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LaserScanDTMs for Modeling Flood Risk Areas

KARL KRAUS, Vienna University of Technology

ABSTRACT

Applying DTMs derived from laser scanner data yields major advantages for modeling flood risk areas. To meet the exceptionally high accuracy requirements as stated by hydrologists, careful application of advanced DTM technology is inevitable. Below, the following points are addressed:

- Geo-referencing airborne laser scanner data,
- Interpolation of DTMs taking into consideration break line information – semi-automatically extracted from the laser scanner data by means of mathematical snake curves,
- Deriving models of buildings and of vegetation models – to serve in taking into consideration surface roughness influencing the runoff of the water,
- Elevation accuracy of laser scanner DTMs, and position accuracy of the border of the flooded area as predicted for floods,
- Supporting documents for flood management.

1. PRELIMINARY REMARKS

Concerning our subject, population and politics have been sensitized by the catastrophic floods in recent years, resulting in increased willingness to invest in relevant data acquisition. At the same time – I have to say: fortunately – recent technological advancements allow for meeting the high requirements of modeling flood risk areas. The most important one of these advancements is airborne laser scanning: data acquired by applying it allow for computing DTMs (Digital Terrain Models) of very high elevation accuracy. Accomplishing this requires exceptional professionalism of the flight missions, and also highly sophisticated methods of processing the data thus acquired. This paper deals with the corresponding data processing methods, and also with some important points of project management.

2. GEO-REFERENCING

In their overlapping regions, adjacent laser scanner strips carry differences often up to half a meter and more; this results in oscillating isolines – an indication of the necessity to improve on geo-referencing. At the Institute of Photogrammetry and Remote Sensing (I.P.F.), block adjustment of strips as independent units has been suggested and realized, with the strips translated, tilted and deformed via additional parameters (Kager, Kraus, 2001). The required tie elements in the overlapping regions of the laser scanner strips are extracted automatically. In the corners of the block, control planes are introduced so to provide for proper fitting into the geodetic frame.

But more recently, we have replaced this specialized height adjustment of such blocks by a three dimensional solution. Unknowns in this process are corrections to the six orientation parameters, i.e. to three co-ordinates on the flight trajectory, and three attitudes of the laser scanner.

3. DERIVATION OF DTMs

From the point cloud as delivered by the airborne laser scanner mission, a DTM is derived. We at the I.P.F. derive the DTM applying linear prediction in a hierarchical approach. The keywords of this principle are:

- Filtering and interpolation take place in one and the same process.
- The weight function is asymmetric and eccentric; it is derived by statistical data analysis.
- The different levels of the data pyramids are created with the original x, y and z co-ordinates, and in the form of a regular raster.

More details on this method are available in the publication (Kraus, Pfeifer, 2001). The current status of this method is summarized in the paper (Briese et al., 2002a).

As part of this hierarchical process, large buildings and areas covered by dense and high vegetation can be eliminated of the laser scanner data. The large gaps in data distribution resulting from this elimination process, prompted us to complement the DTM software SCOP (see both homepages as cited in Section 8) with overlays to represent the quality of the DTM. At this point, we are developing the following three quality layers:

a. To visualize distances between grid points of the DTM as interpolated, and the point of the original data set next to them.
b. To visualize quality measures as derived from the differences between the elevations of the original points and the elevations of the DTM surface at the same locations; the quality measures will be analyzed for minute area cells according to user request.
c. To visualize local densities of the original points classified as terrain points.
d. To visualize elevation accuracy in all grid points of the DTM, computed on the basis of the minimal distances (a.), of the empirical accuracy measures (b.), of the point density (c.), and of the curvature in the grid point in question.

A publication with the corresponding details is in preparation.

4. ADDITIONAL FEATURES RELEVANT TO HYDRAULICS AND HYDROLOGY

In this section, some special relevant extensions are described: additional new features of the DTM as presented in Section 3.

4.1. River Bed and Water Surface

For applications in hydraulics and hydrology, DTMs must carry information both on river bed and on the adjacent terrain surface. Laser scanners yield – depending on the smoothness of the water surface, and also on the partical law of the water – considerably less points for the water surface than for the surrounding terrain. These points scattered on the water surface have to be eliminated of the data set, and replaced by data describing the river bed – gained, e.g., by sonar measurements. A successful project combining airborne laser scanner data with sonar profiles for computing a unified DTM is described in detail in (Brockmann, Mandlburger, 2001). In this method, the acquired profiles are defined as cross sections to the 3D river axis.

