# THREE-DIMENSIONAL MODELLING OF BREAKLINES FROM AIRBORNE LASER SCANNER DATA

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Commission III, Working Group III/3

**KEY WORDS:** Laser scanning, LIDAR, DEM/DTM, Three-dimensional, Breakline, Modelling.

**ABSTRACT**

Airborne laserscanning allows a very detailed sampling of the landscape within a more or less automated recording procedure. For the representation of models computed on the basis of this data mostly raster or triangulated irregular networks (TINs) are used, which do only implicitly store breakline information. For high quality surface modelling breaklines must be explicitly stored within the data structure. Therefore a 3D vector representation of the breaklines is necessary. This paper presents a method for the modelling of 3D breaklines not only from airborne laser scanner data but from any kind of point cloud data. The method is based on a pairwise intersection of robustly estimated surface elements along the breakline. It allows a modelling on the basis of original irregular distributed point clouds even in wooded areas. For this procedure a 2D approximation of the breakline is required. Therefore one section concentrates on the determination of these initial values in order to automate the process. Results of the modelling are presented in an examples section. A summary with an outlook on future developments concludes the paper.

## 1 INTRODUCTION

Airborne laserscanning (ALS, also referred as LIDAR) allows a very dense sampling of the landscape with the help of high frequent range and angle observations. Additional synchronised measurements of the position and orientation of the scanner unit within a global co-ordinate system allow the computation of a geo-referenced point cloud. On the basis of this data and by the use of algorithms with a knowledge base for a specific application a lot of different models (e.g. terrain, building or vegetation models) can be determined (cf. (Axelsson 2000), (Brenner 2000), (Wack et al. 2003)).

For the representation of the surface models generated from ALS data or other automated data acquisition methods (e.g. image matching techniques) mostly raster resp. grid models or triangulated irregular networks (TINs) are in use. In general these models are only computed on the basis of an irregular distributed point cloud and therefore they do only implicitly store breakline information. The quality of the breakline description within these models depends next to the original point sampling interval on the size of the stored raster resp. triangle cells. In contrast to these models without an explicit breakline description, it is essential for high quality surface models (e.g. for hydrological applications) to store breakline information explicitly in the data structure. For this aim a three-dimensional vector representation of the breaklines is necessary. Based on this description an integration of relevant breaklines into a constrained triangulation process or into a hybrid raster data structure ( (Kraus 2000), cf. figure 1) can be performed. Additionally, breaklines are very important for the task of data reduction. They help to describe surface discontinuities even in models with big raster resp. triangele cells.

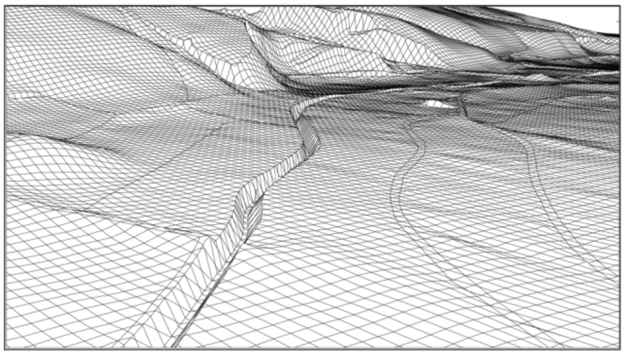

**Figure 1:** Perspective view of a hybrid raster digital terrain model including breakline information.

Next to the fundamental role of breaklines for the final surface models the explicit description of these discontinuity lines is very important for the generation of digital terrain models (DTMs) from ALS data. For the determination of a DTM on this data basis a classification (filtering) of the acquired point cloud into terrain and off-terrain points is required. For this aim a lot of different algorithms were developed (e.g. (Axelsson 2000), (Kraus and Pfeifer 1998), (Vosselman 2000)). An international filtertest (Sithole and Vosselman 2003) showed deficits of all methods used by the participants in the areas of surface discontinuities even when the algorithm has some special rules to avoid misclassification next to breaklines. To cope with this problem an integration of explicit modelled breaklines during the whole DTM generation procedure is essential. However, this makes a modelling of breaklines, based on the original unclassified ALS points, necessary.

