AUTOMATIC BREAK LINE DETERMINATION FOR THE GENERATION OF A DTM ALONG THE RIVER MAIN

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ABSTRACT:

Due to world wide flood events hydrodynamic-numerical (HN) water flow simulation became a topic of highest interest. Next to the consideration of physical properties, a high quality geometric model of the run-off surface is essential for these simulations. In the last years airborne laser scanning (ALS) became the prime data acquisition technique for the modelling of inundation areas. When fully exploiting this technique detailed and accurate surface models that fulfil the HN simulation requirements can be determined. For that aim an adequate georeferencing of the ALS data and advanced modelling strategies are necessary. This paper presents a fully automated procedure for the extraction of break lines from ALS data. These lines should support the generation of accurate digital terrain models. Furthermore, the paper demonstrates the importance of relative georefencing of ALS data in order to allow an accurate break line modelling. Both issues are practically demonstrated by a project along the river Main. Next to documenting the geometric quality of the originally delivered ALS data, the paper presents the results after improving the georeferencing by means of strip adjustment, which for this project had to be realised without trajectory information. Furthermore, the results of the automatic break line determination process are presented. Finally, the paper provides a discussion of the results and an outlook into future work for automated break line determination.

1 INTRODUCTION

Due to world wide flood events hydrodynamic-numerical (HN) water flow simulation became a topic of highest public, politic, economic, and research interest. In order to predict the water flow these complex spatiotemporal models have to consider, next to local physical parameters such as soil type, soil moisture, surface roughness, etc., the geometry of the run-off surface. For the description of the surface geometry a high quality digital terrain model supplemented by all objects that influence the water flow is essential. Furthermore, these surface models have to include the river bed of all present watercourses.

In the last years, airborne laser scanning (ALS, often referred to as airborne LIDAR) has become a prime data acquisition technique for the retrieval of topographic data and is widely used for the surveying of inundation areas. However, in order to determine a geometric model that is suitable for HN simulations a series of processing steps as well as the integration of typically independently acquired river bed data is essential. After the ALS data acquisition campaign, the flight path has to be determined and the estimated laser scanner echoes have to be determined in one common co-ordinate frame. Subsequently, the ALS echoes are typically transformed and mapped into a local co-ordinate frame. In the next step all relevant terrain information has to be extracted from all determined laser echoes. This is typically done semi-automatically by filtering (i.e. the classification of the laser echoes into terrain and off-terrain information). Based on the terrain echoes a digital terrain model (DTM) can be derived and the resulting model can be supplemented by relevant objects and the river bed data (the acquired ALS data on water surfaces has to be replaced by river bed observations or models). These steps lead to a DTM of the watercourses (DTM-W). Finally, it is often essential to perform a data reduction step of the high resolution DTM-W due to the fact that hydraulic simulation software is often restricted to a limited number of nodes and meshes that describe the surface geometry (Mandlburger and Briese, 2007, Mandlburger et al., 2008).

However, in order to fully exploit the capability of ALS sensors quality control has to be performed and fine georeferencing methods can be utilised in order to increase the precision, accuracy, and reliability of the acquired ALS points. Furthermore, full-waveform ALS, that allows to determine additional information per recorded echo, can be utilised to improve the task of filtering and DTM generation especially in areas with low vegetation structures, cf. (Doneus and Briese, 2006). Furthermore, the terrain points can be complemented by additional terrain observations such as topographic relevant linear feature lines such as break lines which describe a local surface discontinuity. The integration of these break lines can help to describe the surface geometry along these linear discontinuities in more detail and can therefore support the HN simulations in these often very sensitive areas. While break line information can be gathered by independent measurement campaigns (e.g. by terrestrial surveying or photogrammetric means) one can think of extracting this linear feature information from the available ALS point cloud due to the implicit presence of this information (Briese, 2004a).

