ACCURACY OF SLOPE INFORMATION DERIVED FROM DEM-DATA

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ABSTRACT

The question of digital elevation model (DEM) accuracy and interdependence of the height errors is closely connected with the question of the surface definition. In practice, the terrain surface is always an artificial surface that is consciously simplified and smoothed in order to obtain appealing or even useable products from the DEM. Thus DEM accuracy has to be defined with respect to the needs of the specific application. The accuracy of slope and all associated values is one important derived product from the DEM. It depends first of all on the height accuracy and on the resolution of the DEM. But it also depends from the systematic parts of the height errors. Height errors yield the impression to be distributed normally when estimated for a larger data set, but usually they show high local correlations. The consequence of ignoring systematic errors is an often unrealistic (i. e. too pessimistic for slope values) estimation of the quality of the derived data. DEMs with high cartographic quality show high correlation of the errors within a local neighbourhood.

A general approach for the influence of non-independent height errors on slope errors is outlined in this paper. With a test data set the correlation of the height errors is checked for several typical cases: The original data and some common techniques for smoothing. Especially the correlation of height errors, which is essentially a result of interpolation and smoothing processes, is an important factor to yield more appropriate first derivatives of the terrain surface. Concluding suggestions arise to define DEM errors not only in terms of the real surface but rather in terms of the wanted surface representation, therefore the results of error estimation should take into account the application specific needs.

KURZFASSUNG

Die Genauigkeit des Digitalen Höhenmodelles (DHM) steht in engem Zusammenhang mit der Frage nach der Definition der Geländeoberfläche. Inder Praxis wird als Geländeoberfläche immer eine künstliche Fläche angesehen, die durch bewußte Vereinfachung und Modellbildung entstanden ist, um für die jeweilige Anwendung möglichst gut geeignete Produkte aus dem DHM zu erhalten. Deshalb ist die Genauigkeit des DHM abhängig von der gewünschten Aufgabenstellung zu definieren. Die Genauigkeit der Neigung und aller damit in Zusammenhang stehenden Größen ist ein wichtiges aus dem DHM abgeleitetes Produkt. Sie hängt in erster Linie von der Höhengeauigkeit und der Auflösung des DHM ab, aber auch von systematischen Fehleranteilen in den Höhenwerten. Die Höhenfehler erscheinen nämlich meist normalverteilt, wenn man sie über einen größeren Bereich hinweg abzuschätzen versucht, sie zeigen aber auch eine höhere lokale Korrelation. Die Folge der Vernachlässigung dieser systematischen Anteile ist eine zu pessimistische Einschätzung der Qualität. Gerade Höhenmodelle mit hoher kartographischer Qualität zeigen jedoch eine starke lokale Korrelation der Höhenfehler.

Im der vorliegenden Publikation wird ein allgemeiner Ansatz zur Berücksichtigung nicht-unabhängiger Höhenfehler bei der Ableitung der Neigungsfehler gebracht. Mittels eines Testdatensatzes werden weiters die Höhenfehler für einige typische Fälle (Originaldaten und häufige Glättungsmethoden) auf ihre Korrelation geprüft. Besonders die Korrelation der Höhenfehler, die im wesentlichen eine Folge der Interpolation und Glättung ist, ist ein wichtiger Faktor, um zuverlässigere erste Ableitungen der Geländeoberfläche zu erhalten. Als Abschluß wird vorgeschlagen, die DHM-Fehler nicht nur auf die wahre Geländeoberfläche zu beziehen, sondern auch auf die gewünschte Oberflächenapproximation, was dazu führen würde, die jeweiligen Anforderungen klarer zu benennen.

1. INTRODUCTION

Several applications in earth and environmental sciences need information derived from the height data of the Digital Elevation Model (DEM). There is a special need for slope values, slope vectors, and slope directions especially in water management, hydrology, and environmental desaster prevention. In Austria slope values are used in cadastral operations in order to estimate standard values for agricultural real estates in mountainous regions. In all these cases it is crucial to obtain slope values with high accuracy.

