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AUTOMATIC MEASUREMENT OF DIGITAL TERRAIN MODELS BY MEANS OF IMAGE MATCHING TECHNIQUES

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1 Introduction

One essential input for information systems managing geodata is the geometric description of the terrain surface. Extraction of geometric data from photogrammetric images based on image matching techniques is the task we want to discuss in this paper. For data acquisition exclusively aerial images are taken into account.

The classical acquisition of digital terrain models (DTM) requires the human operator for the measurement process, being the interpretation and stereo fusion of the imaged part of the terrain which the operator is usually provided through the viewer of a stereoplotter. He aims at efficiently selecting a minimum amount of points to be measured. Well known are sampling strategies like the Selective, Progressive and Composite Sampling, as proposed by Makarovic. For reducing the required efforts refinements of the strategies are developed as suggested by Charif and Makarovic (1988) or Reinhardt (lecture No. 13 at this Photogrammetric Week). Selecting points with assigned geometric attributes, which means extraction of significant terrain relief features represents the essential part of those conventional sampling strategies.

The role of a measured point with regard to the DTM changes drastically if image matching techniques are considered. Measuring points automatically is a low cost procedure, but a single point does not carry special information in that case. The sampling principle in image matching therefore reverts to a contrary strategy: Measuring a large number of points without specific attributes will provide sufficient information for a detailed statistical analysis of the terrain surface and for the derivation of a high quality DTM.

Whilst the requirements for the manual measurements to attain a comprehensive DTM sufficiently accurate and economically efficient are known (Charif and Makarovic, 1988), the demands for automatic image matching programs have to be defined accordingly:

"sufficiently accurate"
- the accuracy niveau of the DTM should be in the range of 0.1 - 0.2‰ of the flying height (Ackermann, 1980), preferably shifting to the high accuracy level.

"economically efficient"
- even though the operator is relieved from routine work, the time required by the automatic procedure to record the DTM of one model should be distinctly less than needed in conventional data acquisition. Desirable from today's view is 1 hour/model, for the time being 2-3 hours are acceptable.
- whilst image processing offers the possibility of a simultaneous or sequentional matching of more than two images, the classical image pair is likely to remain the standard unit for DTM data acqusition.

"comprehensive"
- the term comprehensive refers first to the automatic measurement process, from which a complete recording of the terrain is expected. Depending on image scale trees, hedges, vehicles, houses, .., by Helava summarized as "terrain noise", may cause problems to the matching algorithms, as well as dust, scratches and other disturbancies on the images.
- interactivity between the matching program and the operator is necessary if difficult 3D objects like a bridge over a valley or woodland have to be excluded from correlation. The manual measurements for the orientation of the images and controls of the DTM should at least be supported by the program if there is not an automatic solution.

In literature (cf. references) the terms automatic and accurate, reliable and robust are generally emphasized in the same way. Robustness against disturbancies like terrain noise and reliability in the geometric determination of terrain elevation are general demands. The actual concepts to obtain robust and reliable results vary considerably; they are discussed in chapter 3 and 4 in some detail.

2 Recent Developments of Capturing DTMs by Image Matching Techniques

The algorithmic procedures to derive 3D information from image matching especially are founded on area based and feature based matching techniques. Area based matching techniques are the classical cross correlation (CC), the least squares (LS) and related procedures. Feature based (FB) matching techniques mainly use edges, zero crossing, corners, blobs et.al. obtained by some automatic feature extraction procedures. For all methods (CC, LS, FB) an accuracy potential of better than 1 pixel in correspondence was confirmed in the empirical tests on image matching of ISPRS WG III/4 (Gülch, 1988). The algorithms that excel are using the complementary of the methods to advantage.

Focussing on least squares matching, the evolution started a decade ago based on the simple geometric model of locally approximating the object surface by a tilted plane (Ackermann, 1984). Extensions like estimating parallaxes in several points (Rosenholm, 1986) and multi image matching by taking the collinearity restrictions into account (Grün, 1985) provide more generality in the surface reconstruction. The actual state of the art is characterized by the consequent transfer of the matching process into the object space. The terrain resp. a model of it forms the "unknowns" in the estimation process, the observations are the intensity values (radiometric response) of the pixels in the individual images. This general formulation proposed by Wrobel (1987 a,b) Helava (1987, 1988) and Ebner et.al (1987, 1988) reads as follows:

$$d(x,y) = f(G(X,Y,Z), R(X,Y,Z)) \tag{1}$$

$d(x,y)$ is the optical density, discretely recorded in the pixel system of image j. The digital terrain model is described by two components: The geometric model of the surface $G(X,Y,Z)$ and the reflectance model of the surface (ascribed optical density) $R(X,Y,Z)$. The relationships between object and image are the perspective transformation, which is modelled by the collinearity equations

