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DTM Modelling and Visualization – The SCOP Approach

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ABSTRACT

Digital Terrain Models (DTM) are topic of this paper. The SCOP approach uses hybrid DTMs which combines grid based and triangulated terrain models. A detailed discussion on interpolation and filter methods will be made as they can be employed, for example, to derive DTMs from laser scanning data. Additionally the database of SCOP and the integration into third-party software will be presented. At the end of the paper an outlook is given presenting several innovations which can be expected within the next years. The central idea is to achieve 3D capability without losing 2.5D efficiency.

1. INTRODUCTION

DTMs have been an ongoing topic for several decades. At the beginning the topographic modelling process itself has been the major point of interest. In the course of time and the development of geographic information systems (GIS), however, the underlying data of DTMs came into foreground. Nowadays country-wide DTMs are a matter of course. Nevertheless the quality, the level of detail and the demand of a complete model of the 3D world of DTMs still requires to be improved.

In this paper we focus on the SCOP approach which has its roots at the beginning of the nineteen seventies[3]. Up to now the concept, as it was developed from the start, has proven to be flexible enough to expand SCOP to meet with today's high requirement for DTMs.

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[1] Prof. Dr. Dieter Fritsch invited me to give this speech with the following remark: "Before you will retire we would like to have you once again talking at the Photogrammetric Week." Shortly after this a received an official invitation with the a determined topic. I am very much associated with the Photogrammetric Week. Would you please allow me to enumerate my lectures:

-) Kraus, K., (1971): Interpolation nach kleinsten Quadraten in der Photogrammetrie. BuL 40, S. 7-12, 1972.
-) Kraus, K., Hofmann, W. (1973): Ein System der digitalen Höhenauswertung.
-) Kraus, K., E. Aßmus, A. Köstli, L. Molnar, W. Wild (1981): Digital elevation models: User aspects. 38. Photogrammetrische Woche, Schriftenreihe des Institutes für Photogrammetrie der Universität Stuttgart, Heft 8, S. 165-181.
-) Kraus, K. (1991): The 3rd Dimension in the Geographic Information System. Schriftenreihe des Institutes für Photogrammetrie der Universität Stuttgart, Heft 15, pp. 167-176.
-) Kraus, K. (1995): From Digital Elevation Model to Topographic Information System. In: Fritsch/Hobbie (Eds.), Photogrammetric Week ´95, Wichmann Verlag, Karlsruhe, pp. 277 – 285.
-) Kraus, K., Rieger, W. (1999): Processing of laser scanning data for wooded areas. In: Fritsch/Spiller (Eds.), Photogrammetric Week ´99, Wichmann Verlag, Stuttgart, pp. 221 – 231.
-) Kraus, K. (2003): LaserScanDTMs for Modelling Flood Risk Areas. In: Fritsch (Ed.), Photogrammetric Week ´03, Wichmann Verlag, pp. 241 – 251.

[2] Christian Doppler Laboratory 'Spatial Data from Laser Scanning and Remote Sensing'

[3] This presentation on SCOP in Stuttgart has as well an emotional part. The SCOP story began in Stuttgart at the Institute of Photogrammetry in 1971 under its former director Prof. Fritz Ackermann. At that time the first author dealt with the interpolation by least squares methods, among other things as well as the derivation of Digital Terrain Models from photogrammetrically acquired profile data. The first contour line diagram which was extracted from interpolation by least squares method was published in Kraus 1971. So the name for the software to be developed was obvious:

In the following a few characteristics of the SCOP software packages are presented as they appear from today's point of view. Where appropriate historical roots of the program are described. At the end of this paper several innovations which can be expected within the next years are outlined.

2. THE DTM MODEL

The most common DTM models are

- a regular grid model based on quadratic or rectangular xy-cells and
- a triangulated irregular network (TIN) which is built up on the xy-coordinates for the original surface points.

The SCOP approach is a mixture of both models. In smooth surface regions the surface is represented by a relatively dense regular grid. For areas containing break lines and spot heights a TIN is used to describe the surface and the topology. The triangulation is based on the original xy-coordinates of the structure geometry and uses the line information as constraints (Figure 1). This model is called hybrid DTM. The hybrid DTM provides the advantages of grid models in general and restricts the TIN structure to complex geomorphological areas. Figure 2 shows an example of a hybrid DTM. As early as 1976 the hybrid DTM was implemented in SCOP (Aßmus, 1976).

