

ADVANCED DTM GENERATION FROM LIDAR DATA

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ABSTRACT

The introduction of laser scanning has triggered off a revolution in topographic terrain capturing, especially in the generation of digital terrain models (DTM). In this article refined methods for the restitution of airborne LIDAR data are presented which have been developed at the Institute of Photogrammetry and Remote Sensing (Institut für Photogrammetrie und Fernerkundung, I.P.F.) at Vienna University of Technology. First, a technique for the calibration of laser scanner data is introduced. The (height) discrepancies between overlapping strips, as well as control points with known co-ordinates are utilised for a simultaneous adjustment and transformation of all strips into a state wide co-ordinate system. The next step of LIDAR data processing are the filtering (elimination of vegetation and building points, generally off-terrain points) and the interpolation of the (bald earth) surface. The method, developed at the I.P.F., distinguishes itself in the integration of filtering and terrain interpolation in one process (advantage: even in steep terrain ground points are classified correctly) as well as in the application of data pyramids (advantage: even in very dense forest areas and on large buildings, off-terrain points are eliminated). In order to generate a terrain model with high geo-morphological quality, methods are required for deriving structural line information (e.g. break lines) from laser scanner data. The first method which will be presented, proceeds by a simulation of rain fall over the preliminary DTM (water flow analysis). This yields an identification of the pits with their pit base and the outflow (overflow) point. Subsequently, the terrain shape is changed in order to eliminate the pits. In a further method 3D break lines are derived from the original laser scanner points. The precondition is that the ground plan of the break line is known approximately. The result of this step are 3D-splines which are integrated in the hybrid DTM, combining raster and vector data.

KURZFASSUNG

Das Laser-Scanning hat die topographische Geländeaufnahme, insbesondere die Erstellung digitaler Geländemodelle (DGM) revolutioniert. In diesem Beitrag werden verfeinerte Auswertemethoden vorgestellt, die am Institut für Photogrammetrie und Fernerkundung der TU Wien (I.P.F.) in den letzten Jahren entwickelt wurden. Zuerst wird ein Verfahren zur Kalibrierung von Laser-Scanner-Daten angegeben. Anhand von (Höhen-)Diskrepanzen zwischen den überlappenden Streifen und von koordinatenmäßig bekannten Passpunkten wird eine simultane Einpassung aller Streifen in das Landeskoordinatensystem vorgenommen.

Der nächste Abschnitt ist der Filterung (Elimination der Vegetations- und Gebäudepunkte) und Interpolation der Geländeoberfläche gewidmet. Das am I.P.F. entwickelte Verfahren zeichnet sich dadurch aus, dass einerseits die Filterung gemeinsam mit der Interpolation erfolgt (Vorteil: Auch im steilen Gelände werden Bodenpunkte als DGM-Punkte erkannt) und dass andererseits Datenpyramiden verwendet werden (Vorteil: Auch Laser-Scanner-Punkte in großen dichten Waldgebieten und auf großflächigen Gebäuden werden eliminiert).

Im letzten Abschnitt werden aus Laser-Scanner-Daten Strukturlinien abgeleitet. Im ersten Verfahren werden mittels Regensimulationen im (vorläufigen) Laser-DGM abflusslose Mulden detektiert. Anschließend wird die Form des DGM so verändert, dass die abflusslosen Mulden verschwinden. Im zweiten Verfahren werden 3D-Geländekanten aus den originären Laser-Punkten abgeleitet. Voraussetzung ist dabei, dass die Geländekanten im Grundriss näherungsweise bekannt sind. Das Ergebnis sind 3D-Splines, die im hybriden DGM, das ist ein DGM mit Raster- und Vektordaten, integriert werden.

1 INTRODUCTION

In Europe the term "Airborne Laser Scanning" instead of LIDAR is used frequently. Airborne laser scanning for topographic mapping is a widely used technology. The pros and cons of LIDAR vs. aerial photogrammetry, up to now the method of choice for topographic mapping, are well known. Airborne laser scanning has gained utmost significance for the generation of digital terrain models (DTM). A prospering technology stimulates a continual development and improvement of methods and algorithms. In this article advanced methods for the generation of DTMs from LIDAR data are presented. It will be confined to methods which have been developed at the Institute of Photogrammetry and

Remote Sensing of the Vienna University of Technology (I.P.F.), which have been (and still are) realised in software and put to the test in pilot projects. We will start with a contribution to the system calibration.