$$(x,y) = c(X,Y,Z) \tag{2}$$

and a reflectance transformation, which in special cases neglects the dependency on the illumination and the viewing direction, thus is independent on the geometry $G(X,Y,Z)$ (perfect diffuse reflection)

$$d = r(R). \tag{3}$$

Special interest is given to eqs. (3) and (1) e. g. by Weisensee (1988), discussing the dynamics of the sensor and reflexion models incorporating light sources. The attempt to consider eq. (3) by histogram equalization (Helava, 1988) has the consequence that eq. (3) then is approximated by unity transformation, but then no physical interpretation of the imaging process is available any more.
Under the aspect of economy the orientation (interior, exterior) of the images should not be estimated simultaneously within the reconstruction process, that means, eq. (2) is a given transformation. Furthermore the transfer into the pixel system of the scanning CCD camera (e. g. by an affine transformation) is a known trivial step of calibration.

The geometric part $G(X,Y,Z)$ of the terrain model has been extensively investigated in the past. Usually elevation (Z) and location (X,Y)

$$Z = Z(X,Y) \tag{4}$$

are related by various interpolation functions, by polynomials, finite elements, etc.. Eq. (4) usually is unique and continuous, as discontinuous steps in the elevation or several Z values at the same location (X,Y) are generally not considered. In the standard applications there is no need for.

The reflectance model $R(X,Y,Z)$ ascribed to the terrain can, in a similar way, be defined as another function, described by

$$R = R(X,Y) \tag{5}$$

Under the assumption of perfect diffuse reflection it reduces to a scalar function, i. e. to a second surface over (X, Y) (cf. Wrobel,1988). The photometric calibration is implicitly stated within (3). In case densities relating to the terrain are given, e. g. acquired by photometric measurements at selected places, equation (5) would relate to a superior reflectance reference system. Comparing the reflectance model with the geometric one, $R(X, Y)$ in general has to model higher frequencies, which is taken into consideration in a reflectance grid model by choosing the grid unit sufficiently small. Helava(1988) and Ebner et.al.(1988) proposed to use a grid, related to the pixel size multiplied by scale. To each grid element one unknown densitiy value is assigned. $R(X, Y)$ is formulated as a step function, reflecting the discrect structure of the digitized images.

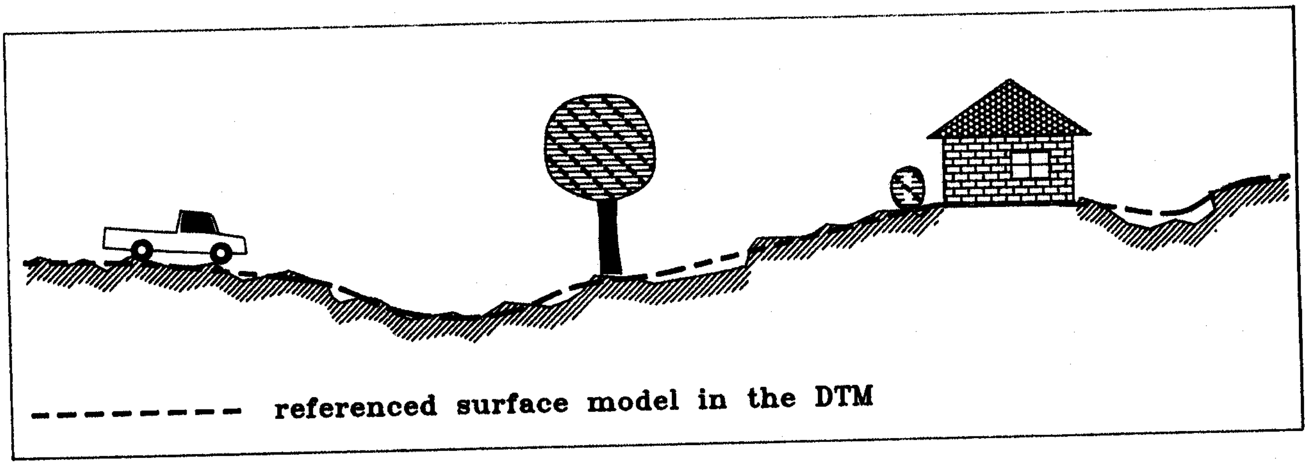

Figure 1: Surface definition for the terrain model

The least squares formulation results from linearizing eq. (1) which includes the chosen parametrization in (4) and (5). Because the optical density responses of the images are only given by discrete values, $d(x, y)$ not being known analytically, the pertubation method is applied for linearization. The stochastic model for the density values in general is not known. Therefore the intensity responses are postulated to be uncorrelated and of equal precision.

The estimation of the parameters of relationship (5), which are the densities of the reflectance grid in a special case, results in the estimated reflectance part $R(X, Y)$ of the digital terrain model. $R(X, Y)$ represents the orthophoto of the terrain, which the adjustment procedure produces simultaneously with the DTM.

