High-Quality Digital Terrain Models - The SCOP Program and Derived Products

F. Ackermann

Stuttgart

1. THE STATUS OF DIGITAL TERRAIN MODELS

The term Digital Terrain Model (DTM) and the concept goes back to 1958, when C.L. Miller and R.A. Laflamme of MIT designed a computerized system for automatic and optimized planning of roads and highways. Because of that origin the DTM used to appear, at conferences during the 1960s, in relation with civil engineering applications.

It took some time until photogrammetry, surveying, and cartography realized the much more general nature and range of application of the concept. Even then the DTM was seen primarily as a tool for the derivation of contour lines for maps. And it still took some more time until cartography recognized the potential of DTMs for producing high-quality contour lines.

During the 1970s, however, it became generally understood that a DTM is a new stand-alone type of product, of independent status and of central independent importance, suited for various applications. It constitutes a basic product, from which a family of subsequent programs generate various derived products. Today DTMs are also seen in relation with information systems, constituting a separate layer in topographic or geographic information systems (GIS), to be combined an interfaced with other types of data.

A digital terrain model is a digital description and representation of terrain surface. It can, of course, also be used for representing other objects surfaces, or equivalent symbolic surfaces. The surface is represented by a grid of points. Common types are either irregular triangular networks or regular rectangular grids of points. The enclosed triangular or rectangular grid meshes are supposed to be small enough to represent all surface points by simple interpolation within a mesh. Thus, digital elevation models describe surfaces only by single-valued functions z=f(x, y) which are not necessarily smooth. With regard to terrain the elevations of surface points are functions of their position (x, y). Therefore, the term digital elevation model (DEM) is used synonymously for DTM, for the time being.

The terrain description by DTM is a special case of 3-D surface representations, being limited to continuous single-valued functions. A DTM should not be mistaken for a more general 3-D surface description, as used in CAD systems, for instance.

The basic tasks of a DTM computer program is to derive surface points from primary data and to generate the DTM. Primary data are usually photogrammetric or field survey measurements, or cartographic data (digitized contour lines). From them a regular grid of points is normally derived by interpolation. Conventional DTM programs are not, or not fully, prepared to handle very dense networks of primary points, as they can be obtained by digital image correlation or image matching from digitized aerial (or space) photographs. Conventional DTMs handle in practice 10^3 to, perhaps, $2 \cdot 10^4$ points per map sheet and produce DTM grids of $5 \cdot 10^3$ to 10^5 points, at the most.

The quality requirements for DTMs are high, in view of their independent importance. We may distinguish quality requirements with regard to high geomorphological quality of a DTM, and with reagard to acceptance of various primary data.

The most important aspect is certainly the high geomorphological quality of a DTM. That implies first, that a DTM consists possibly of a dense grid of points, amounting to usually $5 \cdot 10^3$ to 10^5 grid points per map sheet, derived from the same number of measured points or, mostly, considerably less points (by a factor 5-10). High morphological quality implies secondly that special terrain features are represented. These can be break-lines, ridge lines, lines of steepest descent, from lines, and also special points like hill-tops or depression points. DTM programs must be able to consider such features quite rigorously.

The second feature of quality concerns the acceptance of various types of primary data. These can be regularly or irregularly distributed points, measured sometimes in profiles or as grid points of varying density. Photogrammetry is the main source for primary data. Points are measured manually, partly semi- automated. Sometimes data acquisition is not adequate, leaving certain areas with few or no points. DTM computer programs must be able to handle all cases safely, merge data of different origin, and include checks for acceptance.

The mode of measurements has implied, hitherto, that ussually relatively few points are measured, in such a way that the derived DTM meets the requirements with a minimum number of points. Break-lines etc. must ensure, in that case, the quality of DTM. That philosophy might change, in near future, when automatic point measurement by digital image correlation will become available. In that case the number of points measured may be more than 100 times larger than up to now, allowing the derivation of much denser and more accurate DTMs, and allowing a more detailed local analysis of terrain forms.

It is a typical feature of modern system which handle large volumes of data that beyond the mathematical and algorithmic aspects the data management is of predominant importance. That concerns first the question of efficient data structures, allowing access to local areas for purposes of checking, correcting, updating etc. It also implies interface for a number of follow-up programs, as well as graphic - interfaces for various graphical systems, plotters and screens.

In general, with regard to DTMs, the attention has moved from data acquisition and interpolation methods towards data management, representation of results, quality control, derived products, and integration data bases and information systems.

