A COMPARATIVE TEST OF PHOTOGRAMMETRICALLY SAMPLED DIGITAL ELEVATION MODELS

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ABSTRACT

A working group has conducted an international comparative test based on a resolution from the ISPRS Congress in Hamburg. The objective of the test was to study the relations between methods for data acquisition, interpolation, resulting accuracy and type of terrain.

Six test areas were selected, which have different topographic structures varying from smooth rolling farmland to very steep mountains with forest in the valleys. Fifteen organisations have produced DEMs from aerial photographs in scales 1:4000 - 1:30 000. The DEMs have then been used for the derivation of elevations in a set of check points, the locations of which were unknown when the DEM was measured in the stereoinstrument. The elevations of these check points were then compared with their "true" values.

The "true" errors found in the check points are presented and analysed. After elimination of blunders the remaining errors are composed of systematic and random parts. The systematic parts can originate from the reconstruction of the stereomodel, from the interpolation of the DEM, and from effects of the vegetation height. The size and distribution of the "true" errors are presented in Tables, Diagrammes and Illustrations. Errors of functions of the DEM (e.g. slope and curvature) are also studied.

1 RESOLUTION

The 14th Congress of the International Society for Photogrammetry held in Hamburg 1980 accepted a resolution saying: "The Congress noting that Digital Terrain Models have been studied for a long time and a resolution for continuing those studies was made at the 13th Congress, recognizing the importance of the results of such studies to practice, recommends that further studies, including comparative tests, be performed in such relevant areas as resampling and accuracy aspects". This resolution was the basis for establishing the working group No 3 of Commission III with the name Mathematical Aspects of Digital Terrain Information. K Torlegård was elected chairman of the group and Mr Anders Östman, M Sc, has been appointed secretary, both persons at the Department of Photogrammetry at the Royal Institute of Technology in Stockholm.

2 EXPERIMENTAL PLAN

As stated in the resolution a comparative test has been organised. The main objective of the test can be summarized as to study the relations between methods of sampling (measuring) the terrain, approximation (interpolation) function for the elevations, and the accuracy of derived (resampled) elevations from a digital elevation model (DEM). The test is restricted to photogrammetrically measured digital elevations models available for practical applications. It is recognised that the type of terrain has an important influence on the relations to be studied. For that reason six different areas have been selected for the test.

2.1 Test Material

For each of the six test areas there are two sets of aerial photographs at different scales. The smaller scale photographs are used by the participants to measure the terrain elevation and the larger scale is used for determination of the "ground truth" for the succeeding accuracy analysis. Each participant is asked to derive two DEMs for each area, one DEM more accurate than the other. The accuracy requirement is vaguely stated; in most cases stated as DEMs applied to contouring in given map scale and given contour interval; in a few cases as DEMs applied to volume calculation of earth masses with tolerances in m^3/ha. The test specifications are summarized in Table 1. Each participant was also asked to predict measures of accuracy that he can specify himself. The intention was to check his prediction against the "ground truth". His type of specification of accuracy could be chosen freely, e.g. standard error, maximum error, systematic error, error distribution parameters, etc. Data were collected on instrument type, sampling mode, approximation function, computer used, time and cost estimates for the production of the DEMs, etc.

2.2 Test Measurements

The testing procedure was as follows. The participants were given the aerial photographs, camera calibration data, ground control for orientation, and border lines for the DEM test areas. When they had used the photographs and generated their DEMs they sent the photographs back to the project leaders, and in return they got data for the orientation and size of a test grid. Each test grid comprises some 2500 check points. The participants were asked to derive from their DEMs a new set of resampled elevations in the test grid nodes. Depending on the practical routines of the participant this was a primary or a secondary generation of DEM values.

2.3 Ground Truth

The "ground truth" of the DEM was determined by the test centre in Stockholm using the larger scale photography and static measuring in the test grid nodes.

The test grid nets are randomly located in the test areas (translation, rotation) compared with ground co-ordinate systems. The mesh-width of the grid net is randomly chosen within a range suitable for the size of the test area and under the condition that we want around 2500 check points in each area.

The two German test areas as well as the Norwegian one are very well targetted in both high and low altitude photographs and co-ordinates are available in a common system for each test area. In three Swedish test areas however, we had to establish ground control both in planimetry and elevation. This was done by aerial triangulation of high and low altitude photographs simultaneously.

Measurement of ground truth in low altitude photographs has been performed by two operators and in two different photogrammetric instruments. The instruments used are the analytical plotters Wild Aviolyt AC1 and Zeiss Planicomp C-100. The analytical plotters were available to us by courtesy of the National Road Administration and the National Land Survey.

When comparing the two sets of elevation data (one for each operator) it was found that

1 a number of check points were measured by one of the operators only

2 there existed considerable differences between elevation values for certain check points.

Existing differences are results of lack of unity between operators regarding measuring in dense vegetation (forest) and some gross errors due to inexperience with the software of the analytical plotters. It can also be said that the software used could be better designed in some aspects to enable more operator control.

These differences between the two sets of check data led to the development of a computer assisted editing procedure performed in a Wild Autograph A8. All the low altitude models are worked through in search for check points with only one measurement and check points with large differences between measurements. The check points can be deleted or additonal measurements can be made. The result of the editing is that all check points left in the material have at least two measurements.

The resulting precision of the z-co-ordinates of the check points is now estimated from the differences between the replicated measurements and their corresponding means. To get the final accuracy we have to add the variance components of image and control. The result is shown in Table 2. It is given in meters on the ground and in per mille of the flying height of the DEM photograph.

2.4 The Questionnaire

For each of the DEMs the participants were asked to answer questions concerning photogrammetric instruments, standard errors in relative and absolute orientations of the stereomodels, expected accuracy of the DEM sampling mode, number of sample points, time used, classification of terrain, type of interpolation of DEM, computer used, and cost estimates for the measurements and the computations of the test. The information obtained from the questionnaires is condensed in Tables 3 and 4.

3 RESULTS

3.1 Unfiltered Errors

The differences in the check points between the terrain elevations computed by the participants from their DEMs and the corresponding ground truth elevations are called unfiltered errors. For each DEM has been computed the number of points, the range of the errors, their root-mean-square (rms), mean, standard deviation, median, mode and skewness. Histograms have been plotted. Complete results can be obtained from the author.

The rms of the unfiltered errors are shown in Figure 1. The rms-values have been normalised to the image scale by division by the flying height. The result should then depend on e.g. terrain type, sampling type and density, specified accuracy requirement, DEM interpolation method. The fully drawn lines in Figure 1 show the size of 1/3 of the specified contour interval for high and low accuracy requirement respectively. For area F the volume tolerances are converted to constant elevation errors. It can be noted that most of the DEMs intended to meet the low accuracy requirement do so, except for area D. Just a few of the DEMs can meet the high accuracy requirement. It is not very much difference between the DEMs for high and low accuracy, but on the average those which are intended to be more accurate, they are so.

The maximum errors are plotted in Figure 2. The variation of the maximum error between the areas is similar to that of the rms. The ratios between the maximum error and the rms vary from 4 to 25. The large values appear in area D which has the most rugged, steep and difficult terrain. Except for area D and one single DEM the ratios vary from 4 to 8.