A lot of research work has been done to define the accuracy of the DEM data in terms of height errors, e. g. (Ackermann, 1979), (Zhang, 1988), (Theobald, 1989). Frequently this is done by describing the root mean square (RMS) error of single DEM points. Another more sophisticated approch in order to obtain information about the quality of DEMs is the use of the Fourier Transformation (Makarovic, 1972), which especially allows to take into regard the periodical characteristic of the height errors. Tempfli (1982) shows how the Fourier Transformation can be adapted to the estimation of the RMS errors of derived products such as volumina or slope values. Certainly a lot of work still has to be done in order to implement accuracy information to spatial data bases which is a still missing "jump in quality" (Kraus, 1995), especially in concern of derived products - although interesting approaches have already been published, e. g. (Kraus et al., 1993), (Kraus, 1994), (Hochstöger, 1995), (Goodchild et al., 1989).

A topic of minor interest has been the interdependence of the height errors of DEM points, especially in close neighbourhood, which yields a large impact on the accuracy of all those values that are derived from the elevation data through local operations. Due to measurement techniques and interpolation, there is a positive correlation of the elevation errors within a certain neighbourhood of DEM-points. That correlation of the height errors may show a dependency not only from the point distance but also from the slope itself (Steinmetz, 1992).

In this paper the correlation between the height values of a DEM-point and its neighbours - according to their relative position as seen from the DEM-point - are estimated from a test data set. The DEM is obtained from photogrammetric imagery.

2. THE DIGITAL ELEVATION MODEL

2.1 The Square Grid Model

For the following investigation a grid DEM with square grid is used. This kind of model is ideally suited for statistical analyses. The consequently regular structure (in the projection plane) allows for a lot of simplifications in the algorithms. Furthermore some results, especially the correlation function between the height errors of neighbouring points, may be generalized to irregular models.

It has widely been outlined that the square grid DEM has a lot of disadvantages compared to other types of elevation models, e.g. triangulated irregular networks (TIN-models) or grid models with additional vector information (Hutchinson, 1989; Mark, 1979; Köstli, Sigle, 1986; Toomey, 1988, just to mention some). Especially Mark demands that the phenomenon should be the driving criterion for the representation of data rather than computational considerations (Mark, 1979). The author fully agrees with these opinions. In the case of this paper, however, the nature of correlation between data points shall be estimated, which can only be done in a statistically relevant way, i. e. through a large number of points. Irregular point distributions, however, yield much more complex approaches, and furthermore the derivation of elevation data is frequently done through measurement of square grids (Krzystek, 1991; Theobald, 1989), thus these data can be directly tested, without any additional interpolation to a square grid.

In the square grid some very simple relations are valid. The following local point indices are defined:

		12		
	8	4	7	
9	1	0	3	11
	5	2	6	
		10		

Tab. 1: Relative point indices of neighbouring points (1-12) to any point (relative index 0) in the square grid

These indices are used throughout the paper in order to address the respective neighbouring points to any one grid point. It is assumed that those neighbouring points exist, which is realized if all operations are restricted to the "inner zone" of the square grid model (not using the outermost two gridlines all around the rectangular data set).

2.2 The Data Sets for the Test

For the test two data sets are used: A reference data set with superior accuracy which has been plotted from large scale photographs, and a small scale test data set on which the test takes place. In the actual case a scale factor of 4 has been used between the two data sets, a factor which allows to nearly neglect the influence of the errors in the reference data set. Thus the height values H_{rc} (row, column) of the reference data set are assumed to be "true values", while those of the test data set, h_{rc} are assumed to be erroneous (for the random parts of the errors the influence of the large scale model errors can actually be neglected, while for the systematic parts the estimated error values may be wrong by about 30 percent). The data sets are described as the following matrices, with *nc* as the number of columns and *nr* as the number of rows:

$$\boldsymbol{H} = \begin{pmatrix} H_{11} & H_{12} & \cdots & H_{13} \\ H_{21} & H_{22} & \cdots & H_{23} \\ \cdots & \cdots & \cdots & \cdots \\ H_{nr,1} & H_{nr,2} & \cdots & H_{nr,nc} \end{pmatrix} \qquad (1)$$

is the reference data set and

$$\boldsymbol{h} = \begin{pmatrix} h_{11} & h_{12} & \cdots & h_{13} \\ h_{21} & h_{22} & \cdots & h_{23} \\ \cdots & \cdots & \cdots & \cdots \\ h_{nr,1} & h_{nr,2} & \cdots & h_{nr,nc} \end{pmatrix} \qquad (2)$$

the test data set. Both matrices are equally dimensioned and positioned. The neighbouring points of any grid point H_{rc} or h_{rc} according to the local point indices as defined in Tab. 1, are addressed as $H_{rc,i}$ respectively $h_{rc,i}$ or, for better readability and for simplicity reasons, as H_i respectively h_i in most cases where the indices *r* and *c* do not point to a specific point.