2. THE DTM PROGRAM SYSTEM SCOP

SCOP is a well-established modular computer program system for the generation and application of high quality digital terrain models. It handles primary data of arbitrary origin and has been designed from the beginning on for large volumes of data, i.e. for large DTMs.

It has been developed by INPHO GmbH, Stuttgart, in close cooperation with the Institute of Photogrammetry at Stuttgart University, and the Institute of Photogrammetry and Remote Sensing of the Technical University of Vienna (Prof. Kraus). It started as a program for the generation of rectangular grids from irregularly distributed data by linear prediction. The DTM was intended a prime product from the beginning on, whilst contour-lines were considered a derived product. Soon, the general scope and range of the system was extended to various field of application, taking into account the expanding hardware and software environment. The general features of the system can be summarized as follows:

- rigorous consideration of break-lines and excluded areas in the DTM generation and all DTM application modules.

- efficient data structure with direct access to local areas

- development of a family of programs for the derivation of follow-up products, in particular isolines (contours), derived profiles, derived points, volume computation, perpsective views, digital slope models, slope maps, etc.

- establishment of graphic interface for various plotters, screens and graphic systems.

The more recent development phase has concentrated on DTM intersections with raster or vector models, raster-graphic representation of DTMs, with shading etc., DTM editing, DTM data management and GIS interfaces.

In the following some items are described in more detail.

Input data can be 3-D terrain data of quite arbitrary origin, which may cover the surface in variable density, and in regular or irregular distribution. SCOP distinguishes different classes of points:

- Arbitrary surface points of no special characterisitcs

- Points of special importance, like hill tops etc.

- Singular points which are not part of the terrain surface

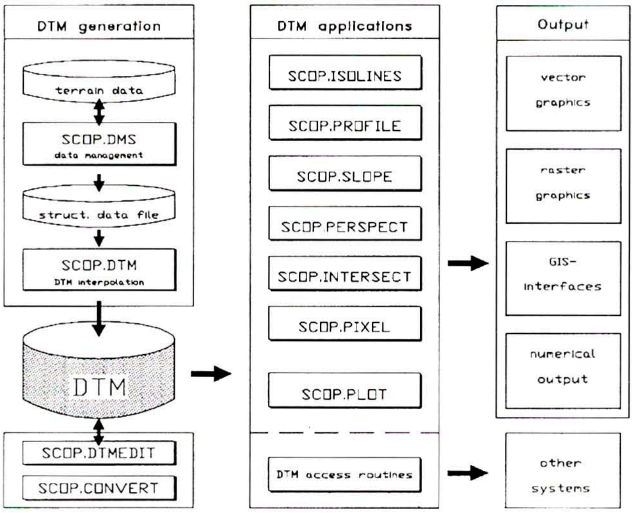
Also various line data may serve as input:

- break-lines which the gradients of the terrain are discontinuous

- form-lines for describing special terrain features, like ridge-lines

- border-lines which limit the DTM area, externally or internally. Border-lines can be given as 3-D or as 2-D lines.

Surface points are just given by their position (x, y) and the height (z), without point number. Numbering is only required for special points and for lines.



The first program module of SCOP (known as SCOP.DMS, data management system) handles the input data and prepares them for the DTM generation. It can cope efficiently with large numbers of observed points, up to hundred thousands of points.

After reading-in the input data the DMS module arranges them in a structured binary data file, for direct access to any part of it. The standard input format WINPUT allows acceptance of mixed types of data, especially of photogrammetric and of digitized cartographic data. There is another data format (DA001), especially designed for tacheometric survey data. Input data can be transformed, if necessary, e.g. for absolute orientation of photogrammetric models.

Input data can be represented, for checking purposes, in forms of lists or in geometric presentation (matrix or quick plot). Especially graphical plots are essential for checking. Here, the system is higly flexible, as the total set of data, windows, or only certain classes of data (e.g. break-lines alone) can be looked at. Output is possible, via a graphics package, on various plotters, screens or graphic systems, also via data base systems.

A number of internal checks routines control consistency and plausibility of the input data (like crossing of lines, empty areas, height differences etc.) For data correction and data cleaning quite a number of updating functions are prepared (like changing, deleting, merging, separating, re-coding etc.).

The central algorithm part of the SCOP system is the DTM generation module SCOP.DTM, as the quality of a DTM, is determined by the DTM data structure and the interpolation algorithm.

