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AIRBORNE LASER SCANNING – HIGH QUALITY DIGITAL TERRAIN MODELLING

Key words: Airborne Laser Scanning, Digital Terrain Model, Break Lines, Filtering, Classification, Data Reduction

SUMMARY

After a short introduction into the Airborne Laser Scanning (ALS), the sampling process and a brief comparison of ALS with other data acquisition methods, the paper focuses on the generation of high quality digital terrain models from ALS data. In the first part the hierarchic robust interpolation method for the automatic filtering and classification, respectively, of an ALS point cloud into terrain and off-terrain (points on buildings or on the vegetation, etc.) is presented. Then, an approach for the modelling of linear features, such as break lines, based on the ALS data is described. Based on the feature lines and the classified terrain points a high quality DTM can be determined. For many subsequent processes the data reduction of the detailed DTM is essential in order to handle the large amount of data. Therefore, the paper presents a data reduction method that guaranties a certain DTM representation quality. Next to the presented algorithms, for each of the mentioned topics, references to other published methods are provided. Furthermore, beside the description of the algorithms, practical examples demonstrate the results of the algorithms. At the end of the paper, an outlook section discusses the advanced possibilities of DTM determination based on full-waveform ALS data.

ZUSAMMENFASSUNG

Nach einer kurzen Beschreibung des Airborne Laserscannings (ALSs) und einer Gegenüberstellung mit anderen Datenerfassungsmethoden, widmet sich die vorliegende Publikation Methoden zur Erstellung von hochqualitativen Digitalen Geländemodellen (DGMen). Dazu wird im ersten Abschnitt auf unterschiedliche Methoden zur Filterung bzw. Klassifizierung von Nicht-Bodenpunkten eingegangen und im Detail die Methode der Hierarchischen Robusten Interpolation vorgestellt. Ein weiterer Abschnitt befasst sich mit der Extraktion von Strukturlinien aus den ALS Daten. Im Anschluss daran widmet sich die Publikation der DGM Erstellung aus den klassifizierten Bodenpunkten und den aus den ALS Daten abgeleiteten Strukturlinien. Dieser Teil befasst sich außerdem mit der Datenreduktion der dichten ALS Geländemodelle und präsentiert eine Datenreduktionsmethode die eine gewünschte Approximationsgenauigkeit garantiert. Praktische Beispiele im Rahmen der einzelnen Abschnitte illustrieren die Ergebnisse der einzelnen Methoden. Am Ende des Artikels wird zudem auch noch auf die verbesserten Möglichkeiten der DGM Erstellung aus full-waveform ALS Daten eingegangen.

АННОТАЦИЯ

После краткого введения в технологию воздушного лазерного сканирования (ВЛС), процесс обработки данных и сравнение ВЛС с другими методами сбора данных, в статье акцентируется внимание на создание высококачественных ЦМР. В первой части описывается метод иерархической робастной интерполяции для автоматической фильтрации и классификации облака точек на точки рельефа и остальные (точки на зданиях или растительности и т. д.). Описывается подход к моделированию линейных элементов, например, линий разрывов, на основе данных ВЛС. Используя структурные линии и классифицированные точки рельефа, можно получить высококачественную ЦМР. Для многих последующих процессов, чтобы обработать большой объем данных, необходимым является редуцирование данных ЦМР. Поэтому в статье рассматривается метод предварительной обработки данных, гарантирующий представление ЦМР определенного качества. С представленными алгоритмами, для каждой упомянутой темы, даются ссылки на другие опубликованные методы. Кроме того, помимо описания алгоритмов, приводятся практические примеры демонстрации результатов использования алгоритмов. В конце статьи, обсуждаются современные возможности создания ЦМР на основе данных двухволнового воздушного лазерного сканирования.

1. INTRODUCTION

Digital Terrain Models (DTMs) are essential for many different applications (e.g. flood risk management, infrastructure planning, water flow analysis, visualisation tasks, etc.) and are nowadays a fundamental data set within Geographic Information Systems (GISs). In the past, analytical photogrammetry was the main measurement technique for gathering topographic information of large (from several km^2 to countrywide) areas with a height accuracy in the decimetre or meter range. However, in the last few years, new and - compared to manual photogrammetric measurements - highly automated measurement techniques like Airborne Laser Scanning (ALS, also referred to as LIDAR (light detection and ranging)), automated image matching, and interferometric synthetic aperture radar (InSAR) became available. All these new techniques have in common that they allow a very dense sampling of the area of interest within a short time. However, in contrast to the “classical” data acquisition systems, where the interpretation and abstraction of the topography is performed manually during the stage of data acquisition by human interpretation, the sampling of these automatic systems is not guided by a simultaneous interpretation of the scene. The interpretation is typically done in post-processing depending on the individual application.

