The Applicability of a Feature Based and a Least Squares Matching Algorithm for DEM-Acquisition

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0. Abstract

Image matching techniques provide the basis for sampling of DEM's. A feature based and a least squares matching algorithm have been used for the purpose of automatic acquisition of topografic surfaces. The paper describes an extensive controlled test. The empirical results are discussed with respect to precision, reliability, versatility and limitation of the method. The automatic measurements turns out to be of comparable precision to the manual results.

1. Introduction

Automatic acquisition of Digital Elevation Models (DEM) has become feasible with modern techniques of Digital Image Processing and Pattern Recognition. Putting the main burden of the measurement process onto the computer classical strategies for DEM-acquisition have to be revalorized. There are various strategies, which are of interest in this context. They have to be compared with respect to the relation between stored DEM data and interpolation complexity and with respect to the need of an interpretation of the terrain or of the images by a human operator:

- Morphological sampling aims at the selection of only those points which are most representative for the terrain. Each point may have attributes which code its role in the sophisticated interpolation process thus carries relevant information. This method obviously requires a well trained operator for terrain interpretation. Due to its complexity this scheme, having its roots in field surveying, is not used in photogrammetric practice.
- Composite sampling (MAKAROVIC 1979) starts with capturing of morphologically relevant terrain features like spot heights or break lines and then applies the strategy of progressive sampling (see below) for filling the areas in between. The selection of the morphological features again requires an interpretation of the terrain which, however seems to be not as complex as in the previous strategy. Composite sampling probably is the strategy which is most common in photogrammetric practice.
- Progressive sampling (MAKAROVIC 1973), developed before composite sampling, starts from the measurement of a coarse grid, which depending on the analysis of the curvature locally densifies this grid. Here no attempt is made to extract morphologically important terrain features. This method, therefore was one of the first to be used in more sophisticated automatic systems. Compared to full grid measurements the number of points to be measured can be reduced to a high percentage, especially in case the terrain has only few structure or break lines and varies in roughness. The price for this reduction is the possibility that the procedure overlooks important terrain features which lie within a cell.

- Grid measurements aim at a direct measurement of the DEM avoiding any type of analysis and usually relying on linear or cubic interpolation between these measured grid data. Obviously this method is not efficient compared with progressive sampling. Moreover it assumes, that heights can be measured at all grid points, which does not hold in all cases. But then the advantage of directly measuring the DEM data disappears, as the operator has to choose terrain points near to the grid points, which on one hand requires an interpolation process to obtain a grid and on the other makes this scheme unappropriate for automatic procedures, unless they have some kind of interpretation capability or are able to handle "disturbancies" like trees or buildings and image areas with no texture. Most automatic systems for DEM acquisition follow this line and provide a facility to interactively help the system solving this kind of problems.
- Sampling by data compression is typical for automatic measurement procedures and relies on the low costs for measuring one point. In contrast to morphological sampling each point does not carry much information and interpolation can be simple. In contrast to the three previous strategies the points need not lie on a regular grid, on the contrary they can be chosen in a way that automatic measurements can be expected to succeed. But this requires an interpretation capability both of the images, namely to choose the measurement positions, and of the terrain, namely to compress the measured data to a representative sample.

This last strategy is the most promising, as it in principle uses all available information and conceptually is closest to morphological sampling as the operator there first builds up a dense image of the terrain with his visual system, interprets it and on the basis of this interpretation selects the appropriate points. Automatic systems for measuring surfaces of irregularily textured object (cf. e. g. BAKER 1983, GRIMSON 1981, OHTA/KANADE 1985) actually replace the interpretation of the terrain surface by an interpretation of the image. This is reasonable as the absence of intensity changes in the image can be used as a good argument for a smooth surface at the corresponding position.

This was the reason to start an investigation on the feasibility of such a type of algorithm for DEM acquisition. The used algorithm (cf. PADERES et. al. 1984, FÖRSTNER 1986) is based on point type image features. Though the selection is based on the expected precision for matching it can not be expected to exploit the geometric precision inherent in the images. Therefore the results of this feature based matching (FBM) algorithm were to be compared with those derived with a least squares matching (LSM) algorithm (cf. ACKERMANN 1984) which is known to be optimal with respect to the precision. However the selection of the points where the LSM is performed has been based on the point selector of the FBM algorithm.