2 SYSTEM CALIBRATION

For transforming laser scanner strips into the national ground survey co-ordinate system using dGPS and INS, we principally need only one ground reference station with known ground survey co-ordinates. Moreover, we also need the form of the geoid. But, in practice, we should not be satisfied with that minimal solution because:

- The form of the geoid is not sufficiently (up to some few cm) known in many regions.
- Nowadays the on-the-fly-initialisation for solving the GPS phase ambiguities is possible for fast moving objects like aircrafts with a r.m.s.e. of about 10cm; this might result in errors of some dm. Usually, neighboring precision of dGPS is better by one order of magnitude.
- The attitudes as delivered from IMUs in use are prone to errors of about $\pm 0.01^\circ$. Errors of IMU attitude also introduce some torsion of the laser scanner strips inducing errors in height on both borders of the strip. Equally, IMU attitudes have a high neighboring precision based on the gyros used; nevertheless, they show drifting phenomena.
- System failure or system instabilities shall be mentioned, too: e.g. the change of the set of available GPS satellites during a strip might cause some displacement; however, IMU data helps to bridge such critical gaps.
- Last, but not least, the missing supervision of the whole measuring process has to be mentioned.

Instead of the minimal solution cited above (single ground reference station and geoid) the subsequent alternative is proposed which eliminates the shortcomings of the above:

- Use of more GPS ground reference stations surrounding the area of interest. Knowing the ground survey co-ordinates of all these ground reference stations, this also eliminates the (unknown) linear portion of the geoid's undulation. The undulations of higher degree remain; they might be neglected for the usually relative small extent of practical projects.
- Some of the GPS ground reference stations may be replaced by ground reference points which can be "identified" somehow in the point clouds of the laser scanner strips. For height fitting, horizontal areas free of vegetation are recommended. In photogrammetric terminology, we usually call those reference points control points.
- Monitoring many height discrepancies in the overlapping areas of neighboring laser scanner strips. The systematic portion of these discrepancies should be eliminated. This can be achieved by computing correction polynomials (of probably quite low degree) for each strip: one strip - one polynomial. This procedure preserves the high neighboring precision of both system components and copes with any drifting phenomena. The adjustment of all these sets of coefficients of the polynomials has to be done simultaneously for all strips of a block (key word: block adjustment by strips) – using the heights of corresponding points in the overlapping areas as observations. The height residuals are to be minimised in the adjustment.

The principles of the height fitting of all laser scanner strips simultaneously can be found in fig. 1. XY-positions are defined in a scheme which is – on the one hand – related to the strip borders and – on the other hand – controllable from outside. This control is performed by selection of an interval of the profiles crossing the strips and of a point interval inside the profiles. The first distance is measured (more or less) along the flying track, the second one perpendicular to the first one. Points are preferably chosen in areas of much overlap. Starting from every scheme point, a search for *suitable homologous patches* is done; 'suitable' means that there is as few vegetation as possible and the area is as horizontal as possible, 'homologous' means that the patch has the same position in every involved strip, 'patch' means a rectangular area (externally controllable) of e.g. 20 points.

The set of surfaces inside a patch region is approximated by a set of parallel (tilted) planes:

$$\begin{aligned}
 v_{t,s,p} &= a_t (\bar{X}_{t,s,p} - X_t) + b_t (\bar{Y}_{t,s,p} - Y_t) + c_{t,s} - \bar{Z}_{t,s,p} \\
 \bar{X}_{t,s,p}, \bar{Y}_{t,s,p}, \bar{Z}_{t,s,p} &\dots \text{ point } p \text{ in patch } t \text{ of strip } s; \text{ "raw" co-ordinates} \\
 X_t, Y_t &\dots \text{ center of patch } t; \text{ constant; modulated as given below} \\
 a_t, b_t &\dots \text{ tilting of patch } t \\
 c_{t,s} &\dots \text{ height of patch } t \text{ in strip } s; \text{ the only parameter of interest} \\
 v_{t,s,p} &\dots \text{ residuals of the least squares adjustment}
 \end{aligned}$$

The search for (X_t, Y_t) follows a spiral pattern in the surrounding of the scheme point until certain quality criteria are satisfied: e.g. freedom of vegetation or other disturbances is judged by a tolerance of the r.m.s.e. of the above adjustment problem. Horizontality can be judged on a_t, b_t . Freedom of vegetation can be accomplished by a sort of robust estimation procedure as outlined in the next section by using a skew (asymmetric) weighting function for the above observation equations. The patch size is chosen in accordance with the geometry of the scanner (point density along and across the strip) to contain about 20 to 150 points per strip overlay. Planimetric discrepancies between the strips don't play a remarkable role as long as the terrain is flat enough.