Hydrologists are frequently predicting the surface of the flood in the form of a 3D river axis with straight, sometimes non-horizontal, 3D cross sections. Therefore, the method developed for modeling of the river bed by profiles can be applied also for modeling of any predicted floods. The predicted water surface and of the DTM corresponds to the border of the flooded area.

4.2. Surface Break Lines

Airborne laser scanning yields a cloud of points but no surface break lines – of great importance for hydraulic and hydrologic applications. 3D break lines improve DTM quality considerably. SCOP DTMs are based on a specific hybrid structure consisting of a regular raster combined with 3D vectors – the latter to carry vector-type data such as break lines (see both homepages cited in Section 8 and Kraus, 2000).

There are various sources and methods to acquire 3D data for surface break lines. At this point, according to our experience at I.P.F. with numerous relevant projects, automatic derivation of break lines from the laser scanner data does not yield satisfactory results. Therefore, outlined below are some successful *semiautomatic* procedures based on other sources. In these interactive procedures, the user – usually a hydrologist – is working with graphical results of preliminary processing, supporting him in specifying his decisions concerning relevant break lines. Depending on the preliminary process, this involves:

a) Layer with Contour Lines:
Deriving and visualizing contour lines of the DTM described in Section 3, with a very small contour line interval. In this case, the swarming contour lines affect a strong plastic impression of the surface, helping the specialist to approximately digitize as 2D lines the relevant break lines. Orthophotos if present are of much value in this process also.

b) Structure Lines Acquired by Photogrammetric Compilation
To start with an example: in Austria, there is a rich set of digital data representing the structure lines of the terrain surface in great detail; they are acquired by stereophotogrammetric compilation (image scale 1:15000, 21cm camera) at the Federal Office of Metrology and Standards, and they are covering practically the entire country (Franzen, Mandlburger, 2003). Figure 1 is an example of these data, laid over the digital surface model (DSM); it is part of a laser scanner project of the Upper-Austrian governmental administration in the Almtal valley. The structure lines have been chosen according to geomorphologic principles for purposes of a hybrid topographic DTM. The hydrologist can select of these lines the break lines relevant to his task – e.g. often only the higher edges of river embankments. Although these lines have been measured photogrammetrically in 3D, only the position of them thus acquired is further applied here: the photogrammetric elevations are not sufficiently accurate for purposes of hydrology and hydraulics – as shown by the following expression:

$$\sigma_H = 0.15 \text{‰ of the flying height } (15000 \cdot 0.21 = 3150 \text{ m}) = \pm 47 \text{ cm} \qquad (1)$$

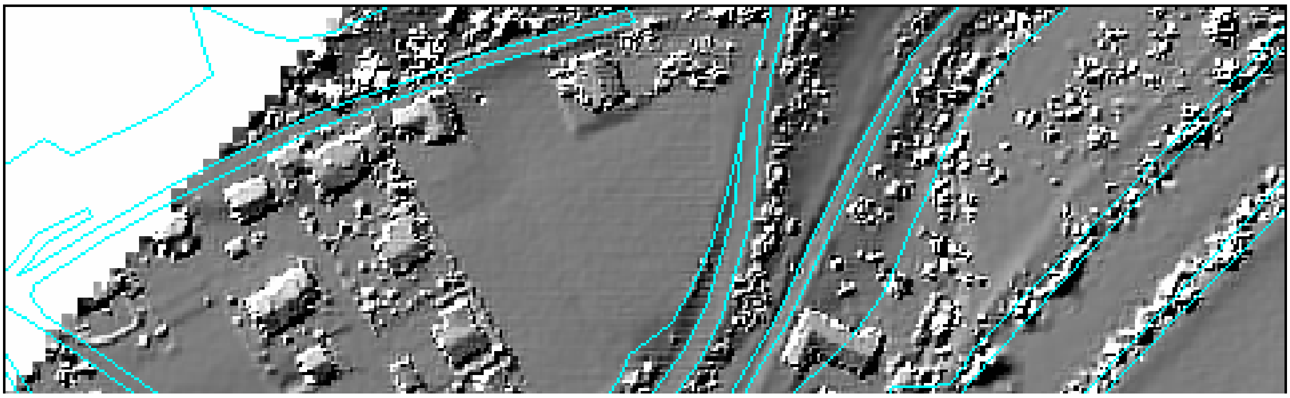

Figure 1: Structure lines acquired by photogrammetric compilation, laid over the DSM derived of laser scanner data.

