Using Airborne Laser Scanning for Improved Hydraulic Models

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EXTENDED ABSTRACT

Due to recent flood events, risk assessment has become a topic of highest public interest. The definition of endangered or vulnerable areas is based on numerical models of the water flow. The most influential input for such models is the topography provided as a Digital Terrain Model of the Watercourse (DTM-W).

For capturing terrain data of inundation areas Airborne Laser Scanning (ALS) has become the prime data source. It combines cost efficiency, high degree of automation, high point density of typically 1-10 points per m^2 and good height accuracy of less than 15cm. For all these reasons ALS is particularly suitable for deriving precise DTMs as basis for Computational Fluid Dynamic (CFD) models. The quality of such models depends crucially on how well vegetation or other off-terrain objects have been removed in the DTM generation process.

The task of removing off-terrain points from the ALS measurements is commonly referred to as filtering. Traditional laser scanners only supply range measurements to the reflecting objects and, thus, the filtering process has to rely on geometric criteria. The latest generation of ALS systems record the full backscattered waveform, from which physical quantities like echo width and backscatter cross section can be derived. An advanced filtering technique based on the well established method of robust interpolation is presented exploiting the echo width for a more robust and reliable classification of the point cloud into ground and off-terrain points resulting in a more precise DTM-W. Besides filtering, exact sensor calibration, fine adjustment of ALS-strip data, proper fusion of ALS and additional river bed data as well as elimination of random measurement errors are important issues for generating a precise DTM-W based on the ALS point cloud.

The higher DTM resolution provided by modern sensors comes along with an increased amount of data. Thus, a direct use of the high resolution DTM-W as the geometric basis for CFD models is impossible. Currently available mesh generators for CFD models basically focus on physical parameters of the calculation grid like angle criterion, aspect ratio and expansion ratio. The detailed shape of the terrain as provided by modern ALS systems is often neglected. A DTM data reduction approach is presented, considering both the physical aspects mentioned above as well as the preservation of relevant terrain details. The method starts with an initial TIN-approximation of the DTM comprising structure lines and a coarse grid. The TIN is subsequently refined by adding additional grid points until a certain height tolerance is met. A spatially adaptive data density, where terrain parts being sensitive for the CFD model are mapped with more details than parts of minor importance, can be achieved by introducing individual height tolerances in the iterative refinement process. In order to obtain a high quality computation grid the resulting surface approximation is professionally conditioned to meet specific hydraulic requirements.

Finally, practical results of CFD models based on different geometry variants are presented and discussed. It will be shown that a very detailed description of the topography can indeed be established in CFD models, resulting in more realistic flow simulations and more precise boundaries of potential flooding areas. An example is shown in Figure 1.

Figure 1. Digital flood risk map of the river Drau (Carinthia/Austria) resulting from a 2D-CFD-simulation based on a high resolution ALS-DTM

1 INTRODUCTION

ALS has become the prime data source for capturing topographic data in the last years. It combines cost efficiency, high degree of automation, remarkable height precision and high point density. ALS is especially well suited for capturing inundation areas as well as river banks under low flow conditions and is therefore widely used as data basis for CFD models today.

However, the application of ALS poses problems as well. Contrary to traditional manual data acquisition techniques like stereo-photogrammetry or tachymetry, ALS comprise both ground points and off-terrain points on buildings, vegetation, power lines, etc. The quality of the derived DTM and, consequently, the quality of subsequent CFD modeling depends crucially on how well off-terrain points have been eliminated within the filtering process. Standard ALS systems provide only range measurements (typically first and last echo per pulse) and therefore the filtering has to rely on geometric criteria only. In addition, the recent generation of laser scanners also provides the full backscattered waveform, which allows to deduct physical quantities like amplitude, echo width and backscatter cross section per echo. The combination of geometric criteria and physical echo parameters improves the reliability of the filtering (Doneus et al. 2007) and, thus, enhances the DTM. Another issue besides filtering is the fusion of ALS and river bed data. This involves the interpolation of river bed cross sections, the determination of a water surface model and the derivation of the water-land-boundary.

Nowadays, most CFD models are solved using a finite element or finite volume approach on the basis of unstructured geometries, i.e. a computation grid based on irregularly distributed points. Many mesh generators are available which build up a network of nodes, edges and polygonal faces covering the entire project area. These mesh generators consider hydraulic parameters like angle criterion and aspect ratio, but normally disregard the detailed topography. The heights are mapped to the hydraulic grid a posteriori. On the other hand, the direct use of the high resolution ALS-DTM as computation grid is impossible due to the enormous amount of data.

