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THE ACCURACY OF DIGITAL HEIGHT MODELS

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Introduction

1. Digital height models have recently become a technique firmly established in the field of photogrammetry. Although their practical applications are not yet routine to the extent that would be desirable, it is obvious that they have taken hold in various fields already and are generally on the advance.

   It is known that the concept and development of digital terrain models can be traced back to Prof. C.L. MILLER of M.I.T. who in the late fifties was thinking of their use in road design. In the meantime, digital terrain models have freed themselves from the tight connection with that specific field of application and are available as a general technique for the geometrical description of areas and bodies, and for the topographic description of the surface of the earth in particular.

2. A description of the surface of the earth by means of a digital height model consists of a sufficiently dense and accurate field of spot heights of given planimetric location. For cartographic purposes or civil-engineering applications, such description of the terrain by spot heights is often not enough. It has to be supplemented by further data, such as break lines, feature lines, singular points, etc. These then are likewise part of the DHM.

   The different types of digital height model are first of all specified by the distribution of points. Depending on the method used to obtain the data, we distinguish between irregular point distribution, regular triangular or rectangular grids, series of points in parallel profiles, in any other profiles or in unique morphological or mathematical lines, such as lines of dip, contours, skeleton, feature or break lines. Combinations of the different arrangements are likewise used. Also, we distinguish between digital height models formed by original measurement points or others derived, completed or constructed from the former, which as a result of interpolation frequently consist of a densified, regular point grid.

   As regards accuracy, it is thus obvious that there are two independent problems: (1) the vertical accuracy of the original and derived DHM points proper, and (2) the problem of how well the points define or represent the ground surface. Part of the latter complex is a fundamental assumption regarding continuity of the terrain, which implies that interpolation is permissible in the point field. These assumptions have, however, not yet been precisely defined.

3. The applications of digital height models have recently become very varied. In conjunction with a discussion of accuracy, we are here primarily concerned with applications in the field of civil engineering (road construction and earth works) as well as topography and cartography. Considerations of accuracy become all the more important if digital height models are to be used to derive functions and by-products which have to satisfy certain accuracy requirements, such as volumes, contours, slope data, etc. It has become expedient even to provide digital height models of entire countries in the form of data banks for a variety of uses (see United States and Sweden), just as topographic contour maps (in the form of analog terrain models) were provided in the past. In this case also, unambiguous and binding accuracy definitions and specifications are indispensable.

   In the following, the uses in the field of large-scale topography and cartography are in the foreground, which are characterized by the need for very high accuracy.

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Accuracy and data acquisition

4. In the development of digital height models, the mathematical technique of interpolation has been the primary consideration regarding accuracy. If we wish to write suitable computer programs, the question first of all is how a digital height model of the highest possible accuracy can be computed from the given data, with due allowance made for the economic aspect of efficient data organization and processing. As a result, there is a large number of computer programs based on quite different principles of interpolation.

   If the original data are identical, the different interpolation techniques undoubtedly will give digital height models of varying quality and accuracy. There is still very little detailed information on practical or methodical comparisons between different techniques. Although it is occasionally tried to make comparative tests, it may be expected for several reasons that the resulting differences between the different interpolation principles will be minor only, at least as far as the mean vertical accuracy of the interpolated DHMs is concerned. There is growing experience and evidence that in practical conditions the accuracy results are not primarily determined by the interpolation principles, although these may differ noticeably in certain details, such as the fidelity of derived contour lines.

5. The primary factor deciding the attainable accuracy of a digital height model is data acquisition. It is here that the facts are set as to what quality level the DHM can possibly attain. The potential level may then be approached to a higher or lesser degree by the different interpolation methods.

   As the beginning of development, the main question was how and with what accuracy digital height models and contours could be derived from the given data or data categories. Consequently it was a point of discussion whether automatic interpolation would at all be capable of generating digital contours satisfying the high quality requirements of topography and cartography. Now that a few efficient program systems have been developed and tested, the question today has to be reversed for all practical purposes: How should we measure or how should a specific ground area be surveyed to ensure that the computed digital height model or the constructed contours will satisfy certain accuracy specifications. Although the interpolation method used does affect this question, data acquisition is actually the dominant aspect.