After a short summary of the current state of research in the area of breakline modelling from ALS data the paper presents a new method for three-dimensional modelling of breaklines. It is based on a pair wise intersection of overlapping robust surface elements (determined with the help of irregular distributed points) along the breaklines. After an introduction into the basic concept the paper focuses on the adaption to the modelling of unclassified ALS data, which allows the determination of breaklines even in wooded areas. Furthermore, the integration of additional data (e.g. information from digital images) into the modelling process is treated. For the modelling a 2D approximation of the breakline is essential. Therefore a further section concentrates on procedures for the automatic determination of these initial values. An examples section demonstrates the practical use of the presented methods and the integration of breaklines into the classification (filtering) process for DTM determination. A short summary with an outlook on further development issues concludes the paper.

## 2 STATUS OF RESEARCH

Up to now the research in the area of breakline extraction from ALS data concentrated on the development of methods for the fully automatic 2D detection of breaklines. For this aim image processing techniques were usually used (e.g. first derivatives (Gomes-Pereira and Wicherson 1999), gradient images (Sui 2002), Laplacian operator (Gomes-Pereira and Janssen 1999)). A summary of some of these and other methods and an additional new method based on hypothesis testing (homogeneity measure: quadratic variation) can be found in (Brügelmann 2000). In general these raster based algorithms are applied to a previously generated (filtered) DTM. The result of these detection methods are pixels marked as edge pixels. In a further raster to vector conversion 2D breaklines can be generated. This conversion includes at large some smoothing in order to eliminate zigzag effects caused by the raster structure. The height of the breakline is independently extracted from a slightly smoothed vegetation free DTM at the planimetric position of the detected breakline.

Published experiments show quite interesting results for the 2D extraction. Especially vegetation free breaklines on dikes can be extracted quite well in 2D, but certain breaklines are only partly detected or some of them were not detected at all. Another problem of these methods is that they operate only in 2D and just interpolate the height from a more or less smoothed DTM, which can be eventually affected by classification errors caused by the DTM generation process (see remarks in the section 1). The height of the breakline is computed totaly independent from the determination of the 2D position. However, for a high quality modelling a method which allows a full 3D determination of the breakline within one process has to be preferred. A basic concept, which allows a 3D refinement of approximately 2D detected or just manually measured breaklines, was already published in (Kraus and Pfeifer 2001) and (Briese et al. 2002). In the following sections extensions based on this basic idea, allowing the modelling of breaklines on the basis of unclassified original ALS point clouds, are presented.

## 3 BREAKLINE MODELLING

The modelling should be performed on the basis of the original point cloud in order to use all possible information and to exclude preprocessing steps, which can lead to a quality reduction (e.g. re-sampling of the point cloud into a regular grid or classification (filter) errors during DTM determination). Additionally to a high quality modelling, the algorithm should deliver accuracy measures in order to get an estimation about the quality of the 3D modelling.

In the following subsection the basic principles of the breakline modelling method are presented. Step by step the method will be extended in order to cope with specific ALS problems (off-terrain points are considered in subsection 3.2). Furthermore the integration of additional information sources (e.g. image data) is considered in subsection 3.3. The basic modelling concept presented in this section is a semi-automated breakline modelling procedure for which a rough 2D approximation of the breakline is necessary. Concepts, which allow to overcome this limitation, will be presented in section 4.

### 3.1 Basic Concept

Basically, the breakline is described as the intersection line of continuously overlapping analytic surface patch pairs (compare figure 2). The determination of the patch pairs is performed with the help of a simultaneous adjustment of both analytic surface pairs supported by the point cloud data within a buffer zone around the approximative breakline. The access to the ALS points within this buffer zone is performed with the help of a topographic database. Before the intersection the point data is classified on the basis of the rough 2D approximation of the breakline into left and right point groups.

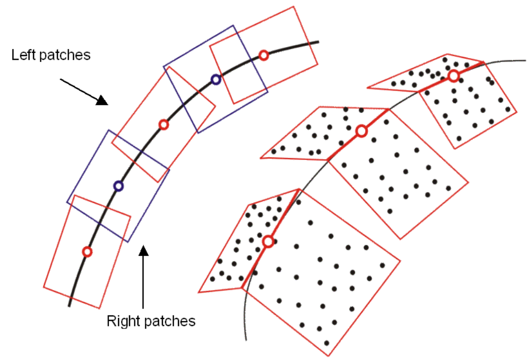


**Figure 2:** Basic concept for the description of breaklines with the help of intersecting patch pairs determined on the basis of surrounding point cloud data; Left: Ground view of overlapping patch pairs; Right: Perspective view of a reduced number of patch pairs (overlapping pairs are removed) with their point cloud support.