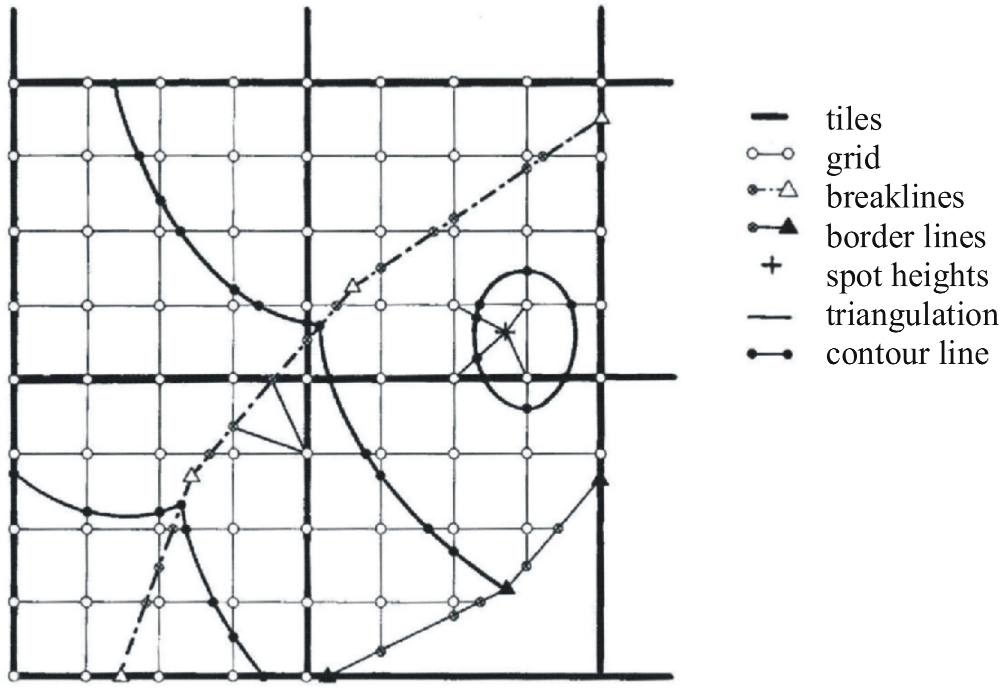

Figure 1: Elements of a hybrid DTM

Stuttgart Contour Program (SCOP). This software was presented at the International Congress of Photogrammetry in Ottawa in 1972 by Mr. Stewardson (Wild company) and Mr. Sonderegger (Contraves company) together with the first author. In the following years this development was very much brought forward by Prof. Ackermann. The first author's call to Vienna University in 1974 came a bit early from the SCOP development point of view. The local separation was overcome by an intensive co-operation and by mutual confidence. This co-operation continues till today. The partners are presently INPHO company, Stuttgart and the Institute of Photogrammetry and Remote Sensing, Vienna Technical University.