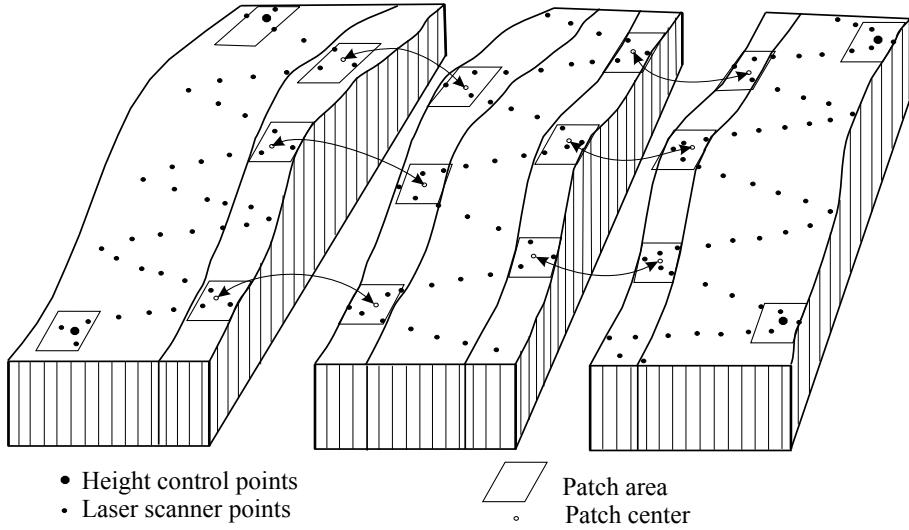


Figure 1: Principle of height block adjustment with laser scanner strips

Subsequently, the points $P_{t,s} = (X_t, Y_t, \bar{Z}_{t,s} := c_{t,s})$ are used as observations in the block adjustment. The unknowns are, as mentioned before, the coefficients of the correction polynomials. The details of the block adjustment with the ORIENT software are described in [Kager and Kraus, 2001].

For a pilot project with the „Bundesanstalt für Gewässerkunde“ in Koblenz (Germany), the “German Federal Institute of Hydrology” we had no suitable control points available. Thus, an absolute fit to the national ground survey co-ordinate system was not possible (no datum given). Nevertheless, the aim of the project was a homogenisation of the block of 56 strips by diminution of the discrepancies between overlapping strips. The scheme points for the automatic measurement of tie points were arranged in profiles at right angles to the main direction of the strips with profile distances of 1000m. (Experiments with smaller profile distances yield approximately the same results.) The height discrepancies between the laser scanner strips prior to adjustment were determined for 1495 patches. The r.m.s.e. was $\pm 10.7\text{cm}$. By the block adjustment we got a reduction of the factor 2.

In a second pilot project – in the framework of European Union INTERREG projects – we obtained an improvement by the block adjustment of the factor 2.5.

3 FILTERING OF LIDAR DATA AND INTERPOLATION OF THE TERRAIN SURFACE

For the time being, filtering shall be used for the elimination of off-terrain points (points on buildings and trees or bushes) in a LIDAR data set. Such a filtering is a classification in terrain points and off-terrain points. Often, the filtering is performed independently from the interpolation of the terrain surface. If the shape of the terrain is not regarded during the filter process – especially in steep terrain – this can lead to wrong classification results.

Fig. 2 can be used to illustrate this. If the points are only analysed with respect to their absolute terrain height, then off-terrain points can be lower than surrounding ground points. In the upper part of the figure this is the case in the second interval, where a point on the low vegetation is lower than the real ground points in the interval. Of course, this can also be the case for points on the higher vegetation and on buildings.

At the I.P.F. a solution has been found, which combines filtering and interpolation of the terrain. It is called a robust interpolation or robust linear prediction. This algorithm was originally designed for laser data in wooded areas. For a comprehensive description see [Kraus and Pfeifer, 1998] and [Pfeifer et al., 2001]. The algorithm is embedded in a hierachial approach, however, the filtering of the laser scanner data on one level will be described first.

In this algorithm a rough approximation of the surface is computed first. Next, the residuals, i.e. the oriented distances from the surface to the measured points, are computed. Each (z -)measurement is given a weight according to its distance value, which is the parameter of a *weight function*. The surface is then recomputed under the consideration of the weights. A point with a high weight will attract the surface, resulting in a small residual at this point, whereas a point that has been assigned a low weight will have little influence on the run of the surface. During these iterations a classification is preformed, too. If an oriented distance is above a certain value, the point is classified as off-terrain point and eliminated completely from this surface interpolation. This process of weight iteration is repeated until all gross errors are eliminated (a stable situation) or a maximum number of iterations is reached.

