Presented Paper to Commission III, 15th ISPRS Congress, Rio de Janeiro, 1984

A DIGITAL ELEVATION MODEL FOR THE STATE OF BADEN-WÜRTTEMBERG

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Abstract: For the complete area of the state, covering 36 000 km^2, vertical profiles, 80 m apart, are available, recorded analogously on storage plates of the Zeiss GZ 1 orthoprojector. These profiles were digitized and are presently used for the interpolation of a digital elevation model in form of a regular 50 m grid by the program SCOP.

The paper describes the processing of the 16 million profile points with particular consideration of the correction of systematic data errors. In addition, the expense for the computations and the application and storage of this national DEM are discussed.

1. Initiation of the DEM computation

Computer programs for the generation of digital elevation models (DEM) have reached a high standard of development and have proven to be quite satisfactory for individual applications. Now the generation of digital elevation models for large areas or for the whole of a country appears as a new task. Presently such developments are discussed or already executed in several countries.

Such a project was started in 1983 by the survey authority of the state of Baden-Württemberg (Fed. Rep. of Germany). In connection with the further production of orthophotos a DEM will be established covering the total area of the state. Orthophotos in scale 1:10 000 are being produced every 5 years for the revision of the topographic maps (Ewig, Riedinger, 1976). The acquisition and storage of the necessary terrain height information was done analogously on profile storage plates for the orthoprojector Zeiss GZ 1 between 1972 and 1981.

In the meantime the GZ 1 instrument was replaced by the digitally controlled orthoprojector Zeiss Orthocomp Z2 (Faust, 1980). In order to further utilize the existing terrain profiles, the storage plates have been digitized and could now be used directly for the orthoprojection, as it is done by the state survey authority of Nordrhein-Westfalen (Tönnessen, Ellenbeck, 1982).

In the case of Baden-Württemberg, some important reasons speak against an immediate use of the existing profiles. Problems have arisen due to the profile acquisition in a local coordinate system for each of the storage plates. The local systems are based on 5 natural control points which are getting lost in course of time. Already now some of the storage plates have become useless.

In addition, the use of the original profiles would prevent a direct production of orthophotos across the boundaries of a storage plate. Therefore a projection in smaller scales or of arbitrary sections would be considerably complicated.

For those reasons the state survey authority has decided to transform the digitized profiles into the state's reference system, the Gauß-Krüger coordinate system, and to interpolate a regular square grid from the transformed profiles for the whole of the state, as it is shown in figure 1.

During these computations the data are subjected to different corrections which lead to a considerable improvement of the height accuracy and of the terrain form representation. Thus, the result will be a DEM which is not restricted to the orthophoto production, but can be used for various other applications.

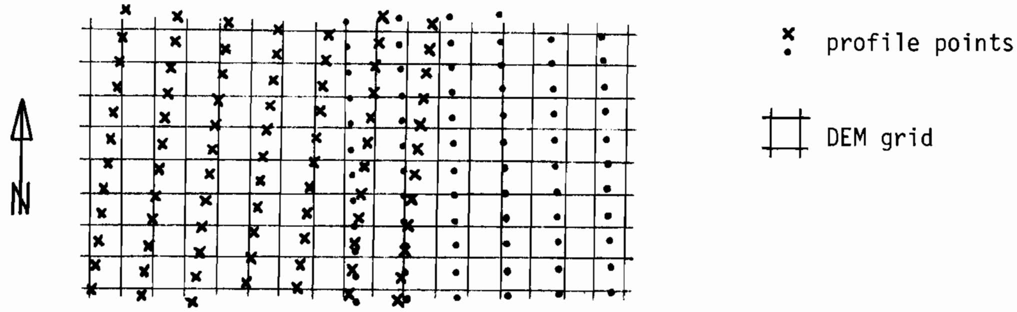


Fig. 1: Arrangement of profile points and DEM grid

2. Requirements for the DEM computation

The computation of the DEM is executed by the computer program SCOP (Kraus, 1973; Stanger, 1973; Kraus etal., 1982; Wild, 1983; Wild, Köstli, 1984) which was developed in cooperation of the Forschungsinstitut für Luftbildtechnik in Stuttgart (Prof. Ackermann) and the Photogrammetric Institute of the Technical University Vienna (Prof. Kraus). SCOP was substantially optimized and extended for further applications during the recent years and is available for numerous computers. A graphic representation of the program's performance is given in appendix 1. Here, only the program features are touched as far as they are essential for the outlined project.