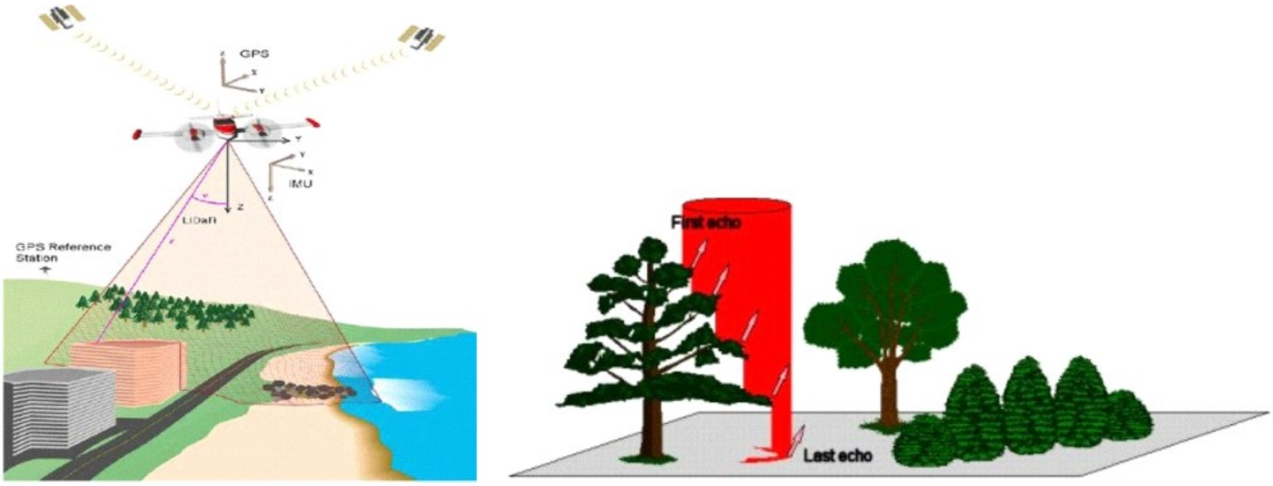

Figure 1 – Left: Principle: Airborne Laser Scanning (ALS, http://www.optech.ca/); Right: Complex interaction of a laser beam with vegetation above the terrain (http://www.toposys.de/).

Especially, ALS with its efficient data sampling capabilities revolutionised the area of topographic surveying (Kraus, 2004). ALS (cf. Figure 1, left) is an active remote sensing technique that utilises a narrow laser beam for a high frequent range determination to illuminated objects (cf. Wehr and Lohr, 1999 and Pfeifer and Briese, 2007). For the range determination all commercially available ALS systems use pulsed lasers. In order to allow an extensive acquisition of the topography the laser beam is continuously deflected across the flight path which leads together with the forward motion of the airborne vehicle to a strip wise acquisition of the landscape (typical point density: 1point/m² or denser). Based on the range measurement, the angle of deflection and the observations of a Position and Orientation System (POS, typically based on a Global Positioning System (GPS) and an Inertial Measurement Unit (IMU)) for direct geo-referencing, ALS allows the direct 3D determination of illuminated object points within one co-ordinate frame. Furthermore, if several objects at different ranges are illuminated by one laser beam (e.g. in the case of vegetation above the terrain, cf. Figure 1, right) a complex interaction of the laser beam can be observed. Due to the ability of separating these individual echoes (limited by the range resolution of the ALS System, typically between 0.5m and 1.5m) ALS systems are able to look through gaps in the forest foliage and record terrain echoes under vegetation cover. Typically, the ALS systems additionally provide the amplitude (also called intensity information, describes the signal strength of the echo) of the individually detected echoes. Advanced systems record the waveform of the returning echo, i.e. the time-dependent variation of signal power and allow to determine the individual echoes and further information about the illuminated objects in post-processing (Wagner et al., 2004, Wagner et al. 2006, cf. section 5). Table 1 provides a list of typical parameters of current available commercial ALS systems.

Table 1 – Typical parameters of an ALS system.