The aim of the investigation was to find out the potential of these automatic mensuration techniques for DEM acquisition. The main limitations of both algorithms are known a priori: they theoretically only are able to yield excellent results in smooth terrain and well textured images. However, due to the robustness of the FBM algorithm single trees or buildings should not disturb the result too much and should be smoothed out. Specifically we are interested in the quality of the DEM depending on test areas with different complexity and on the influence of different parameters (pixel size, patch size, type of algorithm, image content) onto the quality of the result. The ultimate goal was to find out in how far automatic procedures under controlled conditions can reach the DEM quality of an experienced human operator.

2. The Measurement Procedure

The used matching algorithms are well known in literature. For that reason we restrict ourself on giving a short conceptional explanation.

The core of the software essentially is a least squares matching algorithm, from which the the mathematical formulation is given by ACKERMANN (1984), and a feature based matching algorithm, described by FÖRSTNER (1986). The measuring organisation is done according to the strategy presented by SCHEWE and FÖRSTNER (1986). The basic hardware components are the analytical plotter(A900 and Zeiss Planicomp C100) completed by two digital cameras (cf. PERTL 1985 for details).

The setup of the measuring procedure used in this investigation is characterized by the following spotlights:

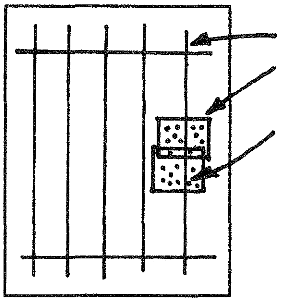
a. <u>Feature based matching (FBM)</u> between two selected patches of the aerial images results in a list of corresponding point pairs. The transformation parameters known from the orientation are used to compute the terrain coordinates of the corresponding points.

b. To improve the accuracy the theoretically most precise but time consuming <u>least squares matching (LSM)</u> is applied. The ground coordinates from the reduced result of the FBM (cf. d. below) serve as approximate values for the least squares match.

Feature based matching and least squares matching are based on the same linear geometric and radiometric model for the transformation between the image patches and on the same principle of estimating the parameters. The parameters are estimated according to a Maximum Likelihood principle. In the FBM algorithm a robust estimation is applied to eliminate wrong matches between the selected points. Considering the shift to be the only unknown parameter in the model, the cofactor matrix of the parameter directly leads to the interest operator for selecting optimal windows or points (FÖRSTNER 1986).

In this investigation both matching algorithms are designed to use the epipolar condition, which is known after the relative orientation of the image pair.

c. The patches are selected according to the <u>measurement strategy</u> described by SCHEWE and FÖRSTNER (1986). The strategy comprises the definition of gridlines in object space which serve as a guide to make sure that the surface imaged in the aerial photographs is completly recorded by the automatic measurement (cf. the following figure).



a. gridlines for controlling the coverage
b. patches used for the feature based matching
c. automatically selected and matched points

Elements of the measuring strategy

The matched points of the individual patches are collected in a large ground file, which in a complete model (9x18 cm²) may contain 50 000 to 500 000 points, thus having a density of 3 to 30 points per mm² in image scale depending on the texture and the pixelsize. The matching can result in a clustering of points as well as in holes in object space. The control parameters within the FBM algorithm, however, are suited to influence the amount of measured points so that in general the terrain is completely described by these points. At the moment no attempt is made to automatically extract break or other feature lines of the terrain.

d. In order to obtain the DEM this large amount of points is reduced resulting in a smoothed sample of representative points which in our case approximately form a grid. The reduced data are the input for the DEM-derivation.

The reduction is based on a grid layed over the terrain, dividing the terrain in a set of non-overlapping ground elements, called groundels. The points within such a ground element are reduced to one point, which is meant to be representative for the groundel. This is done by a median filtering in the height if the surface element is horizontal and with an estimation of an inclined plane in space according to the L1-Norm (BARRODALE and ROBERTS 1973) when the surface element may be tilted. The L1-solution is a generalisation of the one dimensional median and has the same robust properties with respect to outlying observations (cf. HAHN 1985) as they are known from the median. An important feature of this selection procedure is the ability to estimate the accuracy of the raw as well as of the reduced data.

Now we are prepared going on to the empirical investigations and results.