Starting a large project of the size in question a computer program must be available that handles big sets of data. Without any subdivision SCOP considers several 100 000 terrain points even on mini computers.

For the DEM computation SCOP offers different interpolation methods. Besides a fast interpolation for checking purposes, a high quality interpolation, based on the linear prediction method, is available. This method allows a qualified smoothing of the terrain surface and an elimination of systematic scanning errors, which is particularly important in the present case.

Also, the program offers different tools for checks, plots and transformations of the input data, before starting the actual DEM interpolation.

Referring to the DEM application programs, the automatic derivation of contours is to be mentioned in connection with elaborate and most flexible routines (variable size and orientation of map sheets, areas to be excluded, intermediate contours, and indexed contours). Also, the derivation of parallel profiles for the orthoprojection and the perspective representation of the DEM is available, as well as the derivation of digital slope models and of slope maps.

3. Input data

3.1 Scanning and digitizing of profiles

The state of Baden-Württemberg with an area of 35751 km² is covered by about 75 sheets of the topographic map 1:50 000 (TK 50) with about 24,5 x 22 km² each. For each map sheet a pattern of 5 x 5 overlapping orthophotos had been chosen, each of them covered by 2 wide-angle photo-pairs of photo scale 1:30 000. The total number of orthophotos amounts to about 1800.

For the orthoprojection in scale 1:10 000 parallel profiles with a distance of 80 m were used. They were scanned in alternating directions on a Zeiss Planimat D2 and were simultaneously engraved on glass storage plates by the storage unit SG1.

All the storage plates have now been digitized with a point distance of 10 m along the profiles. This leads to about 34 000 points for one storage plate. As no proper scanning device was available, a procedure somehow inverse to the orthoprojection was chosen for digitization. The analogously stored profiles are scanned by the scanning unit LG1 which was equipped with pulse-generators and connected to a recording unit Zeiss Ecomat 11.

3.2. Accuracy of the input data

As it could be expected, the accuracy of the dynamic profile scanning is lower than a static single point acquisition. The reasons are systematic scanning errors on the one hand, appearing as systematic height differences between adjacent profiles, and a smoothed representation of the terrain by the profiles on the other hand.

Accuracy values have been determined by a preliminary test (diploma thesis Drotleff, Wolf, 1982) which was supported by the state survey authority. For each of 6 test areas, with considerably different terrain forms, about 600 points of the digitized profile data and of the interpolated DEM grid have been compared with points measured directly on a Zeiss Planicomp C100 which are accurate from 0.3 m to 0.6 m. A comparison of the digitized and the remeasured data resulted in mean height differences from 1.5 m (flat terrain) up to 5 m (rough terrain), with a considerable systematic component of more than 2 m for some test areas. For forest areas bigger errors occurred because the profiles were correctly scanned over the tree-tops for the proper orthoprojection.

4. Data preparation for the DEM interpolation

4.1. Preliminary data checks

At first, gross digitizing errors were detected by a pre-program which checks the data with regard to completeness, big height differences of adjacent points, and correctness of the height of the coupling point C_0 between the two photogrammetric models forming one orthophoto. In case of erroneous registrations, the digitization of the respective storage plate was repeated.

4.2. Data compression

During the preliminary test (see 3.2) for each test area digital elevation models have been interpolated from the profile data with different densities of points along the profiles. These digital elevation models could be compared with the DEM grid points measured on a Planicomp.