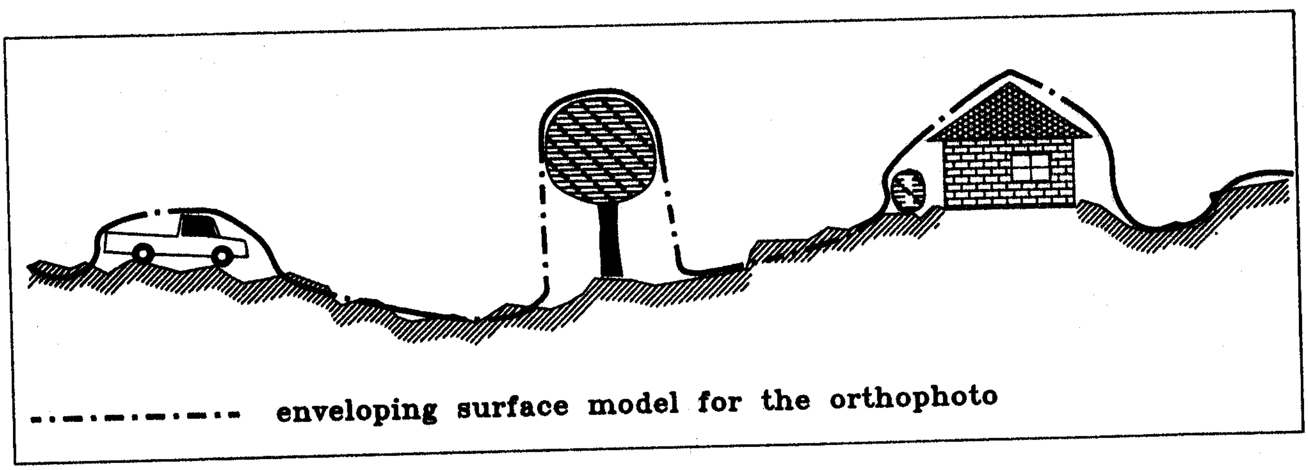

Figure 2: Surface definition for the orthophoho

Considering figure 1, one of the problems arising within the estimation process becomes obvious. The classical surface model, the DTM in the case of topographic mapping is referring to, does not include terrain noise. A second surface model following all these deviations (Fig. 2) is more consistent with the surface to which the object density (5) is related. The orthophoto estimated from multiple images with this model (cf. Fig. 2) has potentially some outstanding features: Houses, trees, bridges etc. are placed geometrically correct in the orthophoto, as far as they are incorporated in the surface model, i. e. without the relief displacement which can not be avoided in classical orthophoto production.

The general view which is given by the combination of matching and object reconstruction within a global solution is the splendid distinctive feature of this method. Other matching algorithms incorporated into this model divide the problem into parts, thus aiming at approximate solutions. In this way high efficiency can be reached, as will be discussed in the next chapter. It is interesting that Helava (1988, p. 326) critically assesses at today's state of global least squares matching: "The global solution is interesting, but in our judgment of little practical value. Besides being computationally overly demanding, it has a significant technical flaw: It does not address the main problem in photogrammetric correlation; that is resolution of ambiguities and occlutions."

3 An Approach for DTM Acquisition by Image Matching

After the review of the general least squares formulation, we now want to break the matching problem (eq. 1) into parts, giving special attention to the DTM capturing problem. It reflects the system realized at our institute for investigation purposes. From this a modular framework will result, which in the approach is characterized by the following sequence of subsequent steps:

(a) - interface to grabbing digital images resp. image patches
(b) - analysis of the image content
(c) - robust correspondence estimation of selected features from stereo images
(d) - transformation to the object space
(e) - analysis of the obtained 3D points
(f) - optionally: improving the precision by least squares matching
(g) - interface to a DTM program.

The interface (a) mainly serves two purposes: It represents first a flexible access to the data storage (image data base or analog images with online A/D conversion). Secondly it includes a resampling process of the image into a normalized image. Taking advantage of the epipolar geometry does increase the efficiency. The determination of the orientation parameters as well as the sensor calibration are arranged within a seperate preparation step. The transformation parameters (d) of the normalized image pair into the object system are given by the orientation. For details concerning coordinate systems and transformations, see Förstner (1986a).