2.3 Errors in the Elevation Data

There is a lot of error sources present in the whole process of obtaining a DEM from photogrammetric material. Generally spoken, three types of errors can be found, defined through their frequency in the spectral space, expressed in relation to the grid width - as the smallest unit - and the whole DEM-area - as the largest unit -, and their impact on the resulting height errors:

2.3.1 Errors with low frequency: These are mainly errors resulting from the photogrammetric orientation process. These processes yield errors that apply systematically on at least a whole photogrammetric model. In terms of their frequency spectrum they are either linear or show wave lenghts of about twice the size of a single photogrammetric model (with model orientation) or even larger (with bundle or model blocks). Since these errors do not change significantly between neighbouring grid points, they have only little influence on the derivation of all those data that are obtained by local height differences. They are critical mainly to the absolute height values.

2.3.2 Errors with medium frequency: These errors show a local systematic behaviour in the sense that they are highly correlated within a few grid widhts. They may result from the measurement itself (inertia of the operator, especially in dynamic profile measurement, or height values from one point that are propagated to the next point as initial height values) or from interpolation techniques applied to the original data. In the last case, the correlation could be available - in theory. In practice, however, the covariance matrices of the interpolation are not available. These errors are the object of this paper.

2.3.3 Errors with high frequency: These are well-known as "random errors". They may result from many sources such as the physical representation of colour in the images (granularity, irradation and so on) or the instability of the sensors used (e. g. scanners, but also the human eye). Since these errors are neither known in their absolute value nor in their direction, they can be treated statistically according to the general laws of random errors.

2.4 Estimation of the Errors in Elevation

The mean height error (RMS) m_h of the test data set - which is the square root of the variance σ_h - and the covariance to the neighbouring point with index i (height value $h_{rc,i}$) can be estimated according to

$$m_h^2 = \sigma_h = \frac{\sum_{r=1}^{nr}\sum_{c=1}^{nc}(h_{rc} - H_{rc})^2}{nr \cdot nc - 1} \tag{3}$$

$$\sigma_i = \frac{\sum_{r=1}^{nr}\sum_{c=1}^{nc}(h_{rc} - H_{rc}) \cdot (h_{rc,i} - H_{rc,i})}{nr \cdot nc - 1} \tag{4}$$

(Note that the range of the indices has to be slightly modified, because of the matrix edges. In practice the best way to do is to limit the range to the interval 3 to nc-2 respectively nr-2.)

For an infinitely large data set the following relations apply:

$$\sigma_1 = \sigma_3, \quad \sigma_2 = \sigma_4, \quad \sigma_5 = \sigma_7, \quad \sigma_6 = \sigma_8, \\ \sigma_9 = \sigma_{11}, \quad \sigma_{10} = \sigma_{12} \,. \tag{5}$$

With an increasing number of points involved these relationships are fulfilled better. In practice they are fulfilled compared to the magnitude of the values and their accuracy even for a few thousand points, as will be shown later. Thus the following relative point indices will be used for the covariances and correlation coefficients from now on instead of the numbers 0 through 12:

		2y		
	e	y	d	
2x	x	h	x	2x
	d	y	e	
		2y		

Tab. 2: Modified relative point indices of neighbouring points to any point in the square grid (relative index h) for the correlation values and covariances

The correlation coefficients r_i between a grid point and its neighbouring point i are estimated according to:

$$r_i = \frac{\sigma_i}{\sigma_h}, \qquad i \in \{x, y, d, e, 2x, 2y\} \,. \tag{6}$$

m_h is composed of a random part r (also "noise") and a systematic part s ("systematic" means here that there is a non-zero (normally positive) correlation between the height errors of a grid point and of any one of its neighbouring points up to a certain distance (i. e. a few grid widths)):

$$\sigma_h = r + s \,. \tag{7}$$

3 THE DERIVED DATA

3.1 Slope and Aspect

The slope vector $\boldsymbol{v}(v_x, v_y)$ in any grid point can be calculated from the height values of the neighbouring points, h_i, and the grid width Δ according to

$$v_x = \frac{h_1 - h_3}{2 \cdot \Delta}, \qquad v_y = \frac{h_2 - h_4}{2 \cdot \Delta} \,. \tag{8}$$