The participants were asked to give estimates of the accuracy to be expected from their DEMs. Most of them used rms and maximum error to estimate the accuracy. One used mean and standard deviation. They were converted to rms. In Figure 3 the estimated rms is plotted against the achieved one. The lines show constant relations between estimated and achieved accuracy. Almost all have underestimated the rms for area D rather much. The estimates for areas A, B and E are fairly good. However, except for area D, the general tendency is that the estimated rms should be increased some 50% to arrive at the real accuracy. It is quite clear that the maximum error is very difficult to estimate and it is recommended not to use it as a predictor of accuracy.

The DEMs noted A, B and C have mixed character of relief, while the D, E and F models are more homogeneous. For A there are parts of forest in the otherwise open landscape. In B there is a stone pit in the natural landscape. In C there are highways passing a wild park. Masks have been defined for the parts of the models where the accuracy is supposed to be inferior due to the effect of vegetation or artefacts. The DEMs over areas A, B and C have been subjected to the same analysis as above but with separation within and outside these masks. The results are shown in Figures 4 and 5.

The rms is larger within the mask than outside. There are just a few exceptions from this rule. The maximum errors on the other hand behave quite different. Their size does not seem to have anything to do with the location within or outside the masks.

The errors of a DEM are not independent. Errors in close points are more correlated than errors in remote points. The autocorrelation of errors as a function of the distance is shown for a typical DEM. The autocorrelation is only computed in the directions of the check grid axes. See Figure 6.

Slope and curvature of the terrain can be computed from DEMs. The errors of them can be estimated from statistics of the first and second differences of the errors of the DEMs. Some results are shown in Figures 8 and 9.

The errors of slope and curvature depend on the lengths in plan over which they are computed. Here we have used the grid width of the check points for the determination of slope and curvature errors. As the grid width varies between areas the lines in Figures 8 and 9 give indices for comparison with consideration of the grid width. Variations around the index lines can be caused by e.g. terrain type, correlation between close points, variation in rms. Area D is probably above the index line because of the terrain, while F may be below because of correlation between points as the grid width is very small.

3.2 Blunders

As we have knowledge of the true elevations in the check point grid we have been able to compute error characteristics that a practitioner never can compute. He can just estimate from his experience and rules of thumb what the accuracy of his DEM might be. Then he delivers the DEM and its errors are of the kind that we have called unfiltered errors in this report.

Snooping for blunders and levelling of the DEM are things that we can do in this test as we know the true elevations in the check points. This is done to help us to understand the nature of DEM errors.

Blunders are located by the following algorithm: For each check point the absolute value of the difference between the error and the median of the errors in the 25 surrounding points was computed. If this value is larger than three times the rms of the DEM the error is regarded as a blunder. As the blunders influence the rms, this procdure is iterated once.

The chosen method to detect and eliminate blunders has a very weak - if any - theoretical basis. As the blunder is included in the rms, the snooping has to be iterated until no more blunders are detected and eliminated. Here the snooping is limited to two rounds. The remaining errors are in the following called filtered errors.

The numbers of blunders detected with this method are shown in Figure 10. It can be noted how the number of blunders per area follows the same pattern as rms and maximum error in Figures 1 and 2. The frequency of blunders within and outside the masks of difficult terrain in area A, B and C can be seen in Figure 11. It is obvious that the relation of blunders to observations is much higher within the mask. There are very few exceptions to this.

3.3 The Control Point Effects

A third step in the analysis is a levelling of the measured DEM on all the check points after the blunders have been eliminated. The residual errors are called levelled errors. The resulting rms of the residuals are and indication of the best possible accuracy of the DEM without any error propagation from the control points for the absolute orientation.

The effect of the control points can be calculated as $\sqrt{(\text{filtered rms})^2 - (\text{levelled rms})^2}$. This error component is shown in Figure 12. The specified accuracy requirement is shown as before. It may be astonishing how large this error component is, sometimes the main part of the total rms. It also shows the importance of accurate and reliable control for the absolute orientation. The rms of the levelled errors is theoretically the best possible accuracy that can be obtained under the condition no orientation errors influence the result. The rms' of levelled errors are shown in Figure 13. The DEMs over area A, B, C and D can meet the low accuracy requirement under the condition that the orientation is completely free from errors.

The correlation of levelled errors is shown in Figure 7. Compared to Figure 6 it is evident that the systematic effects of the errors in the absolute orientation cause a considerable part of the correlation effect.

A visual inspection of the histograms (they are not presented here) of the unfiltered errors indicate that they are not normally distributed with zero mean. After filtering out the blunders and levelling the DEMs quite a number of them seem to show a normal distribution. But several DEMs show peculiar distributions also after levelling, especially those within the masks for forests and artefacts. Statistical distribution tests should be done.

4 DISCUSSION

This report is the first in - as we hope - a series of publications based on the ISPRS DEM test. Anyone interested can have access to the material and data for analysis and further investigations. Here we will give our first remarks on the results on the DEM test.

4.1 Variance Components

The accuracy of a DEM depends on a series of parameters, such as terrain type, density of measured points, type of measurement (selective, profiles, contours, grids, progressive), interpolation method, DEM grid width (if applicable), instrument and operator precision, number, location and accuracy of control, quality of the photographs, flying height. Some of these parameters are varied in the experiment, others are constant.

We assume the total variance of a DEM to be a sum of variance components multiplied by specific coefficients. Some coefficients and variance components are known, others can be estimated in the photogrammetric mensuration process. This is the case for flying height, image quality, error propagation from control, and instrument and operator precision (replicated measurements). Then there are variance components that need experiments like this comparative test to be estimated.

With as many DEMs as in this test it would be possible to estimate several components. But there are limitations because of linear dependences between the coefficients for the unknowns in the stochastic model for how the variance components add up to the total variance of the elevations of the DEM.

4.2 Quality of Photographs

We have used available photographs for the test. In one case (F) we made the test photographs from duplicated negatives. This has lead to an inferior image quality.

4.3 What is a Blunder?

The blunder detection method as such can be discussed. Moreover, the choice of rms as basis for the threshold in the detection is even more questionable. An à priori known σ would be far better to use. But what is the true σ of a particular DEM? It is the objective of this test to find it. As we now have used the rms and not iterated until no more blunders are found, this means that we detect fewer blunders in a DEM with poor general accuracy than in one with higher accuracy.

4.4 Further Work

The objective of the resolution that started this comparative test is to a large extent achieved with this report. We think that the task for the working group has been accomplished.

The test was designed to cover large scale photogrammetry. It could be considered to make a similar test for small scale photography for national DEMs and small scale topographical mapping. New photography would be necessary in such a case.

It would be of interest to see what type of accuracy could be obtained with the automated photogrammetric instruments. No such instruments were used in this test. It would be equally interesting to see what could be obtained with various image matching algorithms working on digitized photographs. Many lessons could be learned for the benefit of the future use of SPOT, Stereosat and similar data acquisition systems.

5 ACKNOWLEDGEMENT

The work of all participants is gratefully acknowledged, as well as the support from those who provided the photographs and control. All are given by name and affiliation in the official report of Commission III in this book. The author Torlegård is responsible for the experimental design. Authors Östman and Lindgren have made all the computer programming for the analyses of the data. Östman has been responsible for the circulation of primary data and for all contacts with the participants. All three authors have co-operated in the analyses.