   As a matter of fact, the data-acquisition aspect is nothing new. Any tacheometric survey has always faced exactly the same problem. And the computer programs for digital height models did try from the very start to admit the necessary and adequate survey data in a very flexible form. A case in point is the inclusion of break lines and other morphological terrain features in interpolation programs. Also, there is a wide range concerning the philosophy of data acquisition: a minimum number of high-quality points on the one hand versus abundant point density but lower individual accuracy on the other hand. An extreme case is the particularly dense DHM produced by the Gestalt Photomapper GPM II (see, for example, ALLAM |1|). In addition, special mention should be made of the technique of progressive sampling (MAKAROVIC |2|) which provides for data acquisition very tightly intermeshing with interpolation.

6. Before discussing the detailed relationships between data acquisition and the accuracy of digital height models, a few preliminary remarks on the definition of accuracy may be appropriate:

   While it is still very difficult to define the accuracy of contour lines, the accuracy of a digital height model, by comparison, can be understood fairly simply to be the average vertical accuracy of arbitrary points interpolated from the DHM in relation to the heights of the respective terrain surface points. In principle, we are dealing with the accuracy of a point field subject to all usual considerations of averaging, correlation, maximum errors, etc., and suitable for deriving the accuracy of subsequent processes, such as contours.

In detail, the following distinctions are here of importance (see Fig. 1):

- The accuracy of data acquisition as such, that is, the accuracy with which the survey points have been measured (recorded). From this we can derive by error propagation the accuracy of interpolated grid points of the derived DHM and of other points interpolated in the DHM[1]).
- The accuracy (or rather fidelity) with which the three different groups of points represent the terrain (survey points, interpolated grid-points, and additional interpolated points) is independent of the accuracy with which they have been determined.

The decisive and most important criterion for judging a digital terrain model is the fidelity with which it represents the terrain. In other words, the result is always a primary function of the terrain. Aside from this, the measurement accuracy of the points is normally of only secondary importance (see also MAKAROVIC |3|).

In the following section, we shall discuss a few empirical studies regarding the relationship between data acquisition and the accuracy of the derived height models in the sense of fidelity of terrain representation. Finally, the last section will briefly outline the theoretical basis for solution of the problem.