For point distances between 10 m and 60 m the accuracy of the interpolated DEM is nearly the same as the accuracy of the profile data as such. Only for point distances which are larger than the profile distance of 80 m, the accuracy is reduced considerably. Astonishingly, this relationship was found to be independent of the terrain form. Therefore, in this case, for rough terrain the same point distances can be used as for flat terrain. This effect is caused by the smoothed reproduction of the terrain surface by the profiles.

To be on the save side, a constant point distance of 40 m along the profiles was chosen. Consequently, about 8500 profile points of each storage plate and about 280 000 profile points for the area of a topographic map of scale 1:50 000 are used for the DEM interpolation.

4.3. Planimetric transformation

The digitized model coordinates of the profile points are first transformed into the state's Gauß-Krüger reference system by plane similarity transformations. For the transformation natural control points, coordinated in the local storage plate system are used. Their Gauß-Krüger coordinates are determined by a planimetric block adjustment with the program PAT-M using visible trigonometric points (e.g. steeples) for planimetric control.

The planimetric transformation of the profile data was done by the program SCOP, whose absolute orientation gives the transformed data in a structured form that allows a very efficient data handling during the DEM interpolation.

4.4. Correction of the vertical orientation

A preliminary test for the DEM interpolation has shown systematic height differences up to 20 m between the heights of different storage plates in their overlapping area. They are caused by errors of the vertical model orientation and by different calibrations of the storage unit and the scanning unit.

By a vertical block adjustment with the program PAT-M, using each storage plate as 2 photogrammetric models, these discrepancies are detected and eliminated. The vertical model connnection is done by small digital elevation models, which are situated with identical planimetric coordinates in the overlapping area of the storage plates. Each of the local DEM consists of 9 grid points of a 100 m square grid which act as vertical tie points for the block adjustment. The digital elevation models for one tie point group are interpolated separately for each of up to 4 storage plates by the program SCOP with the same interpolation method as for the final DEM computation. This is an interesting way of obtaining vertical tie points although they had not been measured as such.

To ensure the absolute heights, about 230 trigonometric points are available for a TK 50 map sheet, in the average. They can be used as vertical control points for the block adjustment, because their heights were determined with an accuracy of 0.1 m. Their model heights are interpolated with SCOP from the profile data, too. Gross height errors are avoided by an elimination of the trigonometric points in forest areas. Therefore the number of vertical control points varies between 0 and 20 for one storage plate.

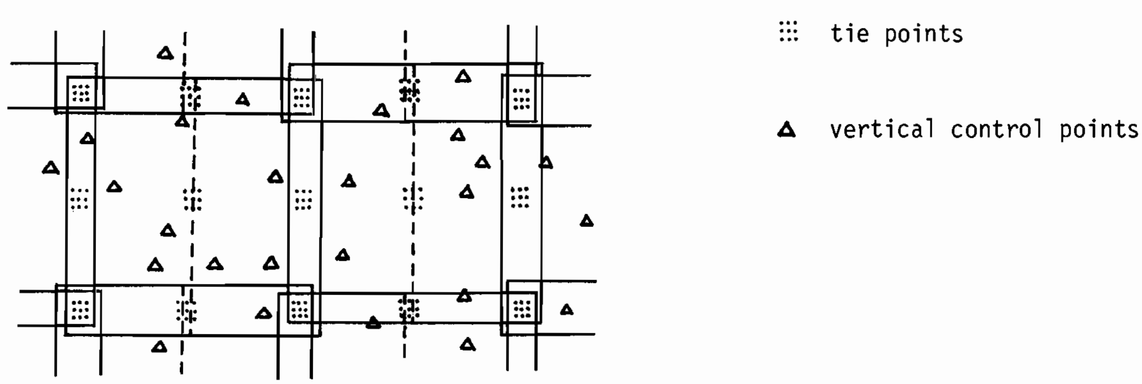


Fig. 2: Point distribution for the vertical block adjustment

The first vertical block adjustment for an area of 4 TK 50 map sheets has resulted in a σ_0 value of 1.6 m. The residuals of the model heights of the trigonometric points have got a mean value of 1.8 m, when the control point heights were given infinite weight. This value may be used as a measure for the DEM accuracy after the height correction. A comparison with the original differences of 3.5 m between model heights and ground heights of the trigonometric points shows the remarkable accuracy improvement.