There are two important entities in this algorithm. On one hand, the stochastic model, which is defined by the weight function, on the other hand, the functional model, which describes the way the surface is interpolated. Obviously, the weight function must assign high values (close to 1) to ground points, which are below or on the averaging surface, and low values (weights close to 0) to the vegetation points which are above the averaging surface. The standard weight

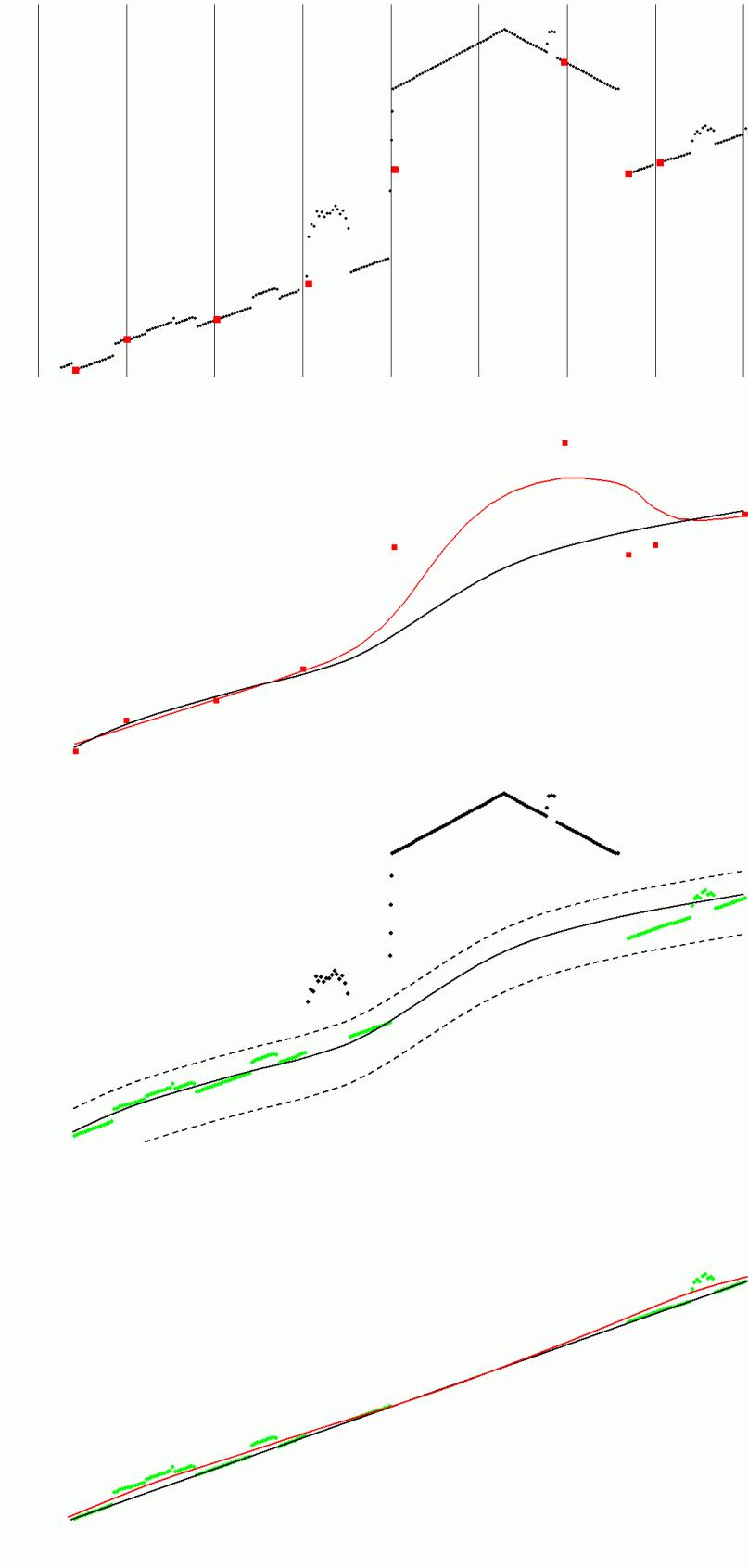


Figure 2: Schematic explanation of hierachic robust interpolation by means of a profile of laser scanner points.

First image: original points, the lowest point in a regular 5m interval (grid in 3D) is marked as larger (red) square.

Second image: selection of points in a regular interval, averaging surface shown as thin (red) line, surface (DTM) after robust filtering with skew gross error distribution as thick line.

Third image: surface of previous step (rough terrain approximation) and original points. The dashed lines delimit a buffer zone around the DTM of the precious step. Points within this buffer are selected.

Fourth image: selected points, averaging surface approximation as thin (red) line, surface (DTM) after robust filtering as thick line. This final surface is the DTM computed from the original ground points.