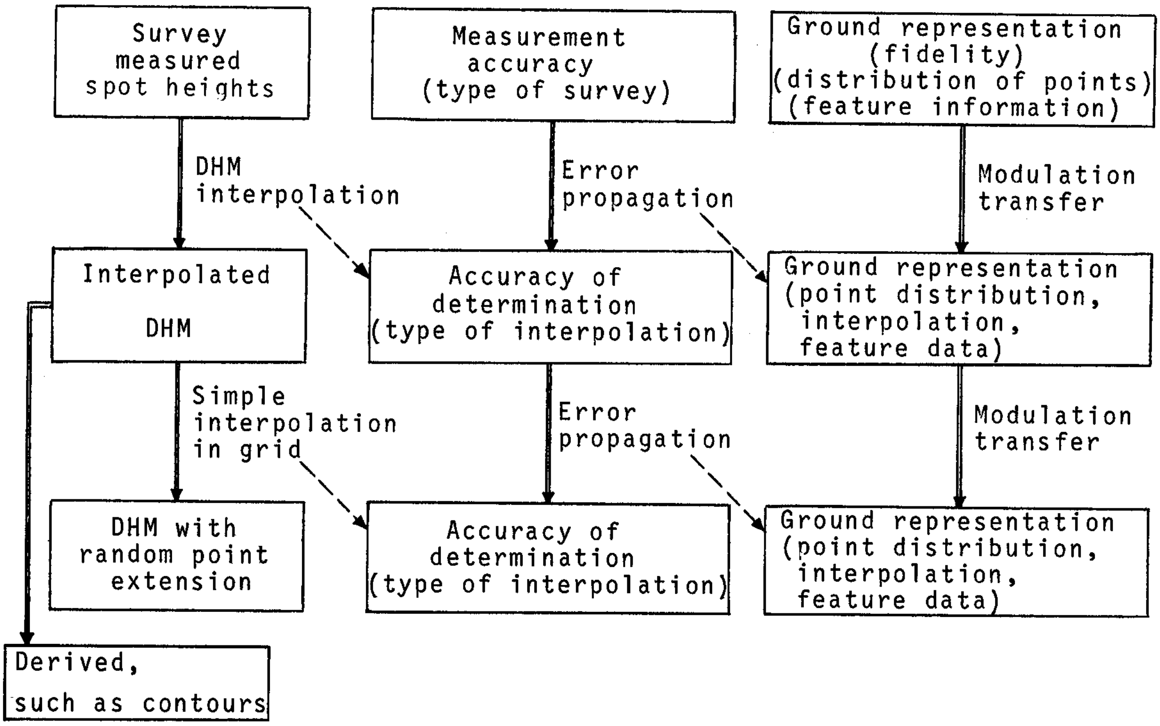

Fig. 1 Concept and relations concerning the "accuracy" of digital height models

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[1]) The term "accuracy of interpolation" used occasionally can actually be understood only as the accuracy with which the interpolated points were determined.

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Empirical results

7. A few results from our own work, referring to the "Söhnstetten" test, will be discussed first. In part, these results have already been published (see |4|). The test covered a large-scale test area in the Swabian Alb mountains, about 1.7 km x 0.9 km in size. For a map scale of 1:2500 and an adequate contour interval of 2.5 m, the terrain is very hilly and of variable topography (winding dry valley, steep flanks turning into a flat upland area). Ground slope goes up to 50 % or about 30°. Elevation differences reach 70 m or 28 contour intervals.

The central part (0.6 km^2) of the terrain was surveyed tacheometrically (RegElta) with over 6000 points of about 15 m average spacing. A second tacheometric survey was performed with a mean point interval of 25 m. Digital height models were computed (and contours derived, although these will not be discussed here) from the two sets of data with the aid of the SCOP program. In addition, various photogrammetric plots were derived from a wide-angle photo flight at 1:10 000 photo scale covering the area with a single model. Reference is here made above all to two profiling runs on a D2 Zeiss Planimat with profiles spaced 15 m and 30 m apart, as well as to a direct contour plotting in a Planimat. The profiling runs were made with a terrain speed of about 5 m/sec = 18 km/h. This corresponds to about 1 mm/sec at the model scale of 1:5000. Profiling resulted in approx. 8000 and 2000 profile points with 1200 additional points on break or feature lines. Like in the case of the tacheometric surveys, the photogrammetric plots were used to compute digital height models of regular 5 m grids and to derive contours from them. Twentytwo representative or specially placed check profiles with a total of 485 check points measured on the ground were used for directly checking the vertical accuracy of the DHM.

8. The results that are of special interest here are shown in Table 1 as well as Figs. 2 and 3. They refer to various types of data acquisition and are represented as a function of ground slope and of the mean point spacings used in the survey. They deserve a few comments:

First of all, Fig. 2 shows a very low overall dependence of vertical accuracy of the digital height models (and thus of the contours derived from them) on ground slope. The extremely "accurate" survey (practically error-free measurement and high point density) reveals almost no dependence on ground slope. Vertical errors increase slowly with ground slope only as point density decreases, that is, as the distance between survey points becomes greater. A vertical accuracy of approx. 20 cm is attained in almost all cases for the flat portions of the terrain. Apparently,

Type of survey	Mean point interval	Mean vertical error of DHM	Dependence on ground slope
Electronic tacheometry	15 m	25 cm	m_h = (0.22+0.13 tanα)m
	25 m	43 cm	m_h = (0.30+0.42 tanα)m
Photogrammetric profiling	15 m	40 cm	m_h = (0.21+0.72 tanα)m
	30 m	59 cm	m_h = (0.21+1.50 tanα)m
Photogrammetric contouring	-	37 cm	m_h = (0.32+0.21 tanα)m