Image matching starts by image analysis (b). Assuming that the aerial images are digitized with 20 μm pixel size there is an immense number of pixels and an enormous amount of image information given by the optical density responses, usually in terms of grey values. Extraction of significant information as an initial step has two functions: (1) reduction of the amount of information and (2) construction of location related features with feature vectors, describing the local environment of the image point. The interest operator proposed by Förstner (1986b) comprises the features "roughness" and "isotropy" for characterizing the intensity pattern at the point location (subpixel estimate). In the oriented image pair the epipolar lines and their directions are fixed. Therefore the one-dimensional version of the operator reduces to an edge operator. That the strength (number of grey value steps) of the edge directly influences the accuracy of the location estimate is well known; for the least squares estimation (topic (f)) this is true as well as for the global least squares solution (eq. 1) because the gradient $\partial g(.)$ / $\partial Z(.)$

$$\frac{\partial g(x,y)}{\partial Z(X,Y)} = \frac{\partial g(x,y)}{\partial l(x,y)} \cdot \frac{\partial l(x,y)}{\partial Z(X,Y)} \tag{6}$$

directly depends on the gradient $g_l = \partial g(.) \ / \ \partial l(.)$ along the epipolar line $l(x,y)$. By the initial feature selection edges of the image space are acquired. Because of the imaging process they can be directly described as features of the reflectance surface model (eq. 5). From this high frequency model it can be expected that features of the surface geometry (inconsistencies, break lines, lines of strong curvature) to some extent cause edges in the grey value images.

If texture is dominated by line structure, as it is the case with ploughed land for instance, the matching accuracy depends on the direction of the lines, if only one image pair covers the terrain. At this point the advantage of multi image matching of the same object is very clear, because the chance is good that at least one epipolar line is roughly orthogonal to the line structure so that also in such cases a homogeneous accuracy could be reached.

The next step (c) is feature based matching according to Förstner (1986b). The robust estimation principle included in the procedure is able to deal with considerable differences between both images (e. g. up to 30% scale difference in radiometry and geometry). At first point-correspondencies are postulated and tested referring to similarity. Here multiple correspondencies due to one point still may remain. Approximating the patch of the terrain by a coarse geometric model (inclined plane in space), wrong correspondencies are treated as outliers with respect to the model and are eliminated by the robust estimation procedure. The finally confirmed point-correspondencies then are transformed into object space, making use of the image coordinates resp. parallaxes.

The second important module after image analysis is the analysis in object space (e). Resulting from matching the points are obtained in the 3D terrain system. The density of the points referring to a predefined grid in the terrain is very high. In comparison with a regular grid as it is common with manual DTM acquisition the automatic measurement will provide about 30 to 50 times more irregularly distributed points, despite the data reduction in image space resulting from the feature selection.

Any single point we can now associate with one of the following three categories:

- either it is a point located at the terrain surface and therefore belongs to the terrain model
- or it is a point referring to terrain noise, representing a correct 3D measurement but not belonging to the terrain model
- or it still represents an erroneous point correspondence and should be eliminated in any case.

Let us choose as a simpliest surface description a regular grid and assign to each grid element one height value. Because of the dense point distribution the grid distance can be selected smaller than is common in the manual mode. More general, the heights within each grid element can be represented by a tilted plane. However then the DTM is a non-continuous linear facet model (Haralick and Watson, 1981). For the geometric modelling of a complete DTM (eq. 4) any non-continuous formulation would seem inappropriate. However in order to obtain an effective data compression within a grid element, both fits (horizontal and inclined plane) have been empirically proven to be applicable (ref. to chap. 4). The estimation process for the data compression is formulated as a robust adjustment (L1-Norm) to filter out terrain noise as well as erroneous measurements, presupposing that the area approximation represents the terrain. Difficult terrain like villages or forests therefore has to be identified interactively and excluded from matching. Of course these decisions depend on the image scale, on the resolution in height and on the grid distance chosen for the reduction process.

Finally, least squares matching (f) as a further possibility is included for improving the result if needed. The well known formulation (Ackermann, 1984), epipolar geometry incorporated, uses the location of selected points, which remain after the data reduction, as approximate values for refined least squares matching. With an interface to a DTM program (g) the automatically recorded DTM is made available for further user specific processing.
The results discussed in chapter 4 are based on the procedure described so far.

We are in the process of refining the procedure with respect to data reduction and computational speed. The data reduction step is formulated as a relaxation procedure, comparable to feature based matching. By choosing a geometric model for the DTM, e. g. a finite element model, the classification of the recorded points can be done within this model. The robust estimation as the most important feature within the relaxation procedure has to eliminate the influence of points which are outliers relative to the model (eq. 4). In principle also break line information, implicitly included in the measured data, are taken into account by automatic weighting, as was shown by Förstner (1986a, p. 144). First experience with such a relaxation module is most promising.

In order to provide good approximate values for the matching procedure the steps (b - f) are embedded in a hierarchical solution. The strategy of proceeding from coarse to fine resolution is well suited for parallel processing. The results of a level serve as input information at the next level below.

4 Empirical Investigations

The pending question of the accuracy and the reliability of automatically measured DTM we want to answer by empirical investigations. The quality assessment of the acquired DTM is derived by manual control measurements, although they are not much more precise than the automatic capturing. Results derived by error propagation could be considered as indicators in the best case, because only the transfer from measurement accuracy into the derived terrain model is treated in this way. Therefore mainly some empirical investigations are presented in the following.

