the bordering meshes are also considered (8 surrounding meshes). The coefficients a_0, a_1, a_2 are computed by the measurements of the height-points P_j within the 9 meshes using an adjustment. This means the moving plane is adjusted to all points within the area of consideration ($j = 1, \ldots, n$; n = number of points within the area of consideration).

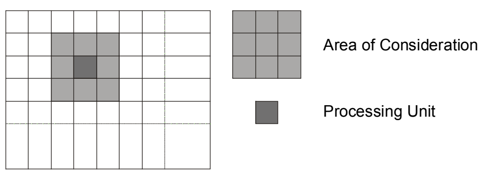

Figure 7: Area of Consideration, Processing Unit

By the separation of the trend-function the centered measurement-values z_i are obtained, which describe the difference to the moving plane. Assuming a normal distribution the standard-deviation s of the centered fit-points is computed and a multiplication-factor *fac* is entered to the program. The program then computes a tolerance-factor l_{tp} with respect to the moving plane.

$$l_{tp} = fac \cdot s \tag{4}$$

The points in the respective area of consideration, whose deviations are above this tolerance, are excluded. The trend-splitting is enforced iteratively, i.e. repeated several times, until no more faulty height-value is recognized. The height-outliers being in the treatment-mesh are deleted from the record. The heights as such recognized in the neighbor-meshes are available for computation of the next mesh again. They only remain unconsidered within the current mesh.
The iterative procedure for trend removing is clarified by Figure 8.
It shows a typical height-profile within a forest. The height-profile comprises 9 measurements. Three of these values are outliers, they deviate strongly from the mid-terrain-level, which has a value of 63 to 64 m. The orientation of the moving plane, represented through a straight line, varies quite strongly with each iteration-step. For each iteration the moving plane is shown in different line-width and tones of gray. The affiliated height-value for each iteration is marked likewise. Four iterations are necessary, until the moving plane fits the terrain-surface optimally and no more blunders are identified. The standard deviation decreases from iteration to iteration drastically. First the largest blunder is removed, then in the following iteration-steps, the smaller blunders are deleted.

The covariance function used within DTMCOR has the following form:

$$C\left(P_i P_k\right) = A \cdot e^{-1{,}30103 \cdot \left(\frac{\overline{P_i P_k}}{B}\right)^2} \tag{5}$$

A and B are parameters, that are defined in the dialogue between the program and the users. A is the vertex-value of the signal-covariance-function, which is restricted within DTMCOR at 0.99. B describes the distance, in which the effect of the covariance function is reduced to approximately 27%. Furthermore its value limits the width of the mesh for the local prediction (Figure 7).

The interpolated surface is defined by equation (1). The principal-diagonal of the matrix $\underline{C}$ contains the variances V_{zz} = 1,0. All measurements are regarded to be of equal accuracy. Since the vertex-value of the signal-covariance-function A was found to be optimal at a value of 0.7, interpolation and filtering is performed.

The higher the vertex-value of the signal-covariance-function is, the smaller is the variance σ_z^2 and the smaller is the filtering effect (Figure 9).