Table 1 Söhnstetten test, accuracy of digital height models

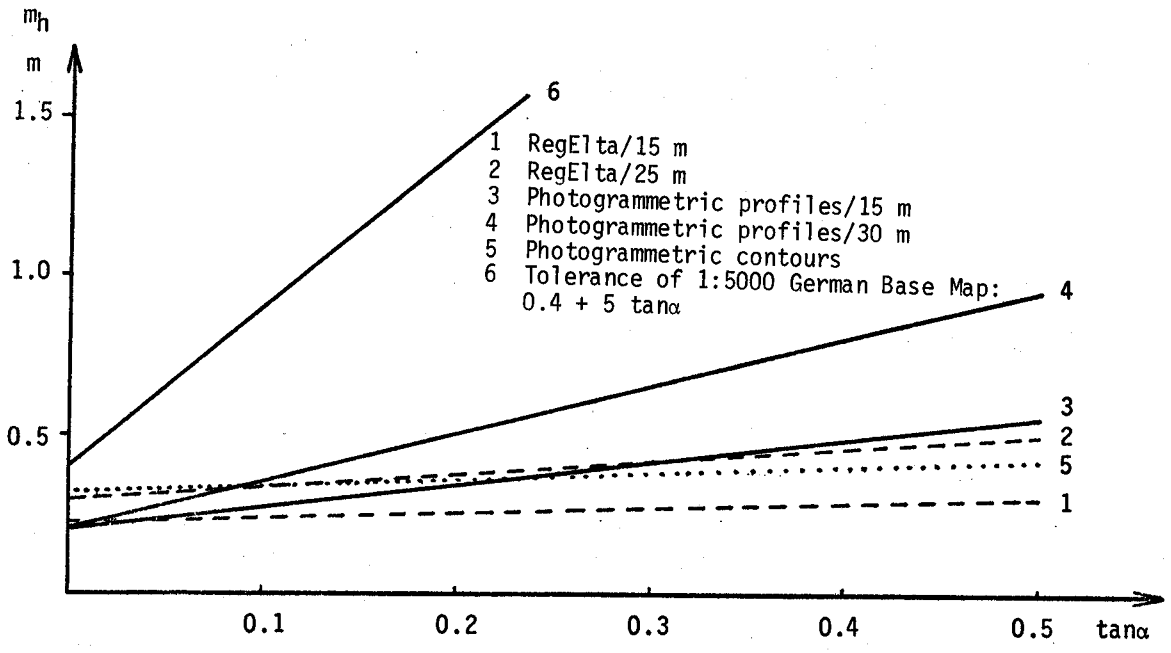

Fig. 2: Söhnstetten test. Vertical DHM accuracy as function of ground slope, for different types of survey.

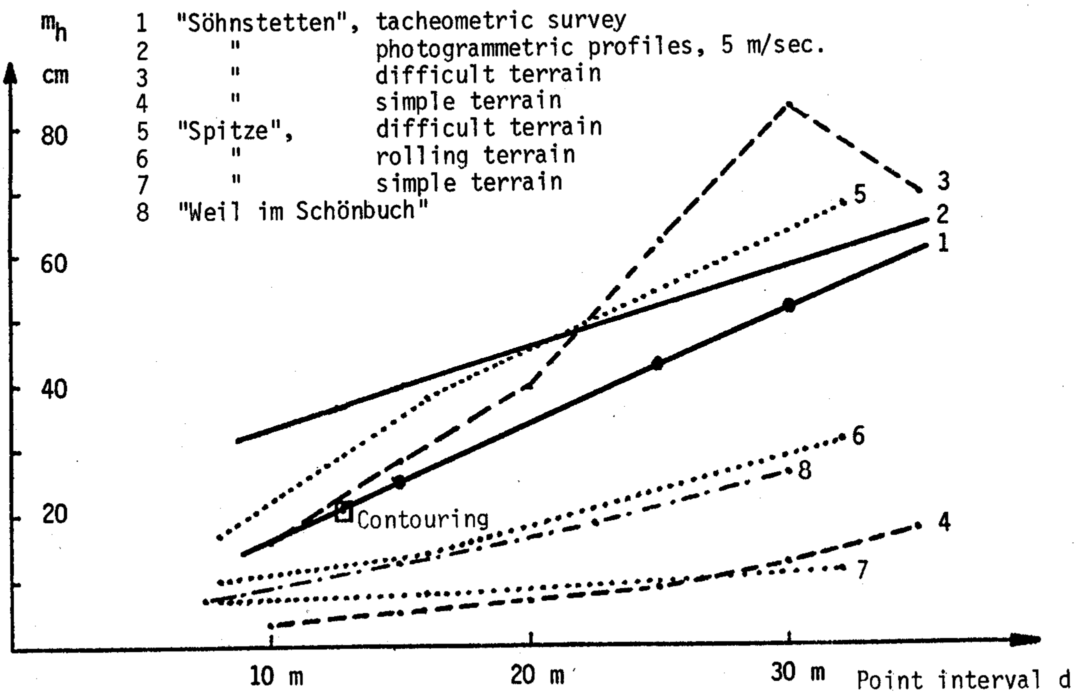

Fig. 3: Vertical DHM accuracy as function of point interval. Various test areas and classes of terrain