Therefore, the ultimate goal of this work is to derive a high quality computation grid considering hydraulic requirements as well as geometric details. In a first step the DTM is thinned out based on a maximum height threshold using an adaptive TIN-refinement approach. The algorithm preserves surface details in rough areas and removes as much points as possible in flat areas. The approximating TIN is analyzed in a subsequent data conditioning step, where the adherence of certain mesh quality parameters like aspect and expansion ratio but also the alignment of the mesh with respect to the principal flow direction are verified. As necessary, additional nodes are added to the TIN resulting in a grid, which fulfills the requirements of a good hydraulic computation grid additionally preserving surface details. In that sense the work at hand has to be regarded as interdisciplinary between the fields of geodesy and hydraulics.

This paper is structured as follows. In section 2 some basic terms necessary for the general understanding are introduced. Section 3 describes the applied data processing methods (DTM-W generation, data reduction and data conditioning). In section 4 some examples of practical CFD simulations are presented and the results using different variants of computation grids are discussed. Finally, the basic findings of the work are summarized in section 5.

2 DEFINITIONS

Since this paper addresses readers from different fields, a short introduction of the terms used is given in this section.

The processing described in this work starts with the ALS point cloud from which a DTM is derived. The DTM is regarded as a continuous description of the earth's surface, mathematically expressed as bivariate function $z = f(x, y)$. Traditional data acquisition methods like terrestrial surveying (Kahmen and Faig 1988) or photogrammetry (Kraus 2007) provide rather few discrete points or lines on the ground. ALS data sets, in contrast, contain up to 10 points per m^2, some of which are reflected from the bare ground but others from natural or artificial objects (vegetation, buildings, power lines, etc.). Thus, the point cloud needs to be classified into terrain and off-terrain points which is often referred to as filtering. To derive the height at any desired location, spatial interpolation techniques are employed. Among a variety of approaches, the linear prediction (Kraus 2000) or the equivalent method of Kriging (Journel and Huijbregts 1978) have to be highlighted since random measurement errors are minimized during the interpolation based on statistical data properties. DTMs are most commonly stored as regular grids or TINs respectively. In contrast, a hybrid DTM structure based on a regular grid with intermeshed break lines and spot heights (Köstli and Sigle 1986) combining the advantages of direct access (grid) and flexibility (TIN) is favored in this work. This structure has proven to be well suited for storage of even countrywide DTMs (Warriner and Mandlburger 2005). For applying in CFD models a specialized DTM variant is necessary, namely the so-called watercourse DTM (DTM-W). It contains the inundation area, the banks, the river bed and all flow

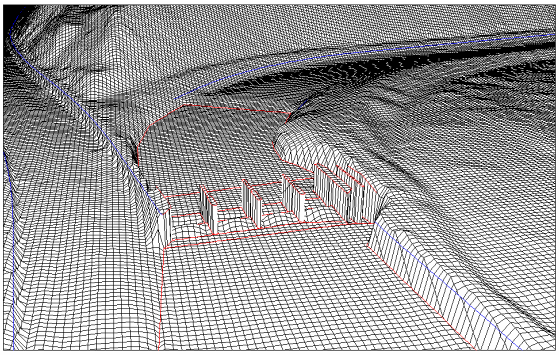


Figure 2. Hybrid DTM-W of the river Saar (Germany) at Schoden derived from ALS points, echo sounder cross sections and data of the power station

prohibiting buildings (Mandlburger and Brockmann 2001). Since the near infrared signal typically used by laser scanners does not penetrate water, it is necessary to combine the ALS data with river bed data from echo sounding or terrestrial surveying to get a DTM-W as it is shown in Figure 2.