This paper presents a full automatic process for the determination of break lines from ALS data for HN simulations. The determined break lines can be used within the filtering of the ALS data and can be integrated into the surface representation. Within the paper the method and processing chain for automated break line determination is shortly introduced and its practical application is demonstrated with the help of results archived within the project

"DTM-W Main-2" of the German Federal Institute of Hydrology ("Bundesanstalt fuer Gewaesserkunde", BfG). The available ALS data set of the test area consists of 61 parallel flight strips (overlap 50%, flown in East-West direction) which cover an area of 10(East-West)*17(North-South)km^2. The point density (considering the last echo points of all strips) was about 4points/m^2. While applying the algorithms for break line determination and modelling, significant height differences in-between the ALS data from different strips could be observed. These strip differences led to unexpected problems in the delineation of the break lines and resulted in a worse detection rate and modelling quality. Therefore, within the previously mentioned project, a detailed quality analysis of the data was performed and the development of a strip adjustment procedure without trajectory data was necessary. Due to the importance for break line estimation these steps are summarised in the subsequent Section 2. The following Section 3 focuses on the full automatic detection (Subsection 3.1) and modelling (Subsection 3.2) of the break lines. Furthermore, it presents the gathered experience with geo-reference errors on break line determination (see Subsection 3.3). The final Section 4 discusses the results and provides a short outlook into future research work.

2 QUALITY CONTROL

As mentioned in the introduction, a DTM for hydraulic applications must meet with very high quality standards; typically a few cm in height - an accuracy ALS is capable of delivering in principle. Before using the ALS data delivered from the flying company for extracting the break lines and generating the DTM, the quality of the delivered ALS data must be checked. The most important quality parameters in this respect are the point density and the geometric accuracy of the delivered data. Sections 2.1 and 2.2 present briefly our methods for checking these quality parameters.

The geometric accuracy of the originally delivered ALS data in this project did not meet with the expectation. This indicates an error in the original georeferencing of the data. Consequently for improving the georeferencing a strip adjustment with the data was computed. In order to realize the strip adjustment rigorously the GNSS/IMU trajectory data must be known - which, however, was not the case in this project. Therefore a strip adjustment model without GNSS/IMU trajectory data, which is described in the paper (Ressl et al., 2009), was developed. After the strip adjustment the geometric accuracy must be checked again. For better comparison, the results of the geometric quality control for the original and the improved georeferencing (after the strip adjustment) are presented side by side in Section 2.2.

2.1 Checking the point density

For the local documentation of the point density, point density maps (cf. (Karel et al., 2006)) of the last echo points were computed with an analysis unit of 5*5m^2 in order to estimate a representative average value and to reduce the amount of unfilled cells due to local point density variation. Next to strip wise point density layers the point density was determined for the whole last echo point cloud. Within the strip wise point density visualisation the varying point density caused by aircraft movements could be observed. In the overall point density map a point density of 4points/m^2 was typically present in areas that were sampled by more than one ALS strip. However, in order to get an idea about the local potential for break line modelling and DTM generation, one has to have a look on the point density of the classified terrain echoes. The filtering of the ALS data (the final classification result was already delivered to us) reduced the point density along vegetated embankments significantly. This fact reduces the possibility to detect and accurately model the break lines and the DTM in these areas due to missing terrain information. Therefore, when evaluating the results of the break line estimation procedures one has to take this highly varying point density into account.

2.2 Checking the geometric accuracy

Geometric accuracy is defined by the quality of the georeferencing of the data and can be divided into an absolute and a relative part. Because of the sampling characteristics of laser scanning the points themselves can not be compared easily - but interpolated surfaces can. Therefore at first for each strip a digital surface model (DSM) is interpolated using moving planes interpolation (local least squares adjustment of a tilted plane). Whereas checking the absolute accuracy requires some sort of external reference data, the relative accuracy can be checked using only the data itself.