The slope value sl is the length of the slope vector:

$$sl = \sqrt{v_x^2 + v_y^2} \,. \tag{9}$$

The slope direction α (aspect) in any grid point, that is the direction of steepest slope, measured as the angle from the x-axis, can be calculated according to

$$\tan\alpha = \frac{v_y}{v_x}, \qquad \text{with } v_x \neq 0 \tag{10}$$

(Note: In the case of $/v_x/$ smaller than $/v_y/$ the slope direction may better be calculated via the cotangent of the inverse fraction of equation (10). In both cases the following considerations remain valid.)

3.2 The Error of the Slope Vector

The slope vector is computed according to equations (8) or, using the matrix nomenclature, as

$$\boldsymbol{v} = \boldsymbol{A} \cdot \boldsymbol{h} \tag{11}$$

with

$$\boldsymbol{v}^T = (v_x \;\; v_y), \\ \boldsymbol{A} = \frac{1}{2 \cdot \Delta} \cdot \begin{pmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{pmatrix}, \quad \text{and} \\ \boldsymbol{h}^T = (h_1 \;\; h_2 \;\; h_3 \;\; h_4) \tag{12}$$

The variance- / covariance-matrix of the slope vector components, $\boldsymbol{Q}_{vv}$, with the variances σ_{v_x} and σ_{v_y} for the components of the vector and the covariance $\sigma_{v_x v_y}$ between the two components, results from the general law of error propagation with the variance- / covariance-matrix of the four involved elevation values h_1 to h_4, $\boldsymbol{Q}_{hh}$:

$$Q_{hh} = \begin{pmatrix} \sigma_h & \sigma_e & \sigma_{2x} & \sigma_d \\ \sigma_e & \sigma_h & \sigma_d & \sigma_{2y} \\ \sigma_{2x} & \sigma_d & \sigma_h & \sigma_e \\ \sigma_d & \sigma_{2y} & \sigma_e & \sigma_h \end{pmatrix} \tag{13}$$

according to:

$$\begin{aligned} Q_{vv} &= A^T \cdot Q_{hh} \cdot A \\ &= \begin{pmatrix} \sigma_{v_x} & \sigma_{v_x v_y} \\ \sigma_{v_x v_y} & \sigma_{v_y} \end{pmatrix} = \frac{1}{2 \cdot \Delta^2} \cdot \begin{pmatrix} \sigma_h - \sigma_{2x} & \sigma_e - \sigma_d \\ \sigma_e - \sigma_d & \sigma_h - \sigma_{2y} \end{pmatrix} \end{aligned} \tag{14}$$

3.3 The Error of the Slope Value

The variance of the slope value can be estimated according to:

$$\sigma_{sl} = \boldsymbol{dsl}^T \cdot Q_{vv} \cdot \boldsymbol{dsl} \tag{15}$$

with ***dsl*** being the vector of the partial first derivatives of the slope value in the two axis-directions:

$$\boldsymbol{dsl}^T = \left(\frac{\partial sl}{\partial v_x} \quad \frac{\partial sl}{\partial v_y} \right) = \left(\frac{v_x}{sl} \quad \frac{v_y}{sl} \right) = (\cos\alpha \quad \sin\alpha) \,, \tag{16}$$

if α is the slope direction. So σ_{sl} results to:

$$\begin{aligned} \sigma_{sl} &= (\cos\alpha \quad \sin\alpha) \cdot \begin{pmatrix} \sigma_{v_x} & \sigma_{v_x v_y} \\ \sigma_{v_x v_y} & \sigma_{v_y} \end{pmatrix} \cdot \begin{pmatrix} \cos\alpha \\ \sin\alpha \end{pmatrix} = \\ &= \frac{\sigma_h - \left(\cos^2\alpha \cdot \sigma_{2x} - \cos\alpha \cdot \sin\alpha \cdot (\sigma_e - \sigma_d) + \sin^2\alpha \cdot \sigma_{2y}\right)}{2 \cdot \Delta^2} \end{aligned} \tag{17}$$