this is the mean "terrain roughness" as referred to a point interval of 15 - 30 m. The photogrammetric surveys based on profiling neatly match the picture of low dependence on ground slope, with an additional error component increasing with slope that is doubtless due to the profiling error which, in turn, is additionally a function of profiling speed. These differences disappear completely in flat terrain. It is interesting to note, however, that also the direct photogrammetric contouring reveals practically no sensitivity to ground slope. And it is clearly less accurate in flat terrain (32 cm versus 21 cm) than profiling, as was to be expected. It may be added that in flat terrain the direct photogrammetric contouring and also, to a lesser extent, the profile plots contain systematic heighting errors of 39 cm and 8 cm, 20 cm, respectively, which tend to decrease in steeper terrain.

Apart from the dependence on ground slope we are here above all interested in how far the vertical accuracy of the digital models is a function of the density of survey points, that is, of point interval. According to Table 1 and Fig. 3, we unfortunately have only two data for each type of survey, and it should be noted that the accuracy values given are something like weighted means for the classes of terrain encountered in the Söhnstetten area. However, it is particularly interesting and important that the RegElta surveys with average point intervals of 15 m and 25 m correspond to mean vertical errors of interpolated terrain points of 25 cm and 43 cm, respectively, which is about proportional to the point interval (25 cm/15 m = $1.66 \cdot 10^{-2}$; 43 cm/25 m = $1.72 \cdot 10^{-2}$). By comparison, the results of photogrammetric profiling lie on a noticeably different curve and do not appear to comply with any law of proportionality with point interval, in view of vertical accuracies of the digital models of 40 cm and 59 cm for profile intervals of 15 m and 30 m, respectively. However, if we assume that profiling itself is composed of an error-free point survey and an additional profiling error, the two curves agree very nicely. For both cases at hand a mean profiling error of about 30 cm (31 cm and 28 cm) can be derived. Thus it is confirmed also for the photogrammetric data acquisition that the vertical accuracy of interpolated models is about directly proportional to the mean point interval if the survey itself has negligible measuring errors (which is realized in photogrammetric data acquisition, when very low profiling speeds or direct spot height measurements are used). With the present data, we obtain a proportionality factor of $\alpha = 1.7 \cdot 10^{-2}$. Evidently, this proportionality can be considered valid only for the range studied. The accuracy of directly plotted contours also seems to fit into this picture. With a mean vertical error of 37 cm, it here corresponds to a profile interval of 12.5 m, which with a contouring error of 31 cm can be reduced to the curve for the error-free survey (see Fig. 3).

9. It may not be assumed, however, that the relationship thus established between the average spacing of survey points and the resulting vertical accuracy of interpolated terrain models were generally valid. For the time being, it only applies to the Söhnstetten test area and undoubtedly depends very much on the terrain features. The results of a few further comparable studies will therefore be included in the investigation and checked for their agreement with the theory of proportionality. This additional material cannot be presented in detail here. The most important results referring to practically error-free point surveys are, however, included in Fig. 3.

In order to check the apparently approximately linear relationship between the vertical accuracy of DHMs and the mean point interval for its dependence on ground features, GORDOGAN |5| made a separate study of two topographically different partial areas from the Söhnstetten test field. He marked these "difficult" and "simple" areas. The former is characterized by steep slope and changes of slope. The latter partial area is marked by very uniformly sloping, well-rounded terrain. The two areas were studied with point intervals of 10 m to 35 m. The curves reproduced in Fig. 3 first of all show that the DHM accuracy in simple terrain ranges from 3 cm to 18 cm and remains less than 10 cm up to a point interval of 25 m. In other words, vertical accuracy is surprisingly good and only

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slightly dependent on point interval. By contrast, the results for identical point interval in difficult terrain are clearly different, with 16 cm and 84 cm. This is convincing confirmation that the relationship between vertical DHM accuracy and point interval is strongly dependent on the topography of the terrain. We understand, therefore, that the aforementioned empirical results for the Söhnstetten test field are primarily due to and composed of the mixture of different types of terrain in that area, the "more difficult" type of terrain apparently being predominant. A second, essential result evident from the curves in Fig. 3 is that these can again be very nicely approximated by straight lines passing through the origin. In other words, the law of proportionality is confirmed to a good degree of approximation for the two types of terrain. The proportionality factors can be estimated to be about $\alpha = 2.30 \cdot 10^{-2}$ for the difficult terrain and $\alpha = 0.45 \cdot 10^{-2}$ for the simple terrain.