For checking the relative accuracy natural surfaces measured independently in different overlapping flight strips are compared simply by computing the difference dZ_{pair} of pairs of overlapping strip DSMs (termed *strip difference*). Because of the sampling distance of ALS points these natural surfaces need to have a certain smoothness otherwise the interpolated surfaces in the individual strips will be too different in shape for comparison. During the DSM interpolation for each strip the estimated accuracy ($\sigma_{Z_{int}}$) of the interpolated height is used to derive a roughness mask for each strip by a simple thresholding; see (Ressl et al., 2008) for details. Only the height differences outside this mask are considered for judging the quality of the relative georeferencing. This strip difference method can be applied provided the strips were flown with sufficient side overlap (typically 20%), which usually has to be done in order to guarantee a gapless data collection.

In this project for each strip a DSM with 1m grid width was interpolated by a moving planes interpolation using the 8 closest neighboured points. The roughness mask for each strip was derived using a threshold of 10cm for $\sigma_{Z_{int}}$. Figure 1 shows an example of a colour coded strip difference dZ_{pair} for the original georeferencing with the roughness mask. Figure 2 shows the same section for the improved georeferencing after the strip adjustment. The left side of Figure 3 shows the histogram of dZ_{pair} (considering the roughness mask) based on all overlapping strips of the project for the original georeferencing. The right side of this figure shows the histogram of dZ_{pair} for the improved georeferencing.

The strip differences dZ_{pair} represent for all errors in the georeferencing their *summed effect on the heights*. However, this does not directly reflect the height accuracy of the ALS data; e.g. horizontal errors induce height differences at inclined surfaces. While dZ_{pair} gives a *quantitative* information about the quality of the heights, the color coded strip differences provide *only qualitative* information on the horizontal quality; e.g. Figure 1 clearly *indicates* horizontal errors at the roofs of the buildings but does not tell their size. Therefore 3D difference vectors between corresponding points in the strips were computed additionally. The corresponding points were measured in the overlapping strip DSMs using *least squares matching* (LSM). In order to avoid the disturbing influence of vegetation and occlusions on LSM (e.g. (Maas, 2000)) the roughness mask was used again and thus only smooth surface cells were used for LSM.

Table 1 shows the RMS values of the coordinate differences of the corresponding LSM points in overlapping strip DSMs before and after improving the georeferencing. There the large planar errors

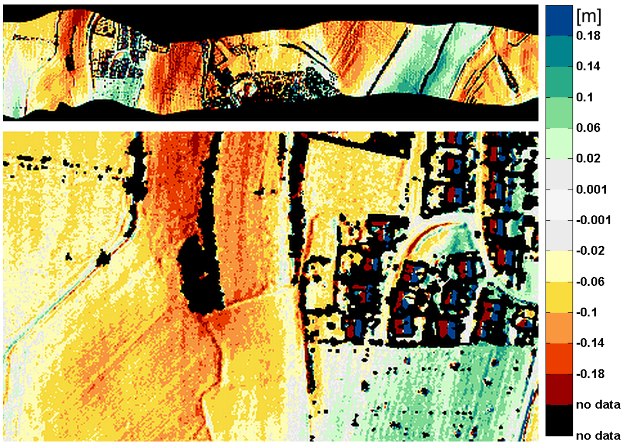

Figure 1: Strip differences for the original georeferencing. Top: Overview of a colour coded difference of two overlapping strips. Bottom: Enlarged detail; observe especially the striking red and blue pattern at the roofs (with height differences beyond ±18cm). This is a clear indicator for horizontal shifts between the two strips. Right: Legend of colour coding. Black is used for the area outside the overlap of both strips, but also for the parts covered by the roughness mask.