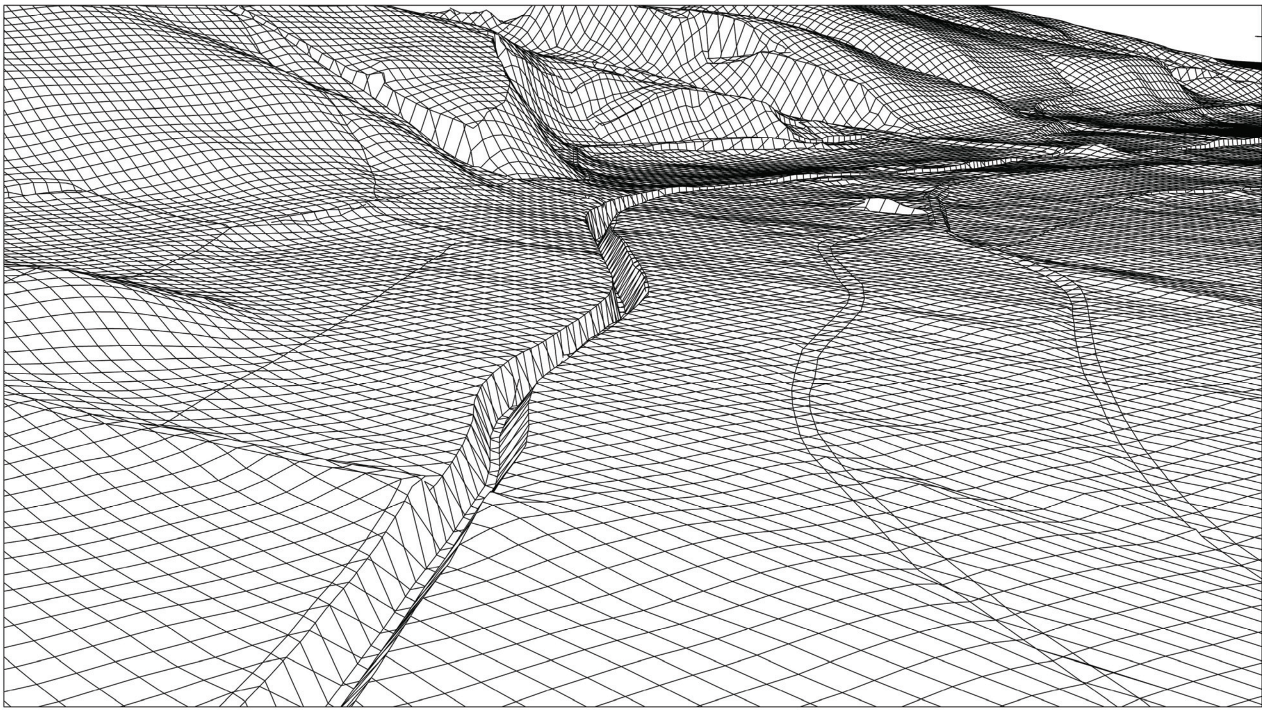

Figure 2: Example of a hybrid DTM

3. INTERPOLATION AND FILTERING METHODS

In smooth surface regions the original, measured, surface points are replaced by dense grid points. In the SCOP approach this interpolation task was solved using the linear prediction from the initial development (Kraus, 1971, Kraus/Mikhail, 1972). This statistical method is also referred to as linear least squares interpolation and it is identical to Kriging (Kraus, 1998); a widely-used method in earth science.

Over the years the capability to perform a simultaneous filtering during the interpolation process has turned out as a major advantage of this interpolation method. Each geometric element group (bulk data, polygon points of breaklines, spots heights, etc.) can be assigned with an a priori height accuracy which allows an adequate consideration of different measurement methods.

The SCOP module LIDAR makes use of the interpolation capability to set individual weights for single laser scanning points. Therefore a first surface is interpolated which allows to compute residuals to each laser point. Then an asymmetric eccentric weight function is determined using statistical analysis based on the computed residuals. Applying this strategy the original linear prediction turned into the robust linear prediction, comparable to the robust least square adjustment (Kraus, 1997, Kraus, Pfeifer, 1998). Deriving DTMs from laser scanning data is a contemporary issue which is why an example will be presented. Figure 3 shows a digital surface model which has been derived from the original point data. The irregular distributed laser points have been re-sampled to a regular grid and visualized using the shading module. To allow a comparison, the DTM computed by the robust linear prediction is shown in Figure 4.

Figure 3: Surface model derived from laser scanner data

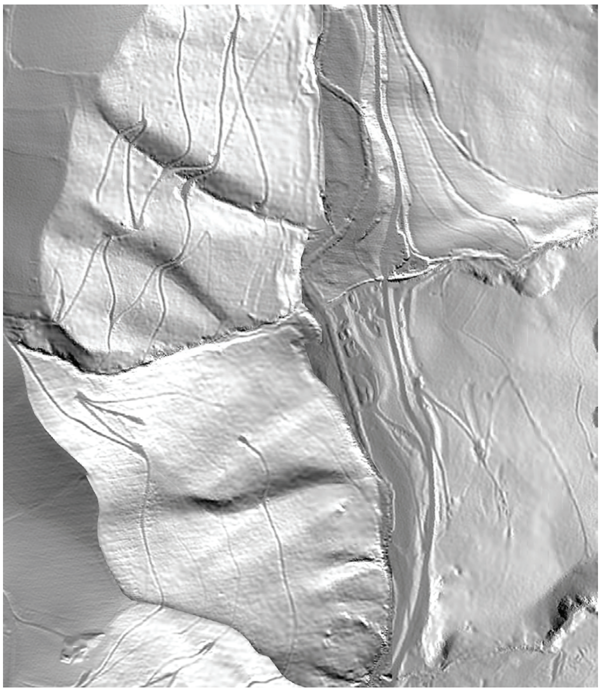

Figure 4: DTM shading using a changing light source (Images by Maria Attwenger using SCOP)

Utilising an iterative hierarchical approach the robust linear prediction can be extended to remove buildings and relatively large vegetated areas which do not contain ground points (Briese et al., 2002). Larger buildings may be removed employing a special SCOP LIDAR pre-processing module which has been developed by A. Köstli (Inpho).