For the test three different terrain types were chosen as characterized in table 1.

project name	characterization	scale	size of patch
Desert (De)	desert area, small forms, sand hills	1 : 15 000	17 x 40 mm^2
Agricult. Area (Aa)	uniform, slightly hilly, ploughed arable land	1 : 8 000	11 x 28 mm^2
Wilderness (Wi)	steep, rough area, breaklines, rock-debris	1 : 10 000	18 x 20 mm^2

Table 1. Project characteristics

A detailed description concerning concept and range of the investigation, especially in comparison of automatic and manual measurements, a full listing of the number of measured points, outlier quotas, internal estimates of the height accuracy and the achieved precision is given in Hahn and Förstner(1988). Here we restrict ourself to discussing only the most important results. The digitized images of the investigated areas are printed in Fig. 3 in order to give an overall impression. The resolution of $20\mu m$ pixel size is, of course, not visible in this print. The digitized images cover about

2 000 x 850	pixels	in the project	Desert
1 400 x 550	pixels	"	Agricult. Area
1 300 x 900	pixels	"	Wilderness .

The number of points selected and measured by the feature based matching is about
28 000 (De), 14 000 (Aa) and 21 500 (Wi),
respectively. It means that there is a considerable reduction of about one point per 50 pixels of the single image. One point represents a reflectance grid element at the terrain of about 7 x 7 pixels. It is interesting to note that for orthophoto production by a screen-process printing a pixel size of $167\mu m$ is considered to be sufficient (Wiesel, 1985). The reflectance grid element of 7 x 7 pixels of $20\mu m$ pixel size thus would meet orthophoto requirements. The distribution of the reflectance ground elements due to feature extraction is irregular, however. From aerial images (e. g. 1: 12000) the orthophotos (e. g. 1: 5000) usually are produced by enlarging scale.

The data filtering in object space implies a similar further step of data reduction combining 30 to 40 points in each geometric ground element. The appropriate size of the ground grid element was derived from profile analysis (cf. Hahn and Förstner, 1988) resulting in units of 15m (De), 7m (Aa), 8m (Wi) extension. They represent equivalent image areas of 0.6-1.0 mm^2 or 40^2-50^2 pixels, respectively.

For comparison purposes first the accuracy and the reliability of the manual DTM acquisition was assessed by carrying out two manual measurements of each project as independent as possible. From computed DTM differences between the interpolated grid points the r.m.s. values are derived. All height differences larger than 3 times the r.m.s. values are declared to be outliers (table 2).

Manual DTM	accuracy		reliability
project	r.m.s. differences		outliers
	[m]	[0.1‰h]	[%]
De	0.20	0.87	1.8
Aa	0.09	0.73	2.4
Wi	0.22	1.44	2.1