3. Description of the Selected Projects

For this investigation three different terrain types are chosen which can be characterized as follows:

	area name and code	characterization	scale size
a	Desert	desert area, small forms sand hills	1 : 15 000
	De1	centre of model	17 x 40 mm²
	De2	border of model	10 x 20 mm²
b	Agricultural area	uniformly, little bended ploughed arable land	1 : 8 000
	Aa1	furrows across	11 x 28 mm²
	Aa2	" parallel to the epipolar lines	13 x 25 mm²
c	Wilderness, Wi	steep, rough area break lines, rock-debris	1 : 10 000 18 x 26 mm²

Table 1 Project characteristics

It can be expected that the automatic procedure has only few or no problems acquiring the DEM in the agricultural areas, some problems may arise in the desert areas and the hardest project shurely is the "Wilderness".

In the models of the desert and the agricultural area we chose two test areas, in order to evaluate the influence of the position of the area within the model and of the direction of the textur onto the accuracy.

4. Investigation Concept

4.1 Scope of the Investigation

The scope of the investigation was to find out the precision and the reliability of automatically generated DEM-data. The term reliability in this context predicates the degree of completeness with which the acquired data are covering the whole area. The term precision is more complex and comprises different objectives:

- accuracy of the '<u>FBM raw data</u>'. In the raw data acquired by the FBM-algorithm a not to small percentage of outliers can be expected, where the term outlier refers to points which do not represent the terrain properly.

- accuracy of the '<u>FBM reduced data</u>'. By the reduction process a filtered subsample of the 'FBM raw data' is obtained, which constitutes the input for the DEM-generation.

- accuracy of the '<u>LSM data</u>'. The 'FBM reduced data' serve as approximate values for the least squares matching . Also these 'LSM data' serve as input for the DEM-generation.

- accuracy of the '<u>DEM</u>'. Besides the measurement accuracy of the DEM input data, from FBM or LSM, the quality of the interpolated grid including the terrain representation is playing the most important role in practical applications.

The accuracy measures are derived from a comparison with manual measurements. Hence it follows that this empirical accuracy statements are limited by the level of precision of the manual measurement. For comparison reasons for each project also two independent manual measurements have been performed.

The accuracy measures always are empirical estimates for the differences between two types of measurements, no attempt has been made to separate the two components involved.

Further objectives are the influence of the chosen pixelsize onto the precision and reliability and the quality of the internal precision estimates determined within the data reduction process. This gives a direct indication about how far the system is able to perform some kind of selfdiagnosis. As already mentioned above also the influence of the position of the measured points within the stereo model and the direction of the texture with respect to the epipolar lines are of interest.

4.2 Robust estimation of the standard deviation

As one can not expect that the differences contain no outliers we use a robust estimate for the standard deviation based on the median absolute difference (MAD). The MAD is defined as the median of the absolute deviations from the median

$$MAD = \text{med}\ \{\,|x_i - \text{med}\{x_i\}|\,\} \qquad (1)$$

where med$\{x_i\}$ is the median of the sample. Taking the asymptotic properties of the MAD to the normal distribution into consideration the standard deviation is related to the MAD by

$$\sigma(MAD) = MAD/0.6745 \approx 1.5\ MAD \qquad (2)$$

where $\Phi^{-1}(0.75) = 0.6745$ can be taken from the inverse cumulative normal distribution (cf. HUBER 1981, p. 108).

The thresholds for testing the data with respect to outliers are then defined by

$$c_{max,min} = \text{med}\{x_i\} \pm 3\ \sigma(MAD) \qquad (3)$$

Data outside the intervall $[c_{min}, c_{max}]$ in this investigation are considered to be outliers.

The median, the robust standard deviation and the number of outliers are used to evaluate the result, both, for the selfdiagnosis within the reduction process as well as for the comparison between different measurements or DEM's. As the thresholds for the outliers are based on the empirical precision and not on a project specific required tolerance, the number of outliers gives an indication in how far the differences follow a normal distribution, or how homogeneous the data are.

4.3 Test performance

In the investigation the following steps are realized:

1. The whole area of the projects is measured fully automatically with the FBM algorithm. Two versions for the 'FBM raw data' are obtained

   - version "w": The selected points are the centres of the windows used in the FBM procedure.
   - version "p": The selected points are the gradient weighted centre points of gravity within the windows used in the FBM procedure.

   Theoretically one would expect version "p" to yield results of higher precision than version "w" (cf. FÖRSTNER/GÜLCH 1987).

   In order to determine the precision of these raw data a sample of a fixed number of randomly chosen points is manually measured, usually 500 in this test. First the differences are used to compute the MAD and the robust standard deviation which forms the basis for rejecting outlying differences. Using the accepted differences the accuracy is determined by computing the bias and root mean square of the differences between automatic and manual measurement.