Specification	Typical Value
Wavelength	0.9μm and 1.5μm
Pulse Duration	5-15ns
Beam Divergence	0.2-1mrad
Pulse Repetition Rate	30-200kHz
Field of View	14-75°
Scan Rate	25-650Hz
Scan Pattern	Zigzag, parallel, elliptical, sinusoidal
Footprint	0.2-2m
Multiple Echoes	2-8 or full-waveform
Echo Amplitude	Yes
Operating Altitude	200-3000m
GPS frequency	1-2Hz
IMU frequency	128-1000Hz
Accuracy (elevation)	0.05-0.20m
Accuracy (planimetric)	0.1-1m

Compared to other automated acquisition systems ALS excels in (i) a direct determination of 3D coordinates based on one line of sight, (ii) an independency of the sun-light (can be operated in the night), (iii) in the ability of separating echoes at different ranges, and finally, (iv) in a high - especial height - accuracy. These advantages make ALS interesting for topographic data acquisition. Currently, mapping agencies of many countries (e.g. The Netherlands, Swiss, Germany and Austria) utilize ALS for the determination of their countrywide terrain models. Next to this large area mapping activities, ALS is currently extensively used along rivers for flood prevention and risk assessment. Currently, the main application of ALS data is the determination of digital terrain models (DTMs), but a significant increase of utilising ALS for other application areas, like corridor, building and vegetation mapping, can be observed.

This paper focuses on the high quality DTM generation based on ALS data. As mentioned in the previous paragraphs, the result of an ALS data acquisition campaign is a huge amount of unstructured point cloud data. Even though ALS systems can distinguish between different echoes at different ranges the resulting last echo point cloud still includes echoes from off-terrain objects like houses, dense tress, cars and other objects above the terrain surface. Therefore, one essential task for DTM generation based on ALS data is the filtering resp. classification of off-terrain objects in the last echo point cloud data. Therefore, the following section focuses on the classification of ALS data into terrain and off-terrain points. After a short overview about several published algorithms, the section focuses on the so-called hierarchic robust filtering method implemented in the commercially available software package SCOP++ (Inpho, 2007). Subsequently, the extraction of linear feature lines, such as break lines, based on the ALS data is discussed and a method for the modelling of lines based on the ALS point cloud data is presented. The following section focuses on the task of DTM generation based on the feature lines and the classified ALS terrain points and discusses the issue of DTM data reduction based on practical examples. Then, advanced DTM determination capabilities using the newest generation of full-waveform ALS systems are discussed. Finally, a short summary with an outlook concludes the paper.

2. CLASSIFICATION INTO TERRAIN AND OFF-TERRAIN ECHOES

During the ALS data acquisition process no interpretation resp. classification of the determined echoes, which were reflected from different objects, is performed. However, for the generation of a DTM the classification of the ALS data into terrain and off-terrain points is essential. This separation, which is often also important for other applications (e.g. vegetation or power line mapping), is often also entitled with the term “filtering”.

In the past, many different solutions for the filtering of the ALS data were published (cf. Sithole and Vosselman, 2004). On one hand these methods can be classified by the input data they use (one type of methods uses rasterised ALS data while others use the original ALS point cloud data) whereas on the other hand they can be grouped by the different concepts they use in order to classify the data. One group of algorithms are the morphological filters (e.g. Vosselman, 2000), which use a small structure element, describing admissible height differences as a function of the horizontal distance. Another group can be entitled as progressive densification methods (Axelsson, 2000, Hansen and Vögtle, 1999). They start with a rough approximation of the DTM with initial terrain points (typically the lowest point within a certain grid cell) and iteratively densify the DTM by the evaluation of a set of rules (e.g. maximal distance to the DTM approximation, angle criteria, etc.). The third group of filter methods work surface based (Kraus and Pfeifer, 1998 and Elmqvist et al, 2001). They use a surface model that iteratively approaches the DTM calculated based on the entire point set by adapting the influence of the individual input points. Finally, recently a set of segmentation based methods were published (Tóvári and Pfeifer, 2005, Sithole and Vosselman, 2005). In the first step, these methods segment the ALS data with a local neighbourhood analysis and subsequently classify the segments by different strategies. Most of the existing methods do not consider further input data (e.g. orthophotos) and just analyse the geometric relation between neighboured ALS points. A comparison of the performance of different methods can be found in a paper of Sithole and Vosselman (2004).

In the following the so-called hierarchic robust interpolation method, which is an extension of the surfaced based method presented in Kraus and Pfeifer (1998) is presented. This approach was developed by the Vienna University of Technology, Institute of Photogrammetry and Remote Sensing, in cooperation with the German company Inpho GmbH and is implemented in the software package SCOP++ (Briese et al., 2002; Inpho, 2007; Pfeifer at al., 2001; http://www.ipf.tuwien.ac.at/eurosdr//index.htm). The method relies on an interpolation technique capable of considering an individual weight per point. The basis of this surface based approach is the technique of robust interpolation. The aim of this algorithm is to compute individual weights for each of the irregularly distributed points in such a way that the finally modelled surface represents the terrain. For this aim, it rests upon the assumption that – in a certain neighbourhood – lower points are more likely to belong to the terrain surface than higher points. Therefore, based on an initial surface (at the begin all points have an equal weight) the weight of the points is altered iteratively by an asymmetric weight function in a way that low points get a higher weight than points above the surface.