From RODENAUER's studies |6|, three curves have been taken over into Fig. 3. These refer to different photogrammetric plots of the "Spitze" test field near Cologne, derived from large-scale photography (1:4000). The three cases refer to interpolation with the DHM program by MBB. The examples cover point intervals of 8 m, 16 m and 32 m as well as three different terrain types called "simple", "rolling" and "difficult". The designations should, however, be seen in relationship with the large photo scale and the desired accuracy (1 m contour interval). The maximum ground slope does not exceed 15°. As is shown by Fig. 3, the result confirms the previous findings. Again, the vertical DHM accuracy and point interval are proportional to a good approximation, in the range studied. However, proportionality factors are clearly different for the three terrain types ($0.4 \cdot 10^{-2}$; $1.0 \cdot 10^{-2}$; $2.2 \cdot 10^{-2}$) so that the topography again appears as the dominating factor.

Finally, Fig. 3 incorporates a result personally communicated which has been obtained in a study presently under way at the Institute of Prof. LINKWITZ, Stuttgart. This particular result is relevant to the question discussed here and also refers to a test-field project (Weil im Schönbuch) characterized by relatively simple topographic conditions which apparently correspond to the rolling type of terrain given by RODENAUER. This series also shows a very clear linear relationship between vertical DHM accuracy and point interval ($\alpha = 0.9 \cdot 10^{-2}$).

10. The studies mentioned up to now were all based on a nominally uniform point interval used for data acquisition, which may not have been strictly observed and might have been varied in some instances, but which constituted a characteristic feature. On the other hand, we all know that strict adherence to given point intervals is neither necessary nor economical in varying terrain, unless it is imposed as a necessity by the data-acquisition technique used. The normal procedure would be to try for qualified point reduction, similar to the basic principle of Progressive Sampling |2|, in order to attain a specified accuracy with a considerably reduced number of points.

GORDOGAN |5| has systematically studied this question of qualified point reduction for the two aforementioned partial areas of the Söhnstetten field. In this case, characteristic mean point intervals were used as a basis, as in the other cases, but additional points were applied wherever ground conditions so dictated. The criterion for densification was a deviation threshold of the ground in relation to simple polynomials, each placed through the corner points of the elementary square as determined by the characteristic point interval. The results are shown in Fig. 4 for the two partial areas with "simple" and "difficult" topography.

The result of point reduction for the simple, uniform terrain shows that the accuracy, which already was very good, can still be considerably increased. With a deviation threshold of 0.3 m, the mean vertical errors of the DHM no longer exceed an amount of 10 cm up to point intervals of 35 m. The effect of point reduction is even more drastic in the case of "difficult" terrain. While at first the errors quickly increased with growing point interval, a maximum reduction to 51 cm (less than 30 cm)