2. The data were reduced with the simple method of subdividing the area in a grid with predefined groundels. The choice of the ground element size has been examined separately with respect to the accuracy of the resulting data. Very helpful was the estimation of the groundel size using representative profiles and a stochasic model which includes the measuring errors, namely an observed autoregressive moving average model (cf. LINDENBERGER 1986).

3. For an internal estimation of the accuracy, which is independent of manual measurements, the data reduction process gives an excellent statistical material. The robust standard deviation yields an estimation of the height accuracy within a groundel. The mean over all the groundels gives an approximation of the accuracy of the raw data and can be compared to the result obtained in step 4. Incorporating the effect of the filtering we get an estimation of the precision of the resulting data. Specifically, if σ_1 is the estimated standard deviation of the individual heights, the accuracy of the selected points can be approximated by $\sigma_1/\sqrt{n}$, where n is the average number of points within a groundel. As this value appeared to be too optimistic we used

   $$\sigma_2 = 2 * \sigma_1 / \sqrt{n} \qquad (4)$$

   as an approximation for the accuracy of the reduced data. This internal estimate can be used as a kind of selfdiagnosis and will be compared with the empirical values derived from the comparison with manual measurements.

4. The result of the data reduction is a filterd subsample of the measured points. To check the geometric precision of the reduced data set, in which each point represents one small ground element, the test is repeated as described in step 1;· i.e. taking a randomly chosen sample of a fixed number of points and controlling it by manual measurements. This allows to derive the accuracy of these data. They can be used as input for a further processing whith a DEM-program.

5. The same sample of points is used as approximate values for the LSM. The expected improvement of the LSM is also controlled manually according to the test in step 1. In principle the points in the sample should be best qualified for the LSM, because they are selected with respect to an expected good precision for the correlation.

6. Steps 4 and 5 are producing terrain data with a known geometric precision of the measured points. To get a quality assessment for a digital terrain modell which is computed from this automatically determined data, a second DEM is manually measured and computed. This DEM is oriented differently compared to the automatically derived one. The manual DEM-acquisition is done in that manner as it is usual in practice. That means, that breaklines and formlines are taken into consideration at the places where it is necessary, i. e. morphological reasonable. The difference between the DEM's (manual-automatic) gives information about the representativity of the input data (FBM, LSM) relative to the acquired terrain. Of course the pure geometric precision is included hereby as well as the effect of the mathematical model on which the DEM-programm is based upon.

5. Results of the empirical investigations

5.1 Groundel Size

We first discuss the selection of an appropriate groundel size as all results depend on this choice. The size of the ground elements has to be chosen in such a way, that by the data reduction an optimal result is reached. If the groundel size is too small, the filtering is not vigourous enough; if the groundel size is too large then the smoothing takes away the fine structure. An objective choice can be made on the basis of the analysis of representative profiles of high point density and deriving the lowest possible point density which guarantees the interpolated profile to represent the real profile accurately enough (cf. e. g. LINDENBERGER 1986). This point density can then be interpreted as the optimal groundel size for our data reduction process.

For checking these recommendations a special test has been performed. The result is collected in table 2.

project	groundel-size [m]	mean # of points per groundel	precision [m]		
			raw data		reduc. data
			int. σ^1	rms	rms
Del (20p)	15	40.0	0.54	0.51	0.19
	10	18.1	0.50	"	0.22
	7	8.8	0.49	"	0.28
Aal (20p)	10	66.3	0.42	0.36	0.11
	7	31.5	0.37	"	0.14
	5	16.6	0.36	"	0.14
	3.5	8.1	0.35	"	0.20

'ARIMA- proposal' for Del: 15 m
Aal: 7 m
explanation of the abbrev.: see table 4

Table 2 Results from different chosen ground element sizes

It is evident that the attempt to use ground elements of smaller size than proposed by the ARIMA analysis has negative consequences for the precision of the reduced data. Larger groundels have not been taken into consideration because of generalisation effects. Large groundels only seem to be reasonable, in case additional morphological important structure lines are measured. Up to now such a feature is not available in the automatic measurement procedure.

5.2 Accuracy of manual measurements

As the manual measurements serve as a reference it is important to determine their precision.