c) Visualization of Local Differences in Curvature

This case involves analyzing the DTM described in Section 3 by applying methods of differential geometry, deriving local differences in the two principal curvatures, and visualizing the data field thus gained. Figure 2 is an example, representing just a single embankment; it is of a laser scanner project of the Austrian Waterway Authority. Figure 3 is showing the differences in the two principal curvatures of the LaserScannDTM; this image – eventually in combination with the DTM (Figure 2) and with a digital orthophoto – allows for digitizing by specialists the approximate position of the relevant break lines.

An improvement on the approximate position of the break lines thus digitized can be achieved by applying mathematical snake curves. In this method, so called *internal energy terms* are responsible for attaining smoother curves; and the *photometric terms* (Figure 3) provide for keeping the curve close to the edge of the image. M. Kerschner has extended the snake method for this purpose in two respects (M. Kerschner (2003) has recently finished his dissertation; it is available from the homepage of I.P.F., see link in Section 8.): First, he applies also the direction of the maximum principal curvature: the corresponding snake must proceed orthogonally to it. And second, he applies *twin snakes*, allowing to derive two snake curves proceeding more or less parallel to each other. In Figure 4 there are two curves proceeding close to each other – indicating that the specialist requests two break lines – both of them upper edges of the embankment. A repetition delivers then the two lower edges of the embankment (Figure 5).

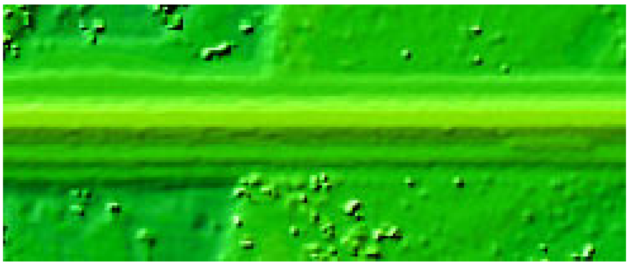

Figure 2: LaserScannDTM

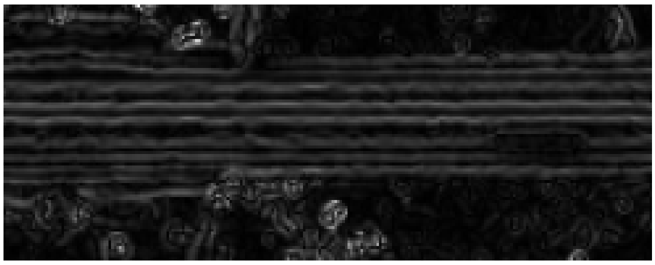

Figure 3: Visualization of local differences in the two principal curvatures

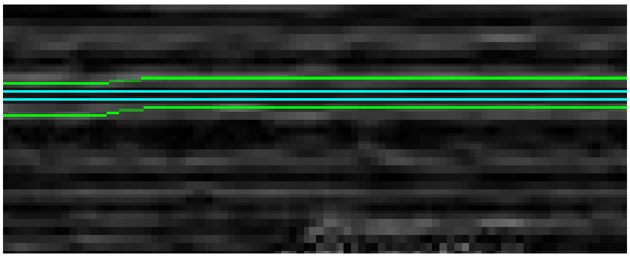

Figure 4: Twin snakes to detect the upper edges of an embankment

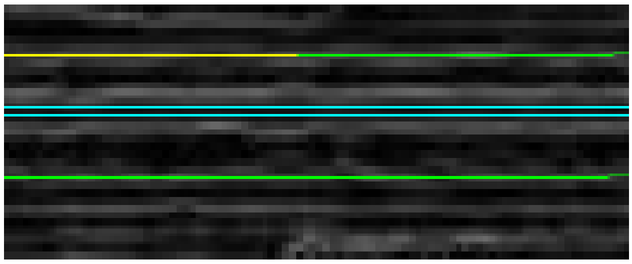

Figure 5: Twin snakes to detect the lower edges of an embankment

With the approximate position of relevant break lines as defined by one of the described procedures (a), b), or c)), an improved (or final) position of these lines in all three co-ordinate directions will be attained by applying the method "*moving pair of planes*". For this, the original laser scanner points have to be used, classified as terrain points in the filtering process described in Section 3. Relevant literature (Briese et al., 2002b, Kraus, Pfeifer, 2001).