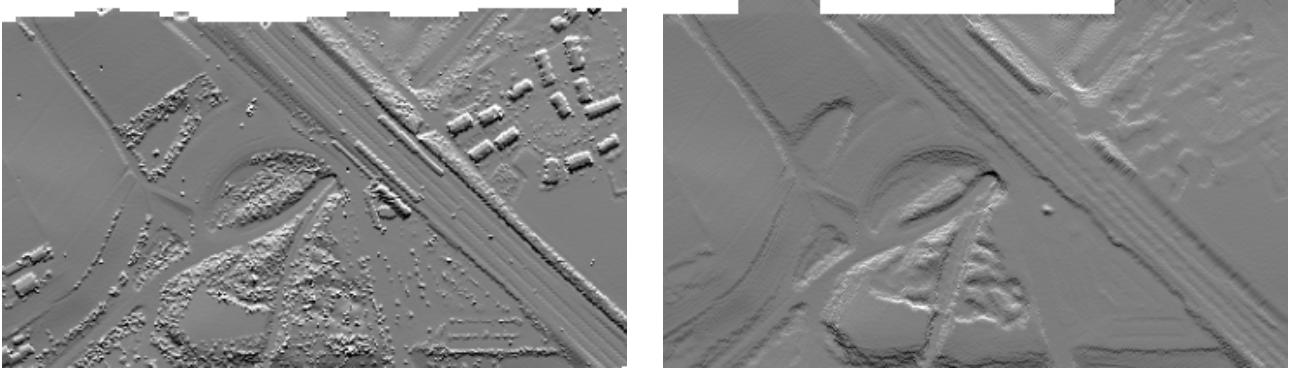


Figure 3: Vaihingen, original (left) vs. filtered data (right) in a shading

function of robust adjustment (used for example in bundle block triangulation) can be adapted to suit the needs for the interpolation and classification of laser scanner data. The function we use is not symmetrical, allowing a sharper decline for values above its origin (residuals belonging to vegetation points), and a slower decline – or no decline at all – for the ground point residuals. Furthermore, the weight function does not need to be centered on the zero-point of the real axis. It can be shifted to the left (into the negative) for the interpolation of laser scanner data. What is more, the shift of the origin can be determined automatically, depending on the given data itself.

For the interpolation (functional model) we use linear prediction which is very similar to kriging [Kraus, 1998]. The covariance function (i.e. the basis function, corresponding to the variogram of kriging) is determined automatically, depending on the data itself. In this method the classification and DTM generation are performed in one step, there is no assumption that the terrain is horizontal. It is applied patch wise to the data, which results in an adaptive setting of the shift of the origin of the weight function. Furthermore, the basis functions are determined for each patch separately, too. The process yields a smooth surface, that means that the accidental (random) measurement errors have also been filtered.

However, the algorithm relies on a ‘good mixture’ of ground and off-terrain (vegetation) points, which can also be seen as a high frequency of change from ground to vegetation points. This is necessary for a reliable determination of the shift value for the origin of the weight function. If this high frequency is not given, we need to provide the input data (i.e. the points) in a suitable form. This can be achieved by inserting the robust linear prediction in a hierachic environment.

The approach is comparable to a hierarchical setup using image pyramids, in our case data pyramids. The structure of these pyramids is regular (as in image processing) and typically two or three levels are sufficient. However, in comparison to image analysis, the reduction function operates on point data, not on pixels. (If the laser scanner data is provided as a digital geo-coded image where the grey values represent the terrain heights, the pyramids would indeed be image pyramids.) The method proceeds as follows (see fig. 2):

1. Create the data sets with the lower resolutions,
2. filter the data with robust linear prediction and generate a DTM,
3. compare the DTM to the data of higher resolution and take points within a certain interval.

This process is repeated for each level. The *surface of a level with lower resolution* is used for a computation of the next surface with the *points of a higher resolution*. Of course, this procedure can be applied to any data set of laser scanner data. However, its advantages become more and more important if the data sets become more and more dense. The method speeds up the filter process, enforces the elimination of houses and dense vegetation and makes the process more robust.

Details of the hierarchical approach, the implementation in the SCOP software and the results of some examples are described in [Pfeifer et al., 2001] and [Pfeifer and Briese, 2001]. Fig. 3 is an example of the OEEPE test Vaihingen. On the left we see the surface interpolated using the original data (0.23 points/m^2). On the right is the DTM derived by the hierarchical approach without any manual intervention.

4 DERIVATION OF STRUCTURE LINES

The laser scanner data are a point cloud without structural line information. A qualified terrain model, on the other hand, excels in the inclusion of structure lines, esp. break lines. A terrain model, integrating a close drawn grid (raster data) and structure lines (vector data), is called a hybrid DTM. The raster data as well as the vector data are smoothed, the hybrid DTM shows discontinuities in the first derivation at the break lines (details: [Kraus, 2000]).