For the left and right patches we used intersecting plane pairs, which should approximate the left and right surface tangent plane as good as possible. Within the 3D modelling procedure the approximation of the breakline is refined step by step (this leads to a reclassification of the points into left and right) until no significant change of the intersection line between the surface pairs can be recognised. In order to reduce the influence of points with a increasing orthogonal distance to the breakline a weight function is used. The weight function (in this case a bell curve) can be parameterised in a way that points near the breakline get a high weight, whereas the weight of points far away from the breakline is decreased. Points with a certain distance to the breakline should have no influence to the run of the surface patches and therefore they should get the weight zero. An example of such a weight function (we use an individual weight function for the left and right points) can be seen in figure 3. Additionally, this weight function reduces the weight of points in a small buffer zone around the breakline itself. This is done to reduce the influence of points very close to the breakline, which are usually affected by small distance measurement errors due to a too big footprint size and furthermore has a positive influence on the iterative refinement of the approximation of the breakline.

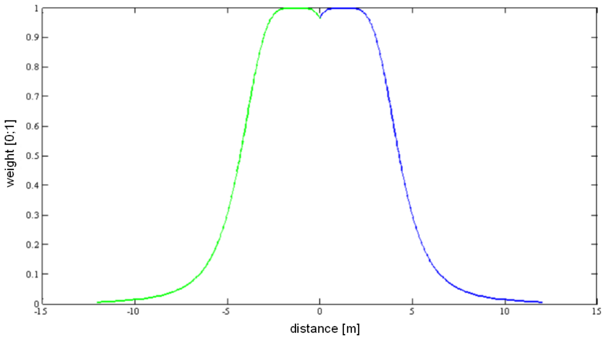


**Figure 3:** Weight functions defining an individual weight for each point depending on the distance to the breakline; Green (negative distance values): Weight function for points belonging to the support of the left surface patch; Blue (positive distance values): Weight function for points of the right surface patch; Additionally points in a small buffer zone around the breakline (distance zero) get a lower weight.

As a result of the modelling procedure one representative point on the intersection line and the direction of the intersection line (tangent of the breakline) are stored per patch pair. An additional interesting result is the intersection angle between the surface patches along the whole breakline, which allows a further analysis. Due to the fact that the surface determination is performed within an adjustment procedure, accuracies for the estimation of the unknowns (plane parameters) can be computed. This allows the computation of further quality measures (e.g. the accuracy of the intersection line) with the help of error propagation.

### 3.2 Robust Modelling

As mentioned before the breakline should be modelled with the help of unclassified originally acquired ALS point clouds in order to exclude preprocessing errors. Therefore we have to adapt the basic concept in a way that the influence of off-terrain-points (e.g. due to reflections of the laser beam on the vegetation or measurement errors caused by multipath reflection ("Long Ranges")) is reduced as much as possible. This is performed with the help of robust estimation and is based on the robust interpolation technique for ALS data presented by (Kraus and Pfeifer 1998).

The robust estimation of the surface patches is forced with the help of a second weight function. Depending on the vertical distance of the point to the intermediate surfaces, this weight function assigns a low weight to potential off-terrain points (mainly above, but also to points significantly below the terrain) and a high weight to terrain points. The robust estimation is initiated automatically if off-terrain points (gross errors in the adjustment) are detected and adjusts itself within a fully automatic procedure using an individual self-adapting weight function for every iteration step (cf. figure 4). Step by step the weight of off-terrain points is reduced. A practical example, which presents the capability of the robust modelling procedure, can be seen in figure 5.

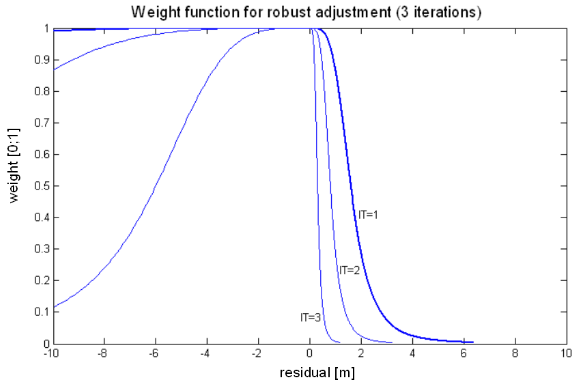


**Figure 4:** Example for automatically determined weight functions per robust iteration step (IT). The function adapts itself step by step depending on the data and allows a separation into terrain and off-terrain points. Positive residuals belong to points above the terrain, whereas points below the terrain have negative residuals. Especially the weight of off-terrain points above the terrain (manly caused by vegetation) is reduced to a high degree.