4.3. Buildings and Vegetation

For modeling the runoff, hydrologists need so called roughness parameters. One of these depend on the presence of buildings. Accuracy requirements are low in this case. Building conglomerates – consisting of multiple prisms corresponding to cells of a dense DTM grid – are considered adequate. F. Rottensteiner (2002) of I.P.F. has published a relevant method; it is currently tested for this purpose.

A second parameter of roughness depending on the vegetation could be determined in the same way of conglomerates as described above for buildings; this idea is also subject to current testing at I.P.F. The vegetation model needed for this purpose is derived by the following steps:

- Extracting laser scanner points with meaningful differences in distances as defined by the first and the last reflected impulse: such points correspond most probably in areas to the vegetation (in this process, points in open terrain and also on buildings are thus eliminated with high probability).
- Deriving the difference model between the digital surface model (DSM) corresponding to the first impulses in the vegetation area, and the digital elevation model of the terrain surface (DTM, see Section 3). This yields the vegetation model as sought.

Figure 6 represents a vegetation model belonging to the project Almtal mentioned earlier. The grey values are rendering the height of the vegetation. The light gaps are an indication of areas without vegetation.

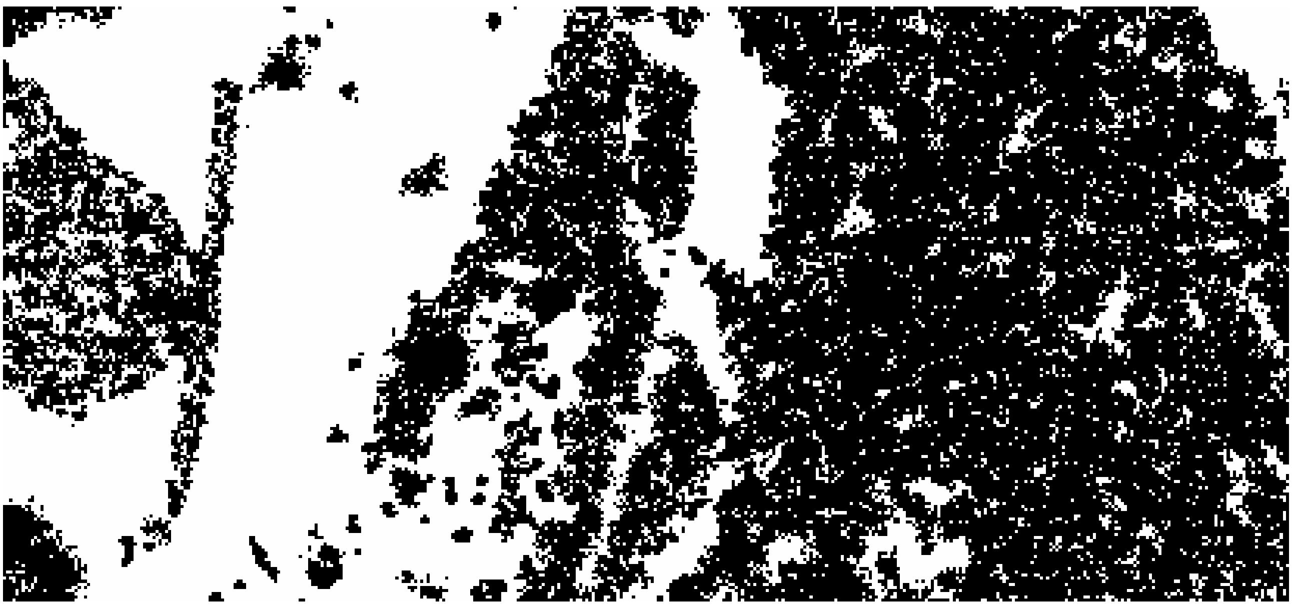

Figure 6: A vegetation model.