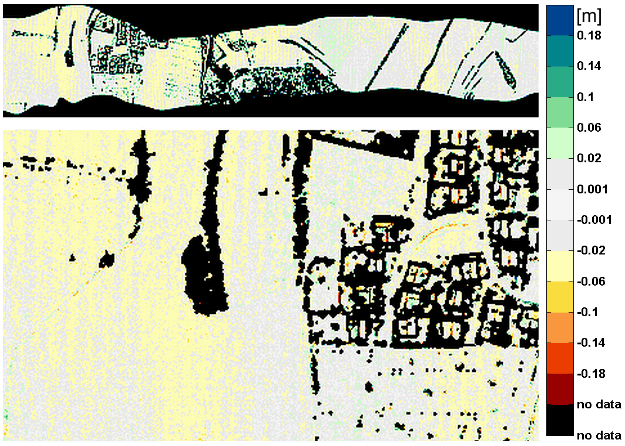

Figure 2: Strip differences for the improved georeferencing after the strip adjustment; cf. fig. 1. Note that the systematic patterns of the height differences, which are visible in Figure 1 (especially at the roofs), have now disappeared to a very high degree.

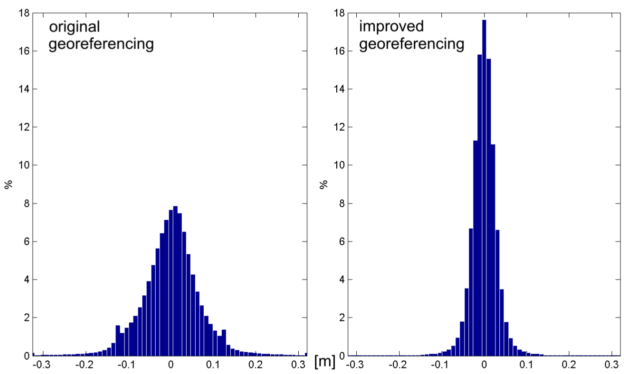

Figure 3: Histogram of the strip differences dZ_{pair} (considering the roughness mask) based on all overlapping strips (ca. 118 million values). Left: original georeferencing (σ_{MAD}=6.2cm). Right: improved georeferencing after strip adjustment (σ_{MAD}=2.9cm). σ_{MAD} is the standard deviation derived from the median of absolute differences (the so-called *MAD*) as $\sigma_{MAD} = 1.4826 \cdot MAD$.

of 59.3cm in X and 23.4cm in Y for the original georeferencing are striking. After the strip adjustment a dramatic improvement with RMS values for X and Y of 7.1cm was derived. It is interesting to point out that actually the RMS in Z is already for the original georeferencing quite good with 4.5cm. After the strip adjustment RMS(Z) improves to 2.2cm. This may be explained by height control areas (e.g. football fields) which were used by the flying company to adjust the vertical alignment of the strips. Again, this example demonstrates the usually worse accuracy in X and Y compared with Z. An observation also reported by other authors; e.g. (Maas, 2000).

georef.	RMS(X) [cm]	RMS(Y) [cm]	RMS(Z) [cm]
original	59.3	23.4	4.5
improved	7.1	7.2	2.2

Table 1: RMS values of the coordinate differences of corresponding LSM points in overlapping strip DSMs before and after improving the georeferencing by strip adjustment. 811 point pairs were used.

In combination, the strip differences and the 3D differences at LSM derived corresponding points, constitute a very good tool for checking the relative geometric accuracy of ALS data: the strip differences, as colour codings and via the histograms, *continuously* describe the remaining height errors in the data, and the 3D differences describe the accuracy in XYZ at *discrete* points.

As mentioned in the beginning of this section checking the absolute accuracy requires external control data, which was only partly available for this project. Only three horizontal control surfaces existed, where the vertical discrepancies ranged from 4cm to 10cm. Only a 2D vector layer (ATKIS digital landscape model) was available, which contained features (street borders, terrain edges, etc.) that can not be easily used to compute 2D offsets. A visual comparison of this layer with a shading of the strip DSMs of the original georeferencing did not show any severe discrepancies. Therefore the absolute georeferencing was considered to be acceptable - however, due to the limited external reference data the absolute accuracy could not be checked to the same degree as the relative one.