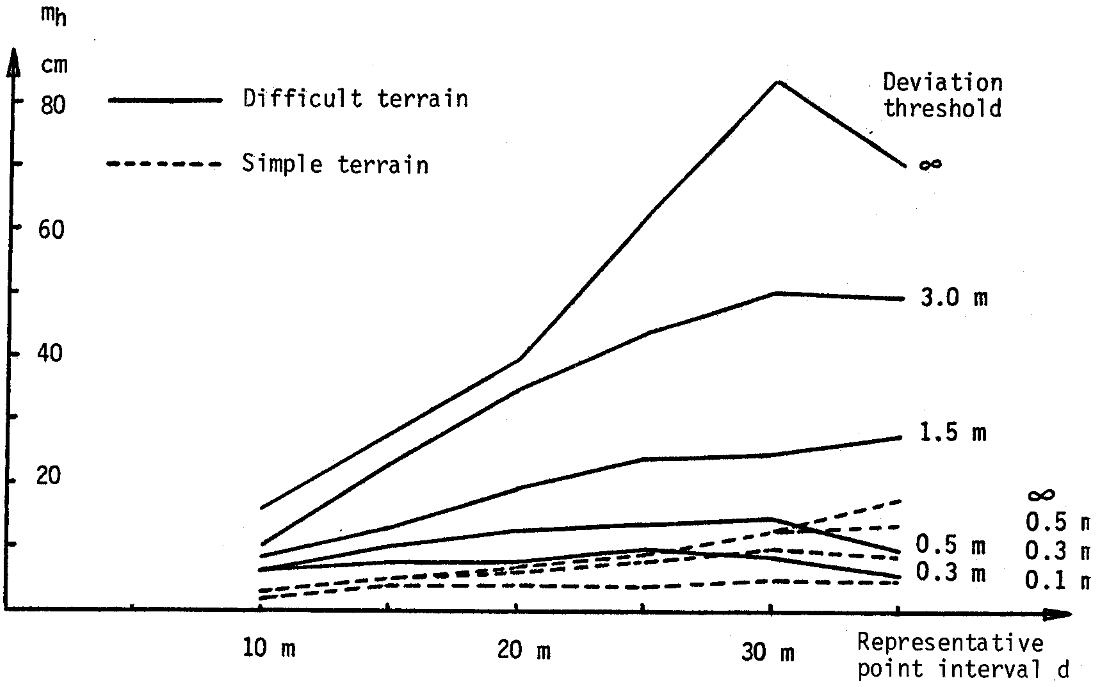

Fig. 4 Söhnstetten test field. Accuracy improvement of DHM in simple and difficult terrain by adapted point densities (after GÜRDOGAN |5|).

was possible with deviation thresholds of 3 m (1 m) for point intervals up to 35 m, until the results once more reached less than 10 cm with a threshold of 0.3 m, as in the case of simple terrain. Apart from the absolute magnitudes of the vertical accuracy attainable by qualified point reduction, it is once again noteworthy that proportionality between vertical errors and mean point interval was preserved to a good approximation in each case. In other words, the linear relationship can be considered sufficiently confirmed to be generally adopted, within the range studied.

11. The empirical test results may be summarized by the following statements:
    - For a given terrain and practically error-free measurement (free from errors by comparison with the smoothness or roughness of the ground surface), the vertical accuracy of digital height models seems, to a good approximation, to be linearly dependent on the mean point interval only (if suitable allowance is made for irregularities and peculiarities).
    - Linear dependence on grid interval is primarily a function of terrain type. Unfortunately the material used here does not yet allow more specific definition of terrain types.
    - If the point density is commensurate with the type of terrain, digital height models may be extremely accurate. Special mention should be made of the method of qualified point reduction.
    - Additional survey errors, such as profiling errors, can be squared and added to, in first approximation.

We can thus express the accuracy of digital height models, to a first approximation, by the following formula:

$$m_h^2 = (\alpha \cdot d)^2 + \beta^2, \qquad (1)$$

where

m_h = standard vertical error of interpolated arbitrary points in the DHM

d = mean (representative) point interval of terrestrial or photogrammetric survey

α = proportionality factor depending on the type and category of terrain. For a summary of values, see Table 2.

β = measurement error (accuracy of determination) of ground survey, including the effect of, for example, vegetation.

For photogrammetric data acquisition, β may be assumed to be composed as follows:

$$\beta = 0.1\ ‰\ h + \text{dynamic component} \qquad (2)$$

(h = flying height).

Study	$\alpha \cdot 10^2$	α reduced to	by deviation threshold of
Söhnstetten, difficult terrain (GÜRDOGAN 2)	2.3		
		1.6	3 m
		0.9	1 m
		0.5	0.5 m
		0.4	0.3 m
RÜDENAUER 3, difficult terrain	2.2		
Söhnstetten, total	1.7		
RÜDENAUER 2, rolling terrain	1.0		
Weil im Schönbuch (Linkwitz Institute)	0.9		
Söhnstetten, simple terrain (GÜRDOGAN 1)	0.5		
		0.4	0.5 m
		0.3	0.3 m
		0.2	0.1 m
RÜDENAUER 1, simple terrain	0.4		

Table 2 Summary of empirical proportionality factors α between vertical DHM accuracy and representative point interval.

Finally, the reservation should be made for the time being, that these results can be taken valid only for the ranges studied. It cannot be expected that the expression (1) would be generally applicable to any point interval and any type of terrain.