5. ACCURACY AND GEOMORPHOLOGIC QUALITY OF LASER SCANNER DTMs

In case of the quality layers as described in Section 3, accuracy measures are centered locally at individual points. On the contrary, in this section, we are dealing with accuracy measures representative for the entire area of interest; correspondingly, this section is of interest primarily for project management.

Empirical elevation accuracy of DTMs derived of laser scanning data can be expressed in general as

$$\sigma_H[\mathrm{cm}] = \pm\left(\frac{6}{\sqrt{n}} + 120 \cdot \tan\alpha\right) \qquad (2)$$

tanα . . . Terrain slope
n . . . Average number of points per square meter

For a point distance in laser scanner data of about 2 m both along and across the flight direction, corresponding to 0.25 points per square meter, formula (2) to express *elevation* accuracy of corresponding DTMs becomes

$$\sigma_H[\mathrm{cm}] = \pm\left(\frac{6}{\sqrt{0.25}} + 120 \cdot \tan\alpha\right) = \pm(12 + 120 \cdot \tan\alpha) \qquad (3)$$

For risk area representations, however, the *positional* accuracy of the border of predicted flood is of central interest, rather than the elevation accuracy of the LaserScannDTM. Figure 7 is an example of a flood risk area. The border of the predicted flood is represented by the contour line with elevation zero; other contour lines indicate by their elevation the depth of the flood. Changes in the position of the border of the predicted flood have considerable economic impact – and therefore, the same can be said of their accuracy σ_{HL} . The latter can be computed, taking into consideration expression (2), as

$$\sigma_{HL}[\mathrm{cm}] = \frac{\sigma_H}{\tan\alpha} = \pm\left(\frac{6}{\sqrt{n}\,\tan\alpha} + 120\right) \qquad (4)$$

In an area with a not untypical general slope of just 5‰ , the position accuracy of a border of the predicted flood is

$$\sigma_{HL} = \pm\left(\frac{12}{0.005} + 120\right) = \pm 2520\mathrm{cm} = 25\mathrm{m!}$$

More details can be found in (Kraus, 2000).

