

DIGITAL ELEVATION MODELS REVIEW AND OUTLOOK

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ABSTRACT

The paper gives a short overview of achievements and problem areas in Digital Elevation Models, together with an outlook into the future. The main points are summarized in the following.

DATA CAPTURE

Data Capture for Digital Elevation Models usually takes place by digitizing existing contour maps or by photogrammetric means.

The costs of manual and automatic digitizing are about equal (in western countries) with typical times for a 1:25,000 map sheet of 50 x 70 cm² (10 contour) as follows

- manual digitizing: 50 - 70 hours
- automatic digitizing: 0.5 hours scanning
8 hours vectorization on VAX
8 - 20 hours editing on
interactive work station

More advanced software is desirable for automatic scanners, enabling the proper reconstruction of the contour lines from disjoint segments, and the attachment of height values (Kubik, 1987).

Photogrammetric data capture is usually done in profiles. Adequate methods exist to enable a (semi-) automated choice of sample density to meet pre-given accuracy specifications (Balce, 1986).

For accuracy reasons, measurements should preferably be done in a stop-start mode at predefined grid points set by the analytical plotter. Measurements in a scanning mode have mean square errors twice as large.

Most DEM programs require the definition of breaklines in order to allow a high fidelity terrain reconstruction. The definition of the proper number and location of breaklines usually poses problems to the operator. The measurements of these lines are usually less accurate than for grid points, as the operator has to control three co-ordinate movements. Inconsistencies as compared to the grid heights may result; these must be corrected in an interactive mode on a graphic work station.

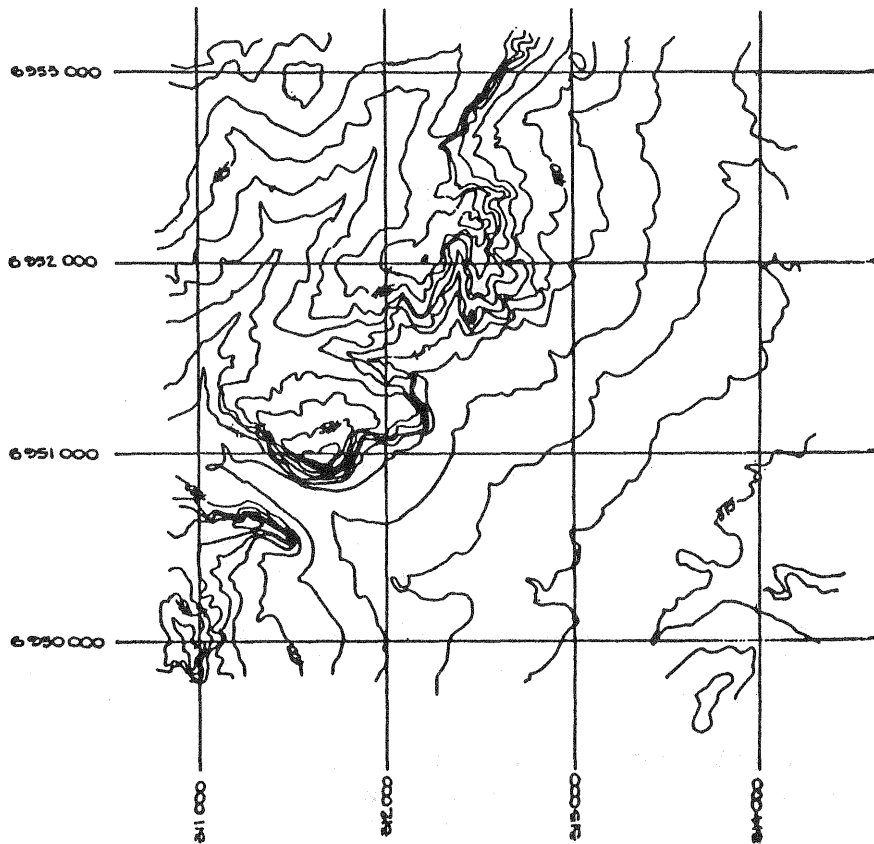


Figure 1: Contour lines of test area (5 metre contours)
7,964 points digitized, 90 minutes measuring time.