The DTM interpolation derives from the given points and lines the heights of a usually densified rectangular network or grid. The grid spacing can be chosen and may vary within a DTM, depending on the degree of smoothness of the terrain.

It is a decisive feature of the DTM data structure that the DTM is more than a grid model. The line structures (break-line etc.) and singular points are integrated parts of the DTM, and are stored within the structure, not separately. Thus the special terrain features can be directly maintained and given access to in all subsequent application programs which make use of the DTM.

The project area is subdivided, with some overlap, into computational units within which the interpolation takes place and which allow fast local access. The computational units are further subdivided in case of break-lines. Also complicated cases can be handle. The subdivision into units allows efficient treatment of large sets data. DTM projects of up to one million points have been trated.

The resulting DTM is stored as binary file with direct access to local area, also in case of very large DTMs.

The DTM interpolation algorithms generates the actual DTM from the given data. The main interpolation algortihm of SCOP is based on a modified version of the method of linear prediction, which has proven to be most versatile. It gives a surface description by summation of weight functions attached to the observed points. From it the heights of any desired (grid-) points are easy to be calculated. The interpolation process has been greatly optimized in order to reach efficient performance, in spite of originally involved mathematical procedure. It is a special feature of the algorithm that the computational effort goes proportional with the number of observed points, whilst the (larger) number of interpolated points has little effect on the computing time. Thus, strong densification of the network is relatively easy to obtain. A second feature of the method is the inherent possibility of filtering of data. As a result, height residuals are obtained, allowing (least-squares) accuracy estimates and blunder detection. A special case is filtering of systematic scan errors in case of parallel profiling.
The modified prediction method constitues the main interpolation algorithm, especially for obtaining high-quality DTMs. However there are two other particularly fast in-

terpolation methods implemented as part of the DTM generation module. They are characterized by the moving average and the moving tangential plane principle. Still another procedure is used if the observed data are given in a, possiby incomplete, grid pattern. The algorithm in that case completes the grid, and incorporates all additional features (break-lines etc.) The program structure of the DTM module is such, that additional interpolation algorithms could be implemented as subroutines, if found desirable.

We do not claim that the SCOP system could not be still further extended or adapted to additional requirements. At present it has reached a good level of maturity, has been confirmed in practical use by a great variety of applications. It represents a fully operational, general-purpose and high-quality DTM system.

The accuracy of a DTM can be defined as the r.m.s difference (in z) between the real (or the idealized) terrain surface and the DTM surface. It is determined in first instance by the data acquisition, i.e. by the fidelity with which the observed points and the structural information represent the actual surface. The accuracy of the observed points is very much less significant, by comparison. The structural features (break-lines etc.) also have normally not much influence on the overall DTM accuracy, although they are of great importance for the representation of local morphological quality.

The interpolation algorithm of a DTM program can also influence the resulting DTM accuracy. It must maintain the inherent accuracy and fidelity potential of the data, as implied in the density of points and the morphological features. Often the data are inadequate to some extent, have gaps or great variation in density. In such cases the interpolation algorithm must not produce non-plausible results (like overshooting), sticking close to linear interpolation. Also, data blunders should be detected automatically. In the SCOP system the filtering of data, producing residual errors on the basis of a minimum principle, allows precision-estimates and analysis of such questions.

Accuracy prediction for DTMs in general is difficult, as it depends strongly on the density of points in relation to the shape and roughness of the terrain. According to empirical results the average DTM accuracy depends about linearly on the average distances between points, for a given type of terrain. Photogrammetric data acquisition from aerial photographs, with the usual point density of about 2 000 points per stereo-pair, gives a DTM accuracy in the order of about h/5 000, for reasonably smooth terrain. Derived contour-lines then have the same vertical accuracy.

The SCOP system has been implemented on a considerable number of computer systems. The programs contain almost no parts which depend on hardware or machine systems. Therefore, they can easily be ported to any new computer system.

Implementation has taken place on the following systems:

- various mainframe computers

- mini-computers and workstations:

  VAX (VMS)
  HP 1000 (RTE-A)
  Siemens Nixdorf (BS 2000)
  Prime (PRIMOS)
  Data General (AOS/VS)

UNIX systems:
- Hewelett Packard (HP-UX)
- Intergraph (CLIX)
- Silicon Graphics (IRIX)
- Siemens Nixdorf (SINIX)
- PCs (XENIX, Interactive UNIX)

- Personal Computers:

MS-DOS (all IBM compatible PCs with processor 80286, 80386, 80486, coprocessor 80207, 80387, hard disc and standard graphics card).