Thereafter, the results of the vertical block adjustment are used for the vertical absolute orientation of the profiles, model by model, with the program SCOP. During this transformation procedure the 98 models of a TK 50 sheet and its margin are combined into a big data file, consisting of about 400 000 profile points, for the DEM interpolation.

5. Parameters of the DEM

5.1. Grid interval

For the 6 test areas of the preliminary test,digital elevation models with different grid intervals have been computed. For an evaluation arbitrarily arranged check points have been compared with the heights derived from the DEM grid.

For grid intervals up to 50 m for each test area no loss of accuracy could be noticed against a 10 m grid. The obtained accuracy values coincide very well with those of the DEM grid and of the digitized profile points. Only for bigger grid intervals the accuracy of the derived points is deteriorating.

Therefore the digitized profiles are adequately represented by a 50 m grid. A smaller grid interval gives no accuracy improvement. It would rather suggest an accuracy that does not exist, and it also would increase the expense for DEM computation and DEM storage.

5.2. Organization of the DEM computation

For the 75 sheets of the TK 50 of Baden-Württemberg a total number of about 16 million grid points of the 50 m grid has to be interpolated. A DEM computation for the whole area without any subdivision highly exceeds the capacity of the available computers. Therefore a subdivision in accordance with the TK 50 map sheets is used.

The chosen DEM limitations exceed the format of the TK 50 sheets for about 1.5 km. In this way it is avoided that in later application small DEM areas near the sheet delimitation would have to be composed from different units of digital elevation models. In total,for the bordered area of 25 x 28 km² of a map sheet about 280 000 grid points have to be interpolated from about the same number of profile points.

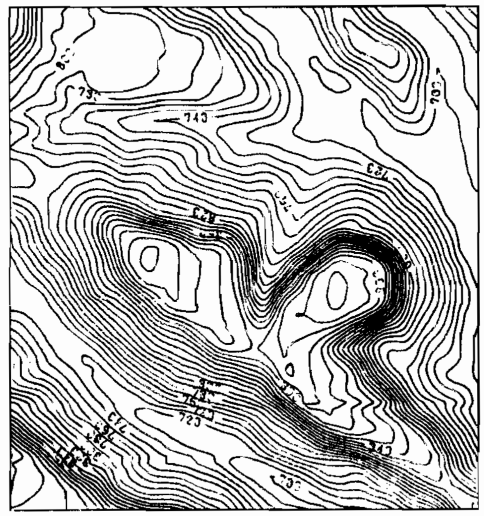
6. DEM interpolation

6.1. Interpolation method

The program SCOP offers different methods for the interpolation of the DEM grid from the acquired profile points. Besides a fast method (moving tilted planes) for checking purposes, different variants of the linear prediction method are available. A comparison has shown the best height accuracy is obtained with the linear prediction method in combination with a filtering of the systematic scanning error. Using the linear prediction without filtering or the fast interpolation, the height errors increase by 5 % and 12 %, respectively.

This result is confirmed graphically by figure 3, which shows a comparison of 2 contour plots of digital elevation models interpolated without data filtering and with filtering of the systematic scanning error.

Linear prediction without filtering of the profile points



Linear prediction with filtering of the scanning error

Fig. 3: Comparison of interpolation variants (Scale 1 : 50 000)

The contours of the unfiltered DEM show the considerable systematic error of the input data in form of obvious wave structures. After the filtering of the scanning error the terrain form representation is considerably improved and has reached good agreement with the topographic maps. Therefore it is indispensable in this case to use an interpolation method that considers the systematic scanning error.