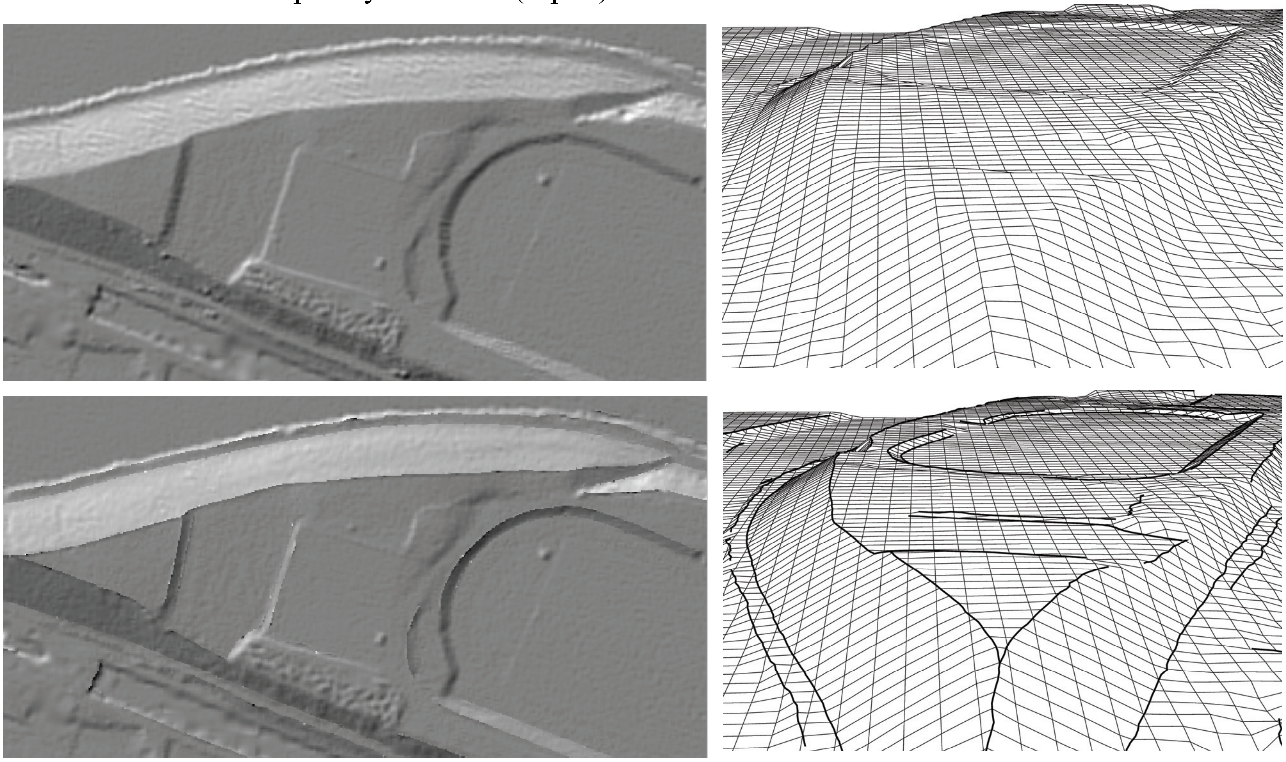

Figure 5: Laser DTM without edges (above) and including extracted edges (below) (Example for the 'Bundesanstalt für Gewässerkunde' in Koblenz, Germany)

Any filtering process smoothes surface edges depending on the parameterisation of the filter. Therefore an algorithm process had been developed which allows breaklines of a laser scanner point cloud to be extracted (Briese, 2005). The extracted edges are then used within the final interpolation process and additionally inserted into the hybrid DTM structure. The effect of this process is visualised with a small example in Figure 5.

In the case of inhomogeneous source data high demands are put onto the interpolation and filter process. As an example, the recently produced Austrian-wide DTM was computed from photogrammetric data acquired over the last 2 decades. The available data were derived from images of varying scales. Additionally, the data varied in point density and the degree of digitised structure lines was highly variable (Franzen, Mandlburger, 2003).