Within the hierarchic robust interpolation method this way of reweighing the points is embedded in a progressive coarse to fine approach. The hierarchic filtering strategy employs four main processing steps referred to as thin out, interpolate, filter, and sort out. These four steps can be applied consecutively, whereby a few rules restrict the order of application. Thin out refers to a raster based thinning algorithm which lays a grid over the complete data domain and selects one point (e.g. the lowest) for each cell (in order to generate a certain data pyramid level). In the interpolation step a terrain model is derived from the current data set by interpolation without classifying data points, whereas the filter step (robust interpolation) classifies the input points into terrain and off-terrain points using the technique of robust interpolation. In the sort out step only those original data points are retained that are within a certain distance (tolerance band) from a previously calculated DTM. The concept of the hierarchic robust filter strategy is quite flexible. So the approach can be easily extended with additional steps (e.g. SCOP++ provides a specific building elimination step) with allows an advanced classification of the ALS data. Depending on the characteristics of the ALS data set, different filtering strategies can be devised. The flexibility in the design of the strategy, combined with the possibility to select a number of parameters in each processing step, has the advantage that, with the exception of few problem areas, satisfactory results can be achieved with a low amount of manual editing. Within SCOP++, a set of pre-defined filter strategies is available. However, the decision which filter strategy is the best requires some knowledge of the terrain (e.g. roughness) and of point cloud characteristics (e.g., density, vertical distribution of points above the terrain). In Figure 2, the result of a classification of the ALS point cloud data of a practical example is presented.

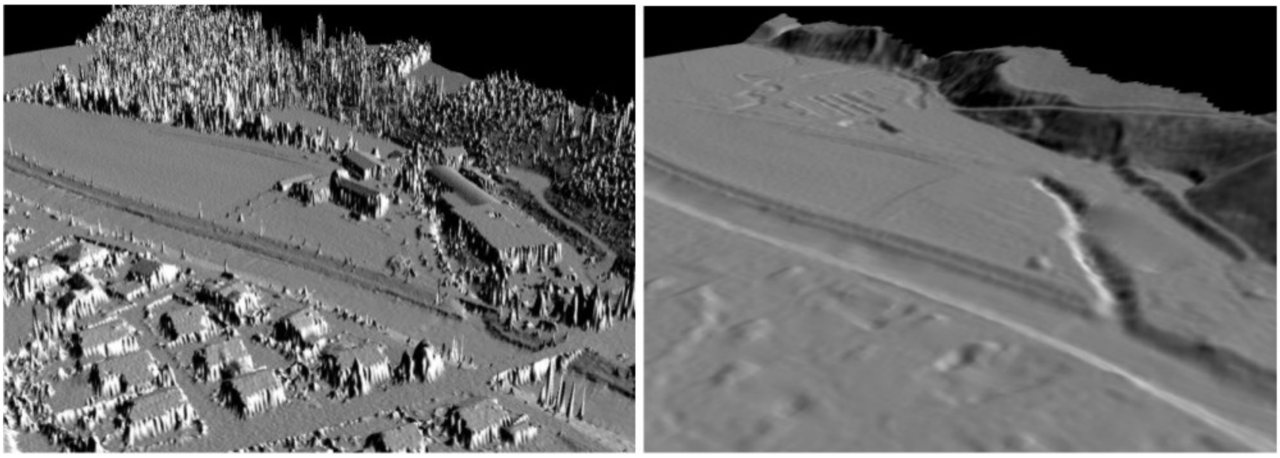

Figure 2 – Left: Digital Surface Model (DSM, 1m grid) determined from ALS data. Right: Digital Terrain Model (1m grid) determined from the classified terrain points.

3. DETERMINATION OF BREAK LINES

For the representation of models generated from ALS data, mostly raster, grid models, or triangulated irregular networks (TINs) are in use, which are usually simply determined based on the irregular distributed ALS point cloud. Due to the lack of structure information, it has to be considered that the description of break lines, which are necessary for a high quality delineation of a surface discontinuity, depends next to the original sampling interval on the size of the stored raster respectively grid or triangle surface cells. In contrast to these models without an explicit feature line description, it is essential for high quality surface models (for example for hydrological applications) to store the lines explicitly in the data structure. For this aim, a 3D vector based description of the lines is necessary. Next to an advanced description of these linear features, the line information can be helpful for the task of data reduction, because break lines allow describing surface discontinuities even in models with big raster or triangle cells (cf. section 4).