In the case of $\sigma_d = \sigma_e$, i. e. the correlations in both diagonals are equal, the components of the slope vector are independent from one another. For this case equation (17) reduces to:

$$\sigma_{sl} = \frac{\sigma_h - \left(\cos^2\alpha \cdot \sigma_{2x} + \sin^2\alpha \cdot \sigma_{2y}\right)}{2 \cdot \Delta^2} \tag{18}$$

The special case of rotational symmetry in correlation furthermore simplifies equation (17), when *2d* is used as the index for grid points in a distance of 2 grid widths along any one of the two axes:

$$\sigma_{sl} = \frac{\sigma_h - \sigma_{2d}}{2 \cdot \Delta^2} = \frac{\sigma_h \cdot (1 - r_{2d})}{2 \cdot \Delta^2} \tag{19}$$

r_{2d} is the correlation coefficient between two grid points that are neighboured via two grid widths along any one axis-direction. The author has shown that for a constant principle distance of the camera of 15cm, a constant grid width in the map of 3 to 5mm, and a scaling factor from the aerial photograph to the map of 3 to 5, above equation yields a constant error for the slope value of about 0.01 to 0.02 (or, 1 to 2%), if an RMS height error of 0.015%H_G (flying height above ground) is assumed for each grid point (Rieger, 1992), a value which has earlier been found by Stechauner and Ehgartner in empirical analyses (Stechauner et al., 1988). This would mean that slope values less than about 1 to 2% cannot be assumed to be significant. For this example, however, it is not taken into regard, that the local correlations in the height errors of medium frequency simulate a random error when the height values are checked over the whole area. Good interpolation methods may - and should - smooth flatter areas significantly, so that the slope value can still be significant even in very flat areas (Steinmetz, 1992).

3.4 The Error of the Slope Direction (Aspect Ratio)

The slope direction is computed according to equation (10). With the partial first derivatives of the aspect value in both axis-directions,

$$\boldsymbol{d\alpha}^T = \left(\frac{\partial\alpha}{\partial v_x} \quad \frac{\partial\alpha}{\partial v_y} \right) = \left(-\frac{v_y}{sl^2} \quad \frac{v_x}{sl^2} \right) , \tag{20}$$

its error is estimated according to

$$\begin{aligned} \sigma_\alpha &= \boldsymbol{d\alpha}^T \cdot Q_{vv} \cdot \boldsymbol{d\alpha} = \\ &= \frac{1}{sl^4} \cdot (-v_y \quad v_x) \cdot \begin{pmatrix} \sigma_{v_x} & \sigma_{v_x v_y} \\ \sigma_{v_x v_y} & \sigma_{v_y} \end{pmatrix} \cdot \begin{pmatrix} -v_y \\ v_x \end{pmatrix} = \\ &= \frac{\sigma_h}{2 \cdot sl^2 \cdot \Delta^2} - \frac{v_y^2 \cdot \sigma_{2x} + 2 \cdot v_x \cdot v_y \cdot (\sigma_e - \sigma_d) + v_x^2 \cdot \sigma_{2y}}{2 \cdot sl^4 \cdot \Delta^2} \end{aligned} \tag{21}$$

Analogous to equation (18), in the case of $\sigma_d = \sigma_e$, equation (21) reduces to:

$$\sigma_\alpha = \frac{\sigma_h}{2 \cdot sl^2 \cdot \Delta^2} - \frac{v_y^2 \cdot \sigma_{2x} + v_x^2 \cdot \sigma_{2y}}{2 \cdot sl^4 \cdot \Delta^2} \tag{22}$$

And in the special case of rotational symmetry in correlation equation (21) furthermore reduces to:

$$\sigma_\alpha = \frac{\sigma_h - \sigma_{2d}}{2 \cdot sl^2 \cdot \Delta^2} = \frac{\sigma_h \cdot (1 - r_{2d})}{2 \cdot sl^2 \cdot \Delta^2} = \frac{\sigma_{sl}}{sl^2} \tag{23}$$

r_{2d} is the correlation coefficient as in equation (19).