3 AUTOMATIC BREAK LINE MODELLING

In the past several different solutions for the determination of break lines from ALS data were published. Most of these approaches determine the break lines with the help of raster based operations (e.g. first and second order derivatives, Laplacian operator; cf. (Brügelmann, 2000, Gomes-Pereira and Wicherson, 1999, Gomes-Pereira and Janssen, 1999, Sui, 2002)). Typically, these raster based algorithms are applied to a previously generated (filtered) DTM and the result of these detection methods are pixels marked as edge pixels. Subsequently a raster to vector conversion is applied and 2D break lines are generated. In a final step, the height of the break line is typically independently extracted from a slightly smoothed vegetation free DTM at the planimetric break line position. A different approach for the determination of break lines from ALS data starting from the irregular distributed unclassified ALS points was presented in (Briese, 2004a) and (Briese, 2004b). This process allows the simultaneous determination of all three co-ordinates of points along the break lines within one process and automatically allows to reduce the local influence of off-terrain points by robust adjustment. However, compared to the raster based approaches this process works in a semi-automated way and requires one manually set 2D-start-point or one 2D-start-segment in the vicinity of each line in order to estimate the whole 3D break line.

The following proposed full-automatic procedure for the modelling of break lines from irregular ALS point cloud data can be basically split into two steps. In the first step potential break line segments are detected (see Subsection 3.1), whereas in the second step the modelling of the whole 3D break lines starting from the detected segments is performed (see Subsection 3.2). For the break line modelling the break line growing concept presented in (Briese, 2004a) and (Briese, 2004b) is utilised. For the first step a new approach is introduced that allows to determine start-segments based on the irregular distributed ALS point cloud, whereas the second step is extended to handle multiple start segments per resulting break line.

3.1 Break Line Detection

As demonstrated by the previously mentioned publications, for the detection of break lines raster based methods can be utilised. However, this makes a rasterisation of the irregularly distributed ALS data necessary. The advantage of these methods is that they can be applied in a very fast way due to the given raster topology, but the disadvantage of the rastered ALS point cloud is that this advantage is bought by a loss in precision (Axelsson, 1999). Break lines that are represented in the point cloud sharply might be smoothed by the rasterisation process and by the usually previously applied filtering processes. In order to avoid these preprocessing steps, a break line segment determination based on the irregular distributed last echo point cloud is proposed in the following.

In contrast to the raster based approaches, the detection of potential local break line segments can be performed by the analysis of a locally determined 2.5D second order surface (quadric) q:

$$q = f(x, y) = \sum_{i+j\leq 2} a_{ij} x^i y^j \tag{1}$$

This quadric can be determined on the position of each given point by the selection of k nearest neighboured points. The adjustment can be performed in a robust way in order to reduce the influence of off-terrain points on the estimated parameters. The resulting surface patch represents the local surface characteristic and allows to determine the local minimal and maximal main curvature κ_{min}, κ_{max} with the help of a principal axis transformation. This allows a classification of the point into a break line or surface point based on the local curvature values. For this classification a threshold for the maximal curvature value κ_{max} and the main curvature ratio $\kappa_{min}/\kappa_{max}$ can be utilised. Furthermore, next to the determination of the main curvature values, principle axis transformation allows to estimate the main curvature directions. Another important advantage compared to other raster based or point cloud based operations is that this approach allows to refine the position of the local break line by the determination of the symmetry point, i.e. the point on the quadric with the maximum curvature value. As a result this procedure delivers the point with the local maximum curvature and the local break line direction (pointing into the direction of the present minimal curvature). The refinement of the position of the local break line is a big advantage compared to other raster or vector based approaches, because instead of a relatively thick band of break line candidate positions along the lines (e.g. several pixels that indicate a high curvature value near the break line) the described procedure allows to determine accurate break line point positions together with its local break line direction in a very small band around the finally estimated break lines. A practical result of this procedure in an area near the Main river is displayed in Figure 4. Within this example the local break line determination was performed in each 5^{th} point in order to save computation time.