The research in the scientific community in the area of break line extraction focused on methods for the fully automated 2D detection in so-called range images determined from the ALS point cloud. The range images are used in order to apply raster image-processing techniques. Most of the methods for ALS data lean ajar algorithms developed for the extraction of break lines from photogrammetric data. Brügelmann (2000) presents one representative method, which introduces a full processing chain starting from an ALS range image leading to smooth vector break lines. Furthermore, Borkowski (2004) presents two different break line modelling concepts - one makes use of snakes whereas the second method utilizes a numeric solution of a differential equation describing the run of the break line. Brzank et al. (2005) presents an approach for the extraction and modelling of pair wise structure lines in coastal areas described by a hyperbolic tangent function.

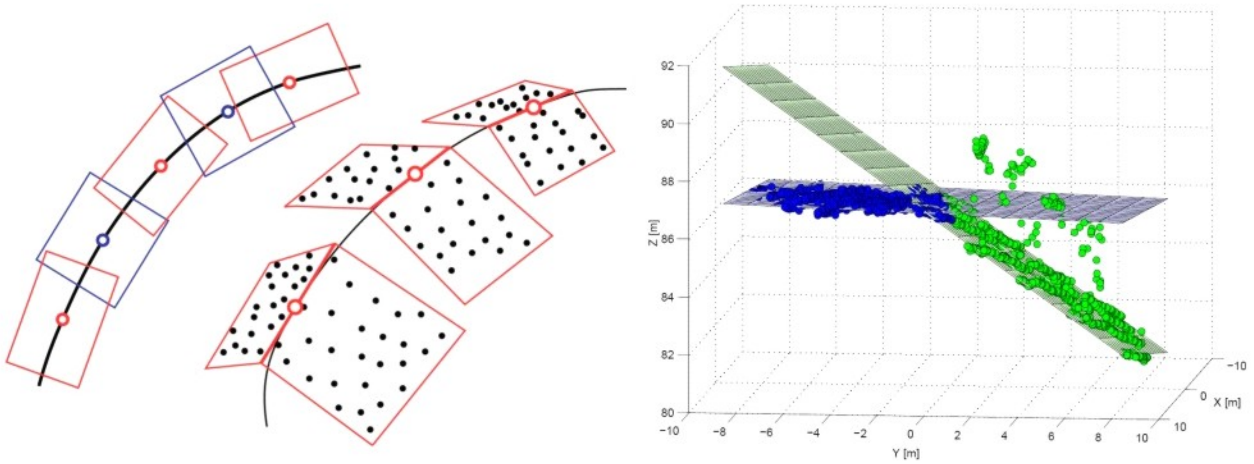

Figure 3 – Left: Basic concept for the description of break lines with the help of intersecting patch pairs (Kraus and Pfeifer 2001). Right: Practical example of a robust estimated plane patch pair (10m by 10m) based on unclassified ALS data (circles). The elimination of off-terrain points allowed to reduce the sigma of the adjustment from previously 0·59m to 0·12m (Briese, 2004b).

In contrast to the previously mentioned approaches for break line modelling, which relay on a previously estimated DTM or a filtered ALS point cloud, the subsequently presented approach uses the original irregularly distributed point cloud data as input (Briese, 2004 a and b). Subsequently, the break lines can be used as additional information in the filtering of the ALS point cloud data. The basic concept of the approach is displayed in the left part of Figure 3. Based on a local surface description on either side of the break line the break line itself can be described by a sequence of locally intersecting surface patch pairs. For the estimation of the patches, the ALS point cloud data in the vicinity of the line can be used. In order to consider off-terrain points, the idea of robust interpolation can be integrated in the local patch determination in order to exclude the influence of off-terrain points on the run of the break line. One example of such a robustly estimated surface patch pair can be seen in the right part of Figure 3. It can be seen clearly that after the robust estimation the off-terrain points do not affect the run of the right (green) patch and that the break line can be approximated by the intersection line between the two plane patch pairs accurately. However, in order to estimate the surface in the vicinity of the break line the 2D approximation of the break line, in order to define the surface patch pairs, is essential. To reduce the effort for a 2D approximation of the whole break line the concept of break line growing was introduced (Briese, 2004 a and b). Based on an initial 2D break line segment the final break line is determined by a step-by-step expansion into forward and backward direction of previously determined break line segments. As long as the determination within the extrapolated patches is successful or a certain break off point is reached, the growing procedure can continue. For the break off point an evaluation criteria that describes the significance of the surface discontinuity (e.g. the intersection angle between the determined “Left” and “Right” surface) is necessary. The practical application of this break line growing scheme applied to ALS data is displayed in Figure 5. Starting from a small break line segment the final break line is displayed at the bottom of the figure.