As mentioned before, the DTM-W is the geometric basis for CFD models describing the water flow. The mathematical and physical background of such models are the momentum equations (Navier-Stokes differential equations), which are solved by aid of other physical fundamentals (energy and continuity equation) and empirical flow formulae (e.g. Manning-Strickler) using a finite element or finite volume approach respectively. Therefore, the entire project area is approximated by a polygonal computation grid. Unstructured grids (i.e. meshes with irregularly distributed nodes) are nowadays preferred to structured grids, because the former allow better consideration of the topography. However, several criteria have to be fulfilled by the grid in order to ensure both good computation performance and physically reliable results. According to Ferziger and Peric (2002) these are: angle criterion, aspect ratio and expansion ratio. In a nutshell, small angles $<10°$ should be avoided, the cells should be aligned to the principal flow direction, the aspect ratio should not exceed 10 (optimum <3) and the expansion ratio must not be greater than 3 (optimum <1.2). Besides geometry, the spatially varying flow resistances are another input for hydraulic models. They are typically considered by applying certain roughness coefficients to each grid cell. In practical flow simulations the CFD model is calibrated by adjusting the roughness coefficients until a satisfactory coincidence of model results and reality is achieved. It can often be observed that a lack of geometric details in the hydraulic grid is compensated by adaption of the roughness coefficients. Therefore, the next section describes a method for constructing a high quality hydraulic grid, which considers topographic details as provided by ALS-DTMs.

3 METHOD

3.1 DTM-W generation

The first step towards a topography-based hydraulic grid is the determination of a precise DTM-W from the given ALS and river bed data. This implies the following steps: Modeling of break lines (Briese 2004), filtering of the ALS point cloud, derivation of the water-land-boundary to split aquatic from non-aquatic domain (Mandlburger and Brockmann 2001) and densification of river bed cross sections considering the curved progression of the river axis (Mandlburger 2000). Not all the mentioned topics can be discussed in this paper in detail but the complete process is described in the author's Ph.D. (Mandlburger 2006).

In the following, the filtering of the ALS point cloud is focused on since the removal of vegetation and other off-terrain points is crucial for the quality of subsequent hydraulic modeling. In the past, many different solutions for filtering ALS data were published (Sithole and Vosselman 2003). All these approaches have in common that they rely only upon geometric criteria (typically the height relation of adjacent points) for the elimination of off-terrain points. The recent generation of laser scanners, however, provides the full waveform of the backscattered signal (c.f. Figure 3) and enables the derivation of additional attributes per echo like the amplitude or the echo width in the postprocessing after the flight mission (Wagner et al. 2006). The robust interpolation approach (Kraus and Pfeifer 1998) developed at the Institute of Photogrammetry and Remote Sensing, Vienna, allows a smart consideration of these additional echo attributes in the filtering process. The principal idea of robust

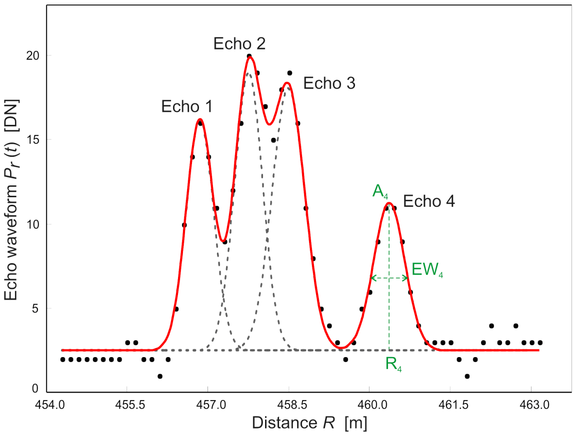


Figure 3. Recorded waveform (black dots) and echo attributes derived by Gaussian decomposition; Echo parameters: distance R_i, amplitude A_i and the echo width EW_i

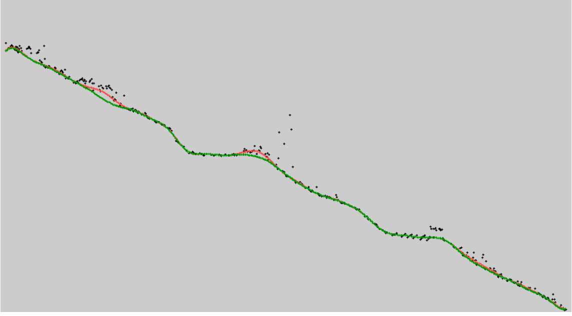


Figure 4. : DTM generation by robust interpolation with a-priori weights determined from the echo width demonstrated by means of a profile; Black dots: Last echo point cloud, Red surface: DTM without considering individual a-priori weights. Green surface: Improved DTM by robust interpolation with echo width dependent a-priori weights