An even higher degree of inhomogeneity appears for the topographic data of the planet Mars. On the one hand high precision laser profile data are available. On the other hand area-wide but lower precision data from the high resolution stereo camera (HRSC) exists. Although the HRSC height data had major blunders in low textured regions it was possible to compute an appropriate surface model using a slightly extended SCOP version (Attwenger, 2005).

4. DATA STRUCTURE AND DATABASE

The SCOP approach uses pointers to model the topology which allows efficient navigation within the hybrid DTM. Figure 6 shows a tile including pointers (It is the lower left tile of Figure 1). Above the tiles one data pyramid level exists. The strategy of spatially tiling the data gives full random access to the geometric information (Köstli, Sigle, 1986).

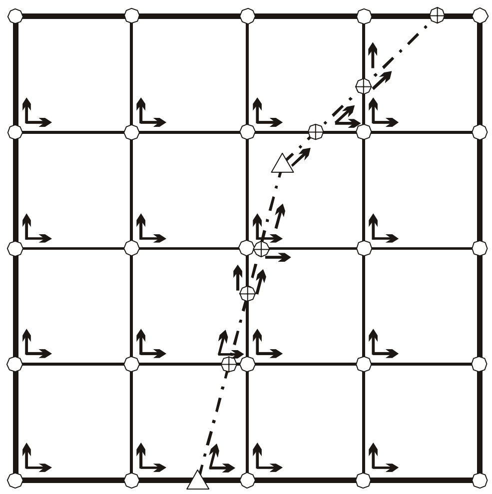

Figure 6: Hybrid DTM including pointers (concept and implementation by Dr. H. Kager)

For storing, managing and archiving nation-wide digital topographic information the software package TopDM (Topographic Data Management) can be used (Hochstöger, 1996). The general strategy is to store the original measured data, and also the derived hybrid DTMs. It is important to archive the original measured point and line data considering the dynamics of control points. Changes of control point coordinates are caused by technology improvements of the satellite-based positioning or by geodynamic effects. Therefore TopDM provides different geo-referencing methods such as map projections, coordinate transformations and geodetic datum transformations.

At this Photogrammetric Week 2005 there will also be a presentation about TopDM and the merging/extraction process of DTMs (Warriner, Mandlburger, 2005).

The central component of TopDM is the relational database TopDB (Topographic Database) which has also been developed at the I.P.F. TopDB is operated by TOPSQL, an expanded version of SQL that includes spatial objects and operators (Loitsch, Molnar, 1991). It is quite remarkable that TopDB was implemented in 1991, where other databases have only implemented similar functionality in recent times. However it should be mentioned that TopDB does not support networking and multi-user access. For this reason an interface to universal database systems (eg. Oracle) had been developed.

5. INTEGRATION OF SCOP INTO THIRD-PARTY SOFTWARE

A central component of the software package SCOP is the DTM generation based on point and line data. The derived DTM can then be utilised by a number of independent applications. Hence it is an absolute requirement that SCOP supports standard DTM formats which have a proven degree of interoperability, such as the standards produced by the Open GIS Consortium Services (OGC). Standards and exchange formats which are currently supported can be found in the present product specifications of SCOP .

In the following sections 5.1 and 5.2 methodical aspects are discussed considering third-party software. In section 5.3 the programmable interface of SCOP is described.

5.1. Grid Based Terrain Models

Powerful software packages can often only handle grid based models. To achieve high quality results very dense grid models are required since grid based models do not support structure lines. In comparison to hybrid DTMs the grid size needs to be approximately a tenth of the hybrid DTM grid size. The interpolation method of SCOP allows such high quality grid models to be derived since the available geomorphological information is always considered (Kraus, 2000, Figure 4.1-8).

Rainfall runoff simulations are interesting applications of DTMs. In comparison with the hybrid DTM structure, the simulation can be performed in highly efficient manner using grid based terrain models. In SCOP the module MATRIX can be used for such rainfall runoff simulations (Rieger, 1992, Gajski, 2005, Dorninger, 2005).