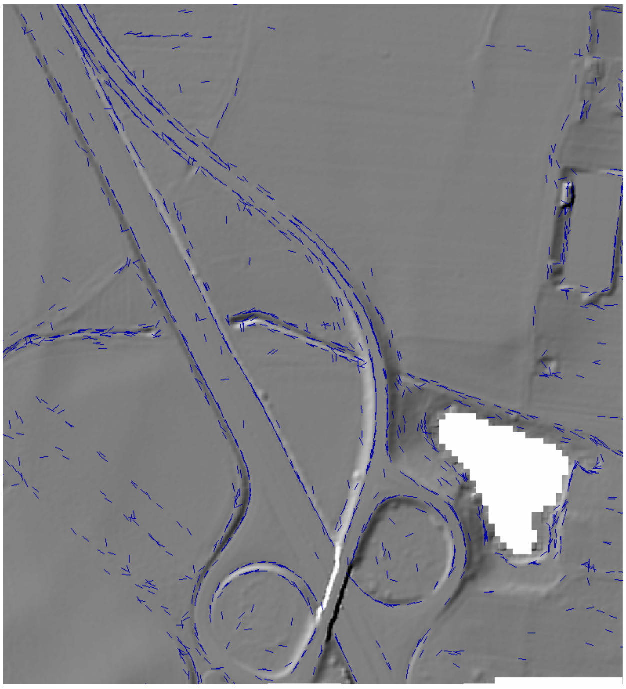

Figure 4: Automatic determined break line segments (refined break line point position with local break line direction) by the adjustment of a 2.5D second order surface and applying principle axis transformation displayed together with a shading (illumination source: North-West) of the respective DTM. These segments are utilised as start values for the subsequent automatic modelling of the break lines.

3.2 Break Line Modelling

In order to generate a linear representation of one break line one can think, in analogy to the raster based methods, of connecting the determined start segments and interpolating the height of the 2D points with the help of a previously generated DTM. However, in contrast to this independent two step process, the following proposed break line modelling concept allows the simultaneous determination of all three co-ordinates of the break line point (and additionally the local tangent direction) simultaneously within one step by the determination of a local valid plane pair that is robustly estimated with the help of the local surrounding last echo point cloud. Furthermore, the delineation of the whole line is not performed by the connection of neighboured and similar oriented break line segments. Instead of this procedure the concept of break line growing was utilised. As mentioned previously, this procedure is based on a semi-automated procedure published in (Briese, 2004a) and (Briese, 2004b). In contrast to the semi-automatic approach with manual user defined start segments, a full automatic processing chain can be generated by the usage of the previously automatically detected break line segments.

In contrast to the semi-automatic solution, where the processing of multiple lines is controlled by the user, within this automatic procedure the redundant modelling of the break lines has to be considered due to the fact that the break line detection step, as described in the previous subsection, delivers multiple break line segments per line. Therefore, it has to be analysed during the break line modelling procedure if the corresponding break line of the next processing segment is already modelled. This additionally check can be performed with the help of a spatial tree (in our implementation a R-tree is used) which stores the already modelled lines and allows nearest neighbourhood queries. This addi-