6.2. Computing times

The DEM computations are carried out on a Harris H 100 computer, a mini computer of medium size, working with 24-bit words. The amount of data and the computing times for the 4 TK 50 map sheet areas treated in a pilot study, are shown in table 1.

map sheet	L 7916 Villingen Schwenningen	L 7918 Spaichingen	L 8116 Donaueschingen	L 8118 Tuttlingen
profile points	276 215	281 025	270 020	265 408
DEM grid points	278 941	278 941	278 941	278 941
computing time (CPU):				
data sorting	36^m24^s	36^m19^s	35^m18^s	39^m19^s
interpolation	$3^h39^m30^s$	$3^h42^m40^s$	$3^h35^m50^s$	$3^h34^m10^s$

Table 1: Data and computing times on a Harris H 100 for the DEM computation of 4 map sheets

Considering the big numbers of points, the computing times are highly satisfactory. Especially the interpolation part is executed very effectively, because the regular point distribution allows a simplified determination of the weight functions (Wild, 1983) for the interpolation of the DEM grid. For a comparison with other computers it may be mentioned, that the computing times needed by SCOP are about the same on a VAX 11/750, two times higher on a HP 1000 F and one twelfth on an IBM 3033, as compared with the Harris H 100, respectively.

In the meantime the DEM project was proceeded routinely for about 20 map sheets. The obtained computing times and accuracy values are confirming the results of the pilot study.

6.3. Storage requirements

For this DEM project an 80 Mbyte disc was used. For the computations mentioned in table 1, about 90 % of the disc capacity were used. This means, that the amount of data to be handled with SCOP is not primarily restricted by the program, but by the available disc space.

7. Checks for the interpolation results

Although the preliminary data checks should have detected most of the gross data errors, a final check of the DEM is carried out by 2 methods.

On the one hand the program SCOP allows to print out those profile points, which are affected by a filter value above a read-in threshold value. This tool should detect the remaining gross data errors effectively, because in case of erroneous registrations a high filter value is to be expected.

On the other hand a contour map in scale 1:50 000 with a 10 m contour interval is derived from the DEM. This contour map gives a visual impression of the interpolation result and can be compared with the existing topographic maps. A part of such a map sheet is shown in appendix 2. The following table presents the amount af data, the computing times (Harris H 100) and the plotting times (Zeiss DZ6) required for the derivation of contours for 4 TK 50 sheet areas:

map sheet	L7916 Villingen-Schwenningen	L 7918 Spaichingen	L 8116 Donaueschingen	L 8118 Tuttlingen
contour points:	157 366	250 725	213 958	195 840
CPU-time	55^m14^s	$1^h46^m19^s$	$1^h21^m52^s$	$1^h09^m15^s$
plotting time	8^h	13^h	11^h	10^h

Table 2: Contour derivation from the DEM

8. Use of the DEM

8.1. DEM applications

After the completion of the DEM computations for the whole of the state, the state survey authority of Baden-Württemberg will be able to give the digital elevation models to interested applicants. That means, the DEM delivery can become a service like that of topographic maps.

Because of the limited accuracy, caused by the data acquisition in this case, large scale applications and the use for detailed planning projects will not yet be feasible. Nevertheless, a lively demand can be expected for small scale applications, for example in the fields of geology, geography, for the planning of transmitter positioning, for perspective terrain representations (see appendix 3) and other applications.

However, the main application will be the production of orthophotos. Therefore an output of the DEM in form of parallel profiles is realized in the program SCOP. Against the former orthoprojection procedure, additional orthophoto applications became possible because of the accuracy improvement, the independence of the storage plate format and the free selection of photo scale and orthophoto scale. A first example is the use of the DEM for the orthoprojection in scale 1:5000 for land consolidation projects.

8.2. DEM storage

For the present time, the digital elevation models for the area of a TK 50 are stored separately on a magnetic tape and have to be read in for application purposes.

On the other hand it would be possible to make the whole DEM of the state available immediately. For that purpose a 300 MByte disc would be required and sufficient. In addition, a DEM structure would be needed,which allows a direct access to any part of the DEM and an integration of more accurate or large scale data into the existing DEM. Such an interface has been realized for the program SCOP during the past months.