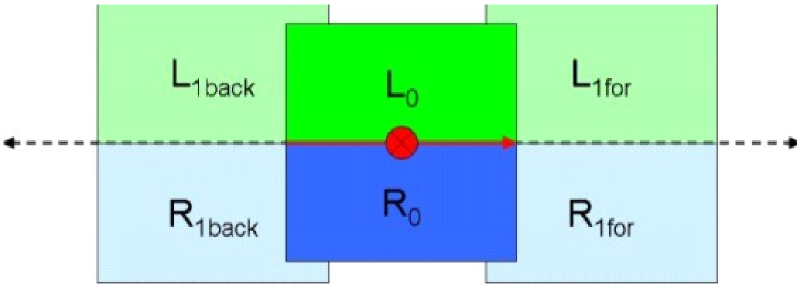

Figure 4 – Left: Scheme for automated breakline growing by step-by-step expansion into forward ($S_{i, for}(L_{i, for}, R_{i, for})$) and backward ($S_{i,back}(L_{i,back}, R_{i,back})$) direction with the help of a start-segment $S_0(L_0, R_0)$ (Briese, 2004 a and b).

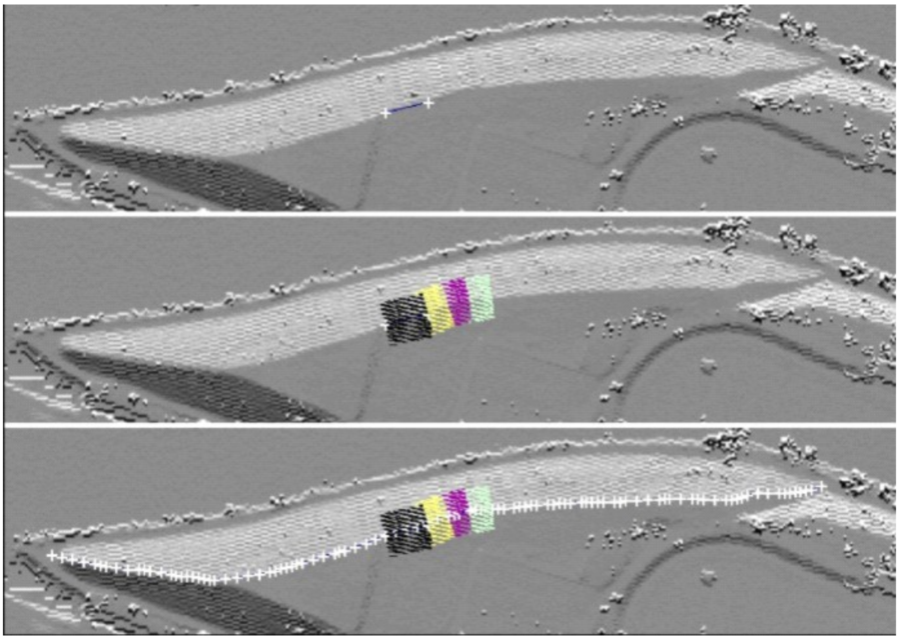

Figure 5 – Break line growing. Top: Shading of a surface model and start-segment; Middle: ALS points within the start patch S_0 (black) and within the three subsequently extrapolated patch areas in forward direction; Bottom: Result of the break line growing procedure (white crosses).

4. DTM GENERATION

Based on the classified ALS terrain points and the determined break lines the high quality DTM can be computed with the help of an interpolation method. In order to represent the line information adequately the lines have to be included into the data structure of the final model which describes the terrain surface. This can be done, on the one hand, by a triangular irregular network (TIN), where the line information acts like a constraint in the triangulation process, or on the other hand, by a hybrid grid, where the line information is meshed into a regular grid by a local triangulation. The resulting hybrid DTM allows a very detailed description using a dense regular grid for smooth surface regions in combination with a locally integrated TIN for the description of discontinuity areas (cf. Figure 6). Random measurement errors can be considered and their impact removed in the generation of the grid, something which is typically not performed in a triangulation.

However, for many subsequent applications such a detailed storage intensive description is not suitable (e.g. for the determination of flood models). Therefore, algorithms that allow reducing the amount of the data used for the description of the DTM are essential. For this aim, Mandlburger (2006) has developed an algorithm that starts with an initial approximation of the DTM comprising all structure lines and a coarse regular grid (the cell size can be specified by the user), which are triangulated using a constrained Delaunay Triangulation. This initial TIN is subsequently refined by iteratively inserting additional points until the previously specified maximal height tolerance Δz_{max} is kept. Based on the described coarse-to-fine approach an adaptive TIN is generated using a noticeable reduced point set of the original DTM that guaranties a certain user specified approximation accuracy. A practical example that demonstrates the effect of data reduction of a hybrid DTM is illustrated in Figure 7. The amount of data for the description of the DTM could be reduced in this example by 94 %.