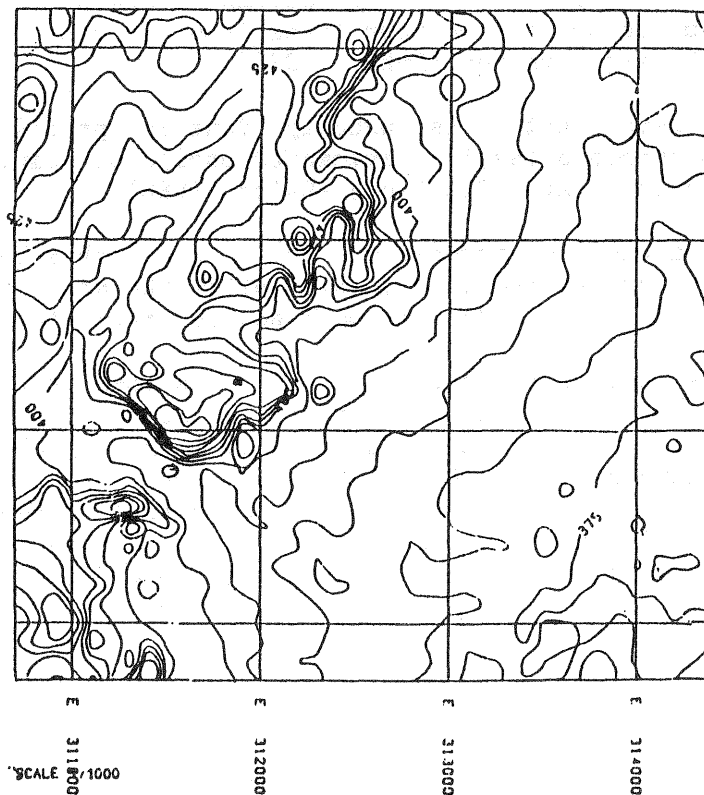


Figure 2: Results of HIFI profiles of 100m spacings;
characteristic profiles selected by operator; no
breaklines (1,162 points digitized, 43 minutes
measuring time)

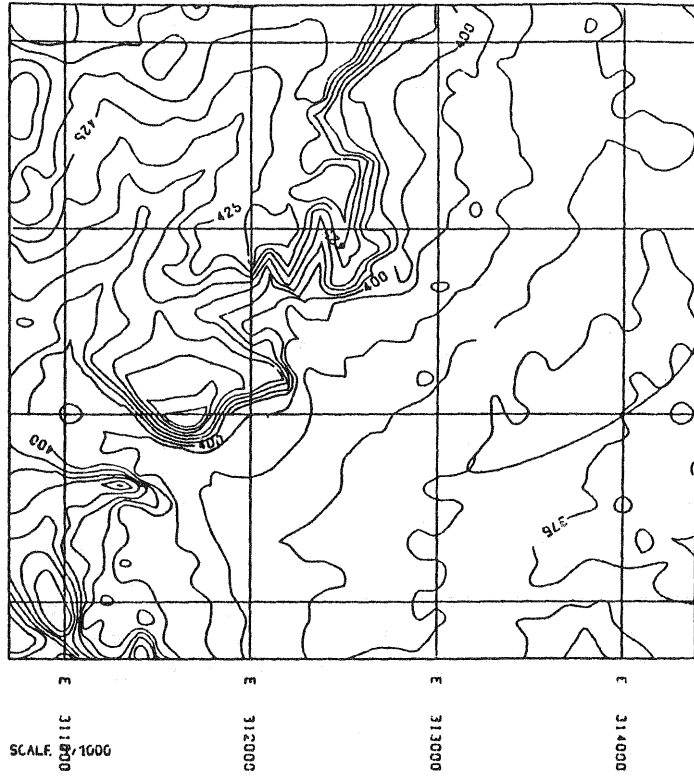


Figure 3: Results of HIFI profiles of 100m spacing operator selected points: breaklines included (1,121 profile points and 2,542 breaklines points digitized, 96 minutes measuring time)

Points along breaklines are digitized two to three times as densely as the grid heights. The time and volume of break line measurements usually exceeds that of grid height measurements. A proper training of the operator and proper preparation of the measuring phase is recommended to facilitate the breakline measurements of the operator (identification of breaklines in mirror stereoscope), see also Toomey, 1986. For Figures 1 to 3 demonstrate the need for breaklines for reliable contour interpolation and the measuring times required.