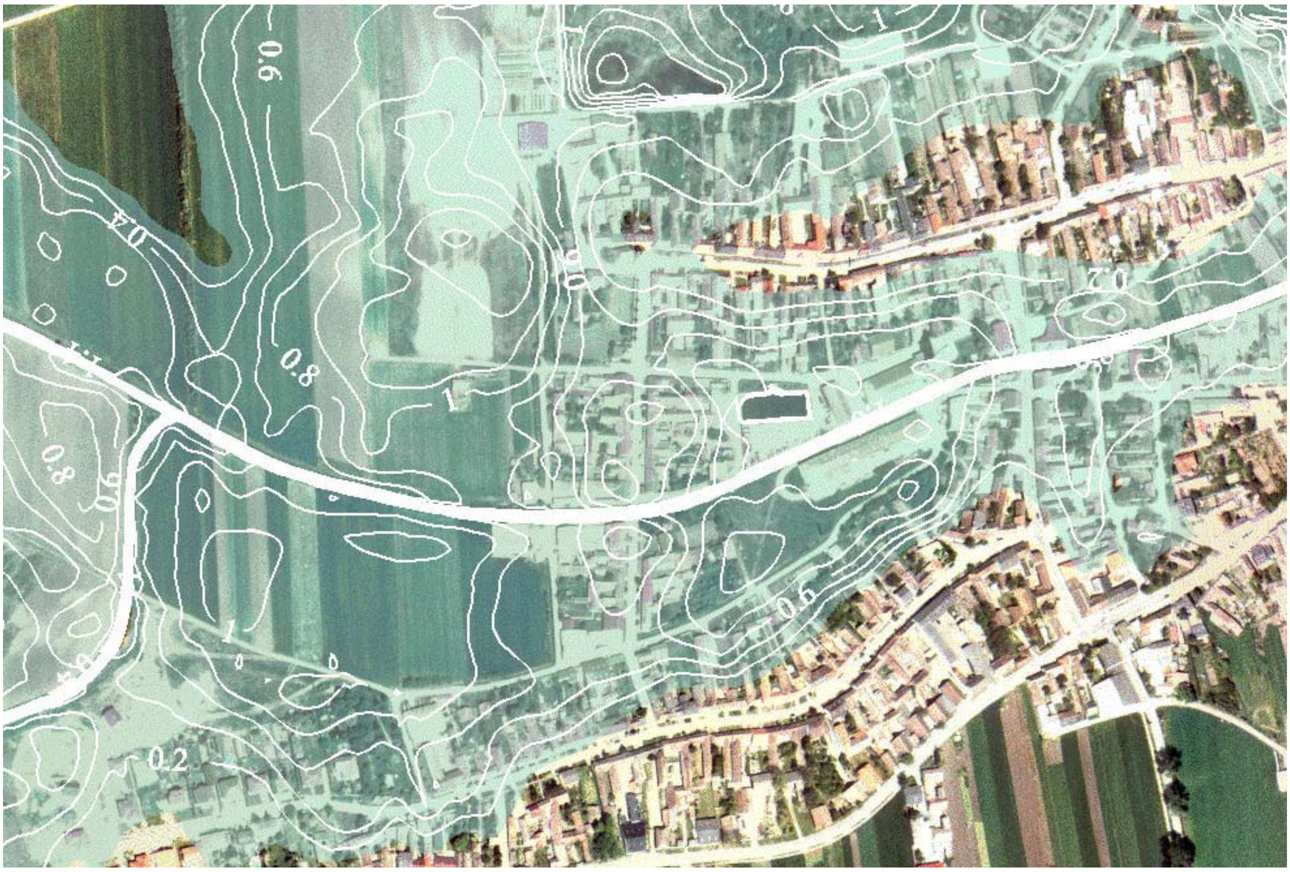

Figure 7: Flood risk area (project of the Lower-Austrian governmental administration)

Not only accuracy but also **geomorphologic quality** is decisively influenced by point density. In laser scanning, points are “digitized” directly on object surface. For wavelike surfaces the scanning theorem yields

$$L_{min} \approx 3\,\Delta \qquad (5)$$

with L_{min} – the minimal wave length, and Δ – the point distance (Figure 8, upper).

As precondition for deriving break lines from laser scanner points, at least two points have to be collected per adjacent surface – e.g. in case of a dam, for the top and for both sides of it. Correspondingly, the relation between the minimal width B_{min} and the point distance Δ in this case (Figure 8, lower) becomes

$$B_{min} \approx 2\,\Delta \qquad (6)$$

Details can be found in the textbook (Kraus, 2003).