The precision derived from repeated measurements is characterized by the mean observational error from the differences (cf. table 3, col. 2).

project	observat. accuracy # = 500 [m]	DEM accuracy				
		# of pts.	bias [m]	rms differences [m]	rms differences [0.1 ‰ hg]	outliers
De	0.13	6000	0.02	0.20	0.87	1.8 %
Aa	0.09	2220	-0.03	0.09	0.73	2.4 %
Wi	0.14	5200	0.10	0.22	1.44	2.1 %

Table 3 Accuracy of manual measurements

For checking the accuracy of the manually acquired DEM two independent measurements of each project are carried out, i. e. for the acquisition of the general terrain points, the structure lines, break lines and spot heights of single points two complete measurements are done as far as possible independent. The results of this comparison of manually acquired DEM's is given in columns 3 ff. of table 3.

In general the DEM accuracy is less than the internal precision, appr. by a factor 1.5. Only in the project "Agricultural area" with very smooth terrain the DEM accuracy is determined by the measuring precision. From the rms. differences a high accuracy of 0.5-0.6 ‰ h_g for the manual measurements for one DEM can be derived in the projects "Desert" and "Agricultural area", while for the rough terrain of project "Wilderness" the known rule of thumb 0.1 ‰ h_g is confirmed. The seemingly high percentage of outliers reflects the non-normality of height differences in DEM's not the weakness of the manual procedure.

5.3 Example for the anlysis

Figures 1 to 5 illustrate the summary of table 4 for the project Aa1 (agricultural area) using FBM and LSM with 20 µm pixel size.

Fig. 1 shows the accuracy of the measured raw data. The relative frequency of the differences (manuell - automatic) is plotted as a function of the differences in units of 0.1‰ of the flying height. The histogram can be well approximated by the normal distribution. The number of outliers is three times higher than in the normal distribution which should be 0.3 %. The thresholds for the determination of the outliers according to eq. (3) are marked in the histogram.

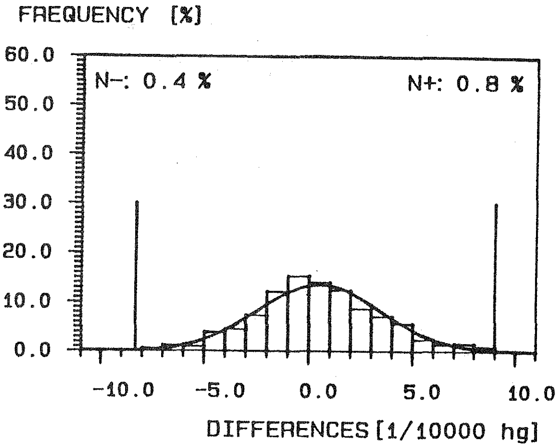


Fig. 1 Precision of the raw data

Fig. 2 shows the point accumulation over the area. By framing the area in groundels of size 7 x 7 m² the histogram shows that about 30% of the groundels include (25-30) points. A few clusters occur in groundels with up to 135 points and no groundel contains less than 4 points.

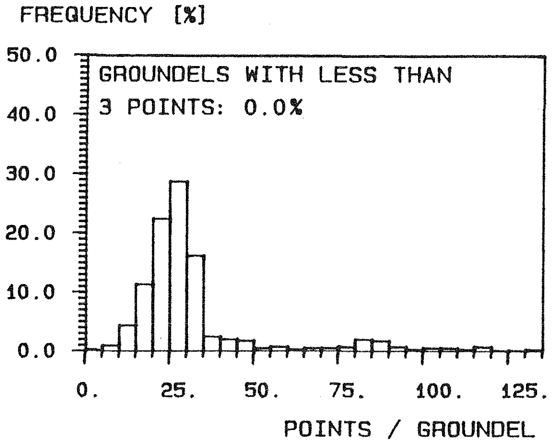


Fig. 2 Points per groundel

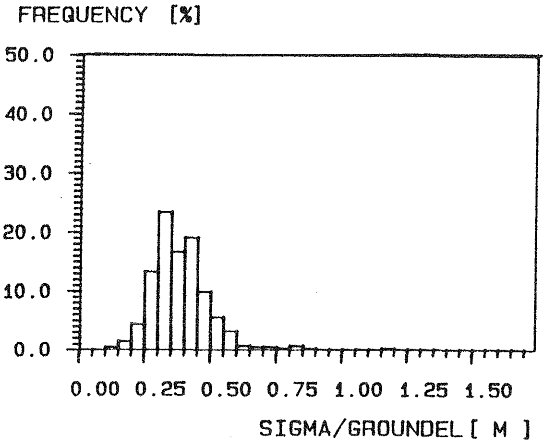


Fig. 3 Sigma per groundel

The internal estimates of the precision of the raw data are shown in the histogram of Fig. 3. In about 3/4 of the groundels the estimated precision lies within the narrow range of (25-50) cm and only single estimates deviate to larger values up to 1.35 m in this example. The mean value over all these estimates approximates excellently the value determined by the manual control (see table 4).