DEM INTERPOLATION

The commercially available DEM programs are usually incompletely documented. The user has to be aware of the details of the interpolation method in order to make a proper decision regarding breakline definition, input parameters and quality control. Many programs contain (one or more) smoothing parameters, which should be set with utmost care to get a proper representation of the terrain. The author prefer that no smoothing be done, as the measuring errors are small compared to the possible terrain undulations. When more than one smoothing parameter is required in the input, the smoothing effects are (usually) cumulative, resulting in a very smooth surface between the break lines. Many smoothing parameters have numerical limits beyond which the computation becomes unstable. There is usually no error message, but the results are erroneous.

Local interpolation routines (local interpolation using the surrounding points) usually behave poorly in areas of rapid curvature change (riverbeds and similar features). Interpolated elevations should not exceed local minima and maxima, as the operator is instructed to measure these points in the terrain. Many DEM-programs do not include this precaution.

Proper formal terrain description and properly tuned interpolation routines can reduce the need for breakline definition, see Appendix A.

The accuracy behaviour of interpolation is well understood and documented (Frederiksen et al, 1986). With proper use, the different classes of interpolation methods give comparable accuracy results, see also Appendix B.

The problem of automatic generalization is not yet solved. Conceptual breakthroughs are still needed in order to find methods acceptable to the cartographer.

STORAGE AND APPLICATION

Large Digital Elevation Databases are generated and stored in the USA, Canada and Europe. Storage is usually in a grid, with sample spacings of 100m upwards. It is advisable to also store the measured data and break lines and local accuracy parameters for the data.

Storage often requires high storage capacities (often exceeding 10^{10} words). Techniques for data compression have still to be investigated in order to reduce storage requirements. Major users of these databases are defence, oil companies (Canada; Toomey, 1986), engineering companies, telecommunications (determination of radio horizon), offshore and hydrographic agencies.

Rapid Terrain Simulations are in great demand (e.g. for flight simulators). Proper artificial roughness must be superimposed on the generated surface to enhance the realism of the simulation.

The databases may also be used to derive (simulated) reflection of microwaves and other radiation (radar clutter). For this purpose, additional parameters (local roughness figures) have to be stored. An increasing part of these databases is (being) classified.

Minor data bases are generated in other institutes in connection with orthophoto mapping projects, enabling a rapid periodic renewal of the orthomaps by using the existing DEM.

Many users require digitally generated contours in photogrammetric mapping projects. Although contours derived from scan lines may look more aesthetic (smooth), they are on the average less accurate than classical contouring.

OUTLOOK

Much interest is given to full- or semi-automated data capture for DEM, using automatic correlation and image matching techniques, together with special air- or space-borne sensors. In its final product form DEM generation gets combined with automated feature recognition. Major interest in these developments is expressed by defence and by industry (robotic vision, online quality control in production).

International activities and inventories in this field are organized around others by the Working Group "Digital Elevation Model" of the International Society for Photogrammetry, co-chaired by the authors and Prof. Jacobi of Techn. University of Denmark (1984-1988).

APPENDIX A

NEW INTERPOLATION METHODS - MINIMIZING OTHER DERIVATIVES

The classical interpolation programmes use relatively inflexible interpolation functions. By minimizing the average second derivative of the interpolation function, these methods (approximately) describe the bendings of a mechanical spline or plate, but not the undulations of a cartographic line. As an alternative, we may try to model the behaviour of this line by the differential equation

$$z^{(n)} = \varepsilon \quad (1)$$

where $z^{(n)}$ denotes the n -th derivative of the values z , and ε is an independent random variable (white noise). Here n may also be non-integer. In that latter case this fraction n -th derivative is defined by continuous interpolation into the integer differences (Frederiksen et al, 1984).

This differential equation (2) may now be chosen as a model for interpolation, for instance in L-spline or finite element interpolation. The proper functional to be minimized is then

$$J = \int_{\Omega} \left\{ \frac{\partial^{(n)} z}{\partial x^{(n)}} \right\}^2 dx \rightarrow \min. \quad (2)$$

The results of the L-spline interpolation are identical to the results of the Wiener prediction method using a proper variogram or covariance function, as it was shown already in 1971 by Kimeldorf and Wahba (see also Dolph and Woodbury, 1952 and Kubik, 1973).

Figure A.1 shows examples of interpolation according to these new principles. The digitized points represent the profile of a well known cartographer. For $n = 1$ we obtain piecewise linear interpolation (linear spline), for $n = 2$, piecewise 3rd degree interpolation (cubic splines) and for n between 1 and 2 we obtain interpolation forms which properly model break points in the terrain profile while preserving relative smoothness in the other profile sections. From extensive analysis of various terrain forms, the authors found n values in between 1.2 and 1.4 as most appropriate for use in DEM applications. Manmade cartographic lines are modelled on the average with a slightly larger n value. Algorithms for online determination of the proper n value for individual lines were developed by the authors to enable proper interpolation according to the line structure inherent in the digitized points (Kubik and Loon, 1985).