3. APPLICATION PROGRAM

It has been stated that a DTM is considered a stand-alone product. It is therefore edited and stored independently, for direct use.

However, the great importance of the DTM is tied to the fact that is also a base product for a great variety of applications. Hence a DTM program system includes a whole family of follow-up programs with which derived graphical or numerical products are produced. The package of derived products is open, in principle, depending on the development of applications. We may distinguish three groups of programs:

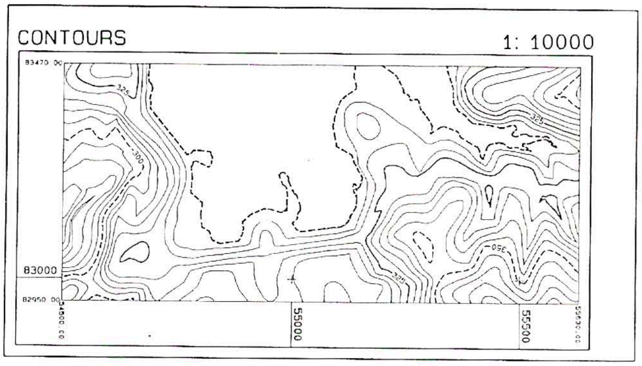
(1) Programs for representation of DTMs, in particular: contourlines (isolines), derived profiles, perspective views and raster representation, including shading.

(2) Directly derived products, such as slope models, slope maps, slope vectors, aspect maps, visibility maps.

(3) Derived functions which operate with DTMs. Here especially intersections of DTMs and other digital models are referred to.

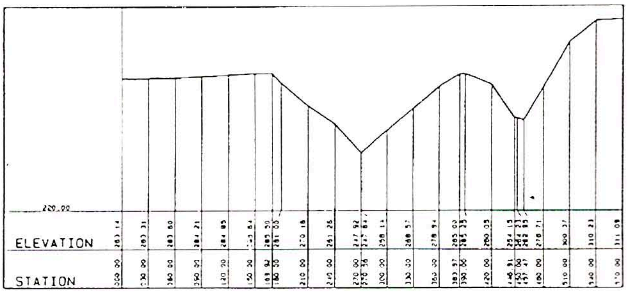
The SCOP system has a family of application program modules which derive graphical or numerical products. They all maintain the efficient DTM data structure, including the morphological features. In the following some modules will be briefly commented. It is understood that a discussion of DTM application, as in civil engineering, navigation etc., is outside the scope of this paper.

Quite a number of modules are available for the representation of DTMs. The first and most conventional cartographic representation is by contour-lines. The module SCOP.ISOLINES is applicable to any model with the DTM data structure, thus producing isolines for instance in slope models or in height difference models. Contour intervals can be chosen and automatically adapted to various degrees of slopes. Morphological features like break- lines are rigorously considered, also in complicated cases, leading to possibly sharp angles in contour-lines. The representation of isolines by strings of points can be adapted to the available plotter, some of which have splin interpolation. In addition, all cartographic editing features, including automatic numbering, are prepared.



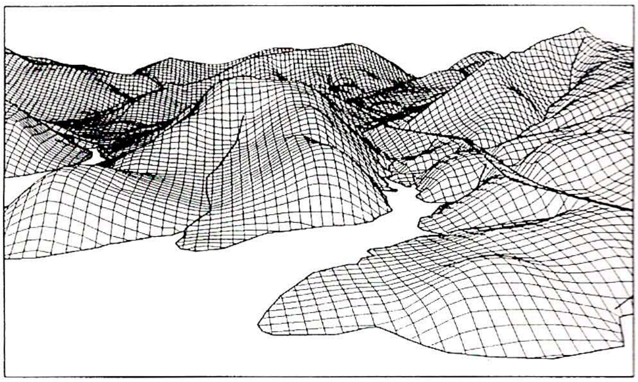
The module SCOP.PROFILE is designed to interpolate and derive any vertical profiles from the DTM, if the traces are given or can be computed. Special cases are longitudinal profiles or cross sections along projected road axes, for road design. The profiles can be represented in graphical plots. Other applications might be parallel profiles for orthophoto-projection (although analytical orthoprojectors can operate with the DTM directly).