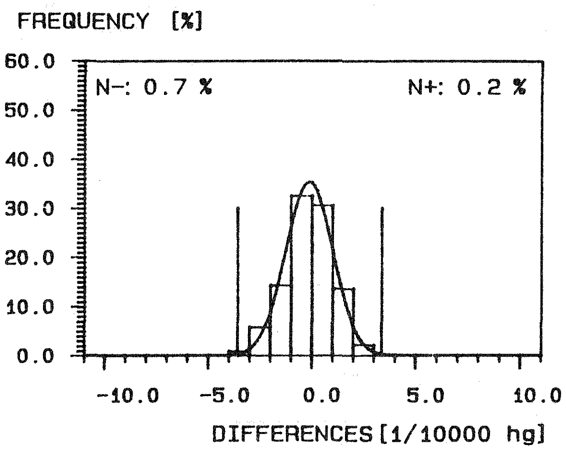


Fig. 4 Precision of the FBM reduced data

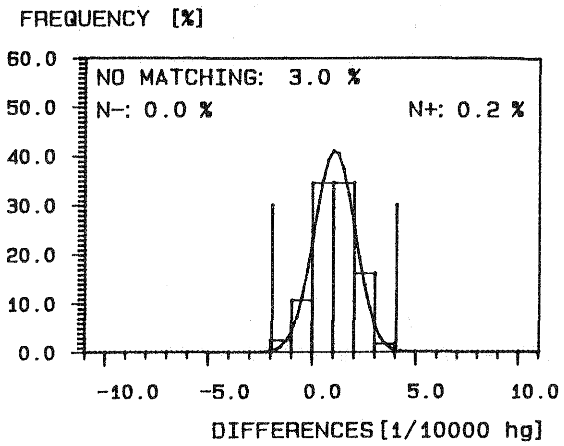


Fig. 5 Precision of the LSM data

The data resulting from the data reduction are a filtered subsample of the original measurement. The histogram of the differences to the manual measurements are plotted in figure 4. The increments on the abszissa in the histogram are chosen in units of 0.1‰ hg as in fig. 1. The comparison of the two figures gives an impression of the improvement of the accuracy caused by the filtering.

This set of points is used as approximate values for the LSM. The improvement of the accuracy by LSM is evident from fig. 5. In this example at 3 % (12 out of 400) positions the LSM has not been successful. Reasons are tight thresholds to avoid outliers on one hand and possibly disturbancies in the images (scratches, dust, single trees or houses e.g.) on the other hand. A further reason might be that the window sizes for the point selection in the FBM (3 x 5 pixels) and the LSM (22 x 22 pixels) are different.

In how far this has consequences for the DEM becomes clear when considering the DEM comparison. The computation of the DEM's is executed with the program system SCOP (KÖSTLI, SIEGLE 1986). From the input data a elevation model (grid) is interpolated. To compare two DEM's the heightdifferences in the grid points are computed, i. e. one DEM serves as reference and the other one is interpolated to the grid structure of the first. Considering the figures 6 and 7 gives an impression of the differences between the DEM's " manual - automatic ", whereby the latter one is

- based on the FBM reduced data (fig. 6)
- based on the LSM data (fig. 7).