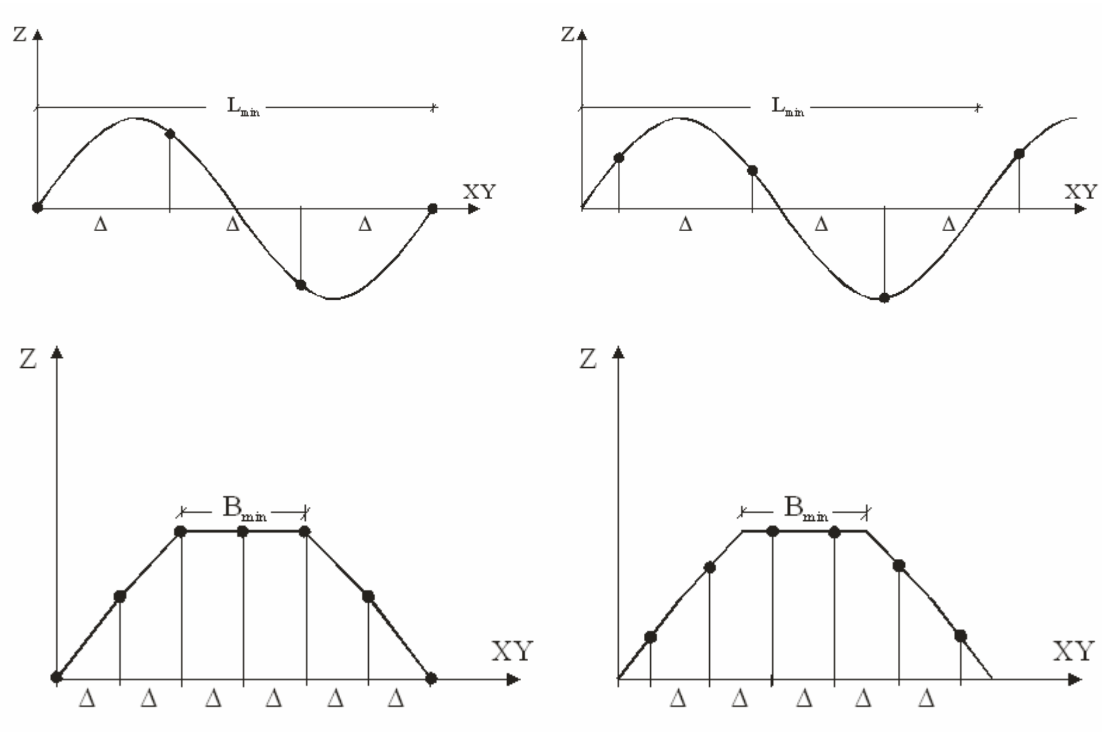

Figure 8: The minimal wave length of a terrain profile (upper sketch), and minimal crown width of a dam in a cross section (lower sketch), in each case with two sets of points from data collection (Δ – the point distance).

6. DATA REDUCTION

The very high density of points as delivered by laser scanning is of great advantage for improving quality of the DTM – but it confronts data management with severe difficulties. Recently, Lenk (2003) proposed a method based on triangulation for reducing the amount of original data. Applying it neglects the considerable accuracy potential carried by the high data redundancy; and also, it worsens the chances of eliminating (filtering) off-terrain points (trees, buildings, etc.). As proven by practical application, the effectiveness of most methods of filtering is growing with higher data redundancy. Therefore, data reduction should apply the information carried by the DTM derived of the complete original data set.

The method for data reduction as proposed and implemented at the I.P.F. (Briese, Kraus, 2003) reminds the step-wise data acquisition by progressive sampling (Makarovic 1976). Over a dense DTM derived from the original data set, radii of curvature R and slope values are derived, local to the individual grid point to be eliminated ("reduced"). This information allows for defining the maximal allowable distance to the next neighbor so to remain within a threshold of dZ_{max} for approximation accuracy. Figure 9 contains an X-profile. The maximal allowable distance is labeled as E_X . Figure 10 shows results for a small example. In a case with 4 millions of grid points and with a user defined threshold of dZ_{max} = 25cm, the reduced grid carried 1.3 million points. This reduction, including output of the reduced set in ASCII, took 4.75 minutes on a 2 GHz computer.

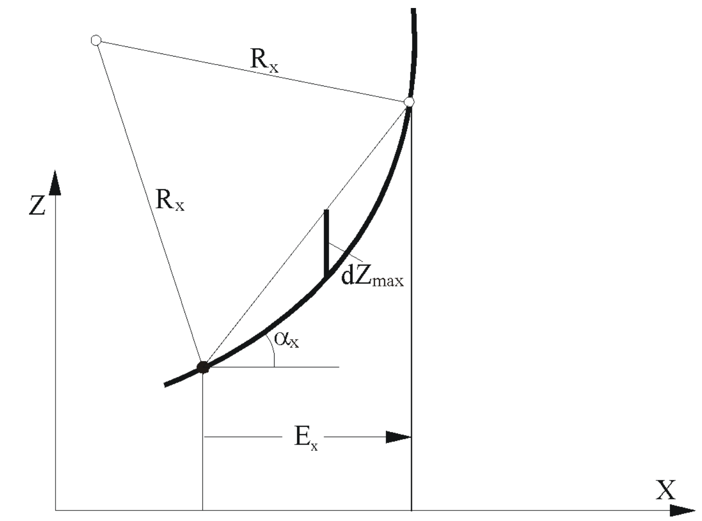

Figure 9: Maximal allowable distance E_X as defined by the radius of curvature R_X, by terrain slope $\tan\alpha_x$, and the threshold for approximation accuracy dZ_{max}.