A more simple version of the profile program interpolates arbitrary points from the DTM. It is often used for accuracy checking at check points and includes the necessary statistics.



longitudinal profile

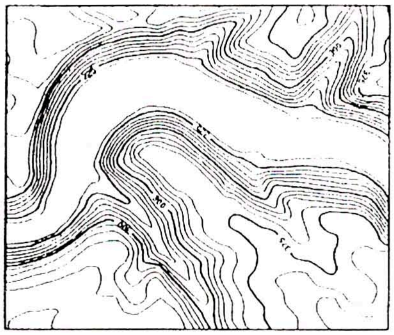
It is very common, nowadays, to produce perspective views (or parallel projection) of DTMs. The module SCOP.PERSPECT handles the parameter required for selecting, limiting and providing the views with hidden areas suppressed, the DTM data structure being maintained. Also visibility maps can be derived. Perspective (or parallel) views are represented as vector plot (wire models) in which the special morphological features (break-lines) are rigorously represented. The latest development of the program module concerns the raster representation, including raster shading. A special case of it is conventional hill-shading of the DTM (in vertical parallel projection) in raster-graphical representation.



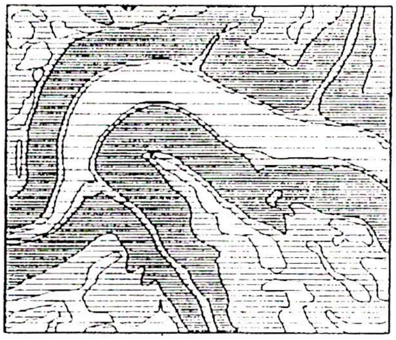
perspective view

From a DTM other digital models can be directly derived. Best known are digital slope models and their representation in slope maps. Aslo aspect maps, showing the exposition of the terrain, are in the same category.

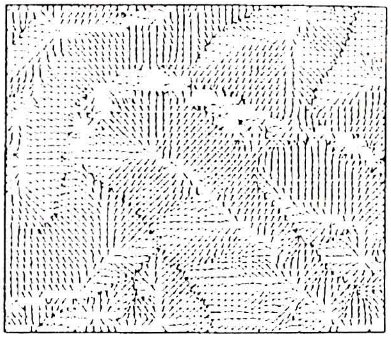
The SCOP system includes programs for such derived products in which again in break-lines and other morphological features are considered rigorously. Slope models require some additional smoothing, as generally gradients are higly noise-sensitive. The slope model has the same



contours



slope map



slope vectors

grid structure and the same data structure as the DTM. Hence other program modules, especially the isoline program, can directly be applied, as well as all graphics routines.

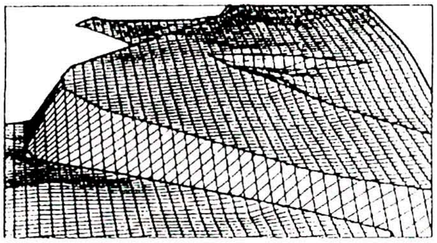
Slope maps represent slopes in distinct slope classes. The graphical representation allows hatching and colour distinction. Because of the consistent data structure those modules can also be applied to the original DTM.

A derived product are slope-vectors, showing the lines of steepest descent as vecor data.

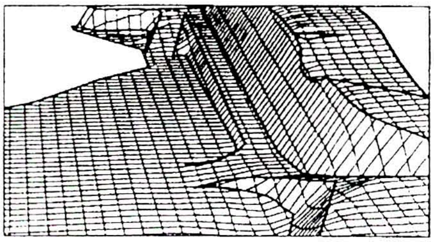
A second class of follow-up programs (module SCOP.INTERSECT) operates with DTMs or derived models by combining them, or interrelating them, with other kinds of area-data. The prime example is the intersection of two different DTMs of the same area, forming a difference model from which also volumes can be calculated, for instance.

The difference model is a special case of relating two overlapping DTMs via arbitrary functions of their z-values. The intersection of DTMs can be generalized to the intersection of a DTM with other digital models which may be defined by polygon surfaces, or plane area patches associated with different attribute values. Hence, for instance, A DTM or a slope model can be intersected with cadastral maps, with soil maps, pollution distribution, rainfall models etc.

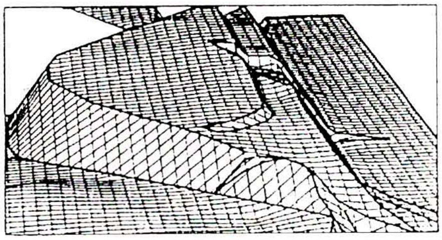
The SCP.INTERSECT module is developed to handle such cases efficiently. It is a generally appicable program for intersecting and interrelating different models, even if they have a vector data structure. In that case the different data structures are made compatible to the SCOP data structure. Examples are the intersection of a slope model and/or soil classes with cadastral parcels, from which evaluation functions can be derived as they are needed by the offices of land consolidation.