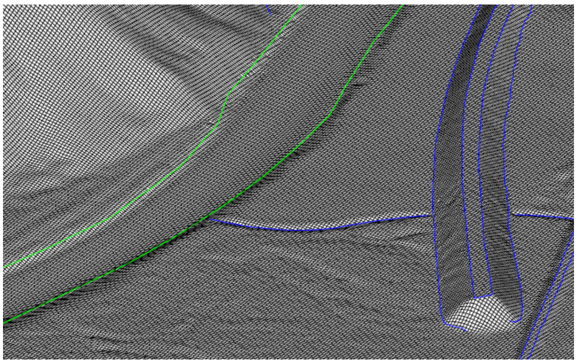
interpolation is to start with a surface to which all ALS points contribute equally, i.e. all points have the same weight. Subsequently the weight of each point is adapted according to its vertical distance form the averaged surface, where points above the surface get smaller weights. The additional echo attributes from full waveform signal processing can now be used to assign a-priori point weights, thus, speeding up the iterative filtering process and increasing the reliability of the classification (Mandlburger et al. 2007). Figure 4 shows the result of such an advanced robust filtering for a terrain profile using the echo width (EW) for the determination of a-priori point weights. The echo width describes the height variation of different targets (e.g. different branches of a tree) contributing to a single echo. In vegetation areas a widening of the echo width can be observed. Thus, points with a small echo width should get higher a-priori weights than points with a high echo width. This is achieved by applying the weight function $w(EW) = \frac{1}{1+a\,EW^b}$, where the coefficients a and b define how fast the weight function drops to zero. As can be seen in Figure 4, the DTM determined without a-priori weights is too high in areas covered by low vegetation due to the fact that the last echo is a mixture of reflections of small objects at different ranges above the DTM surface. Using robust interpolation with echo width dependent a-priori weights leads to a more reliable DTM, especially near the road in the middle of the profile. It is less affected by reflections in low vegetation.

3.2 Data reduction

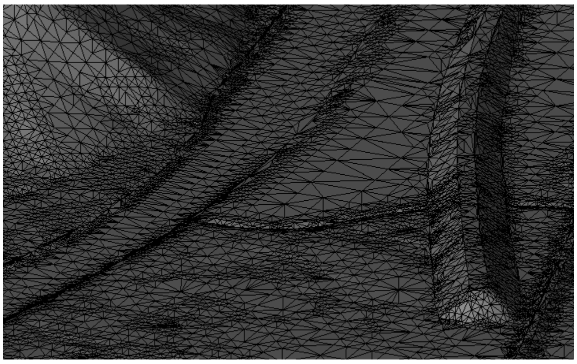
Most implementations of CFD models are restricted with respect to the maximum number of cells in the hydraulic grid (usually <500.000). By contrast, ALS-DTMs typically consist of millions of points and therefore surface simplification becomes inevitable. According to Heckbert and Garland (1997) mainly regular grid algorithms, decimation and refinement techniques are in use. The regular grid approaches are widespread, simple and fast, but they are not adaptive and produce poor approximation results. Better approximation quality can be achieved by applying decimation and refinement methods based on general triangulation algorithms like Delaunay triangulation. Decimation methods work from fine-to-coarse and are not suited for processing large high resolution ALS-DTMs since they require a triangulation of the entire point set. Refinement methods represent a coarse-to-fine approach starting with a minimal initial approximation. In each subsequent pass one or more points are added as vertices to the triangulation until the desired approximation tolerance is met or the desired number of vertices is used.

The performance of DTM data reduction is highly influenced by the existence of systematic and random measurement errors. Therefore, refinement approaches as described above based on the original ALS point cloud directly are not the first choice. Systematic errors have to be removed first by exact sensor calibration and fine adjustment of the ALS-strip data. Furthermore, random measurement errors of the ALS points should be minimized by applying a DTM interpolation strategy with measurement noise filtering capabilities. Good results can be achieved using linear prediction or Kriging respectively. High reduction rates can only be obtained for DTMs free of systematic and random errors.