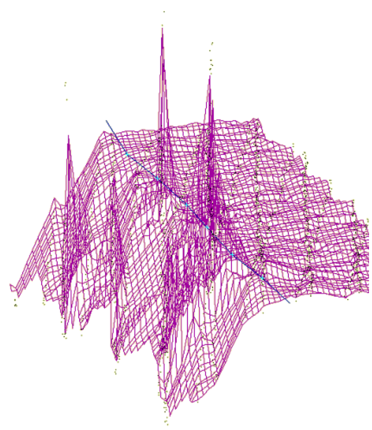

**Figure 5:** 3D modelled breakline determined on the basis of unclassified ALS data.

Summarising the types of iterations within the whole breakline determination procedure, iterations per patch pair for the robust estimation have to be distinguished from additionally iterations per breakline. Robust estimation is performed for each patch pair until the influence of all off-terrain points is reduced as much as possible. On the other hand the iterations per breakline, which perform a reclassification of all ALS points into left and right points on the basis of the refined breakline, lead to an iterative refinement of the breakline. It is performed until no significant change of the breakline can be recognised.

### 3.3 Integration of Additional Observations

A benefit of the proposed method is that additional information within the breakline modelling procedure can be introduced. Further observation equations can be easily integrated in the adjustment for the determination of the surface patches.

This extension allows the integration of both, high quality 2D breakline information (e.g. given by manual measurement using image data) and high quality height information from ALS data within *one process*. The influence of the different observations can be easily controlled by an additional weight factor that depends on the individual observation accuracy. Furthermore the same additional equations allow the consideration of the accuracy of the 2D approximation of the breakline.

## 4 AUTOMATISATION

As mentioned before, the method introduced for 3D breakline modelling with the help of unclassified ALS data relies on a 2D approximation of the breakline. Therefore the following subsections concentrate on methods, which allow the determination of this initial values. Basically, two basic concepts can be distinguished in the area of automated breakline extraction.

The main group of algorithms tries to extract (generally in 2D) the whole breakline within one process (cf. section 2). In contrast to these methods a different concept for the automatic or at least semi-automatic breakline modelling is presented in the following. It is based on 3D breakline growing and tries to overcome the must of the modelling method presented in section 3 of a entire 2D approximation of the breakline. For the start of the growing procedure the approximation of one breakline segment (one point near the breakline and the approximative breakline direction, cf. section 4.1) or just one point near the line (cf. section 4.2) is necessary. The growing is performed with the help of the ALS point cloud stored in a database.

### 4.1 3D Breakline Growing on the basis of a Start Segment

This subsection presents the 3D breakline growing scheme on the basis of a 2D start segment (e.g. manually digitised). Based on this start segment the 3D breakline within this segment is determined with the help of robust surface patches. Afterwards the growing into both directions on

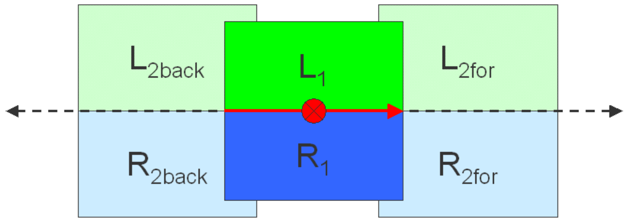


**Figure 6:** Scheme for automated breakline growing (forward and backward) with the help of a start segment ($L_1/R_1$).

basis of the refined segment (forward and backward, cf. figure 6) is performed. This growing method proceeds in both breakline directions in the following way:

1. Compute the patch pair with the help of robust surface patches (cf. section 3) and store the results. In the first step the initial segment ($L_1/R_1$) and in the following steps the extrapolated patch areas ($L_{ib}/R_{ib}$ and $L_{if}/R_{if}$) are used.
2. Compute the boundary for the next patch pair on the basis of the previous line direction (extrapolation).
3. Export the unclassified ALS data within the new patch boundary from the database.