The expression (1) may serve to answer in each particular case the question asked at the beginning, namely how a given terrain should be surveyed if a certain accuracy is desired. The task still remains, however, to set up and define criteria of classifying the types of terrain and to determine the related proportionality factors α.

Theoretical situation

12. It is no longer the subject of this lecture to discuss the theoretical determination of the accuracy of digital terrain models. Nevertheless, the theoretical possibilities and studies should be briefly mentioned in closing.

In principle, it is quite possible theoretically to compute the final accuracy of a digital height model, that is, the fidelity with which it represents the terrain, for given interpolation methods, if the topographic properties of the ground are known and given. This already indicates that complete control of this complex either calls for a classification of the terrain in categories of known properties or that the classification is determined from the actual measurement data or by preliminary studies.

Either stochastic criteria (correlation functions or transition probabilities in the sense of stochastic processes) or frequency spectra are suitable to describe terrain properties.

In several works (see |7| - |9|), KUBIK and his collaborators made theoretical studies of the accuracy of interpolated height models for different interpolation methods and as a function of point interval. In these studies, the terrain properties were assumed to be known and described by a given covariance function. Up to now, the results have not yet been compared with empirical results, but their general trend should more or less agree with experience. A study would be required to see how well covariance functions can describe real terrain and which functions should be assigned to the different types of terrain.

MAKAROVIC (see |10| and |11|) uses the approach to describe the terrain by means of frequency spectra and Fourier analysis. In this case the study can be limited to sinusoidal oscillations and gives a clear statement on the relationship between point density and the fidelity of ground reconstruction. Transfer functions can be derived for the different interpolation techniques, and the accuracy capabilities of different digital terrain models can be compared for different terrain types. In principle, this theory is complete. If the frequency distribution of a terrain is known, all questions regarding point density, interpolation method and accuracy can be answered according to MAKAROVIC. The task remains to investigate the frequency distribution of different terrain types and to relate the corresponding theoretical and empirical accuracy results.

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Abstract

During the development of digital terrain models the aspects of interpolation methods and of computer programming were quite predominant. In the meantime experience and theory have pointed out strongly that data acquisition determines as a primary factor the obtainable height accuracy of DTM.

The paper reviews some empirical material about the influence of data acquisition on derived digital height models. Also recent attempts are discussed to establish the necessary concepts and formulate theoretical relations.

Zur Genauigkeit digitaler Höhenmodelle

Zusammenfassung

Bei der Entwicklung der digitalen Höhenmodelle standen zunächst die Gesichtspunkte der Interpolationsmethoden und der Rechenprogramme im Vordergrund. Inzwischen gewinnt im Zusammenhang mit den verschiedenen Zweckbestimmungen und Anwendungen der DHM die Erfahrung und Erkenntnis zunehmend an Gewicht, daß die Ergebnisse stark von der Datenerfassung abhängig sind.

In dem Vortrag werden empirische Ergebnisse über die Genauigkeit digitaler Höhenmodelle in Abhängigkeit von der Datenerfassung besprochen und neuere Bemühungen erläutert, die Zusammenhänge begrifflich und theoretisch zu erfassen.

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Sur la précision des modèles altimétriques digitaux

Résumé

Lors du développement des modèles altimétriques digitaux, les méthodes d'interpolation et les programmes de calcul furent les premiers aspects considérés. Mais depuis, les expériences acquises en rapport avec les divers objectifs et les différentes applications des modèles altimétriques digitaux, nous font croire de plus en plus que les résultats dépendent fortement de l'acquisition des données.

Dans la conférence, nous considérons des résultats empiriques sur la précision des modèles altimétriques digitaux en fonction de l'acquisition des données, et expliquons les efforts les plus récents qui sont faits pour essayer de définir les rapports existants, de façon abstraite et théoretique.

Sobre la exactitud de modelos altimétricos digitales

Resumen

En el desarrollo de los modelos altimétricos digitales se pensó primordialmente en los aspectos de los métodos de interpolación y de los programas de cómputo. En relación con las distintas finalidades y aplicaciones de los modelos altimétricos digitales, adquiere cada vez más importancia la experiencia y el conocimiento de que los resultados dependen fuertemente de la adquisición de los datos.

La conferencia explica los resultados empíricos respecto a la exactitud de modelos altimétricos digitales en función de la adquisición de datos y expone los esfuerzos más recientes para entender las relaciones mútuas práctica y teóricamente.

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