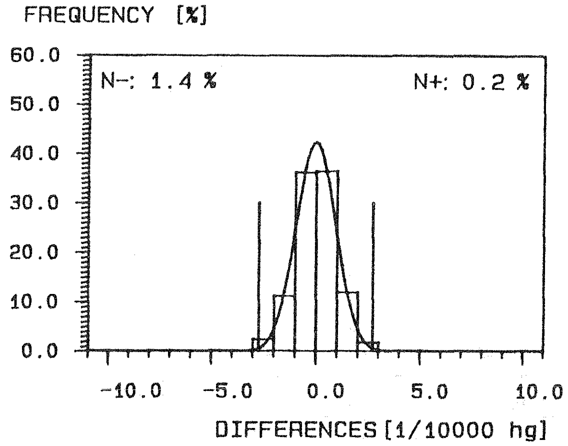


Fig. 6 DEM precision of FBM reduced data

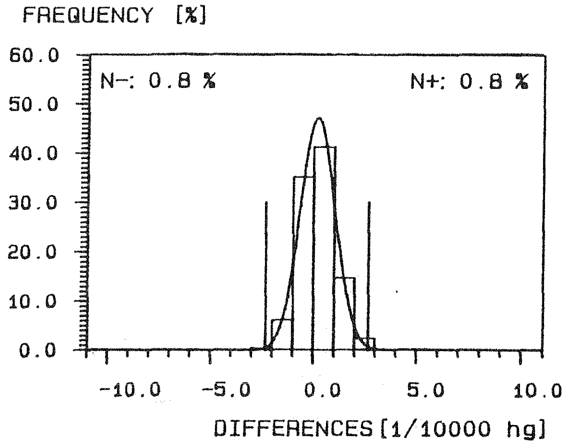


Fig. 7 DEM precision of LSM data

The two figures are very similar which reflects in the nearly identical rms values for the differences of 0.11 m and 0.10 m or 0.94 ‰hg and 0.84 ‰hg for the DEM's from FBM and LSM data resp..

5.4 Absolute accuracy of the automatic procedure

Table 4 contains the main results of the investigation with respect to the precision of the matching procedures. Altogether 14 versions in the 5 selected areas are analysed. For each type of terrain a sequence with different pixelsizes has been analysed with altogether appr. 185 000 points matched by the FBM algorithm. The manual checks contained appr. 30 000 points. The accuracy of the raw and the reduced data are reflected in the bias, rms height differences in m and in ‰ h_g and the outliers in a sample of appr. 500 manually controlled points. The selfdiagnosis with the internal estimates for the precision also shows the average number of points per ground element. The final check of the reduced data, both from the FBM and the LSM and the corresponding DEM's also yielded the bias and the rms height differences for the 14 versions.

Several conclusions can be drawn from this table:

1. The precision of the raw and the reduced data (col. 6 and 10) of the FBM measurements can be very well approximated by the estimates which can be determinated within the data reduction step. Only in the project "Wilderness" the internal estimates are too optimistic still by a factor 2.

Feature Based Matching FBM																		Least Squares Matching LSM					
				manual - automatic							internal estimates				manual - automatic								
pro- ject (scale)	pixel size [µm]	FBM typ	num. of measur. points	raw data (#=500) bias [m]	rms [m]	outliers N-	N+	reduced data bias [m]	rms [m]	[0.1‰h]	size groundel [m]	pts	raw σ1 [m]	reduc. σ2 [m]	DEM bias [m]	rms [m]	[0.1‰h]	(reduced data) bias [m]	rms [m]	[0.1‰h]	DEM bias [m]	rms [m]	[0.1‰h]
De1	20	w	27 900	-0.03	0.49	6	8	-0.01	0.20	0.88	15.	39.4	0.59	0.19	-0.18	0.23	1.00	0.00	0.16	0.70	-0.08	0.22	0.97
(15000)	20	p	28 300	-0.07	0.51	2	10	-0.01	0.19	0.83	15.	40.0	0.54	0.17	-0.20	0.22	0.94	0.10	0.17	0.73	-0.12	0.22	0.95
	40	p	10 200	-0.31	0.71	11	9	-0.33	0.29	1.28	30.	51.9	0.79	0.22	-0.33	0.33	1.45	-0.25	0.21	0.92	-0.25	0.39	1.68
	60	p	5 000	-0.36	1.07	11	12	-0.47	0.38	1.64	45.	56.6	1.10	0.29	-0.49	0.45	1.95	-0.21	0.31	1.35	-0.22	0.47	2.05
De2 (15000)	20	p	9 500	-0.41	0.52	6	7	-0.44	0.18	0.78	15.	44.4	0.53	0.16	-0.42	0.14	0.63	-0.29	0.16	0.71	-0.29	0.14	0.59
Aa1	20	w	14 000	0.08	0.40	2	6	0.08	0.15	1.23	7.	31.2	0.44	0.16	0.07	0.10	0.83	-0.01	0.11	0.96	-0.01	0.10	0.81
(8000)	20	p	14 200	0.06	0.36	2	4	-0.02	0.14	1.13	7.	31.5	0.37	0.13	0.00	0.11	0.94	0.13	0.12	0.97	0.02	0.10	0.84
	40	p	5 500	0.12	0.50	7	5	0.11	0.14	1.19	15.	52.3	0.59	0.16	0.03	0.12	1.02	0.13	0.11	0.92	0.04	0.10	0.87
	60	p	2 900	0.09	0.68	8	7	0.00	0.17	1.42	22.	54.1	0.86	0.23	-0.03	0.17	1.43	0.13	0.12	0.97	0.09	0.17	1.43
Aa2 (8000)	20	p	14 300	0.20	0.57	4	15	0.23	0.22	1.80	7.	31.0	0.57	0.20	0.06	0.20	1.65	0.20	0.21	1.72	0.02	0.20	1.68
Wi	20	w	21 500	-0.16	0.37	15	8	-0.08	0.23	1.47	8.	27.9	0.29	0.11	-0.02	0.30	1.91	-0.06	0.17	1.11	0.01	0.25	1.59
(10000)	20	p	21 200	-0.11	0.31	21	13	-0.02	0.23	1.49	8.	27.4	0.27	0.10	0.08	0.27	1.76	-0.10	0.18	1.17	-0.03	0.25	1.64
	40	p	7 000	-0.26	0.44	22	10	-0.11	0.29	1.90	16.	34.2	0.43	0.15	-0.04	0.41	2.66	-0.07	0.24	1.52	-0.06	0.34	2.19
	60	p	3 900	-0.22	0.60	15	13	-0.11	0.38	2.43	24.	39.5	0.65	0.21	-0.03	0.58	3.76	-0.01	0.30	1.91	-0.03	0.50	3.20