Table 2. Accuracy and reliability of manual DTMs

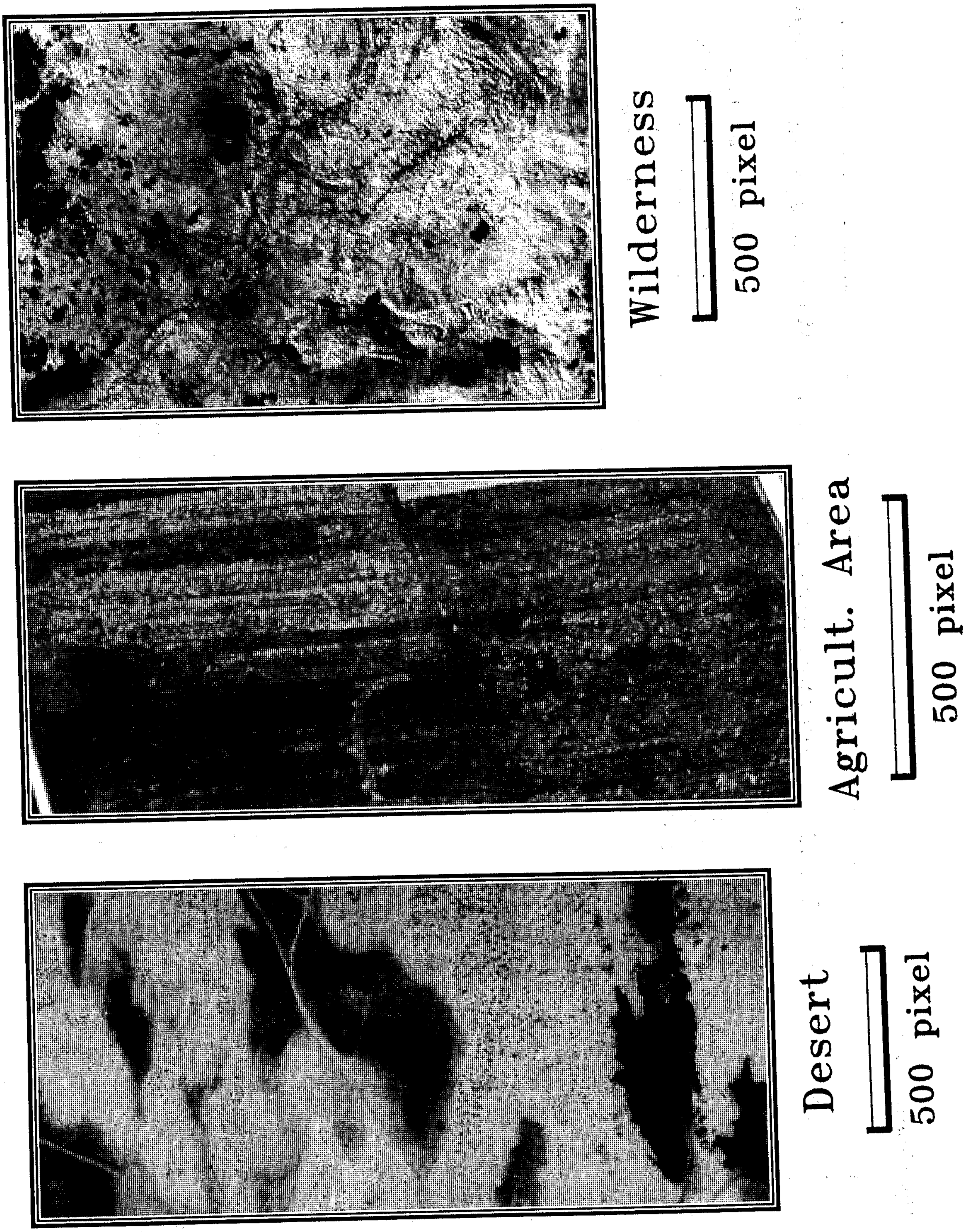

Figure 3: Images of the investigated projects

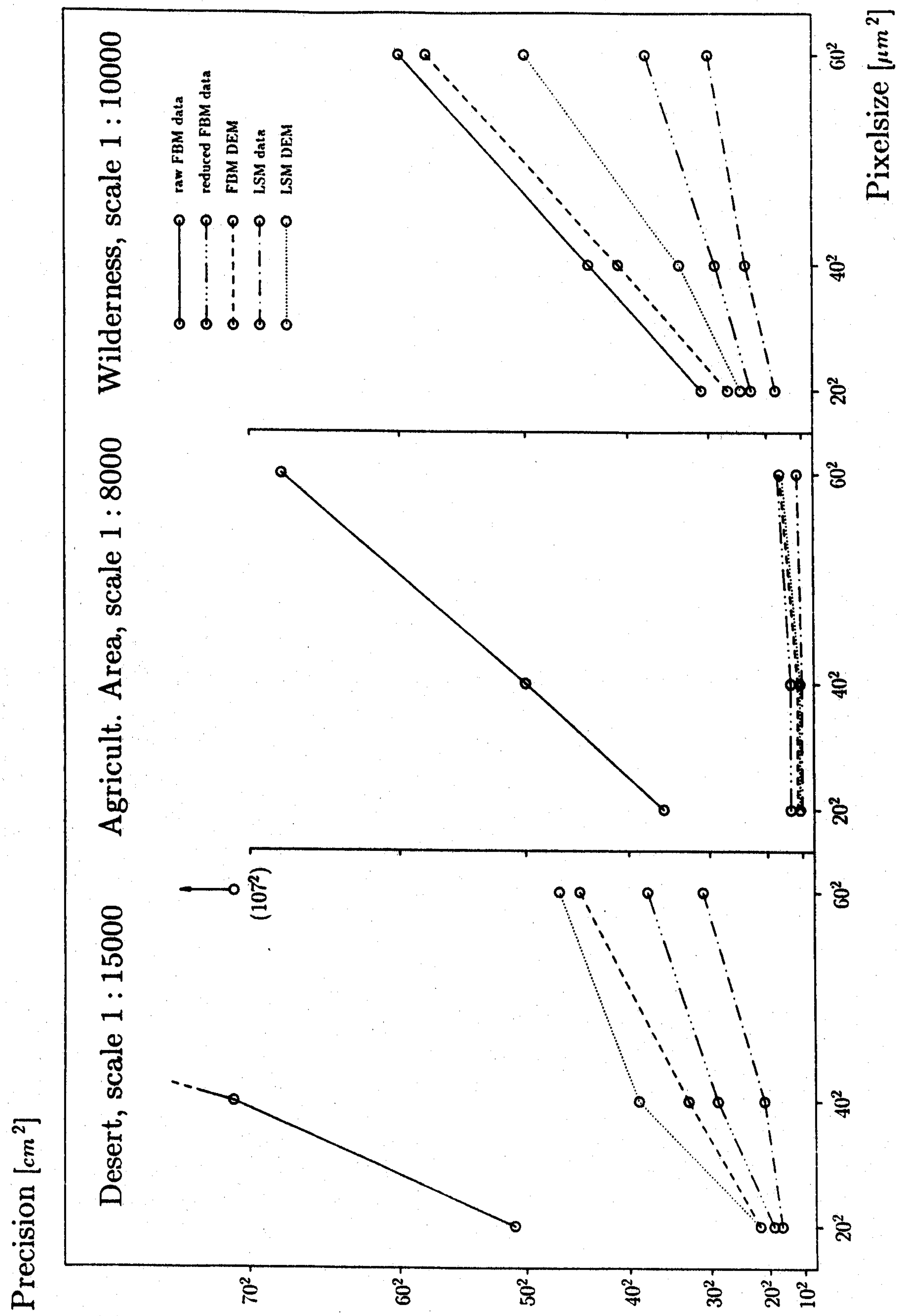

Figure 4: Empirical accuracy of the automatic measurements

The quota of approximately 2% reflects the effects of different data acquisition and of non-captured morphological features onto the interpolated grid heights. The carefully capturing of the DTMs is done by experienced operators.

In the original data measured automatically by feature based matching small gross errors prevail (up to 5% at project Wi) from imperfect correspondencies and terrain noise. Within the geometric filtering step in object space the error quota is reduced to less than 0.5% . An absolute assessment of the accuracy of the automatically derived DTM is here not possible. However it can be compared with the DTM derived from manual measurements. The height differences at the interpolated grid points of the automatically derived DTM to the manually controlled DTM are listed in table 3. The terrain model resulting from feature based matching is signed 'FBM DTM', the one resulting from additional least squares matching is given the short form 'LSM DTM'.

	FBM DTM			LSM DTM		
	accuracy		reliability	accuracy		reliability
project	r.m.s. [m]	differences [0.1‰h]	outliers [%]	r.m.s. [m]	differences [0.1‰h]	outliers [%]
De	0.22	0.94	2.4	0.22	0.95	2.8
Aa	0.11	0.94	4.2	0.10	0.84	2.6
Wi	0.27	1.76	9.0	0.25	1.64	8.2

Table 3. Accuracy and reliability of automatically derived DTMs, as compared with manual measurements

The outlier quotas for the projects De and Aa agree with that of the manual DTMs. The exactness of acquisition and modelling of the terrain shape judged by the reliability term 'outlier quota' is in the same range for the manually and automatically recorded DTM. The uncertainty increases by a factor 4 referring to the manual result for the project Wi. For valuation of this quota the threshold is lifted to 5 times the r.m.s. of the manual DTM accuracy (Table 2). The resulting outlier quota is then less than 0.5%. The differences in project Wi are mainly explainable by the measured breaklines and formlines included into the manual DTM.