4 THE EMPIRICAL TEST

4.1 The Test Area

The demands on the testing area were manifold: Since the correlation between the height errors shows dependency from the steepness of the terrain (Steinmetz, 1992), an area with differing slope values was necessary. There should have been as much free view to the ground as possible, so the testing area had to be mainly agricultural land. And last but not least aerial photographs had to be available in two scales, differing by a factor of larger than 3, flewn as close in time as possible. Thus an area was chosen in the Northwestern part of the province of Upper Austria. The terrain is hilly with nearly no forest and houses. There were available false colour infrared aerial photographs in the scales 1:8.000 respectively 1:32.000, stemming from a project to examine the condition of the forests in Austria. The two flights were done within two hours, so that there was no change in vegetation height - a nearly ideal situation. The only disadvantage is the usage of a relatively large principal distance of 30cm for the image size of 23 x 23 cm^2, so that the reachable height accuracy is much worse than with a wide angle objective. Because of the triangular geometry of photogrammetry, the results remain valid also for other principal distances, if one applies the respective factors.

About 5.000 points were manually plotted at an analytical plotter by static profiling in both data sets. Especially the large scale data set was measured with great care. In a second step the small scale images were scanned on a Zeiss Photo Scanner PS-1, and the software Match-T was used to automatically derive a DEM at an Intergraph Image-Station 1.

4.2 The Correlations Between the Height Errors

4.2.1 The Strategy: The test data set was used to create a series of DEMs by different interpolation techniques. For all the resulting data sets the correlation coefficients were computed for a submatrix of 9x9 points (i. e. up to 4 grid points distance from the center point) according to equation (6). The next step was to examine the relation between the correlation coefficients and the local terrain slope in the grid point. To do so, the terrain was subdivided in several zones of hill-slope. For all zones the calculation of the correlation was repeated. The result were the same 9x9-correlation matrices as mentioned above, but now one matrix for each slope-zone. At last the relation between correlation and slope was tested by statistical analyses (regression).

4.2.2 The Analysis: The test data set $\boldsymbol{h}$ was used to test the correlation between a grid point and its neighbours. First of all the differences in all grid points between the test data set $\boldsymbol{h}$ and the reference data set $\boldsymbol{H}$ were calculated, resulting in the matrix of the "true errors", $\boldsymbol{d}_h^*$:

$$\boldsymbol{d}_h^* = \boldsymbol{h} - \boldsymbol{H} . \tag{24}$$

The "true errors" are reduced by their mean value in order to eliminate the region wide constant error which does not have any influence on the slope vector, resulting in the matrix of the height errors, $\boldsymbol{d}_h$:

$$\boldsymbol{d}_h = \boldsymbol{d}_h^* - \frac{\sum_{r=1}^{nr}\sum_{c=1}^{nc} d_{h_{rc}}^*}{nc \cdot nr} \tag{25}$$

For $\boldsymbol{d}_h$ the covariances are computed according to equation (4) and the correlation coefficients according to equation (6) for the 9x9-neighbourhood of any grid point. The test was done with three different computation levels: a) The original data as plotted at a Zeiss P3 Analytical Plotter; b) interpolation of the grid through a convolution operation; c) interpolation of the grid via a weighted average function. Tab. 3 to Tab. 5 show the resulting submatrices of the correlation coefficients for the three stages (the original data set was smoothed by a convolution, too, though the influence of the smoothing operation was small on the results of the correlation coefficients of the test data set):

0.06	0.10	0.15	0.21	0.27	0.27	0.24	0.19	0.14
0.10	0.15	0.23	0.32	0.40	0.37	0.30	0.21	0.14
0.14	0.21	0.32	0.46	0.56	0.49	0.35	0.22	0.14
0.14	0.22	0.39	0.59	0.74	0.61	0.40	0.22	0.14
0.15	0.26	0.46	0.74	1.00	0.74	0.45	0.24	0.15
0.13	0.23	0.40	0.61	0.74	0.58	0.36	0.19	0.13
0.11	0.20	0.34	0.49	0.56	0.46	0.30	0.18	0.13
0.11	0.19	0.28	0.37	0.40	0.32	0.22	0.15	0.11
0.10	0.18	0.24	0.28	0.28	0.22	0.15	0.11	0.09

Tab. 3 Correlation coefficients for the original data

0.49	0.51	0.58	0.55	0.64	0.55	0.59	0.52	0.52
0.53	0.56	0.65	0.62	0.73	0.62	0.65	0.55	0.54
0.57	0.61	0.73	0.71	0.85	0.70	0.73	0.60	0.58
0.60	0.65	0.80	0.78	0.94	0.78	0.79	0.65	0.61
0.61	0.67	0.83	0.82	1.00	0.83	0.83	0.69	0.64
0.59	0.65	0.79	0.78	0.94	0.80	0.80	0.68	0.64
0.57	0.61	0.73	0.71	0.85	0.73	0.75	0.65	0.62
0.54	0.58	0.67	0.65	0.75	0.65	0.67	0.61	0.58
0.52	0.55	0.62	0.59	0.66	0.59	0.60	0.56	0.53