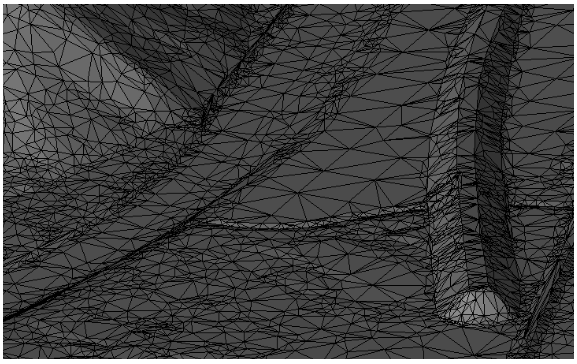
In contrast to the previously mentioned refinement approach, which relies on the original point cloud, the subsequently presented refinement framework uses the filtered hybrid DTM (regular grid with break lines, structure lines and spot heights) as input (Mandlburger 2006). The basic parameters for the data reduction are a maximum height tolerance Δz_{max} and a maximum planimetric point distance Δxy_{max}. The latter avoids triangles with too long edges and narrow angles. The algorithm starts with an initial approximation of the DTM comprising all line information and a coarse regular grid (cell size=Δxy_{max}=Δ_0), which are triangulated using a constrained Delaunay triangulation. Each Δ_0-cell is subsequently refined by iteratively inserting additional DTM grid points until the height tolerance Δz_{max} is met. These additional vertices can either be inserted hierarchically or irregularly. In case of hierarchical division, the grid cell is divided into four parts in each pass, if a single grid point within the regarded area exceeds the maximum tolerance Δz_{max} resulting in a quadtree-like data structure. By contrast only the grid point with the maximum deviation is inserted when using irregular division. Higher compression rates (up to 99% in flat areas) can be achieved with irregular point insertion, whereas the hierarchical



(a) Original hybrid DTM-W, grid width: 2m



(b) Adaptive TIN, hierarchic division, Δz_{max}*=0.25m, compression rate: 83%*



(c) Adaptive TIN, irregular division, Δz_{max}*=0.25m, compression rate: 94%*

Figure 5. DTM-W of the river Drau (Carinthia/Austria); High resolution DTM-W (a) and approximating TINs (b) and (c)

mode is characterized by a more homogeneous data distribution. Using the terms of hydraulics, the hierarchic division produces an adaptive cartesian grid whereas irregular division yields an unstructured grid.

Furthermore, the described framework is flexible concerning the reduction criterion. The decision to insert a point can be based on the analysis of local surface slope and curvature derived from the DTM or on the vertical distance between the DTM point and the approximating TIN. A comparison of an original high resolution DTM-W with its approximating adaptive TIN variants using hierarchic and irregular division is shown in Figure 5.

3.3 Data conditioning

What has been achieved so far is an approximation of the DTM with respect to geometric criteria only. However, the resulting TIN is not an appropriate computation grid for hydraulic modeling since no physical requirements have been considered.

Therefore, the next step is to condition the grid and to adapt the data distribution for special zones of interest. From a modeling point of view the following zones can be differentiated: River bed, river bank, surrounding and extended inundation area. The river bed is characterized by a permanent flow of water. The flow direction - approximated by the progression of the river axis - is the predominant direction of force. Thus, to achieve physically reliable results, the cells of the computation grid have to be aligned alongside the current within the domain of the river bed. Quadrilateral cells with the longer sides in and the shorter ones perpendicular to the flow direction proportional 3:1 (optimum aspect ratio) have turned out to produce good modeling results. The same applies for the river bank.

Beyond the embankment the water flow is no longer strictly parallel, thus, irregular data distribution as described in the previous subsection is appropriate. However, the river bank surroundings should be modeled in more detail than remote or elevated areas since they are more endangered by potential flood events. Height approximation errors of a few centimeters can well have severe effects on the adjacent estates, which may be of particular importance for residential areas. With increasing distance from or height above the river bank the influence of the topography on the results of the CFD model decreases, thus, allowing a coarser approximation of the terrain. Within the data reduction process the different demand of approximation precision can be controlled by spatially variable maximum height tolerances. Mathematically this can be expressed as $\Delta z_{max} = f(x, y)$. Distances from the river bank or relative height differences respectively can be used to control the tolerances, but a simple zonal model has turned out to be best suited. The delineation of the different accuracy zones can be derived from a pilot survey (e.g. a preliminary 1D-CFD simulation), from DTM visualizations like hill shadings, from existing maps or the like.