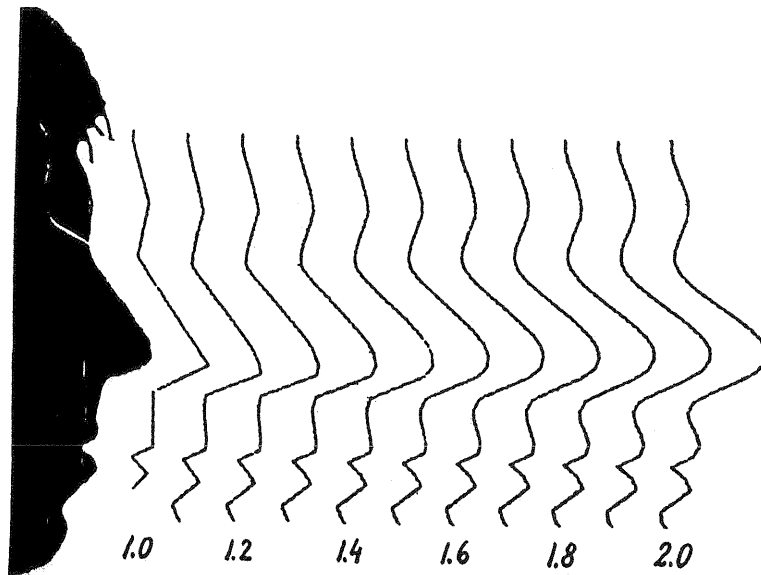


Figure A.1: Interpolation with fractional derivatives; use of different values of n for interpolation

NEW INTERPOLATION METHODS - MINIMIZING OTHER FUNCTIONALS

The above idea can be further generalized by minimizing well chosen functions of the derivatives, instead of their square sum:

$$J = \int_{\Omega} f\left(\frac{\partial^{(n)} z}{\partial x^{(n)}}\right) d\Omega \rightarrow \min. \quad (3)$$

In order to illustrate this principle, we consider the simple functionals

$$J_p = \int_{\Omega} \left| \frac{\partial^2 z}{\partial x^2} \right|^p d\Omega \quad ; \quad 0 < p < 2 \quad (4)$$

minimizing the integral of non-integer power of the second derivative of the line.

The numerical interpolation methods for solving (4) are analogous to the methods described before. In order to demonstrate the effect of this class of interpolation principles, we choose again the profile of a well known cartographer (Figure A.2)). Classical cubic spline interpolation (using $p = 2$) yields unsatisfactory results and would need the definition of numerous break points to yield an acceptable result. A.2 shows the interpolation results for decreasing values of p . Notice that the profile becomes more recognizable for decreasing values of p , with an optimal choice of p equal to 1.2. Lower p values yield an increasingly rough profile, with piecewise linear interpolation obtained for $p = 1$.

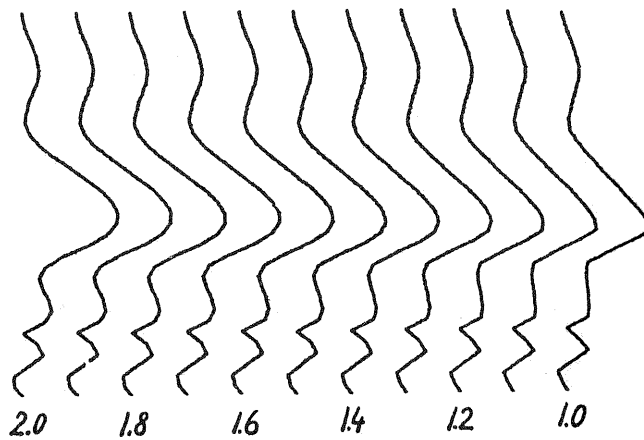


Figure A.2: Interpolation with fractional powers; use of different values of P for interpolation

Thus, with the principle (5), we have obtained a new transition of interpolation forms from a cubic spline to a linear spline, different from figure A.1. In both cases, no break points were needed to yield realistic interpolations, which are close to the lines drawn by draftsmen.