Tab. 4 Correlation coefficients for the convolution

0.15	0.18	0.23	0.30	0.29	0.28	0.35	0.34	0.28
0.22	0.18	0.26	0.37	0.40	0.41	0.37	0.29	0.30
0.27	0.31	0.40	0.43	0.49	0.56	0.46	0.34	0.32
0.24	0.36	0.52	0.58	0.67	0.58	0.43	0.42	0.37
0.31	0.40	0.48	0.71	1.00	0.70	0.46	0.39	0.32
0.34	0.42	0.44	0.58	0.67	0.56	0.50	0.34	0.24
0.28	0.33	0.46	0.56	0.49	0.42	0.39	0.29	0.28
0.27	0.28	0.38	0.41	0.39	0.37	0.24	0.17	0.24
0.23	0.32	0.35	0.27	0.27	0.28	0.20	0.17	0.17

Tab. 5 Correlation coefficients for the interpolation through weighte average.

The original data have been measured in West-East direction. The correlation is slightly higher in that direction, but the difference is small enough compared to the value in order to assume rotational symmetry. The correlation in all diagonal directions is constant, so equations (19) respectively (23) may generally be used instead of the much more complex forms for the non-symmetric cases. Generally, the following conclusions can be drawn from the tests:

- Rotational symmetry is always fulfilled for the diagonals and the second neighours along the axes. That is one more advantage when the slope vector is calculated from the differences of the neighboured points to a grid point rather than involving the grid point itself, as shown in equation (8).

- The elevation errors of photogrammetric data obtained through static profiling are nearly uncorrelated from one point to its second neighbours. Furthermore the correlation is independent from the axis-direction (scanning direction).

- The algorithms implemented in the software MSM of the Image Station do not show any dependence from the hill-slope. This is contrary to the results Steinmetz has found out for the program system SCOP, where there is a very strong dependence between the correlation coefficient and the flatness of the terrain, yielding correlations of nearly 1 in flat areas (Steinmetz, 1992).

- For an experienced operator there does not seem to be a dependence between the correlation coefficient from the original data (obtained from an analytical plotter) and the hill-slope up to a hill-slope of 50%.

5 CONCLUSION AND FINAL REMARKS

The influence on the correlation between the elevation errors seems mainly to be an effect of the interpolation technique, when static profiling is used on an analytical plotter. On the other hand, precisely a high correlation of the elevation errors in flat areas is necessary in order to obtain a smooth surface. Falling short of this, the results are crossing slope vectors or noisy hill-shading representations in flat areas. On the other hand well-designed low pass filters just pretend a higher accuracy through the higher correlation; that is one reason for the small correlation of the height errors when compared to a data set of superior quality as done here, even when using low pass filters.

Quality information for the DEM frequently is given through the RMS error of point elevations. This RMS error is still a very good means to describe a DEM's quality, since it takes into consideration the deviations from the smoothed, "artificial" surface which is often wanted from DEM- and GIS-users for more appealing products. It should, however, kept in mind that this error is not really an "error", but rather a wanted deviation from the real surface. So the RMS error is partly a real error, partly the result of modelling an approximate but smooth surface. The small correlation of the height errors especially in flat terrain as shown in this paper partly reflects the roughness of the terrain against the artificial (i. e. modelled) surface.

Nevertheless there is a need for as exact surface representations as possible, especially in mountainous areas, in order to model environmental hazards like river floods or avalanches. For that purpose further investigation work will be done in order to check the behaviour of manual measurement from aerial photographs (on an analytical plotter) as well as image matching techniques in dependence from hill-slope, especially in steep areas where there is a strong need for quality control of the slope. This leads very close to the question how to define the surface, which certainly has to be done specific for the respective application: There is still a lot of effort to be done in order to define the real demands of the user on the DEM.

It should be a task of photogrammetry to provide the user not only with realistic estimations for the quality of its products but also to consult him in learning about his real needs.

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