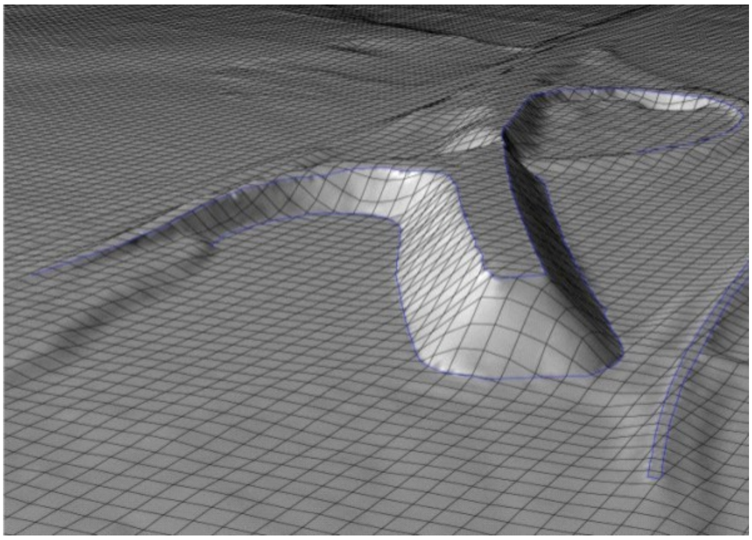

Figure 6 – Perspective view of a hybrid DTM derived by hierarchic robust interpolation considering break lines determined from the original unclassified ALS point cloud using robust surface patch pairs (data source: GeoConsult, Vienna).

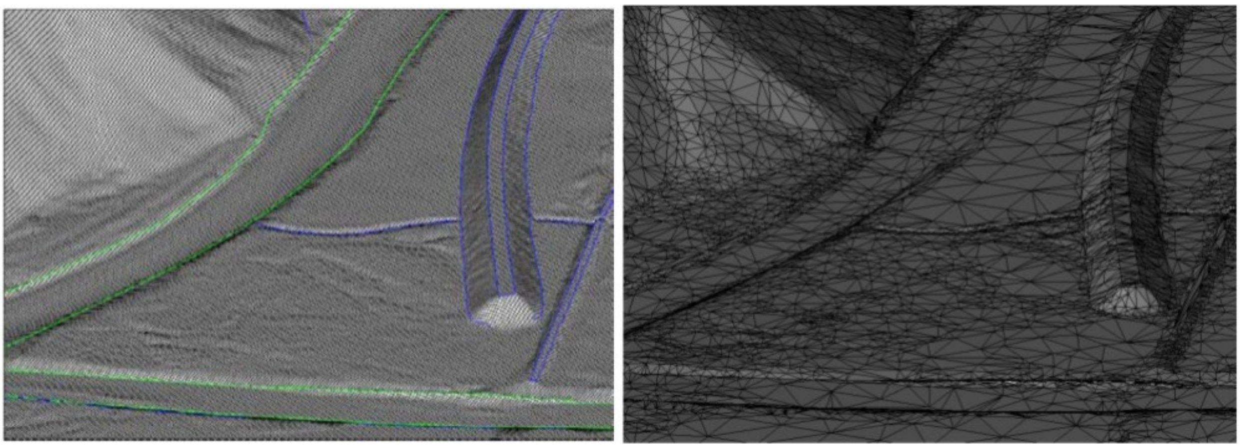

Figure 7 – Left: Original hybrid DTM (1m grid); Right: Data reduction with a height tolerance value of 0.2m (data source: GeoConsult, Vienna; Mandelburger, 2006).

5. OUTLOOK – FULL-WAVEFORM LASER SCANNING

As mentioned in the introduction, the new generation of ALS sensors, the so-called full-waveform (FWF)-ALS systems, are able to record the complete backscattered waveform. In contrast to the conventional discrete echo systems FWF-ALS sensors allow to determine the object echoes in post-processing and additionally allow to resolve further attributes per echo, i.e. the echo width and echo amplitude (Wagner et al., 2006). Whereas the echo amplitude describes the backscattered signal strength, which depends on the range, atmosphere, the backscattering characteristics of the target, and the ALS sensor, the echo width describes the range variation within one determined echo. If several close objects at slightly different ranges contribute to one echo, the echo width compared to the width of the emitted pulse will be increased. Alternatively, if the range variation within the footprint is low, the echo width will be quite similar to the width of the emitted laser pulse.

In order to study the advanced capabilities of FWF-ALS systems Doneus and Briese (2006) studied the ability of using the echo width for the removal of low vegetation that can be eliminated only hardly during the filtering procedure. Figure 8 presents one sample data set where the advanced capability of FWF data for DTM determination is demonstrated. One can recognise that the echo width in areas with low vegetation is – compared to open or wooded terrain with high trees – significantly increased. Therefore, a pre-filter step that eliminates echoes with a significantly higher echo width was proposed and included into the DTM processing sequence. As can be seen in the lower right part of Figure 8 this pre-filter step lead to a significant improvement of the DTM with a better surface representation quality compared to the DTM without this pre-elimination step (upper right part). However, up to now, the ability of the additional FWF information for advanced modelling task is not studied in detail, but this example demonstrates some of the potential of FWF-ALS data that can be used for an advanced DTM generation from ALS data.