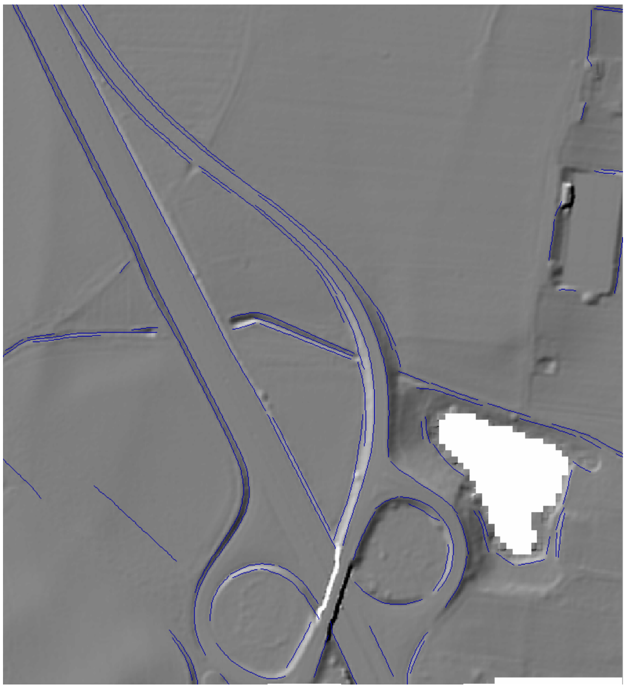

Figure 5: Automatically generated break lines with the help of the previously estimates break line start-segments (see Figure 4) displayed together with a shading (illumination source: North-West) of the respective DTM. The break line is described by a sequence of break line points together with their local tangent direction.

tionally necessary check is performed at the begin of the modelling of each detected break line segment and has to be repeated during the whole break line growing procedure after each extrapolation step.

Next to the resulting break lines, this break line modelling procedure delivers further adjustment information (precision values (error ellipse per break line point (Briese and Pfeifer, 2008)), number of eliminated points during robust adjustment, etc.) and geometric properties (e.g. the local intersection angle of the plane pair) along the whole modelled line. A practical result of this full automatic second step of the same area as displayed in Figure 4 can be inspected in Figure 5. After the automatic modelling of all break lines, an additional refinement step that improves the final resulting lines by removing short gaps in between neighboured lines (e.g. caused due to missing terrain information and separate computation units) and by removing short line segments turned out to be useful. This step allows to reduce the manual correction and completion work.

3.3 Influence of Georeferencing Errors on Break Line Determination

As mentioned in the introduction, in the first computations based on the original delivered ALS data a significant influence of systematic relative georeferencing errors on the process of automated break line determination could be observed. As already shown in Subsection 2.2, significant strip differences could be observed prior to a strip adjustment of the available ALS data. The present planar errors result in height differences near break lines (e.g. on embankments, dams, dikes, etc.) due to the presence of surface inclination in these areas. While the planar errors hardly affect the DTM in flat regions, a significant effect in inclined regions (see Subsection 2.2) could be observed. Next to the influence on the break line modelling these errors may affect the filtering process (were typically the lowest points will get a higher influence than the others) as well as the final DTM generation process.

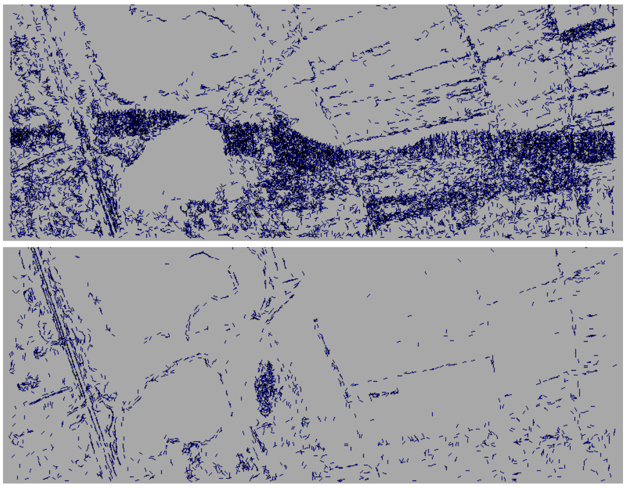

Figure 6: Top: Detected break line segments from the original delivered ALS data of all strips with planar relative georeferencing errors that resulted in a local higher surface roughness. The strip boundary can easily be recognised in this visualisation due to the higher amount of wrongly determined start segments in the overlapping area. Bottom: For comparison this image presents the extracted break line segments based on the original delivered ALS data of just one ALS strip.