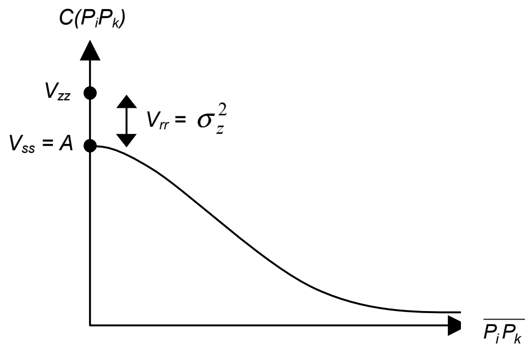

Figure 9: Covariance function

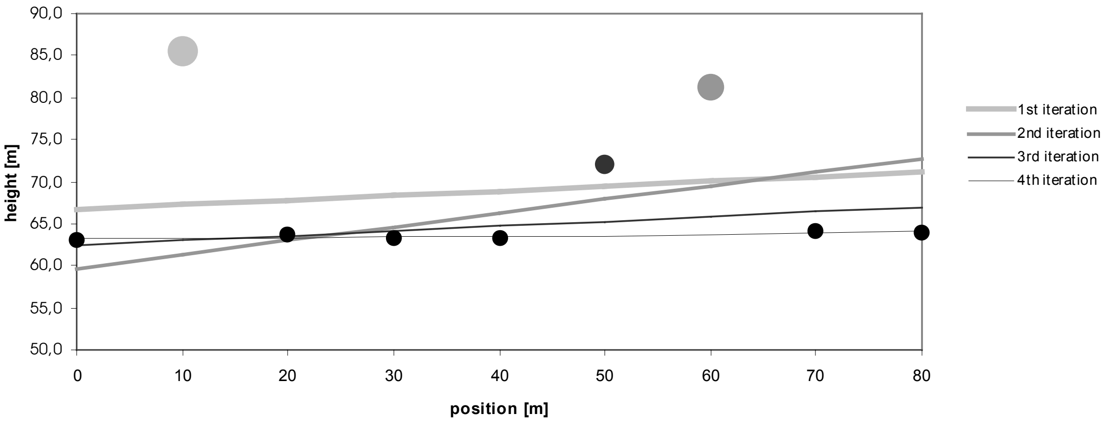

Figure 8: Principal of iterative trend removal

The difference between centered measurement-value z_i and the value calculated by prediction u_i is formed in the point P_i:

$$\bar{z}_i = z_i - u_i \qquad (6)$$

If the resulting values $\bar{z}_i$ are bigger than a predefined threshold, these points are also eliminated.

4.3. Results of filtering with DTMCOR

The filtering of digital-surface-models with help of the program DTMCOR is analyzed on the basis of a test-site. The area is covered with dense coniferous-forest, but also some streets are present. The area in total is about 3,2 km².
A reduced 10-m grid has been used as basic data set.

31.783 points with a grid spacing of 10 m are included within this surface model, out of which 4.317 points or 13.58% had been found by DTMCOR as not belonging to the surface. 3.855 points had been deleted by the iterative trend removal and 462 points were found outside the tolerance to the predicted surface. By looking at the filtered height-values it becomes obvious, that there are small areas in which points are eliminated linewise (Figure 10). These areas are considered to be embankments as well as breaklines within the terrain. By abrupt height-alterations of the terrain, ground-points are deleted from the record, the terrain is smoothed. These facts demonstrate the problems in areas with rapid changing slope (breaklines).

5. CONCLUSIONS

While the height-precision of a Digital-Terrain-Model produced through laser-measurements can be declared to be within 1 to 3 dm, the horizontal-precision in this case was unexpectedly found to be in the order of a few meters. Systematic errors are the main reason for this imprecision. Uncertainties in the GPS-Position - and INS-orientation and the use of inappropriate reference material may be responsible. The minimization of these systematic influences as well as an improvement of the existing filter methods will help to improve the quality and accuracy of these types of laser-scanner height-data.
If the linear prediction is chosen for filtering of digital-surface-models, a local adoption to the existing topography has to be done. Areas with big height-undulations represent problem areas and an further improvement of the existing algorithms is necessary.

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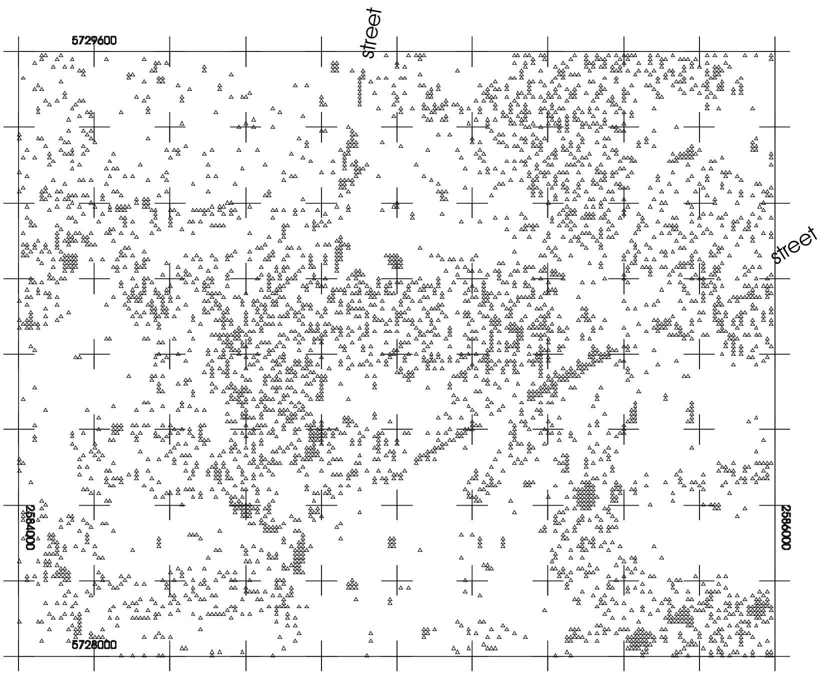

Figure 10: Results of Filtering with DTMCOR, eliminated points

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