6 LITERATURE

Lindgren Ralf. The Establishment of Ground Truth for the ISPRS Working Group III:3. Colloquium Proceedings Mathematical Aspects of Digital Elevation Models. Department of Photogrammetry, Royal Institute of Technology, Stockholm 1983, 4 p

Torlegård Kennert. Mathematical Aspects of Digital Terrain Information. Report of the Working Group III:3 of Commission III for the Period 1980-1984. International Archives of Photogrammetry, Rio de Janeiro 1984, 5 p

Östman Anders. An Outline of an Analysis of the ISP DEM test. Colloquium Proceedings Mathematical Aspects of Digital Elevation Models. Department of Photogrammetry, Royal Institute of Technology, Stockholm 1983, 12 p.

TABLE 1 International comparative test on photogrammetrically measured digital elevation models.
Data on the test material

	Area name	Type of Terrain	DEM Photo Scale	Check Photo Scale	Accuracy requirement Scale-Equidistance/Volume tolerance	
					Low	High
A.	Uppland Sweden	Farmland and forest	1:30 000	1:6 000	1:10 000 - 5 m	1:2 000 - 2 m
B.	Bohuslän Sweden	Rugged granite bedrock without soil cover	1:30 000	1:5 300	1:10 000 - 5 m	1:2 000 - 2 m
C.	Stockholm Sweden	Urban communication areas	1:20 000	1:4 000 1:5 000	1:10 000 - 5 m	1:2 000 - 2 m
D.	Drivdalen Norway	Steep and rugged mountains	1:17 000	1:10 000	1:10 000 - 5 m	1:2 000 - 2 m
E.	Soehnstaetten Germany	Hills of moderate height	1:10 000	1:3 000	1:5 000 - 5 m	1:1 000 - 1 m
F.	Hannover Germany	Smooth terrain	1:4 000	1:1 500	$P(\varepsilon > 1\,000\ \frac{m^3}{ha}) < 5\%$	$P(\varepsilon > 400\ \frac{m^3}{ha}) < 5\%$

TABLE 3 Summary of the Questionnaire: Generalities about the DEM Systems of the Participants

Organisation	Instrument	Type of sampling	Type of interpolation	Breaklines		Computer-aided sampling	DEM storage media			
				meas	interpolation		computer type	during generation	in application	when transf
1	Zeiss C-100	Composite-selective grid	Simultaneous patchwise polynomials	Yes	Yes	Yes	16 bit mini	Disc	Disc or mag tape	Mag tape
2	Kern DSR1	Composite-selective grid	Simultaneous patchwise polynomials	No	No	Yes	16 bit mini	Disc	Disc	Mag tape
3	Santoni 2C	Profiles + spots + breaklines	Interpolation in rectangular grid	Yes	Yes	No	16 bit mini	Disc	Disc	Mag tape
4	a) GZ-1 b) Digitizer table	a) Profiles b) Contours	Interpolation in rectangular grid	No	No	a) Yes b) No	32 bit mini	Cassette	Disc	Mag tape
5	Photoco-ord digitizer	Grid	Moving surface	No	No	Yes	Mainframe and 16 bit mini	Computer		
61	Zeiss C-100	Grid + breaklines	Moving surface	Yes	Yes	Yes	Mainframe	Disc	Disc	Mag tape
62	Zeiss C-100	Grid + breaklines	Moving surface	Yes	Yes	Yes	Mainframe	Disc	Disc	Mag tape
7	Wild A8	Profiles	Interpolation in rectangular grid	No	No	Yes	Mainframe	Disc	Disc	Mag tape
8	Zeiss C-100	Grid + breaklines	Interpolation in rectangular grid	Yes	Yes	Yes	24 bit mini	Disc	Disc	Mag tape
91	Kern DSR1	Grid	Moving surface	Yes*	Yes*	Yes	16 bit mini	Discette	Disc	Mag tape
92	Zeiss-Jena Stereometrograph	Profiles	Summation of surfaces	No	No	No	16 bit mini	Paper tape	Disc	Mag tape
93	Wild A7	Grid	Moving surface	Yes*	Yes*	No	16 bit mini	Paper tape	Mag tape	Mag tape
94	**	**	Interpolation in rectangular grid Interpolation in net of triangles	**	**		16 bit mini	**	Disc	Mag tape

* in the majority of sampled DEMs

** data from organisations 91 and 92

TABLE 4 SUMMARY OF THE QUESTIONNAIRE: PARTICULARITIES OF THE DEMs OF THE TEST

DEM	Rel or		Abs or Plan		Elevation		Expected accuracy of DEM				Sampling point density					Time used		Cost USD	
ID	s_o µm	df	s_o mm	df	s_o mm	df	rms m	av err m	st dev m	max err m	Points/ha	Profiles/Contours between m	Profiles/Contours within m	Grid interval m	No of sampled points	Preparation (min)	Sampling (min)	DEM interpolation	Total cost
1 Fa	5	9	72	7	48	7	0.15							10	2321	70	500	10	
1 Ea	5	15	110	6	57	9	0.53							20	3262	70	585	10	
1 Aa	4	14	474	6	497	5	0.68							28	5390	70	750	15	
2 Aa	4	1	530	6	510	3	1.5			5				100	299	40	35		
2 Ab	4	1	530	6	510	3	1.0			2.5				70	614	40	55		
2 Ba	4	1	460	4	450	3	2.0			6.0	1			90	586	40	55		
2 Bb	4	1	460	4	450	3	1.3			4.5	1			60	1007	40	70		
2 Ca	10	1	430	4	510	3	2.0			6.0	2			90	382	40	40		
2 Cb	10	1	430	4	510	3	1.5			5.0	2			60	735	40	60		
2 Da	8	1	200	10	340	4	3.0			10.0				75	746	40	130		
2 Db	8	1	200	10	340	4	2.0			7.5	0.7			75	1016	40	200		
2 Ea	13	1	130	8	270	3	1.2			4.5	2			50	408	40	65		
2 Eb	13	1	130	8	270	3	0.8			2.5	2			35	635	40	90		
2 Fa	1	1	114	6	49	2	0.25			1.0	4-5			25	364	40	60		
2 Fb	1	1	114	6	49	2	0.10			0.75	4-5			15	745	40	75		
3 Ab			400	4	1140	9	1.52					40.5	15.0		14 000	60	120	100	300
3 Bb			1430	5			0.93					40.5	15.0		7000	60	60	100	300
3 Cb			810	7	80	5	0.61					27	10		8000	60	120	100	300
3 Db			410	8	170	9	0.52					23	8.5		37 000	60	270	100	300
3 Eb			850	7	70	11	0.31								19 000	60	240	100	300
3 Fb			70	8	22	8	0.12					5.4	2					100	300
4 Aa							2-3					60	30		1600				
4 Ba			1580				2-3					5.0	50		(3965)				
4 Ca							2-3					60	30		775				
5 Ea	6		90							2.0				18	2500	30	60	5	15
5 Eb	5		80							0.5				9	9 000	30	400	20	70
5 Ec	5		80							0.5				6	20 000	20	600	20	70
61 Aa	3	8	230	10	220	7	0.6				3			40	3000	80	390	300	770
61 Ba	2	6	270	14	250	6	0.6				4.5			30	3990	130	480	320	930
61 Ca	2	4	220	12	180	3	0.6				15			30	2728	90	360	960	1410
61 Da	2	6	140	20	240	8	0.6				2			30	3300	120	360	560	1140
61 Ea	2						0.6				9			35	845	110	90	370	570
61 Fa	2						0.6				5.6			25	456	90	50	140	280