Obviously, other functionals (4) may be chosen, which may give both worse and better interpolation results. However, proper use of these new principles allows a very effective interpolation of cartographic data, and considerable savings in data capture, as compared to classical methods.

APPENDIX B

PLANNING PARAMETERS

In order to plan the sample spacing and estimate the accuracy of a digital elevation model, the terrain is described by its variogram.

The variogram for the terrain surface proves - from theory as well as experiments - to be of the form

$$V(d) = k \cdot d^{\beta} \quad (1)$$

where k is the value of $V(d)$ for the distance $d = 1$ unit (Berry and Lewis, 1980), (Frederiksen, Jacobi and Kubik, 1983).

On a log-log plot the variogram appears as a straight line with the slope β . The slope tells about the roughness of the terrain.

The variogram of a rough surface as a slope close to zero, while a very smooth terrain has a steep variogram.

The required accuracy σ (mean square error or standard deviation) of the elevation model must also be given. The parameter σ may either denote the average standard deviation σ_{mean} of elevations extracted from the model or it may refer to the maximum standard deviation σ_{max} .

The final accuracy of the digital elevation model is composed of the accuracy of data acquisition and the accuracy of interpolation:

$$\sigma^2 = \sigma^2_{\text{interpol.}} + \sigma^2_{\text{sample points}} \quad (2)$$

The inaccuracy of data capture may be due to the process of measurements (i.e. photogrammetric height measurements), or it may be due to the uncertainties in the measured phenomenon (i.e. uncertainties of a contour line to be digitised, or uncertain definition of the terrain surface when measured photogrammetrically).

We relate the sample spacing to $\sigma_{\text{interpol.}}$, and thus the accuracy specification must be reduced by the sample variation

$$\sigma^2_{\text{interpol.}} = \sigma^2 - \sigma^2_{\text{sample points}} \quad (3)$$

INTERPOLATION ACCURACY AND SAMPLE SPACING

We limit ourselves to the study of interpolation in profiles of sample points. When a set of surface heights $z_1 = z(x_1, y_1)$ is given, various interpolation procedures may be applied to compute an approximation z^* to z at a required location (x, y) .

The usual interpolation rules can all be written as

$$z^*(x,y) = \sum a_i z_i \quad (4)$$

because all these rules estimate z^* as a linear combination of the sample points.

With respect to the unknown true value z at the location (x, y) , the error of the interpolated height is

$$e(x,y) = z - z^* = z - \sum a_i z_i \quad (5)$$

and the standard deviation of the interpolation error σ_e can be computed for the terrain using the variogram model in equation (1). The standard deviation is expressed in units of the constant k . It is assumed that the errorfree sample points are equally spaced with the spacing L and that intermediate points have to be interpolated.

To demonstrate the accuracy estimation procedure the accuracy of interpolated heights is computed for prediction interpolation.

For interpolation in profiles it holds

$$\frac{\sigma^2_{\text{mean}}}{k} = L^\beta \left(\frac{1}{6} + \frac{2}{(\beta+1)(\beta+2)} \right) \quad (6)$$

This accuracy result is plotted in Figure B.1.

The figure relates the sample spacing - expressed in units of L - to the accuracy of interpolation - expressed in units of k - for different values of the terrain characteristic parameter β .

Further details are described and other interpolation procedures investigated in (Frederiksen, Jacobi and Kubik, 1983).

When planning the sample spacing, one enters the figure with the required accuracy of interpolation along the vertical axis, draws a horizontal line to the proper line for β and reads off the value L from the horizontal axis.

In order to find the accuracy for a given sample spacing, the figure is used reversely.