legend : FBM-typ: w - window
p - point
= sample size

σ_1, σ_2 internal estimated height precis. for raw resp. reduced data
N+,N- outliers in the pos.,neg. range

bias : system. difference between manual and

rms : standard deviation without outliers

Table 4: Summary of the results concerning the investigated precision

2. Differences beetwen the estimation of optimal points within a window and using the centre of the window within the FBM algorithm are not significant (cf. the results in col. 10/11 and 17/18 of the projects with 20w and 20p in col. 2). However, in the project "Wilderness" the difference is significant. The use of the weighted centre of gravity leads to an improvement of a factor 1.6 (0.176 ‰ h_g vs. 0.282 ‰ h_g), though the window size of the point selector is only 3 x 5 pixels.

3. The improvement of the precision of the FBM data (based on the filtered result) by use of the LSM-technique is possible in a certain range. For the highest accuracy potential of the 20 µm size measurements an improvement of 10-60% is obtained. Again the increase in accuracy is highest in the project "Wilderness". This suggests that in smooth terrain the selected points are more precise than in rough terrain. The differences between the two algorithms reduces to less than 15 % when comparing the DEM accuracy (cf. col. 17/18 and 23/24). Obviously the terrain representation is dominating the measuring accuracy.

4. Comparing the results of the projects De1 and De2, which were taken from different positions in the image - De2 being from the border part of the image - show a difference in the DEM accuracy - De2 being a factor 1.5 better. Thus there is no reason to assume that areas at the border can be measured with less accuracy than areas in the centre of an image.

5. Comparing the results of projects Aa1 and Aa2 which contain texture of different orientation - the texture in Aa2 being parallel to the x-axis - do show a significant difference in precision in all cases, which is to be expected.

6. The accuracies obtained with different pixel sizes clearly show an increase of the rms differences with the pixel size. The increase however is not proportional to the pixel size, partly it is negligible. This opens the possibility to use larger pixel sizes, especially when applying LSM and in case the precision requirements can be relaxed, e.g. in case the DEM is solely used for orthophoto production.

7. Finally, when comparing the accuracy of the manually measured DEM's from table 3, with 0.20 m, 0.09 m and 0.22 m for the three types of terrain with the best results achieved with FBM (0.22 m, 0.10 m, 0.27 m) and with LSM (0.22 m, 0.10 m, 0.25 m) the conclusions are clear: Both automatic procedures are able to produce Digital Elevation Models with the same accuracy as an operator. In absolute terms these values lie significantly below 0.1 ‰ h_g for the "Desert" and the "Agricultural Area" imagery and are just above this standard requirement for the project "Wilderness".

Altogether the results of this extensive test are encouraging and make the effort for increasing the versatility of the procedures worthwhile.

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