TABLE 4 CONTINUED

DEM ID	Rel or		Abs or Plan		Elevation		Expected accuracy of DEM				Sampling point density					Time used		Cost USD	
	s_o µm	df	s_o mm	df	s_o mm	df	rms m	av err m	st dev m	max err m	Points/ha	Profiles/Contours between m	Profiles/Contours within m	Grid interval m	No of sampled points	Preparation (min)	Sampling (min)	DEM interpolation	Total cost
62 Aa	3	8	230	10	220	7	0.6							35	2900	80	380	200	660
62 Ba	2	6	270	14	250	6	0.6							35	1880	130	230	280	640
62 Ca	2	4	220	12	180	3	0.6							35	967	90	130	220	440
62 Da	2	6	140	20	240	8	0.6							20	3340	120	370	140	630
7 Aa			270	10	220	5		1.33	1.81	6.9		25	25		3145	90	225	3	
7 Ab			270	12	320	6		0.50	0.33	8.7		15	15		8380	0	465	7	
7 Ba			400	8	50	3		0.96	0.64	8.2		20	20		4560	90	355	5	
7 Bb			400	8	50	3		0.79	0.42			10	10		8360	0	745	8	
7 Ca			90	10	600	5		0.78	1.15	8.8		25	25		1200	90	255	1	
7 Cb			90	10	250	5		0.56	0.88			15	15		3330	0	325	3	
7 Da			110	4	80	8		0.30	1.42			25	25		2407				
7 Db			120	4	130	8		0.67	1.20			15	15		10 934				
7 Ea			150	16	110	8		0.68	1.09			30	30		3215	120	485	4	
7 Eb			120	14	100	7		0.24	0.44			10	10		11 240	30	1175	13	
8 Ab	10	5	475	12	437	6	0.5			2				30	2942	78	240		470
8 Cb	9	8	300	10	270	2	0.7			3.5				25	2354	95	263		470
8 Da	5	13	127	18	246	8	1.25			10				20	9234	60	1060		1210
8 Eb	6	10	86	12	85	9	0.26			1.2				15	4183	97	380		610
8 Fb	5	6	51	10	89	5	0.10			0.3				15	1346	55	185		360
92 Aa	20	1					0.5			1		40	30		1017	90	600	300	500
914 Ab	10	8	200	6	200	7	0.3			0.5				20	5355	60	240	200	500
92 Ba	20	1										40	30		768	90	540	200	400
924 Ba	20	1										40	30		768	90	540	100	300
914 Bb	10	8	200	7	200	10	0.3			0.5				20	4731	50	210	150	400
93 Ca			490		130		0.21			0.5				33	1195	100	220	200	500
91 Cb	10	8	200	6	200	6	0.3			0.5				20	4000	60	400	200	500
93 Da			210		250		0.5			0.5				33	4560	150	140	300	600
93 Db			210		250		0.5			0.5				20	11 600	150	290	400	1000
93 Ea			100		80		0.5			0.5				25	1617	80	50	200	400
93 Eb			100		80		0.5			0.5				10	7163	80	84	200	400
91 Eb	10	8	200	6	200	9	0.3			0.5				20	3600	60	360	200	500
914 Fa	10	8	200	8	200	8	0.3			0.5				20	378	60	30	100	300
92 Fb	20	2										10	10		1399	90	600	200	300

TABLE 2 Accuracy of check point elevations.
Variance components in [m]

Area	Image	Control	Operator mean	Operator max	Total accuracy $[m]^2$	Total accuracy ‰ H(DEM)*
A. Uppland	$(0.017)^2$	$(0.117)^2$	$(0.090)^2$	0.20	$(0.149)^2$	0.032
B. Bohuslän	$(0.016)^2$	$(0.090)^2$	$(0.100)^2$	0.21	$(0.135)^2$	0.029
C. Stockholm	$(0.026)^2$	$(0.070)^2$	$(0.090)^2$	0.20	$(0.117)^2$	0.039
D. Drivdalen	$(0.068)^2$	$(0.050)^2$	$(0.150)^2$	0.30	$(0.172)^2$	0.067
E. Soehnstetten	$(0.019)^2$	$(0.038)^2$	$(0.030)^2$	0.07	$(0.052)^2$	0.034
F. Spitze	$(0.006)^2$	$(0.030)^2$	$(0.025)^2$	0.05	$(0.040)^2$	0.067

* The check point accuracy is here given in relation to the flying height of the photographs used for the DEM production

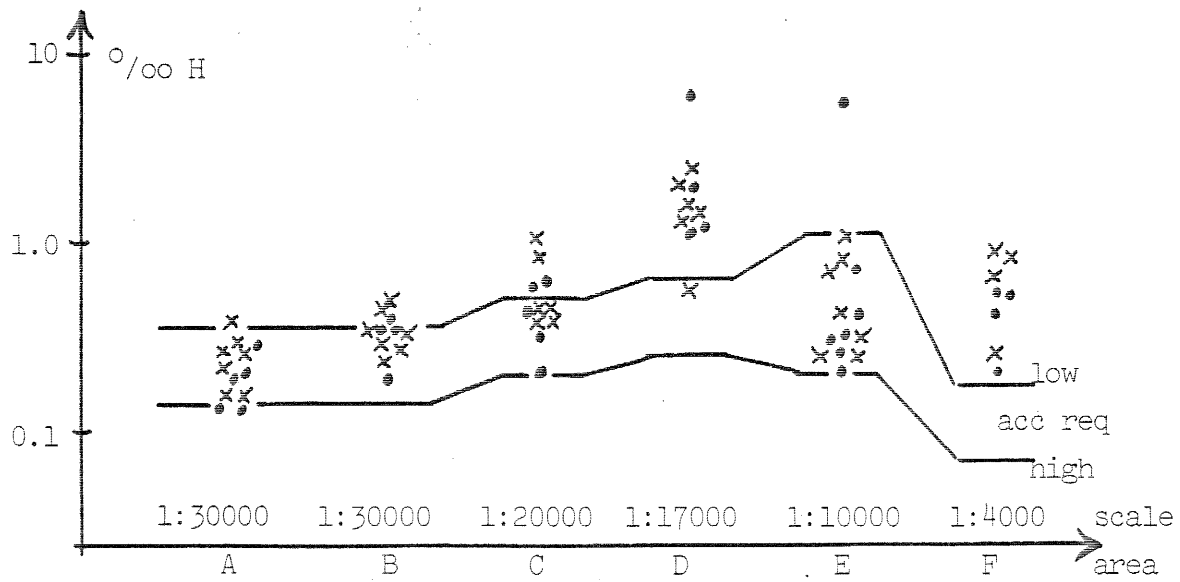

Figure 1 RMS of unfiltered errors in per mille of H (log scale).
DEMs intended for low (x) and high (●) accuracy