4.1 Water Flow Analysis

DTMs which are derived from filtered and interpolated laser scanning data have low geo-morphological quality. In valleys there are many spurious pits. The hydrological and geo-morphological tradition suggests that fluvially dominated

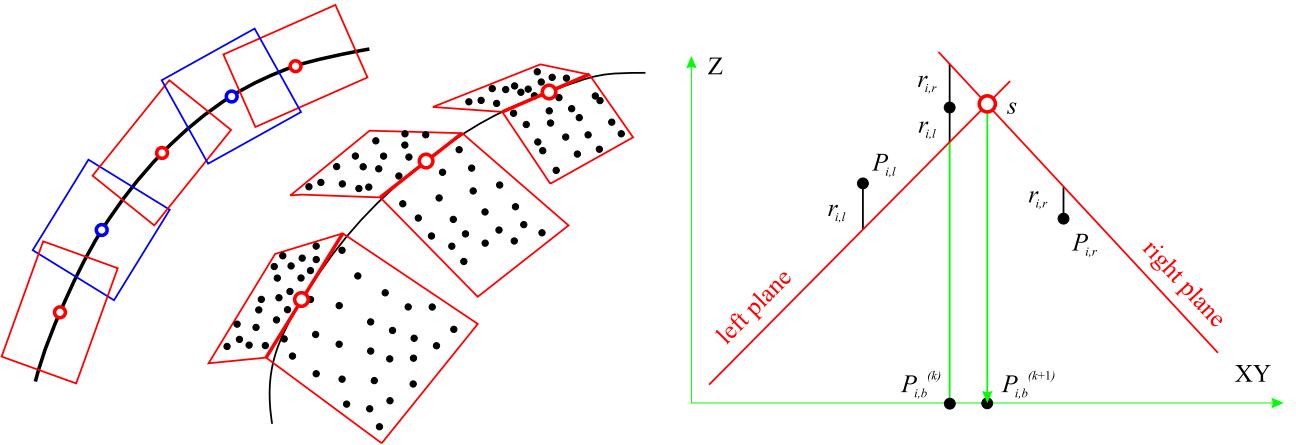


Figure 4: Left and middle: overlapping plane pairs along a break line in a ground plan and axonometric view. Right: one plane pair, the intersection line s appears as a point in this view.

landscapes rarely contain pits since the process of water transport and erosion precludes their development. Thus, the spurious pits in the DTMs must be removed. One standard method of identifying morphometric features is to apply a water flow analysis on the DTM [Rieger, 1992]. As a result of such a procedure 3D structure lines – i.e. river lines, which show the highest amount of water transport within a catchment area – are obtained. These lines are included in the following interpolation process as break lines. The new DTM has no (artificial) pits anymore. Details on this method and its performance for laser scanner data can be found in [Gaisky, 2000].

4.2 Derivation of Break Lines

In the course of a diploma thesis – carried out by Mr. A. Brzank from Dresden University of Technology at our institute – a new method for the derivation of break lines emerged. This method requires that the run of the break line is known approximately in the ground plan. For this task, the planimetric derivation of break lines, different solutions exist (e.g. [Rieger et al., 1999] and [Brügelmann, 2000]), which use digital image processing tools.

The principle is sketched in fig. 4 (left part). The approximation of the break line provides a classification (separation) of the laser scanner points in ‘left’ and ‘right’ (subscripts l and r). Furthermore, the points are grouped into overlapping patches along the break line. In each patch a so-called ‘plane pair’ is determined. It consists of two planes which intersect in the line s . The two planes of one pair are determined simultaneously with the following equations for a least squares adjustment (right part of fig. 4).

The equations for the adjustment are (r are the residuals):

$$\begin{aligned} \text{3D points } P_{i,l}, \text{ left side:} \quad r_{i,l} &= +\underline{a_l}X_{i,l} + \underline{b_l}Y_{i,l} + \underline{c_l} & -Z_{i,l} \\ \text{3D points } P_{i,r}, \text{ right side:} \quad r_{i,r} &= +\underline{a_r}X_{i,r} + \underline{b_r}Y_{i,r} + \underline{c_r} & -Z_{i,r} \\ \text{2D points } P_{i,b}, \text{ prel. break line:} \quad r_{i,l} &= +\underline{a_l}X_{i,b} + \underline{b_l}Y_{i,b} + \underline{c_l} - Z_i & -Z_i \\ & r_{i,r} = -Z_i + \underline{a_r}X_{i,b} + \underline{b_r}Y_{i,b} + \underline{c_r} \end{aligned}$$

Each 3D-point contributes with one equation to the least squares adjustment, each 2d-point (the ones on the preliminary break line) with two equations. The unknowns, underlined in the equations, are

- the six parameters of the two planes,
- the heights Z_i of the break lines points. (These unknowns can be eliminated easily from the equation system, which allows a faster computation. However, a different weighting of these two equations would not be possible anymore.)