This growing procedure (step 1 to 3) is continued until the adjustment is unsuccessful or a certain break off point (e.g. threshold for the intersection angle between both surface pairs) is reached.

### 4.2 3D Breakline Growing on the basis of one Start-Point

In a similar way breakline growing based on just one initial 2D point next to the breakline can be performed. For this extension the breakline direction must be estimated in a first additional step. For this aim a lot of different approaches (e.g. determination of the maximum curvature based on differential geometry in the surrounding of the start point) can be considered. In the example, presented in figure 7, an adjusting quadric, supported by the ALS points near the start point, is used. The determination of the breakline direction can be easily performed by an analysis of the main axis transformation. The approximation of the breakline direction is given by the eigenvector of the smallest eigenvalue (cf. figure 7). Afterwards the breakline growing can be performed with the help of the procedure presented in the previous section.

## 5 EXAMPLES

This section demonstrates the capabilities of the presented methods for breakline modelling and growing. An additional section shows the improvement of the integration of breaklines within the classification (filtering) process for DTM generation using ALS data. Most of the results were obtained within a test project initiated by the German federal agency for hydrology ("Bundesanstalt für Gewässerkunde").

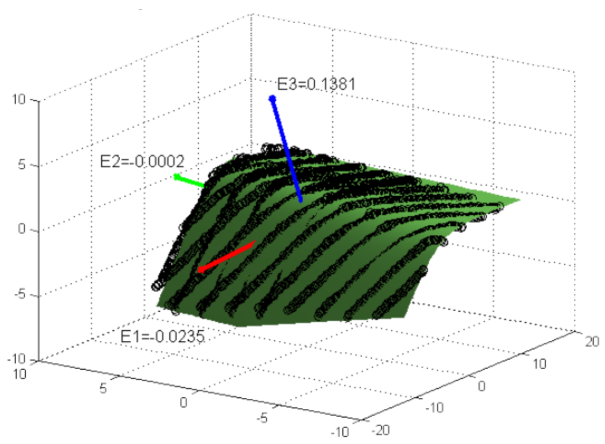


**Figure 7:** Determination of the breakline direction (eigenvector of the smallest eigenvalue, in this example E2) with the help an adjusting quadric on the basis of the ALS point cloud.

### 5.1 Modelling based on a 2D Breakline Approximation

The example in this section presents the result of a 3D breakline modelling procedure based on original unclassified ALS data. Figure 8 shows the intermediate steps within the modelling procedure starting with a rough approximation of the breakline (upper part of the image). In the next step the boundary for the data selection and the ALS point cloud within this area (black dots) can be seen. In the lowest part of the figure the refined 3D modelled breakline is presented. In this example the size of the surface patches was 5m (along the breakline) by 10m (across the breakline). The overlap between neighbouring patches was 50 percent.

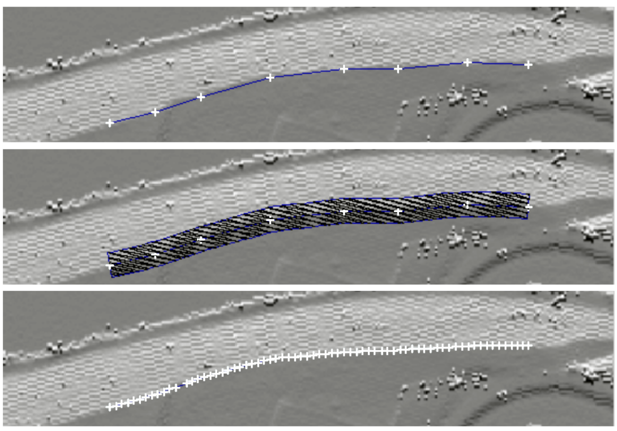

**Figure 8:** Work flow (beginning at the top) of the 3D modelling based on a 2D approximation of the breakline demonstrated on a practical example. The middle part shows the buffer zone around the breakline approximation and the ALS point cloud (black dots) inside this area. In the lowest picture the refined robustly estimated breakline is presented.

### 5.2 Modelling based on 3D Breakline Growing

The demonstration of the 3D breakline growing (cf. section 4) is presented on the previous breakline example. The growing in this example (cf. figure 9) is performed into both directions. The final resulting breakline can be inspected in the lowest part of the figure. The break off point is defined by an intersection angle smaller than 10 degrees. The patch size is 10m by 10m with 50 percent overlap between neighbouring patches. This results in a breakline description with a point distance of 5m. The patch size for the growing is bigger than in the previous example in order to make the process more robust. The result can be refined (if necessary) in a further modelling procedure.