That way, a computation grid with a spatially adapted data distribution and approximation accuracy is derived from the high resolution ALS-DTM according to the needs for hydraulic modeling. For the resulting TIN the adherence of the quality criteria (angle, aspect and expansion ratio) has to be checked in a last step. Several tests with real-world data have shown, that the angle criterion and the aspect ratio are within

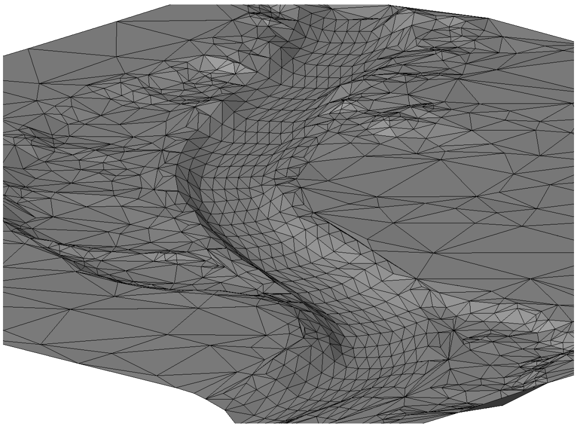


Figure 6. Hydraulic grid derived from a high resolution ALS-DTM considering both geometric and physical requirements

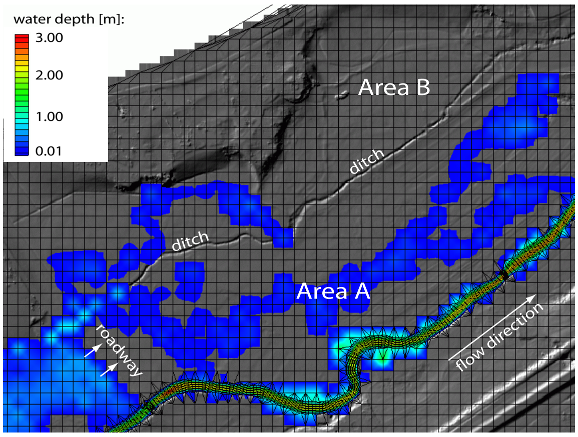
the valid range in the majority of cases using the described method. However, expansion ratios of >3 can be observed occasionally. From a geometric point of view this is a desired property of the reduction algorithm since it demonstrates a rapid transition from flat to rough terrain parts within the approximated surface. This shows clearly that it is necessary to combine geometric as well as physical aspects in order to obtain a high quality computation grid. A small section of a final hydraulic grid is shown in Figure 6.

4 RESULTS

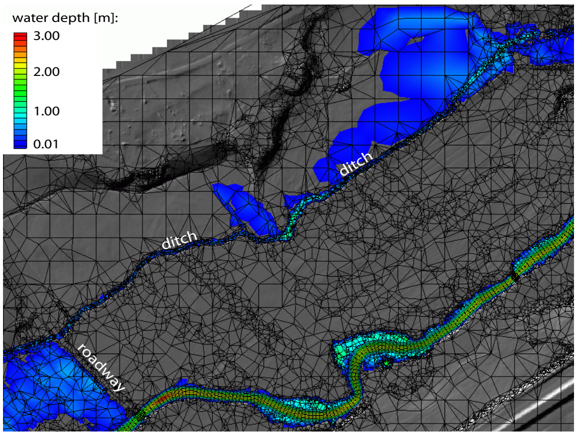
Based on the methods described in the previous section computation grids were derived for a section of the river Lainsitz in Lower Austria (ordinal number 5 according to Horton-Strahler, average slope 0.25%, meandering river type). The last echoes of an ALS flight campaign (point density: 1 pt/m^2) and river bed cross sections measured with terrestrial dGPS (profile distance: 100 m) were used to derive a high resolution DTM-W (grid width: 1 m) as described in section 3.1. Additionally, break lines (bridge piers) were integrated in the DTM-W and the data reduction and conditioning techniques explained in sections 3.2 and 3.3 were applied to the DTM-W. The resulting computation grid was used as the geometric basis for subsequent CFD modeling. The results of flow simulations based on two different geometry variants are shown in Figure 7, where the parts to the north of the river are of special interest.

The water levels presented in Figure 7a were obtained using a very simple regular grid reduction of the ALS-DTM. However, the application of such poor reduction techniques is still popular. It can clearly be seen that the detailed shape of the topography (c.f. the underlying hill shading) is insufficiently represented in the computation grid. Relevant flow prohibiting or flow enabling features like the roadway and the ditch are not represented in the surface approximation and, thus, the estimated water levels are incorrect, as Area A is flood-affected rather than the correct Area B. By contrast, the results shown in Figure 7b are based on an elaborately reduced and conditioned computation grid as described in sections 3.2 and 3.3. As in the former example, the river bed and the embankment are modeled using elongated quadrilaterals aligned to the river axis. Furthermore, the surrounding river foreland including the roadway and the ditch is approximated very detailed (Δz_{max}=10 cm) and less geometric details are provided in more distant and elevated areas. Figure 7b shows that the roadway acts as an exact flow barrier whereas a confined run-off is enabled through the narrow ditch. The availability of geometric details allows a more realistic simulation of the water flow and consequently a more precise determination of inundated areas.