5.2. Generation of TIN DTMs Using SCOP

The other group of software packages requires TIN structures. Usually the triangulations are built on the original unfiltered geometry data. F. Ackermann and K. Kraus (2004) have argued against such strategies. The most important arguments are stated below:

- Usually the data measurement method (eg. laser scanning) does not consider geo-morphological characteristic of the terrain. Consequently there is no need to preserve the original data arrangement within the DTM structure.
- A TIN based model on the original point and line data can lead to degenerated triangles.
- The original data are usually used unfiltered. Since any measured data will contain errors, these random errors are then introduced into the DTM.

Nowadays, however, it is important that TIN DTMs are supported. For this reason SCOP provides the module DTM-REDUCE which allows the generation of TIN structure without the previously mentioned disadvantages. Utilising the SCOP strategy the triangulation is computed along a data reduction step (Briese, Kraus, 2003). The algorithm is outlined below:

- First a threshold dZmax is chosen, defining the maximum approximation error of the TIN DTM with respect to the original hybrid DTM.
- Then, for each grid point, the maximum surface curvature is computed considering the full geomorphological information of the hybrid DTM.
- Using the curvature and slope information at each grid point, a radius E can be computed based on the above mentioned dZmax. Region defined by the radius E do not require additional point information.
- Based on the radius E the DTM grid points can be reduced.
- Structure lines are treated separately employing additional reduction criteria which are also based on the curvature.

Finally the remaining points are triangulated. In comparison to the conventional TIN approach, the TIN DTM generated by the SCOP algorithm provides several advantages:

- The density of the triangulation vertices depends on the surface properties rather than on the original point arrangement.
- Terrain structure lines are added in adequate form to the triangulation.
- Additionally, the triangles are better formed compared to the triangles of the conventional approach (the maximum length of the triangle edges is smaller than a threshold of the previously computed radius E).
- Since the filtered geometric information of the hybrid DTM is used to build the triangulation, random errors are largely removed.
- Consequently even degenerated triangles do not affect the surface.

For completeness it should be mentioned that a triangulation is currently implemented into SCOP which uses the original measured geometric information. Utilising such a triangulation, large regions without terrain information and highly irregular point distributions can be compensated, as described in section 3. Additional applications exist for special data acquisition methods. For example, in DTMs derived from tachymeter measurements the measured height information is usually considered as error-free.

5.3. Programmable Interface of SCOP

In addition to different exchange data formats SCOP offers a Programming Application Kit (SCOP.PAK) which allows the addition of SCOP technology to any proprietary development (at the current stage SCOP.PAK is available for C/C++). The interface allows a seamless integration of SCOP into existing GIS software to combine both, high quality DTM generation and high level GIS functionality.

6. VISUALISATION AND OTHER PERIPHERAL SOFTWARE

Within SCOP the visualisation of the computed results is of high priority. The module which fulfils this task is called VISUALIZER. Information about its functionality can be found in the product specifications (see Section 5). A few attractive Examples will be presented in the presentation. In the future, however, it is planed to use existing visualisation tools. As an example MapObject of ERSI should be mentioned.

The development of SCOP and peripheral software is limited to special applications emerging from huge topographic data sets which have not been solved (or at least unsatisfactory solved) by other commercial software packages. DTM-REDUCE and MATRIX have been mentioned in section 5.1.

Additionally the SCOP module INTERSECT is mentioned; a component of SCOP ANALYZER. INTERSECT allows different surface data (hybrid DTM, digital slope models, digital soil value models, etc.) to be combined based on mathematical functions (Sigle et al., 1992).

The peripheral module MORPHUTILS has been developed for hydrological applications. A laminar data set of the riverbed can be computed by employing a morphing process between each cross section, which is usually combined with the DTM utilising the linear least squares interpolation (Mandlburger, 2000).

Finally a new module, which is currently being developed by the I.P.F., should be mentioned. Utilizing this new module an estimation and a graphical representation of the grid point accuracies within a hybrid DTM can be made (Karel, Kraus, 2005).

7. OUTLOOK

New data acquisition methods such as laser scanning and digital photogrammetry have dramatically changed the DTM data acquisition process of the last decade. Combined with the increase in computational power more accurate DTMs including a higher level of detail can be derived which has opened up a new range of applications (eg. Flood risk area modelling, automated extraction of power lines (Melzer et al., 2004) and high-quality buildings (Rottensteiner, 2003)). However the development of the laser scanning technology is far from over yet. Multi pulse scanner, full-wave scanner, along with general enhanced remote sensing sensors will bring further improvement to the DTM generation process.