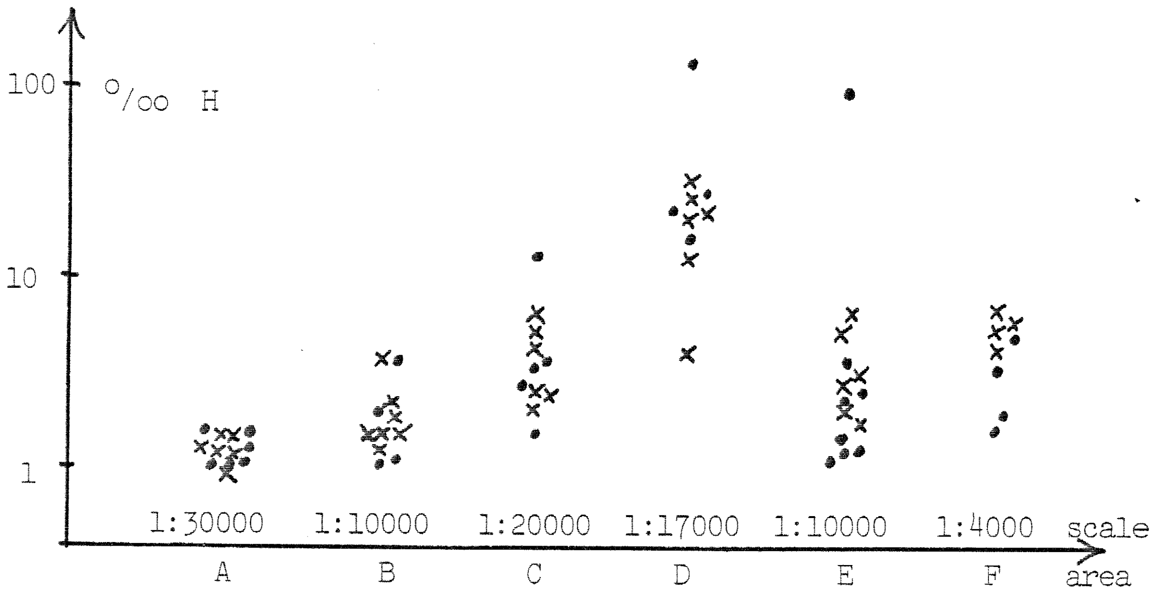

Figure 2 Maximum errors (unfiltered) in per mille of H (log scale)
DEMs intended for low (x) and high (•) accuracy

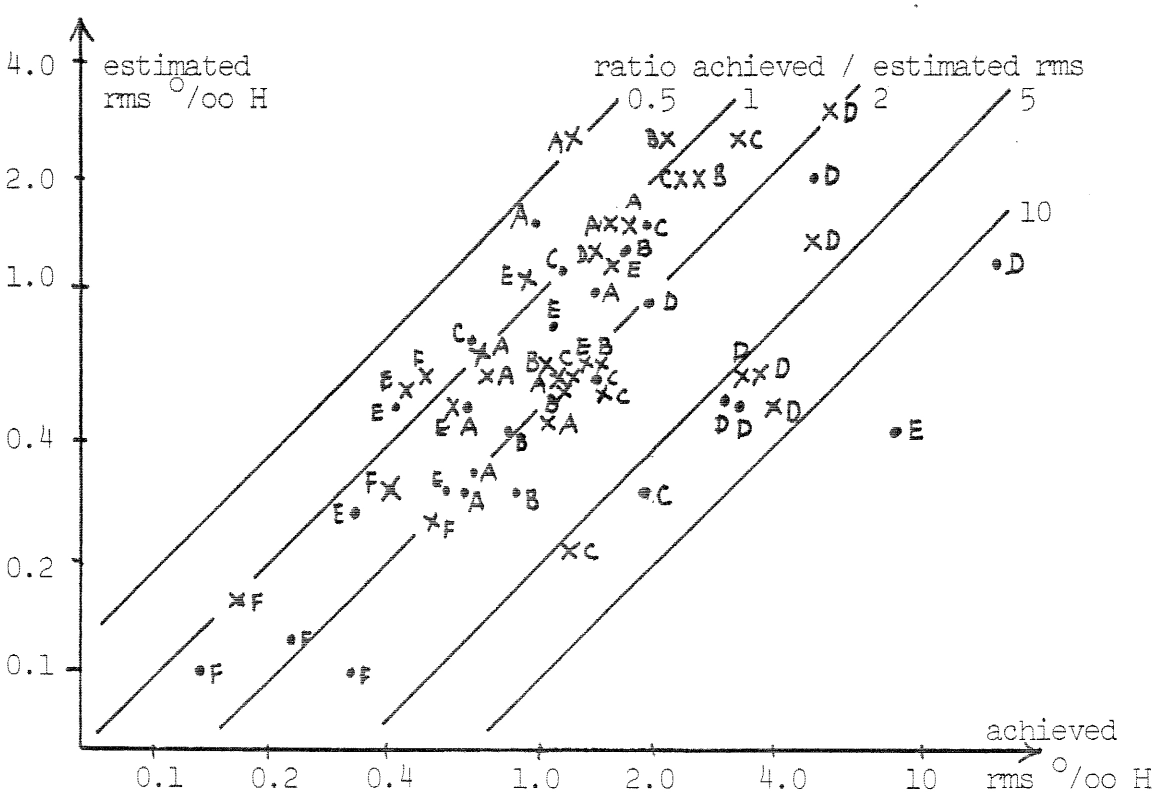

Figure 3 Estimated versus achieved accuracy
RMS in per mille of H (log - log scale)
DEMs intended for low (x) and high (•) accuracy

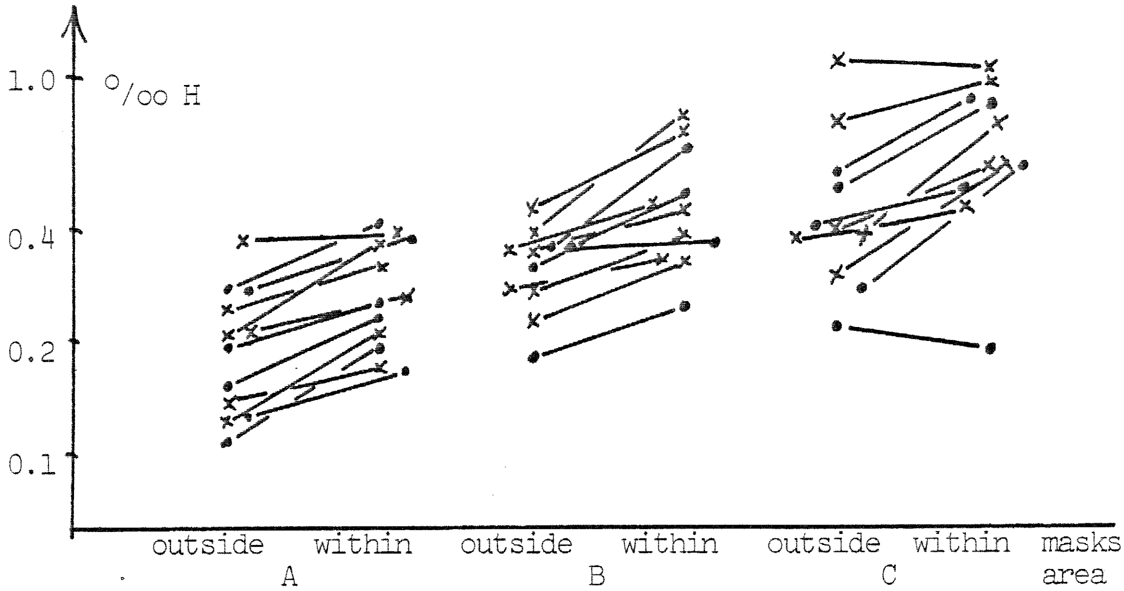

Figure 4 RMS of unfiltered errors with respect to masks in per mille of H (log scale)
DEMs intended for low (x) and high (●) accuracy