A summary of the achieved accuracy is plotted in figure 4. The logogram 'raw FBM data' stands for the raw data acquired by feature based matching, 'reduced FBM data' indicate data resulting from the filtering in object space and 'LSM data' are the points estimated from least squares matching, where the reduced FBM data serve as approximate values. The digital terrain models 'FBM DTM' and 'LSM DTM' derived from the reduced FBM data and LSM data, respectively, have been already adressed in this chapter. The mean square deviation (termed precision in Fig. 4) between automatic measurements and manual control are plotted as a function of the pixel size. Essentially a linear dependency between precision and pixel size is to recognize, which in the case of the agricultural area becomes partly negligible. By DTM interpolation for the project Aa a small improvement is achieved, for the project De it is just inverse. In both projects the precision of 0.1‰ of the flying height is achieved (cf. also table 3). Because of the roughness of the terrain in the project Wi significant differences between measurement precision and DTM accuracy as well as between FBM and LSM results are found. The LSM data with an accuracy of 0.11‰h are about 40% more precise than the reduced FBM data. This propagates into the DTMs with the precision of 0.16‰h (LSM) and 0.18‰h (FBM). The manual result with 0.14‰h confirms that the precision of both results, LSM as well as FBM, is really good.

Altogether the test has shown that using the automatic procedure an accuracy level of 0.1 - 0.2 ‰h is obtained, which was one of the most important demands formulated in chapter 1.

REFERENCES

Ackermann, F. (1980): The Accuracy of Digital Height Models; Proceedings of the 37th Photogrammetric Week 1979, Schriftenreihe des Instituts für Photogrammetrie der Universität Stuttgart, Heft 6.

Ackermann, F. (1984): High Precision Digital Image Correlation; Proceedings of the 39th Photogrammetric Week 1983, Schriftenreihe des Instituts für Photogrammetrie der Universität Stuttgart, Heft 9.