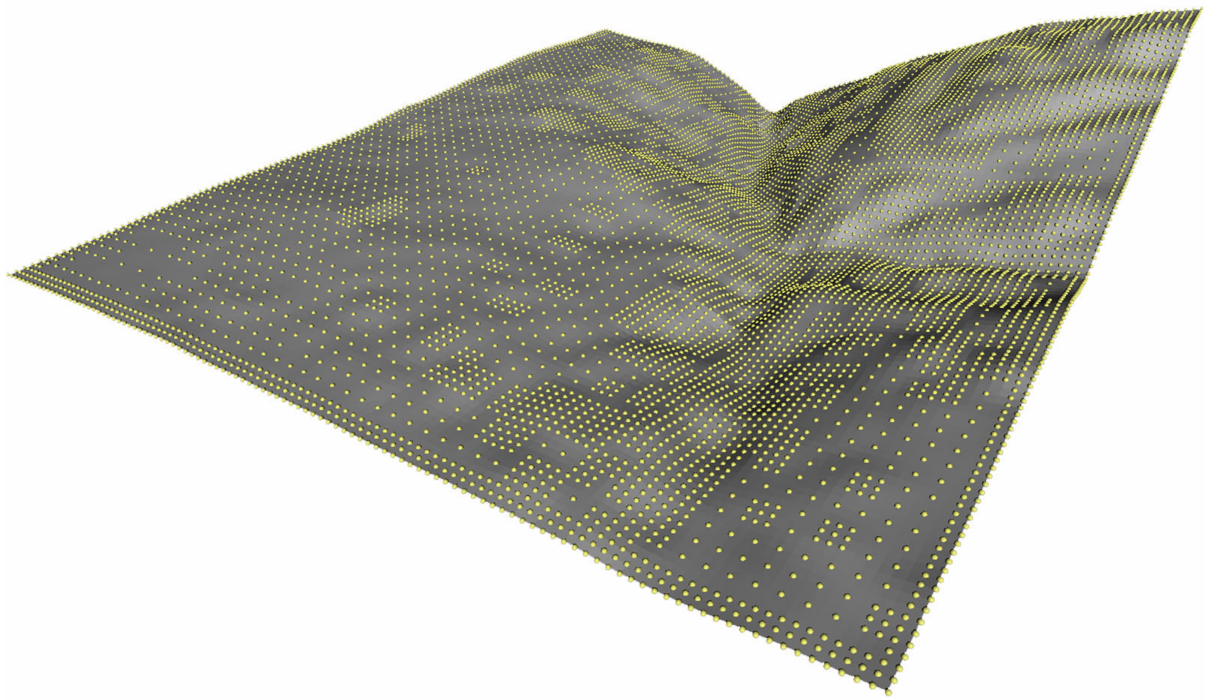

Figure 10: DTM grid past its reduction.

7. MONITORING FLOODING CATASTROPHES

Precise DTMs yield highly valuable services also in actual flooding catastrophes. DTMs enable the compilation of photographs taken of the flood, by applying *monoplotting* (Kraus, 2003). Such images should be geo-referenced, preferably by applying a satellite positioning system (e.g. GPS), and an inertial measurement unit (IMU). With parameters of inner and outer orientation of the photographs, monoplotting allows for digitizing spatial curves with 3D geodetic co-ordinates – representing for example the border of the flooded area. Given the actual border of the flooded area as defined via monoplotting, hydrologists can make comparisons with the flooding as predicted – and to improve on their models to prognose such situations.

Precise DTMs provide also different possibilities for catastrophe management. A relevant scenario could involve, e.g., the following:

- Acquiring by monoplotting the flooding water level and the border of the flood, both corresponding to the time the photographs have been taken.
- Given near-term prognoses of precipitation, hydrologists can predict with relatively high reliability the corresponding rise in water level.
- The actual water level as acquired by monoplotting, increased by the predicted rise in it, allows for predicting of the border of the flood risk area applying DTM intersecting techniques to the precision DTM of the area. This way areas at immediate risk can be plotted.
- Analyzing such plots and materials, catastrophe management can take important decisions very fast and very reliably – and inform those affected.

Such scenario is only realistic if the time passing from taking the photographs to getting the final results is not much longer than one day. With making the investments in the infrastructure needed by this technique, remaining within this time frame is certainly realistic. The bottleneck is most probably at taking the photographs in such extreme circumstances. It can beyond doubt help in extreme cases, if the monoplotting technique is prepared for different types of photographs – including such taken with amateur cameras, and with oblique axes. It is not seldom to have extreme weather conditions in flooding periods, so it might be important to involve microwave sensors also.

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