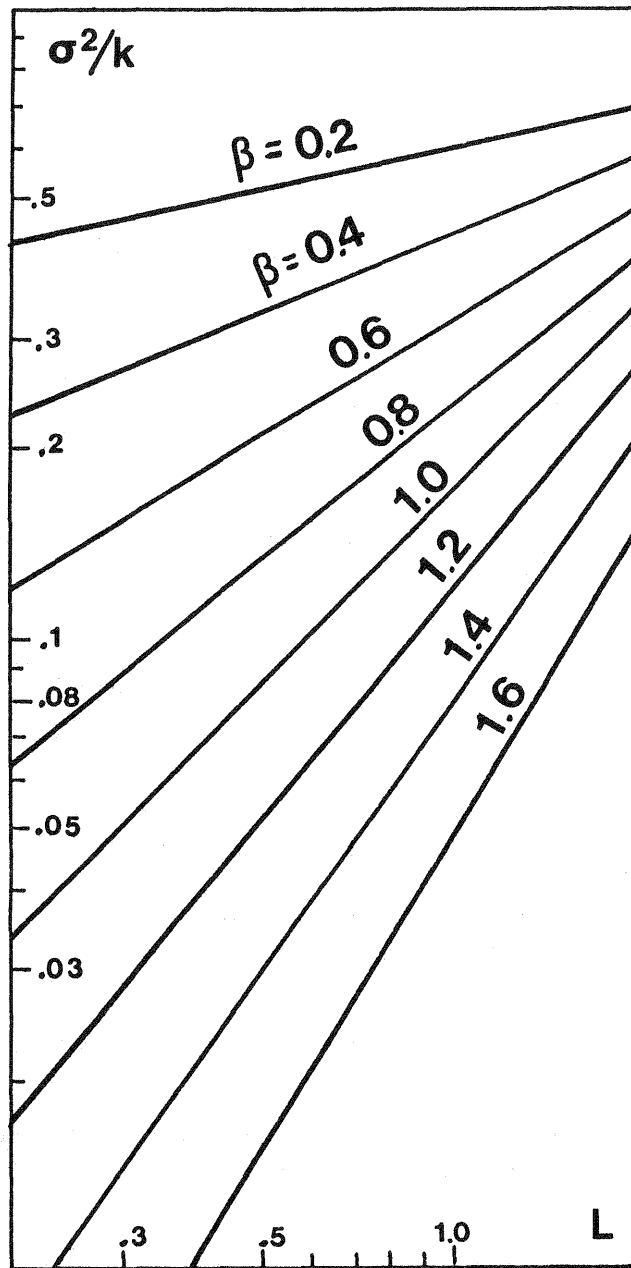


Figure B.1
 Linear and prediction interpolation.
 L is expressed in units of D as used
 for determining the factor k from the variogram

REFERENCES

- Balce, A. 1986: Determination of Optimum Sampling Interval in Grid Digital Elevation Models Data Acquisition, Proceedings ISPRS Commission III Symposium, Finland, Int. Archives of Photogrammetry and Remote Sensing, LVo.. 26, Part 3.1, p. 40-55.
- Berry, M.V. and Lewis, 1980: Proceeding of the Royal Society, London.
- Frederiksen, P; Jacobi, O. and Justesen, J: 1978: Fourier Transformation von Hohenbeobachtungen, ZfV, 103.
- Frederiksen, P; Jacobi, O. and Kubik, K; 1983: Measuring Terrain Roughness by Topological Dimension. Proceedings. Internat. Coll. on Mathematical Aspects of Digital Elevation Models, Stockholm.
- Frederiksen, P; Jacobi, O. and Kubik, K: 1984: Accuracy Prediction for Digital Elevation Models. XV Congress of ISPRS, Comm. III, Rio de Janeiro.
- Frederiksen, P; Jacobi, O. and Kubik, K: Optimum Sampling Spacing in Digital Elevation Models, Proceedings ISPRS Commission III Symposium, Finland, Int. Archives of Photogrammetry and Remote Sensing, Vol. 26 Part 3.1, p. 252-260.
- Frederiksen, P, Jacobi, O, Kubik, K: 1985. A Review of Current Trends in Terrain Modelling, ITC Journal 1985-2, plot 106.
- Kubik, K. 1985, A Digital Elevation Model for Queensland - Feasibility Study, Report of the Queensland Institute of Technology, Brisbane, Australia, 400 pp.
- Kubik, K. and Loon, J. 1985, On Local Fractional Integration, Israeli Annals of Physics, 6 pp.
- Kubik, K. 1987 editor: Digital Elevation Models, Proceedings of ISPRS Workshop, Working Group III.3, Report of the Department of Geodetic Science and Surveying, The Ohio State University.
- Kubik, K. and Loon, J. 1987: Perfecting Automatic Line Drawing, Proc. 1987 AUTOCARTO Conference, Baltimore, Maryland.
- Matheron, G., 1971: The theory of regionalized variables and its applications: Les Cahiers de Centre de Morphologie Mathematique, Ecole National Superieure des Mines de Paris.
- Toomey, M. 1986: Digital Elevation Models in Alberta, Proc. 1986 ACSM-ASPRS Annual Convention, Vol. 4, p. 220-229.