DTM A



DTM B



difference model

area no.		area	volume
1	cutting:	25402.48	144809.41
	filling :	921.57	204.08
2	cutting:	1357.36	15569.44
	filling :	0.00	0.00
3	cutting:	2219.11	6358.70
	filling :	189.90	107.49

results of volume computation

Another example is the derivation of soil erosion risk maps. In that case models are intersected which have an influence on soil erosion (like a slope model and a soil class model). With a given functional relation (universal soil loss equation) an erosion risk model can be established and graphically represented.

4. INTERFACES

A universal DTM system with derived product must be able to operate in different environemnt and must be adaptable to external operating conditions. Therefore, SCOP has modules to convert for instance a DTM on a binary file to an ASCII file for the purpose of DTM transfer. Also the graphic plots can be specified for certain instruments (plotters or screens) or made generally accessible on a metafile format. Also variations in the desired representation of plots may be wanted and must be possible easily.

Another class of features refers to the convenient use of a program and to interfaces to various other systems and hardware.

SCOP is monitored via an elaborate command language which is designed for batch mode and interactive mode of operation. For easier handling in case of interactive operations also menus can be used.

There is a DTM interface for access from outside to the DTM, allowing interpolation within the DTM and extraction of profiles. In this way DTM applications can be realized without knowledge or specific consideration of the data structure. For calling upon local height information only one or two (at the most) disc accesses are required, even in case of very large DTMs.

There is also a multitude of interfaces for graphical systems, plotters and screens. Graphic representation is taken care of by a SCOP graphics package which operates on all SCOP program modules.

In a similar way a package of DTM utilities has been prepared for managing corrections and the administration of DTMs. Making use of the DTM data structure local corrections can be applied to the DTM without repeating the interpolation of the complete DTM. Also patches or parts of a DTM can be replaced, in case new data ask for modification. The administration module can handle DTMs for instance, for which a hierarchical series of different levels of accuracy or of a resolution is given.

Lately the interfacing of DTMs with geographic information systems (GIS) is drawing great interest, for the purpose of processing and merging 3-D terrain data with other layers of GIS data. In the SCOP system such interfaces are realized partly as data interfaces, partly as program interfaces. Some information systems can directly read-in SCOP data formats, allowing interactive graphical data handling and processing. Also the DTM access routines of SCOP can be used directly for fast extraction of DTMs of parts of them within GIS. In general it is intended to integrate SCOP modules as subordinates in information systems, below their user surface. The first step have been taken.

REFERENCES

Ackermann F., "The Accuracy of Digital Height Models". Proceedings of the 37th Photogrammetric Week, Stuttgart, 1980.

Hochstöger F.; Ecker R., "Application and Visualization Techniques for Digital Terrain models". Presented Paper, Symposium of ISPRS Commission IV, Tsukuba, Japan, 1990.

Köstli A.; Sigle M., "The Random Access Data Structure of the DTM Program SCOP". Presented Paper, Symposium of ISPRS Commission IV, Edinburgh, 1986.

Köstli A.; Wild E., "Digital Elevation Model Featuring Varying Grid Size". Presented Paper, ISPRS Commission III, Rio de Janeiro, 1984.

Kraus K.; Assmus E.; Köslti A.; Molnar L.; Wild E., "Digital Elevation Models: Users' Aspects". Proceedings of the 38th Photogrammetric Week, Stuttgart, 1982.

Kraus K., "Welche umweltparameter kann man mit Photogrammetrie und Fernerkundung erfassen?" Zeitschrift für Vermessungswesen, Heft 8/9, Stuttgart, 1991.

Sigle M., "Der Aufbau landesweiter digitaler Geländemodelle am Beispiel des DGM Baden-Württemberg". Festschift Friederich Ackermann zum 60. Geburtstag. Schriftenreihe des Institut für Photogrammetrie der Universität Stuttgart, Heft 14, 1989.

Wild E., "Die Prädiktion mit Gewichtsfunktionen und deren Anwendungen zur Beschreibung von Geländeflächen bei topographischen Geländeaufnahmen". DGK, Reihe C, Heft Nr. 277, München, 1983.