As mentioned earlier, the SCOP approach has proven to be suitable and adaptable to all requirements which have arisen within the last 30 years. However, there is a limitation which cannot be overcome by the current strategy. The SCOP concept is based on a 2.5D approach. This means that each 2D coordinate pair can have only one height value. Mathematically speaking, the terrain heights are described by a bivariate function over the ground plan domain. Whereas it is still possible to 'numerically' model vertical elements in 2.5D, the current approach is unable to describe general 3D structures such as overhangs, caves or complex artificial building. From an application point of view this has been of minor concern so far since it was not possible (or least far too expensive) to capture detailed 3D data in a large scale.

Over the last years, however, situation has started to change, mainly caused by the huge improvement in both, air-born and terrestrial laser scanning technology. 3D models of several cities already exists which cannot be described by a 2.5D approach any more. Hence, it is just a matter of time until applications arise which require the full 3D information within the corresponding DTM. As an example, hydrological applications should be mentioned, where it is necessary to model the course of rivers with as much details as possible. However 2.5D models cannot represent the river and bridges at once why such objects are usually removed from the DTM. To overcome these shortcomings a new concept had been developed which will be presented in the following section.

7.1. The Next Generation of DTMs

The SCOP approach has generally turned out as flexible and efficient for many DTM applications since approximately 95 % of our environment ‘is’ 2.5D. Within areas where 3D structures would have been necessary, so far, the objects were reduced to 2.5D depending on the purpose of the DTM. Starting from this consideration a new concept was developed which combines both, 2.5D and 3D structures. But why not generally switch to a full 3D approach? A major problem of a 3D point cloud is that, comparing to the 2.5D case, the uniqueness of the topology cannot be guaranteed as indicated in Figure 7. Moreover, 2.5D DTMs can be efficiently administered and stored in very compact forms such as the current SCOP DTM structure. This is irrelevant for small DTMs but crucial for high resolution country-wide or planet-wide elevation models.

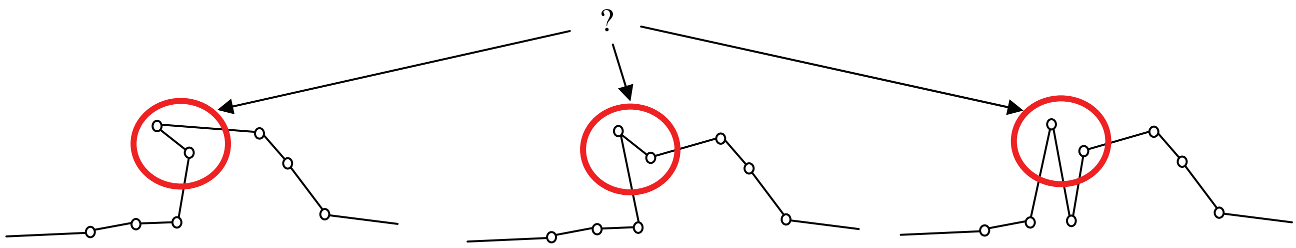

Figure 7: The uniqueness of the topology cannot be guaranteed for 3D point clouds

The new concept relies on a 2.5D base model which may contain enclosed 3D objects. In the following such 3D objects are referred as enclaves. For 2.5D areas approved algorithms of SCOP will be employed. Only within the enclaves new 3D strategies will be applied. Utilizing this concept 2.5D efficiency and 3D capability can be combined.

7.2. Interpolation of a 2.5D DTM Containing 3D Enclaves

A 3D enclave is defined as anything that cannot be described in 2.5D. So from the interpolation point of view different enclaves will have different surface properties. For example, artificial objects have to be treated differently to natural overhangs. To meet the different requirements for different enclaves an object oriented strategy was designed. This means that each enclave object has to provide a set of functionality such as a triangulation strategy, an interpolation method, etc. The object oriented enclave approach is flexible to extensions and allows to be implemented step by step (object by object).

The interpolation process is currently being implemented into the next generation of SCOP. In the following section details about the implementation process are presented. The algorithm allows processing 2.5D DTMs containing 3D enclaves (see Figure 8). The crucial point of this approach is to realize smooth transitions between the enclaves and 2.5D areas. This can be achieved by a hierarchical process which, first, interpolates the 2.5D base surface. In addition to the source data within the 2.5D area, the algorithm also collects geometry information from the 3D enclave objects which belong to the 2.5D base surface. After interpolating across the complete model domain, the algorithm passes the 2.5D surface to the enclave object which stores or withdraws the information within its boundary. This allows automatic modelling of the earth surface below building (eg. bridges, eaves, porches, etc.) and inside enclaves (eg. courtyards). Additionally the 2.5D interpolation explicitly stores the height and tangential plane information along the enclave boundary lines which is required to achieve a smooth transition. In the last step each enclave object is modelled by its own interpolation strategy which considers the previously computed height and tangential plane information at the boundary.