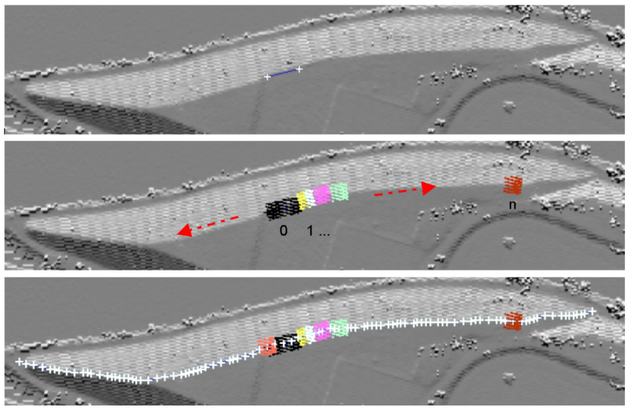


**Figure 9:** Breakline growing (beginning at the top) based on a manual digitised start segment.

### 5.3 Integration of Breaklines within the Terrain Determination Process (Filtering)

A small example for the consideration of breaklines within the filtering process is presented in figure 10. The derived DTM shows a high quality enhancement in the areas of sharp ridges due to the explicit 3D modelling of the breaklines. For the DTM generation robust interpolation (cf. (Kraus and Pfeifer 1998)) was used. Within this process the previous determined breaklines were considered to be free of gross errors. The final DTM of this example has a hybrid raster data structure.

## 6 SUMMARY

This paper presents a method for 3D modelling of breaklines based on the original unclassified ALS point cloud. The modelling is performed with the help of robustly estimated surface patch pairs along the breakline. The elimination of the influence of off-terrain points within this estimation process works in a fully automated way and adapts itself to the data. This modelling starts from a 2D approximation of the breakline, which is iteratively refined. Additional observations (e.g. acquired using image data) can be easily integrated into the modelling procedure. A further section focuses on methods for the automatisation of the whole process.

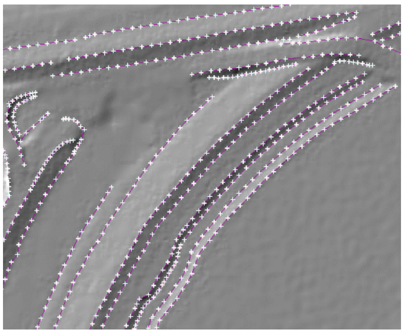

**Figure 10:** DTM model based on a hybrid raster structure. The modelled breaklines were integrated in the classification (filtering) process for DTM determination.

First tests of this method for 3D breakline modelling on large data sets showed that this method can be successfully applied to unclassified ALS data. Nevertheless, one can think of a lot of further developments in order to enhance its capability. Next to improvements in the weight model (e.g. no strict separation of left and right points) a combined adjustment of more than one patch pairs would on one hand improve the capabilities of the breakline estimation in dense wooded areas (larger areas with only a view terrain points can be bridged) and on the other hand constrains between neighbouring patch pairs can lead to a homogenisation of the resulting breakline. Potentially for certain breaklines the surface model should be more flexible in order to avoid errors caused by model deficits. A big lack is that up to now the implemented algorithm does not consider jump edges. On these edges the coupling of both surface pairs (forcing an intersection of the surface patches) must be cancelled. Instead of an intersection line two breaklines (one belonging to the lower and one to the upper surface) must be determined in order to allow a modelling of a step edge.

In the future a detailed quality analysis of the results of the presented 3D modelling procedure will be performed in order to recognise some deficits of the method and to get an idea about the possible accuracy in respect to reference data. Still the fully automated extraction of breaklines from irregular distributed point clouds is not visible, but some methods for automatisation do exist, which are able to reduce the manual work. Finally, the importance of breakline modelling must be stressed. Explicitly modelled breaklines allow a high quality improvement within the ALS classification (filtering) process for DTM determination and offer, next to a better morphological modelling, a higher data reduction of the final models.

## ACKNOWLEDGMENTS

This research has been supported by the Austrian Science Foundation (FWF) under project no. P15789.

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