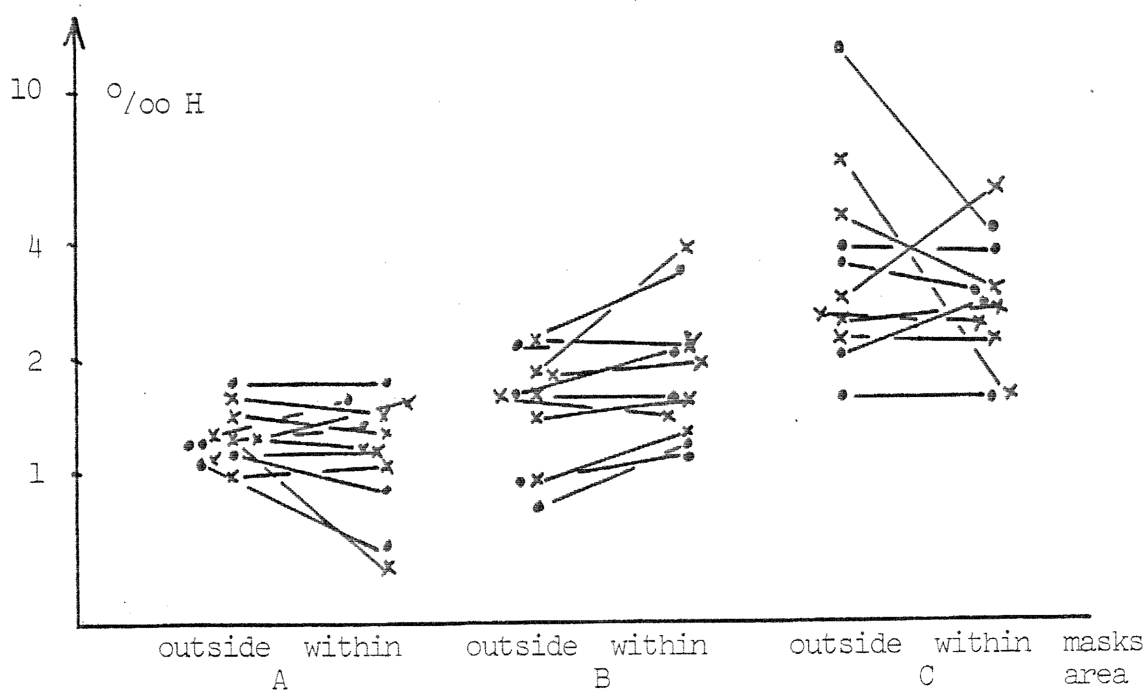

Figure 5 Maximum error (unfiltered) with respect to masks in per mille of H (log scale)
DEMs intended for low (x) and high (●) accuracy

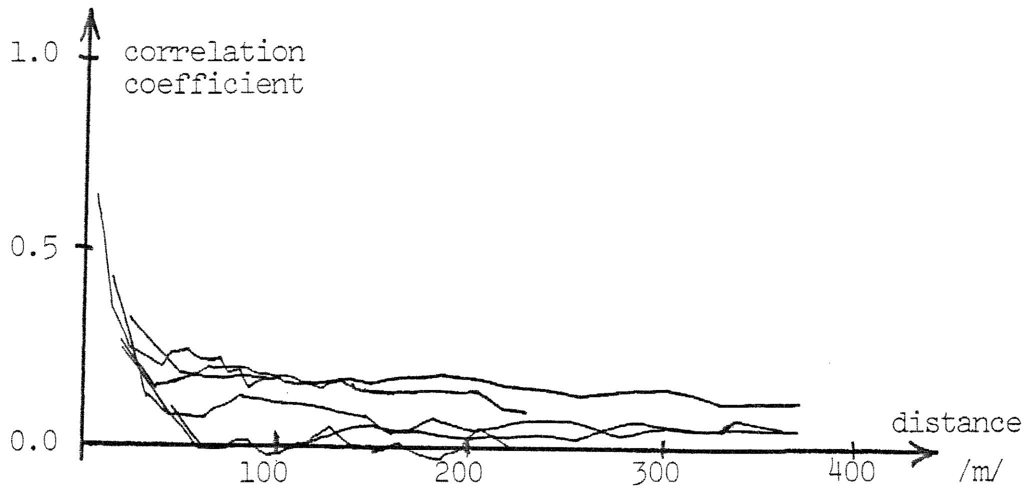

Figure 6 Autocorrelation between unfiltered errors in the DEMs measured by organisation 61.
Positive correlation at long distances because of constant errors in absolute orientation

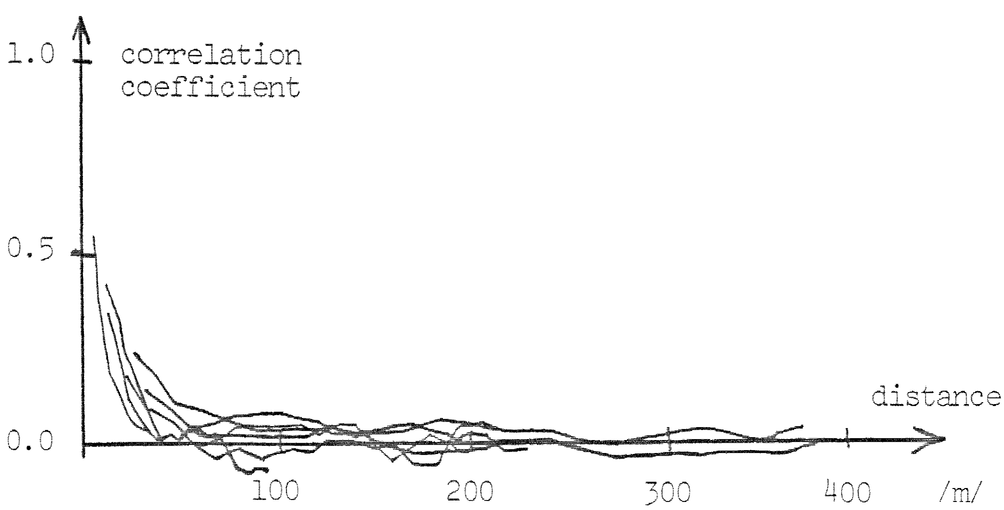

Figure 7 Autocorrelation between levelled errors in the same DEMs as in Figure 6.
After levelling the DEMs on all check points the correlation is zero for distances longer than 40 - 60 meters.