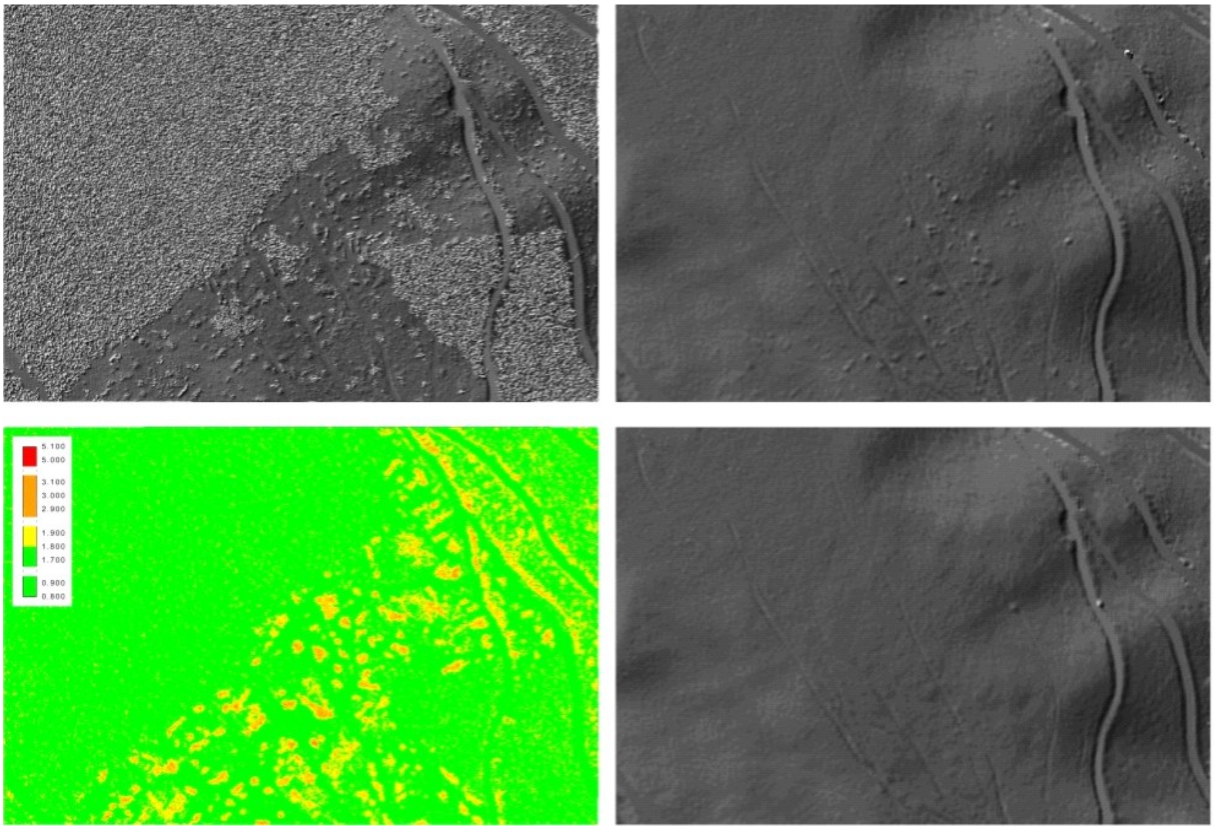

Figure 8 – Upper Left: DSM based on the ALS data; Upper Right: DTM after hierarchic robust interpolation without consideration of additional FWF information; Lower Left: Mapped echo widths determined from the FWF-ALS data; Lower Right: DTM with pre-elimination of points with large echo width (Doneus and Briese, 2006).

6. SUMMARY

The paper summarised techniques for high quality determination of DTMs from ALS data. Next to the important task of classification resp. filtering of ALS data a method for break line modelling is presented. Furthermore, the practical usage of data reduction methods is illustrated and a short outlook into the advanced capabilities for the detection low vegetation with FWF information is provided.

Airborne laser scanning is still developing, especially the point density is increasing. In addition, advances in precision are possible. Likewise, the flying height for data acquisition has been "going up" in the last years and this trend is expected to continue. Some of these aspects will make laser scanning commercially even more interesting for country wide topographic data acquisition, including the DTM. Other aspects (e.g. point density and precision) will allow using the technique for engineering projects where measurements have so far been acquired by terrestrial surveying.

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