Besides the water depth, CFD models also provide additional flow parameters like flow velocity and flow direction. Figure 8 shows a comparison of these

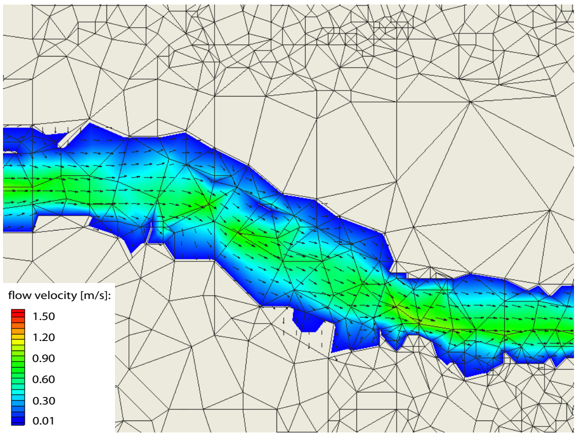


(a) regular 16m-grid, river bed: cells aligned to the flow direction

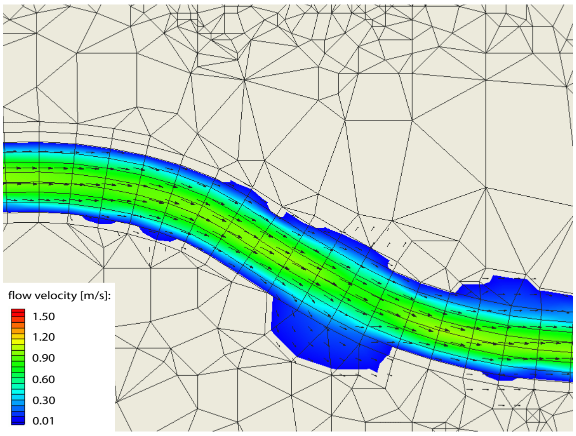


(b) adaptive TIN, Δz_{max}=variable=zone-dependent, river bed: cells aligned to the flow direction

Figure 7. Water depths for high flow conditions (HQ$_5$, 30m^3/s) resulting from a 2D-CFD-simulation based on the geometry variants (a) and (b); Data: river Lainsitz (Lower Austria)



(a) adaptive TIN, Δz_{max}=const=20cm, no additional data conditioning



(b) adaptive TIN, Δz_{max}=variable=zone-dependent, river bed: cells aligned to flow direction

Figure 8. Flow vectors and velocity distribution for mean flow conditions (MQ, 2.2m^3/s) resulting from a 2D-CFD-simulation based on the geometry variants (a) and (b); Data: river Lainsitz (Lower Austria)

parameters again based on two different geometry variants for a small section of the river Lainsitz. The computation grid shown in Figure 8a was deducted from the ALS-DTM using the data reduction approach described in section 3.2. It represents a correct approximation of the high resolution DTM-W with respect to a maximum vertical tolerance of 20cm. However, the cells are not aligned to the direction of the water flow resulting in an artificial geometric roughness. Consequently, the calculated flow vectors and velocity distribution are implausible. In other words, to obtain a high quality hydraulic grid it is insufficient to apply geometric criteria only. By far better results can be obtained using cell elements aligned to the principal flow direction within the river bed and embankment as can be seen in Figure 8b.

5 CONCLUSIONS

This paper has presented the potential of high resolution DTMs for improved hydraulic models. The main goal of exploiting the full information provided by ALS can only be achieved by establishing a complete processing chain from the raw ALS point cloud, via a precise DTM to the well-conditioned hydraulic grid. The basic input for CFD models is a precise DTM of the watercourse free of any systematic and random errors. This requires thorough orientation of ALS-strip data, proper filtering of off-terrain points, correct fusion of ALS and additional river bed data and, finally, DTM interpolation including elimination of random measurement errors. An advanced approach for filtering ALS point clouds based on robust interpolation combining geometric criteria and additional echo attributes derived from full waveform data analysis has been presented. By means of the echo width it was shown that additional echo attributes can very well be used to improve the reliability of the classification and the quality of the DTM especially in low vegetation areas.