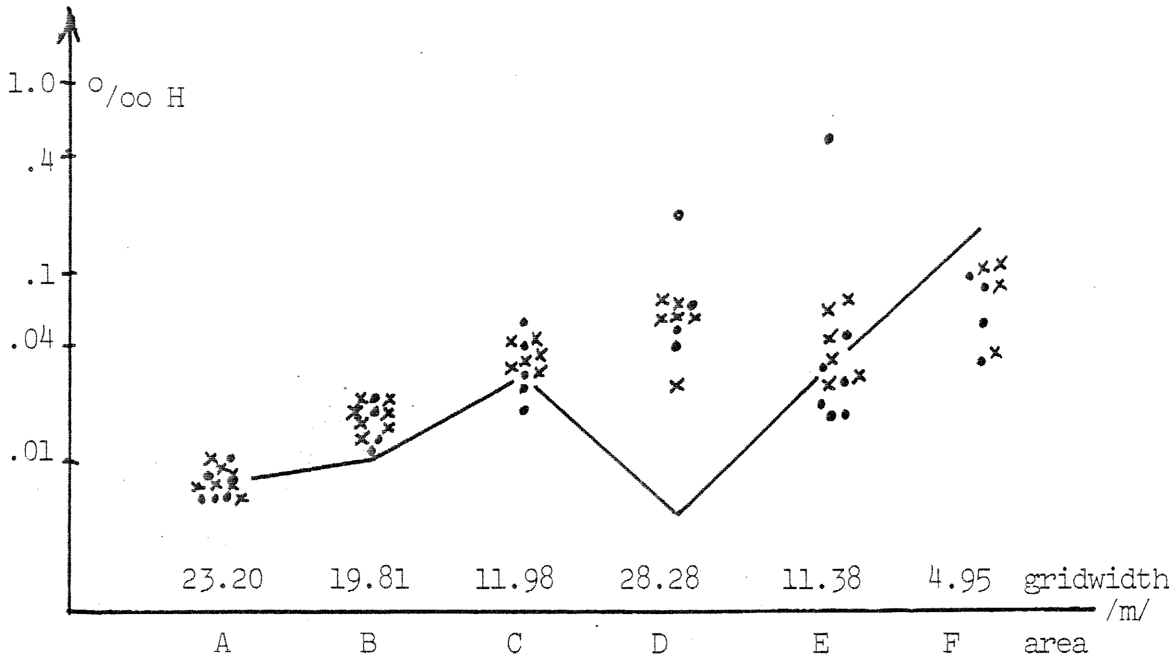

Figure 8 RMS of slope errors from unfiltered DEMs in per mille of H.
The line shows constant/grid width (log scale).
DEMs intended for low (x) and high (•) accuracy

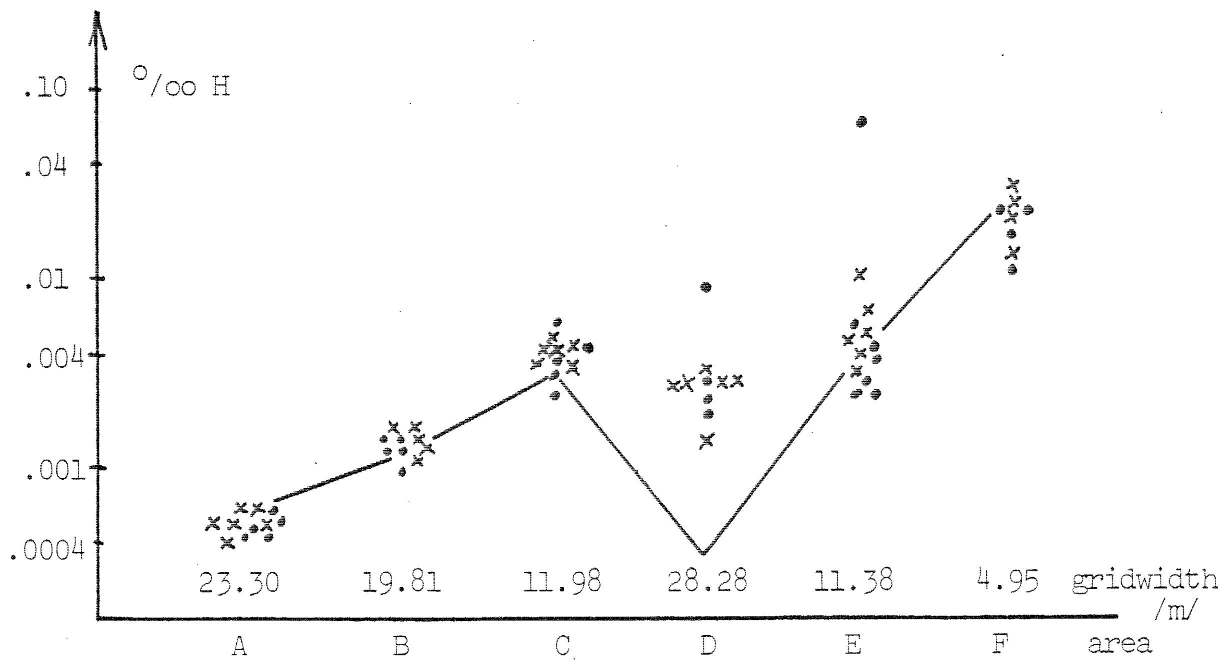

Figure 9 RMS of curvature errors from unfiltered DEMs in per mille of H.
The line shows constant/(gridwidth)^2 (log scale)
DEMs intended for low (x) and high (•) accuracy

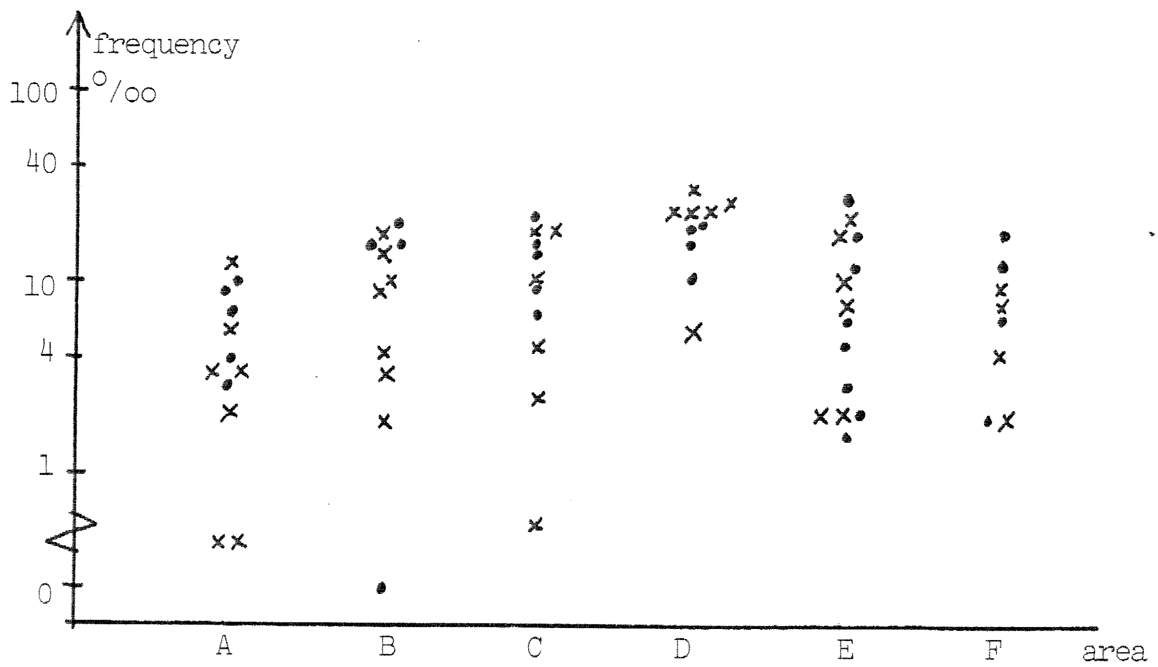

Figure 10 Frequency of blunders in DEMs (per mille in log scale). DEMs intended for low (x) and high (•) accuracy