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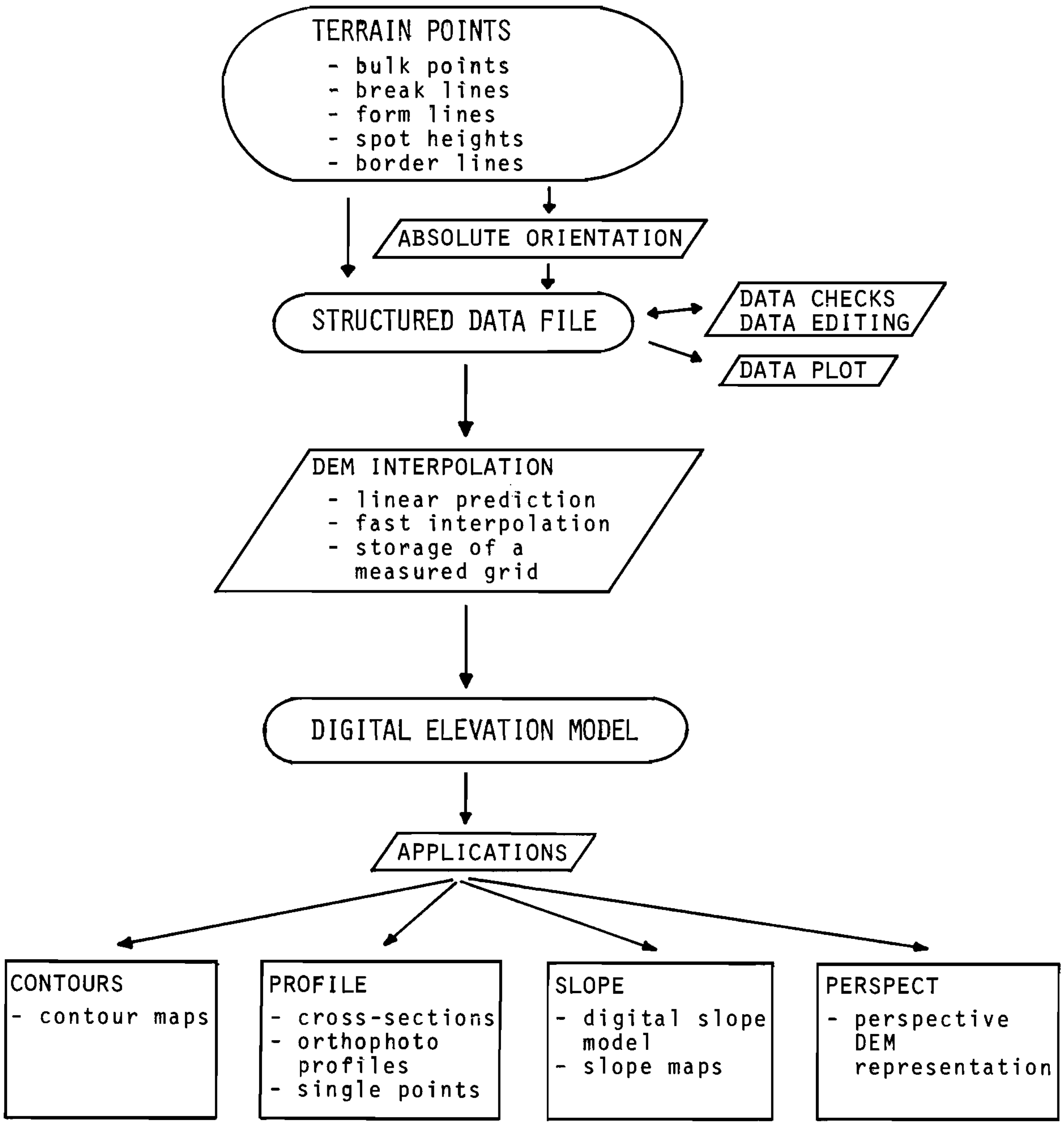