Minimising the residuals r results in a plane pair, which approximates the given 3D-points $P_{i,l}$ and $P_{i,r}$ as good as possible on one hand, and on the other hand has an intersection line s which keeps close to the points $P_{i,b}$ of the preliminary break line in the ground plane. The intersection line s found in such an adjustment is used for the second adjustment as an improved approximation for the break line in the ground plan. Potentially this leads to a new classification in left and right points. After the second adjustment a third one might follow. The result of this iteration process is an intersection line s in 3-space. At this intersection line a 3D-point is computed in the middle of the patch.

The 3D-points and the intersection lines of all patches describe the 3D-break line as spline function. The points are the vertices and the lines are the tangents in these points. Break lines found in this manner can be regarded subsequently in the derivation of the hybrid DTM.

Fig. 5 shows an example. In the upper part the shaded DTM without special treatment of the terrain data is shown, in the lower part, the terrain under special consideration of the break lines is presented. The success can be assessed better

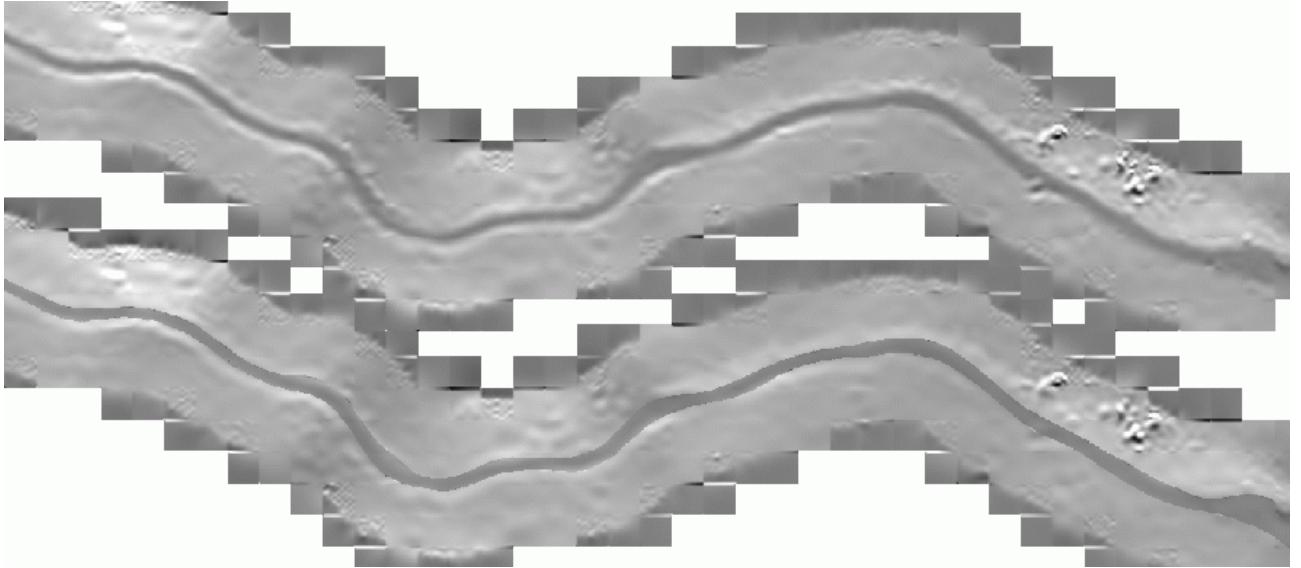


Figure 5: Shading of the DTM without break line (upper part) and with the break line (lower part)