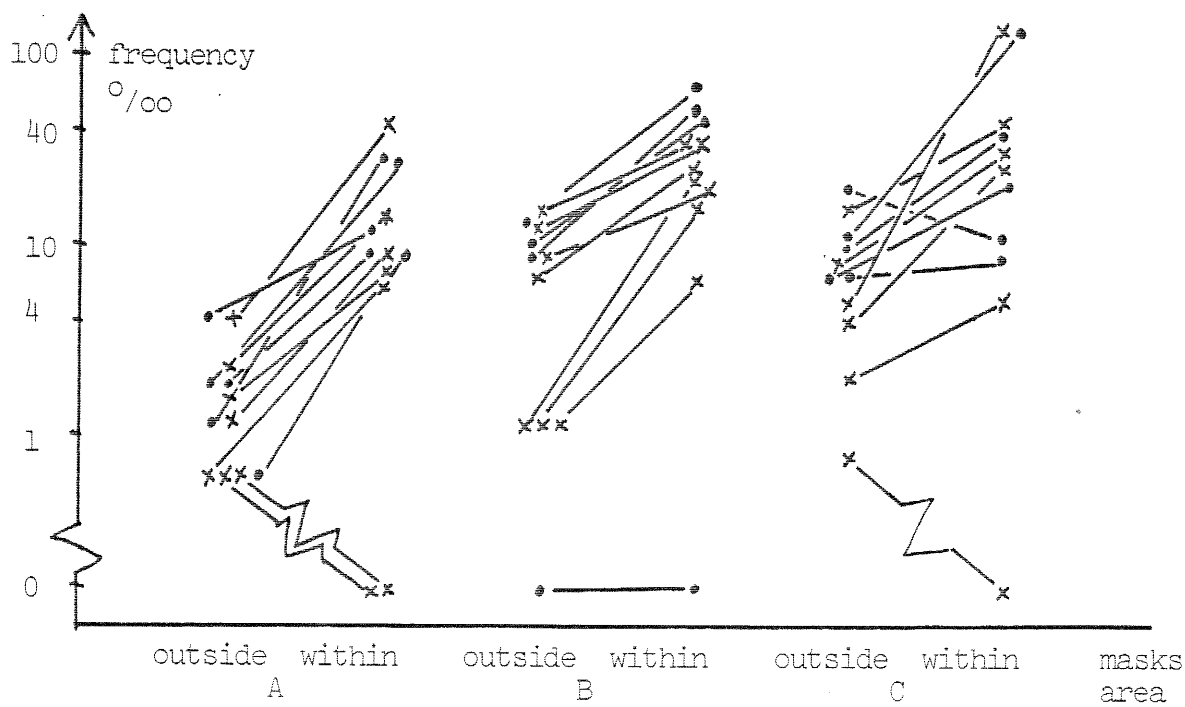

Figure 11 Frequency of blunders with respect to masks (per mille in log scale)
DEMs intended for low (x) and high (•) accuracy

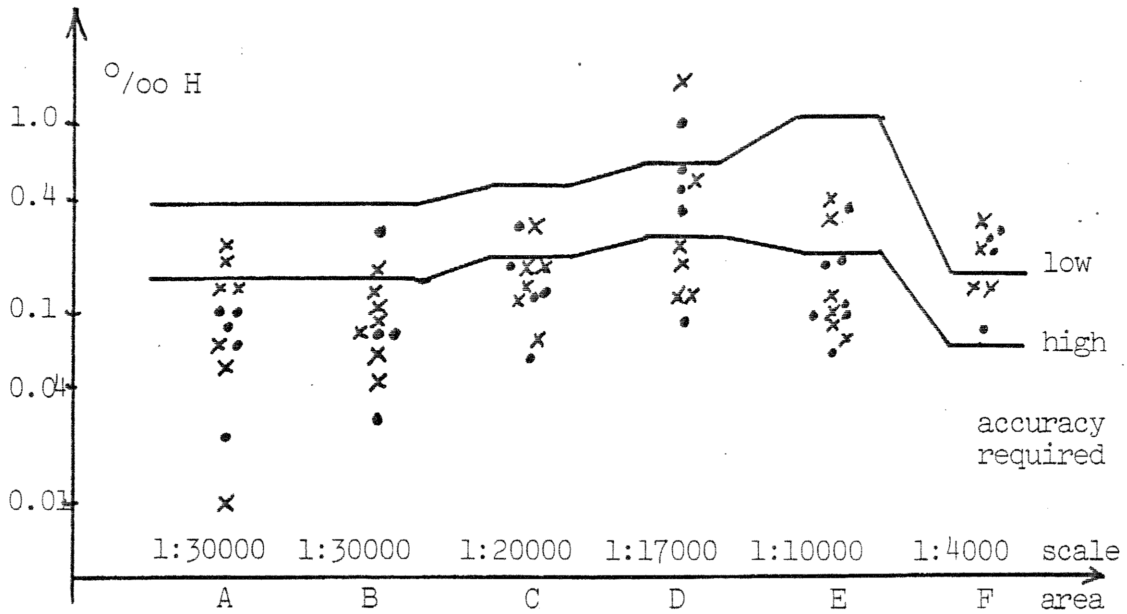

Figure 12 RMS of errors propagated from control points = $\sqrt{(\text{filtered rms})^2 - (\text{levelled rms})^2}$ in per mille of H (log scale). DEMs intended for low (x) and high (•) accuracy

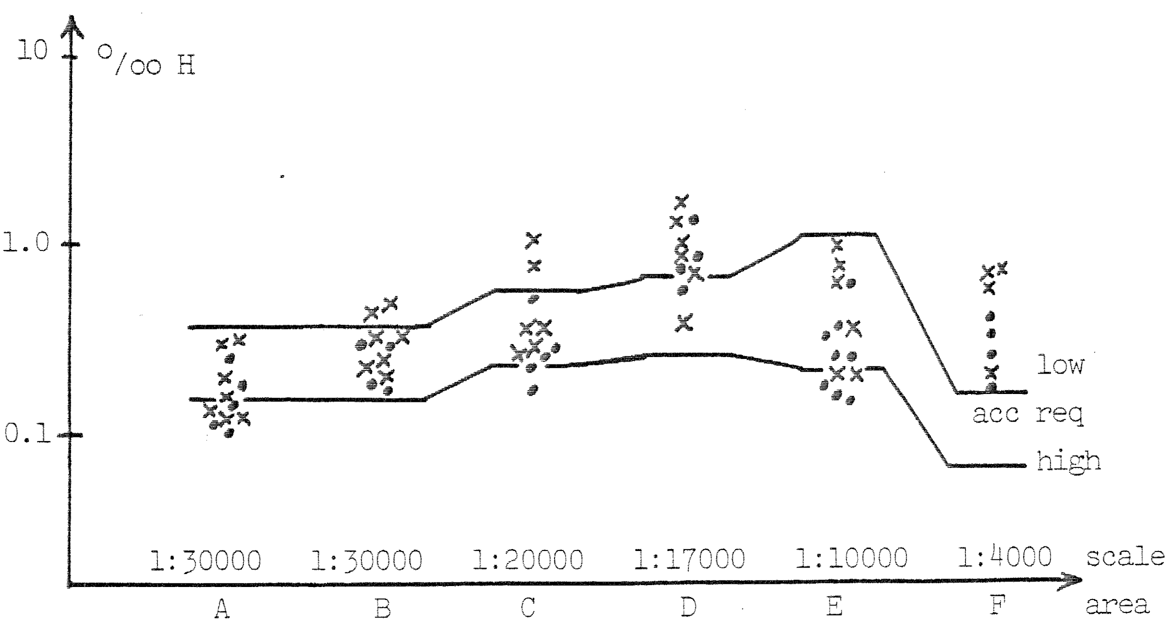

Figure 13 RMS of levelled errors in per mille of H (log scale) DEMs intended for low (x) and high (•) accuracy