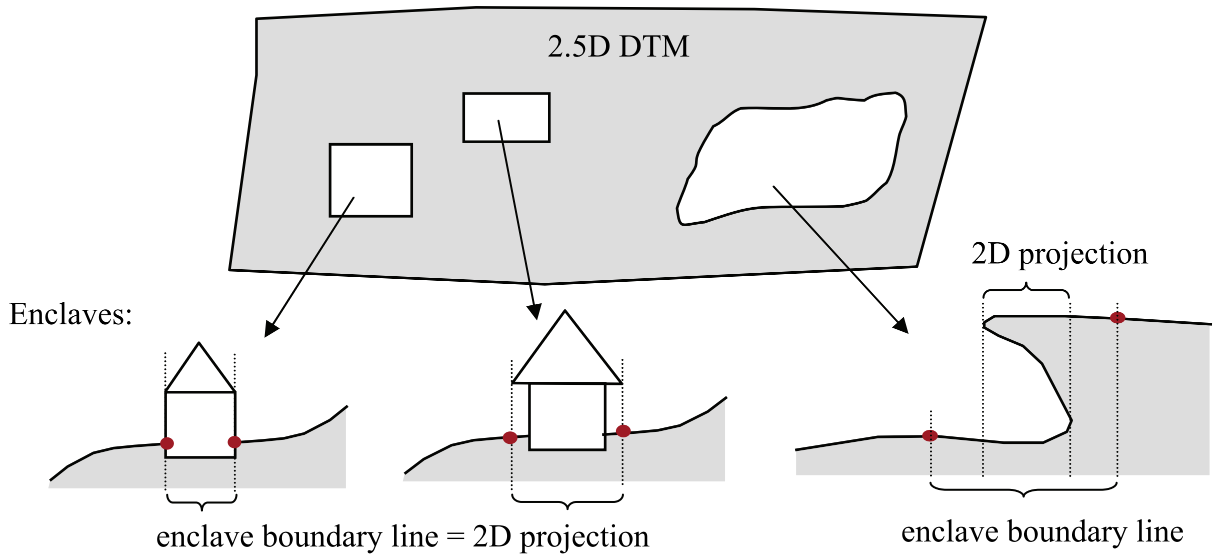

Figure 8: Examples of various 3D enclaves including their 2D projection and boundary line

A detailed discussion of 3D interpolation strategies goes beyond the scope of this paper, however, a few remarks should be made. A 'simple' triangulation of the original geometry information does not result in high quality models since measurement errors will cause rough surfaces especially in case of dense point data. Hence appropriate filtering processes are a necessity for high quality surfaces. Additionally, the interpolation method must support breaklines since most of the 3D enclaves will be artificial objects. Whether subdivision algorithms or other the methods produce satisfying results is, up to a certain degree, still outstanding and will be investigated at the I.P.F in the near future (For more details see Pfeifer, 2005, which has given a strategies to achieve smooth 3D surfaces)

7.3. Additional Aspects for the Next Generation

The quality demands on DTMs have steadily increased which is why a few additional ideas are tried to be realised in SCOP of the next generation. So far only linear structure lines can be handled by the interpolation process. Therefore an extension to high order structure elements is considered to improve the optical appearance of strongly magnified DTM regions.

As mentioned in Section 6 it is possible to estimate the accuracy of the derived DTM based on a comparison of the original data and the DTM. Using the SCOP interpolation method, however, the accuracy of each grid point can be estimated already during the interpolation process. This mathematical strategy will be used in the future to derive appropriate quality layers.

For information concerning the development status of new modules the reader is referred to the product specification of SCOP (see Section 5). The current SCOP team consist of Dr. C. Briese, W. Karel, Dr. I. Kolcon, G. Mandlburger, C. Nothegger, Dr. J. Otepka, B. Wöhrer at the I.P.F. in Vienna and D. Dörsam, A. Köstli, C. Lemaire at the Inpho in Stuttgart.

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