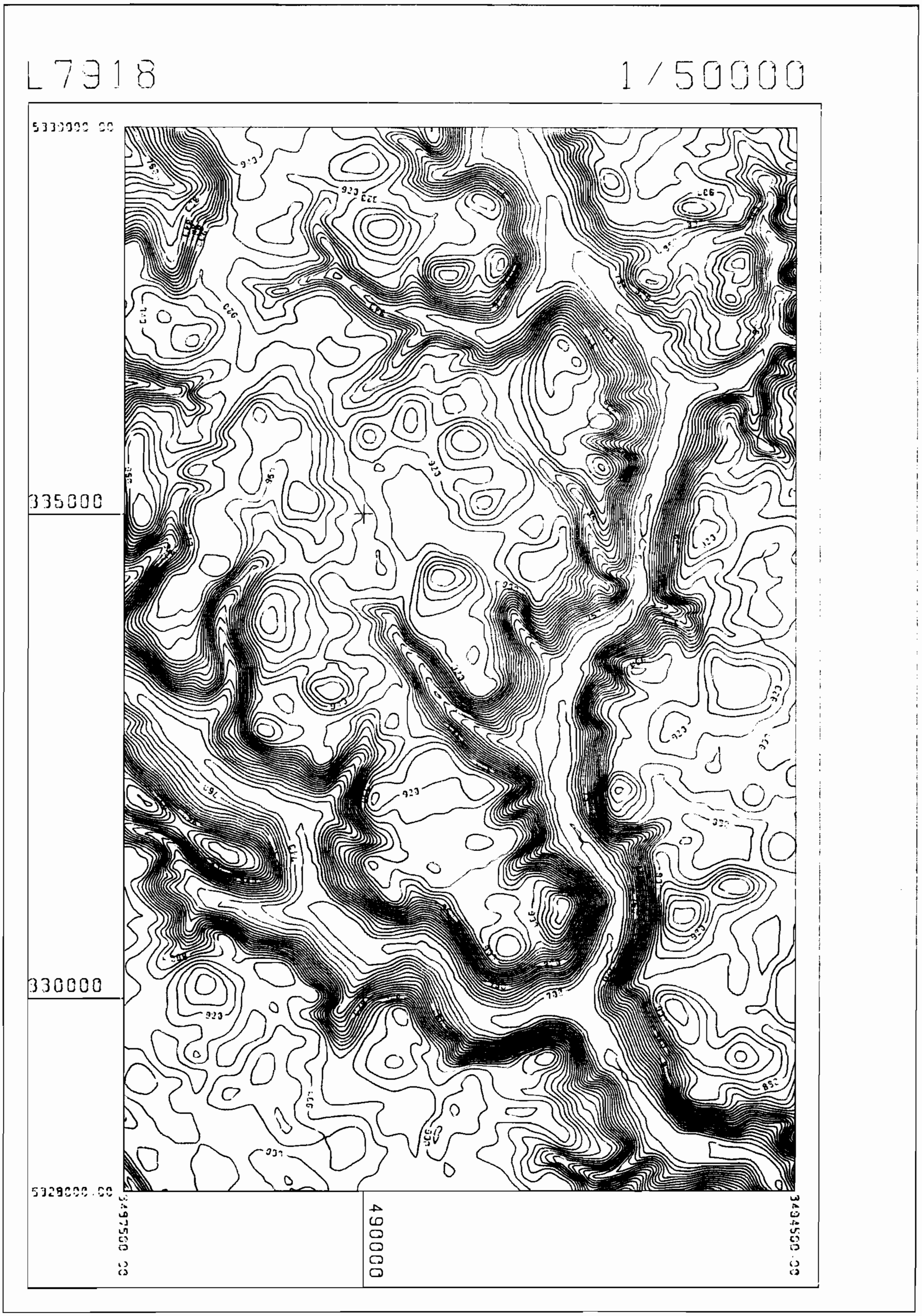
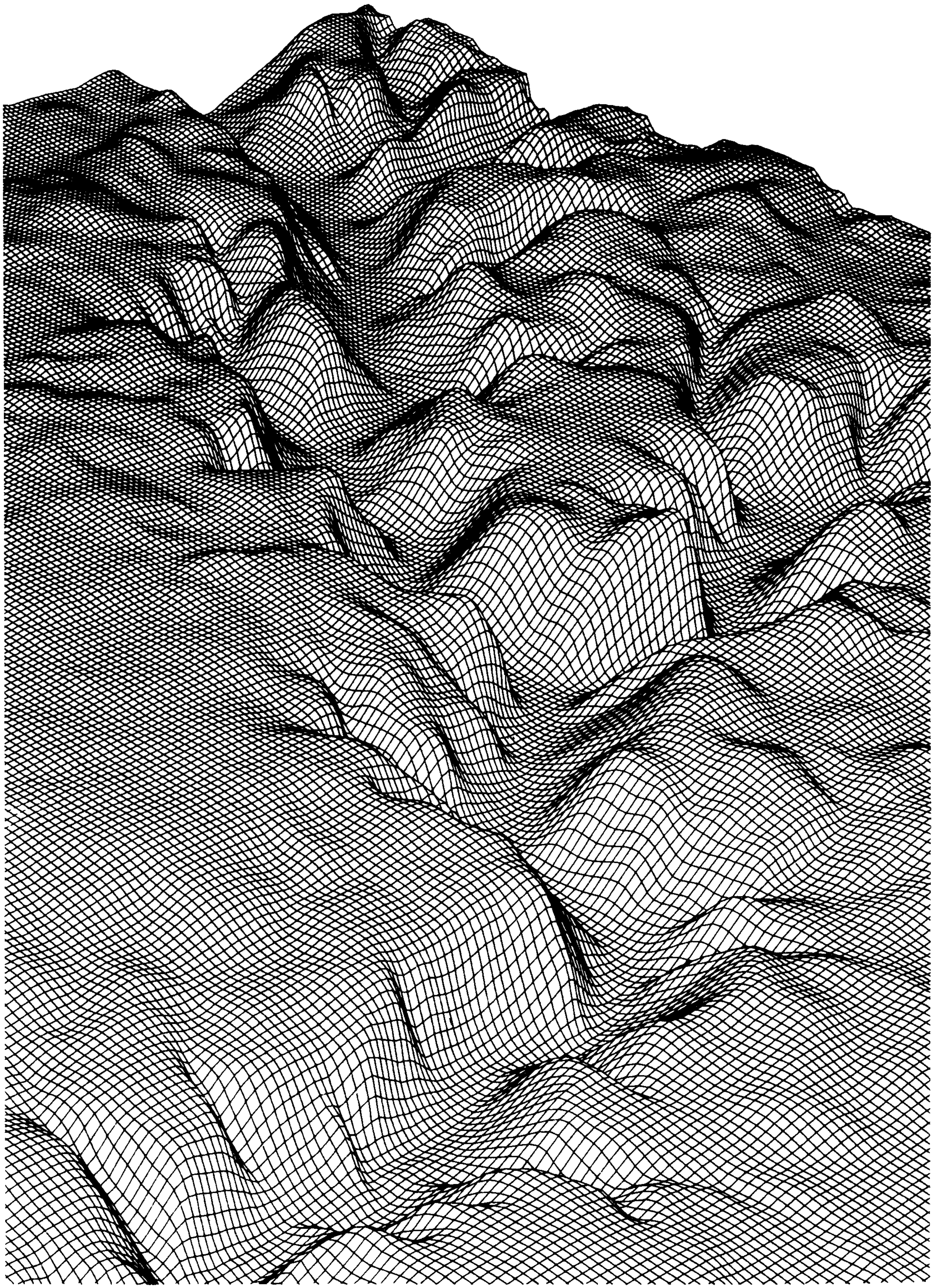


APPENDIX 1: The computer program SCOP



APPENDIX 2: Contour representation of the DEM



APPENDIX 3: Perspective representation of the DEM