Charif, M. and Makarovic, B. (1988): Optimizing Progressive and Composite Sampling for Digital Terrain Models; International Archives of Photogrammetry and Remote Sensing, Vol. 27, pp. III-264 III-280.

Ebner, H.; Fritsch, D.; Gillessen, W. and Heipke, C. (1987): Integration von Bildzuordnung und Objektrekonstruktion innerhalb der Digitalen Photogrammetrie; Bildmessung und Luftbildwesen, pp. 194 - 203.

Ebner, H. and Heipke, C. (1988): Integration of Digital Image Matching and Object Surface Reconstruction; Intern. Archives of Photogrammetry and Remote Sensing, Vol. 27, pp. III-534 - III-545.

Förstner, W. (1986a): On Automatic Measurement of Digital Surface Models; Proceedings of the 40th Photogrammetric Week 1985, Schriftenreihe des Instituts für Photogrammetrie der Universität Stuttgart, Heft 11.

Förstner, W. (1986b): A Feature Based Correspondence Algorithm for Image Matching; International Archives of Photogrammetry and Remote Sensing, Vol. 26, Part 3, Rovaniemi.

Grün, A. (1985): Adaptive kleinste Quadrate Korrelation und geometrische Zusatzinformation, Vermessung, Photogrammetrie, Kulturtechnik 9, pp. 309 - 312, Zürich.

Gülch, E. (1988): Results of Test on Image Matching of ISPRS WG III/4; Intern. Archives of Photogrammetry and Remote Sensing, Vol. 27.

Hahn, M. and Förstner, W.(1988): The Applicability of a Feature Based Matching and a Least Squares Matching Algorithm for DEM - Acqusition; Intern. Archives of Photogrammetry and Remote Sensing, Vol. 27.

Haralick, R. and Watson, L. (1981): A Facet Model for Image Data; Comput. Graphics and Image Processing, Vol. 15, pp. 113 - 129.

Helava, U. V. (1987): Digital Comparator Correlation System; Proceedings of the Intercomm. Conference on Fast Process. of Photogr. Data, Interlaken.

Helava, U. V. (1988): Object Space Least Squares Correlation; Intern. Archives of Photogrammetry and Remote Sensing, Vol. 27, pp. 321 - 331, Kyoto.

Rosenholm, D. (1986): Accuracy Improvement of Digital Matching for Evaluation of Digital Terrain Models; Intern. Archives of Photogrammetry and Remote Sensing, Vol. 26, Part 3/2, Rovaniemi.

Weisensee, M. (1988): Models of Light Reflection for Facet Stereo Vision; International Archives of Photogrammetry and Remote Sensing, Vol. 27, pp. III-360 - III-367.

Wiesel, J. (1985): Herstellung digitaler Orthophotos; in: Digitale Bildverarbeitung - Anwendungen in Photogrammetrie und Fernerkundung. H. P. Bähr (Ed.), Wichmann-Verlag, Karlsruhe.

Wrobel, B. (1987a): Digital Image Matching by Facets Using Object Space Models; Fourth Intern. Symposium on Optical and Optoelectr. Appl. Science and Engineering. Proc. of the International Society for Opical Engineering, The Hague.

Wrobel B. ((1987b): Facet Stereo Vision (FAST-Vision) - A New Approach to Computer Stereo Vision and to Digital Photogrammetry; Proceedings of the Intercommission Conference on Fast Process. of Photogr. Data, Interlaken.

ABSTRACT

Referring to general least squares matching formulations for surface reconstruction from digital images we discuss a special approach of automatic DTM capturing. The characteristic steps are the analysis in image space (feature selection and correspondence), the analysis in object space (analysis of the 3D points resulting from matching) and least squares matching for improving accuracy if needed. The reliable determination of the DTM and the achieved accuracy level of 0.1 - 0.2‰ of the flying height have been empirically verified by extensive controlled tests.

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Automatische Messung digitaler Geländemodelle mit Bildzuordnungsverfahren

ZUSAMMENFASSUNG

Bezugnehmend auf allgemeine kleinste Quadrate Ansätze zur Rekonstruktion von Oberflächenmodellen mit Bildzuordnungsverfahren werden Charakteristika eines speziellen Verfahrens zur Erfassung digitaler Geländemodelle diskutiert. Dies sind vor allem die Analyse im Bildraum mit Merkmalsextraktion und die Analyse im Objektraum mit der Datenreduktion der 3D Punkte, welche die Oberfläche sehr dicht beschreiben. Um die Genauigkeit in gewissem Maße zu steigern, kann die kleinste Quadrate Bildzuordnung verwendet werden. Der Nachweis einer zuverlässigen Bestimmung des DTMs mit einer Höhengenauigkeit von 0.1-0.2‰ der Flughöhe erfolgte durch umfangreiche empirische Tests.

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