The negative influence of an inadequate georeferencing could be especially observed in the break line detection step, where the local surface curvature was estimated. The georeferencing errors resulted in high curvature values in areas were two or more strips overlap. Therefore, the determined break line segments were determined next to correct ones along surface discontinuities also in smooth areas. Furthermore, the determined break line directions within this wrongly determined segments showed a very random distribution. The negative influence of georeferencing errors present in the original delivered ALS data on break line detection can be inspected in Figure 6.

Next to the previously mentioned effects on break line detection, the mentioned relative planar errors do also affect the break line modelling process. Due to the different shifted band of points from the individual strips the resulted local plain pair might lie in between both bands or if the height off-set is big enough (on very steep slopes) the lower points will become a higher influence due to the utilised robust adjustment which gives a higher weight to terrain points (that are assumed to be lower than vegetation echoes (further details see (Briese, 2004a))). This results in systematic planar and height errors of the resulting lines. Practical studies documented these significant effects. They varied within the project area significantly due to the fact that the resulting error was influenced by the actual relative georeference errors, the local surface structure as well as the ALS strip layout.

All this observations in the initial project phase demonstrated the need of strip adjustment in order to determine reliable break lines that could be used as an additional information source within the geometric description of the landscape. The strip adjustment procedure as presented in Subsection 2.2 allows to reduce these effects to a very high degree. Finally, break lines with a low amount of systematic errors caused by planar relative georeferencing errors could be determined.

4 DISCUSSION AND FUTURE WORK

This paper presents a full automatic method for break line determination based on ALS data. The practical application of the developed method showed that break lines can be extracted automatically based on the unclassified irregular ALS last echo data. The resulting break lines show up a high degree of detail and completeness. Especially long straight lines, e.g. on road embankments, can be extracted quite well and nearly do not need any manual correction work. Problems in the break line modelling mainly occur on small curved lines and on parallel lines where the point density is sometimes too low resp. the modelling parameters are not flexible enough to avoid that the growing procedure jumps from one line to the other. Further problems can be found in areas with very dense vegetation, where the growing sometimes stops too early or the robust adjustment is not able to eliminate all off-terrain information. The practical evaluation of the results with independently terrestrially acquired reference data showed similar results (long straight break lines fit very well, while smaller highly curved lines may show up a higher difference). A more detailed accuracy report concerning this analysis will be presented in subsequent publications.

The practical application of the developed methods for break line detection and modelling showed up that a high quality georeferencing prior to any modelling step is important. Systematic errors (planar as well as height errors) in the data can lead to significant systematic effects (planar errors can result in height errors on inclined surfaces) in the derived products. Especially in the break line detection phase this became obvious (visible strip boundaries when looking on the planar distribution of the extracted break line segments). Within the modelling step the problems were not so obvious, but a detailed analysis showed up significant systematic effects introduced by the original georeferencing errors. Therefore, this paper highlights the importance of quality control and strip adjustment. The practical application of this process showed up the potential of a high quality georeferencing of the data. The final improved point cloud was a good basis for the subsequent modelling of the break line and most of the effects caused by the relative georeferencing errors of the original ALS point could be eliminated.

Furthermore, the practical application of automated break line determination showed up that further research work is necessary in the local adoption of the processing parameters. At the moment all relevant parameters have to be fixed at the begin of the processing and are fixed for the whole processing chain. Practical tests showed that a local variation of the parameters can be very useful in order to consider different surface properties (e.g. the presence of parallel break lines). Furthermore, the process of break line growing in areas of strongly curved lines has to be improved in the future. Finally, the line topology has to be considered. In the current implementation each line is treated independently and correct line intersections are not supported. Future research work is necessary in order to determine a reliable break line network.

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