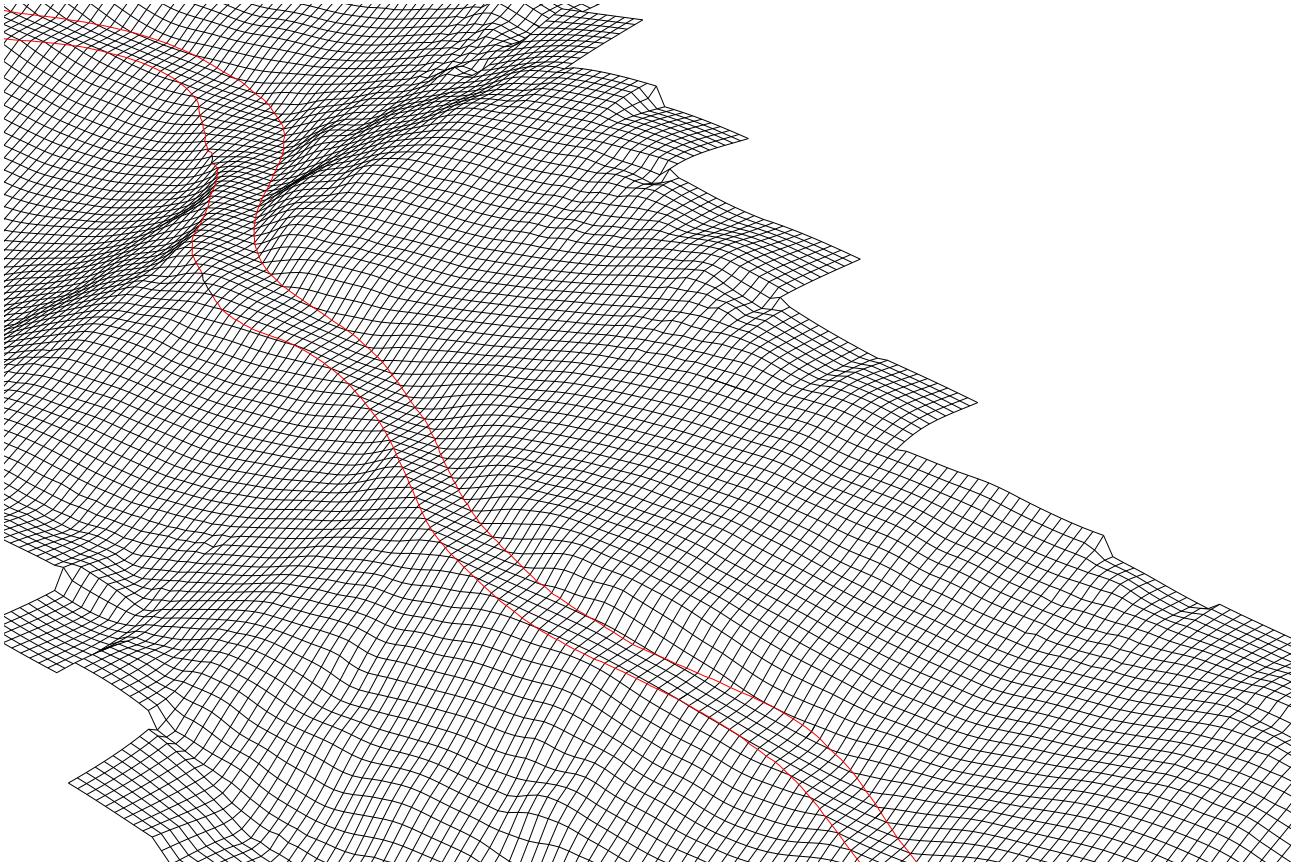


Figure 6: Perspective view of the DTM with automatically measured break lines

by looking at a perspective view of the terrain with the break lines. In fig. 6, which is a view from north west on the DTM of fig. 5, the discontinuities of the first derivatives in the hybrid model stands out clearly.

Empirical investigations on the accuracy improvement are currently running. The gain in absolute accuracy is less important than the strongly improved geo-morphological quality, which can be achieved by this method.

Concluding this section, two extensions should be noted: First, instead of planes polynomials of higher degree could be used, especially in areas with higher curvature. Second, not only plane pairs, but also triples or n-tuples of planes can be determined with this method simultaneously. For example, for a dike and its crest the usage of 3 planes (one horizontal

and two sloped) stands to reason. Another setup with three (or even more) planes can be found at the intersection of break lines (network of break lines).

5 CONCLUSION

The geometric component of airborne laser scanning has stimulated many research groups to solve problems which have been restricted to photogrammetry so far. In this article methods have been presented, which have been developed at the Institute of Photogrammetry and Remote Sensing of the Vienna University of Technology.

Three domains of LIDAR data processing have been touched in this article. The first one, the *elimination of systematic errors* originating from the measurement system, can be extended in many ways. So far, the algorithm is confined to height correction, but planimetric correction could be performed, too. The algorithms of the second domain, the *filtering and classification* of LIDAR data have been applied in many projects at our institute and have proven to be efficient and reliable tools. The last area mentioned, the *derivation of structural line information*, will play an important role in our research to come.

Other groups around the world have solved similar tasks, but different problems (e.g. automatic building modelling) have been approached as well. With (airborne) laser scanning photogrammetry has been provided a new tool. The advancements in the instruments (registration of first and last pulse and of the intensities, increased flying height, ...) as well as the methodical developments supplement each other very well and envisage a promising future.

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