Due to the enormous amount of data, the high resolution DTM-W cannot be directly used as geometric basis for hydraulic modeling. A method for DTM data reduction by adaptive TIN-refinement was presented, which preserves topographic details in rough areas and removes redundant points in flat terrain parts. Depending on the terrain type compression rates of up to 99% can be achieved. In order to obtain a high quality computation grid for CFD modeling special zones of hydraulic interest and additional physical requirements (angle criterion, aspect and expansion ratio) have to be considered. Thus, the preliminary TIN approximation is further improved by aligning the cells to the principal flow direction within the river bed and the bank and by establishing a spatially adapted data distribution within the inundation area in a subsequent conditioning step. That way, computation grids considering both geometric details provided by high resolution ALS data and physical requirements can be generated and successfully applied in CFD models. This result should be the initiation of a deeper collaboration between geodesists and hydrologists in order to integrate the knowledge of both disciplines for an improved flood risk assessment.

6 REFERENCES

Briese, C. (2004). *Breakline Modelling from Airborne Laser Scanner Data*. Ph. D. thesis, Vienna University of Technology.

Doneus, M., C. Briese, M. Fera, and M. Janner (2007). Archaeological prospection of forested areas using full-waveform airborne laser scanning. *Journal of Archaeological Science*, Article in press.

Ferziger, J. H. and M. Peric (2002). *Computational Methods for Fluid Dynamics* (3 ed.). Springer, Berlin.

Heckbert, P. S. and M. Garland (1997). Survey of polygonal surface simplification algorithms. Technical report, School of Computer Science, Carnegie Mellon University, Pittsburgh, PA.

Journel, A. and C. J. Huijbregts (1978). *Mining Geostatistics* (1 ed.). Academic Press.

Kahmen, H. and W. Faig (1988). *Surveying* (1 ed.). Walter de Gruyter.

Köstli, A. and M. Sigle (1986). The random access data structure of the DTM program SCOP. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXVI, Comm. IV*, Edinburgh, Scotland, pp. 42–45.

Kraus, K. (2000). *Photogrammetrie, Band 3, Topographische Informationssysteme*. Dümmler. An english edition by Taylor and Francis (translator: H. Rüther) is in preparation.

Kraus, K. (2007). *Photogrammetry, Geometry from Images and Laser Scans* (2 ed.). Walter de Gruyter.

Kraus, K. and N. Pfeifer (1998). Determination of Terrain Models in Wooded Areas with Airborne Laser Scanner Data. *ISPRS Journal of Photogrammetry and Remote Sensing 53*, 193–203.

Mandlburger, G. (2000). Verdichtung von Echolot Querprofilen unter Berücksichtigung der Flussmorphologie. *Österreichische Zeitschrift für Vermessung & Geoinformation 4*, 211–214.

Mandlburger, G. (2006). *Topographische Modelle für Anwendungen in Hydraulik und Hydrologie*. Ph. D. thesis, Vienna University of Technology.

Mandlburger, G., C. Briese, and N. Pfeifer (2007). Progress in LiDAR sensor technology - chance and challenge for DTM generation and data administration. In *Proceedings of the 51th Photogrammetric Week, D. Fritsch (ed.)*, Heidelberg, Germany. Herbert Wichmann Verlag.

Mandlburger, G. and H. Brockmann (2001). Modelling a watercourse DTM based on airborne laserscanner data - using the example of the River Oder along the German/Polish Border. In *Proceedings of OEEPE Workshop on Airborne Laserscanning and Interferometric SAR for Detailed Digital Terrain Models*, Stockholm, Sweden.

Sithole, G. and G. Vosselman (2003). Comparison of filter algorithms. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, 3/W13*, Dresden, Germany, pp. 71–78.

Wagner, W., A. Ulrich, V. Ducic, T. Melzer, and N. Studnicka (2006). Gaussian Decomposition and Calibration of a Novel Small-Footprint Full-Waveform Digitising Airborne Laser Scanner. *ISPRS Journal of Photogrammetry and Remote Sensing 60/2*, 100–112.

Warriner, T. and G. Mandlburger (2005). Generating a New High Resolution DTM Product from various Data Sources. In *Proceedings of the 50th Photogrammetric Week, D. Fritsch (ed.)*, Heidelberg, Germany, pp. 197 – 206. Herbert Wichmann Verlag.