

# EXPERIENCE WITH AUTOMATIC DEM GENERATION

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## ABSTRACT:

The development of methods for the automatic generation of digital elevation models (DEM) by digital image processing has made great progress recently, and computer programs are becoming available. The paper refers to the MATCH-T system which claims particularly high performance. Several DEMs, derived automatically from digitized aerial photographs, are analysed with regard to accuracy and speed of operation. The results confirm that the conventional standards of DEM generation are surpassed with regard to accuracy and economy.

**KEY WORDS:** DEM, Digital Image Processing

## 1. The MATCH-T System

One of the recently developed systems for the automatic DEM generation by digital image processing is the MATCH-T system. It is based on original research at the University of Stuttgart (Förstner, Hahn 1988; Hahn 1989) and has been developed as a program at INPHO GmbH, Stuttgart (Ackermann, Krzystek 1991; Krzystek, 1991; Krzystek, Wild 1992). This paper is only concerned with empirical results. Therefore the system features are only recalled very briefly.

The MATCH-T system operates with pairs of digital or digitized aerial photographs. The image data are digitally oriented and normalized in order to have the benefit of epipolar geometry. The method is based on extraction of feature points in both images, by using the Förstner interest operator. The feature points are matched to pairs of points and analytically processed to terrain points. The DEM is derived patch-wise by robust fitting of finite elements to the terrain points. The system is designed for high performance. Therefore, the processing goes through pyramidal data structures (image pyramid, feature pyramid, 7 or 8 levels), in order to be fast and autonomous, i.e. practically independent of pre-knowledge about the terrain. The number of extracted feature points is very high, leading usually to about 500 000 terrain points per stereo-pair. The derived DEM may consist of 50 000 to 80 000 grid points. Thus, a finite element grid unit may contain perhaps 10 terrain points. This redundancy allows outliers (i.e. points on trees or houses, and remaining mismatches) to be automatically recognized and eliminated. The redundancy is also the basis for high DEM accuracy, and it allows the derivation of an internal accuracy indicator. It is based on the empirical residuals and theoretical propagation of errors ( $\hat{\sigma}_{\text{int}} =$

$$\sigma_0 \sqrt{Q_{zz}}).$$

## 2. Controlled Empirical Results

### 2.1 The test material

In this paper, without further theoretical discussion, some empirical investigations and results are presented concerning the accuracy performance and the time performance of the MATCH-T system. All results refer to the batch version of the program and to the processing on the Silicon Graphics 4D35 UNIX workstation. The system is currently being transferred to the Intergraph image workstation. The photographs were digitized with the Zeiss PhotoScan PS1, at 15  $\mu\text{m}$  pixel size.

The tests with five different stereo-pairs are summarized hereafter. A very detailed description is not possible nor necessary. In table 1 the essential features of the five projects are collected.

The photographs were digitized for the areas of stereo-overlap. The DEM computation covered the model areas in principle completely. Only some small built-up areas and forest areas were defined by border lines and excluded from the accuracy evaluation, although they were included in the DEM computation. The terrain areas are reasonably suited for automatic DEM generation, as they are mostly open, although covered with scattered vegetation and houses which the system must be able to handle automatically. The first three projects relate to rather smooth terrain and large-scale photography. Projects 4 and 5 apply medium-scale photography and concern hilly and finally very rough and rocky terrain.

The figure 1 gives an impression of the types of terrain and surface coverage.

specifications	project 1	project 2	project 3	project 4	project 5
photo scale:	1:7000	1:14000	1:12000	1:22600	1:30000
flying height :	1000 m	2100 m	1900 m	3200 m	4500 m
size of DTM:	543 x 1247 m <sup>2</sup>	552 x 1075 m <sup>2</sup>	1450 x 2100 m <sup>2</sup>	2,3 x 3,8 km <sup>2</sup>	3,5 x 5,5 km <sup>2</sup>
grid width:	3m (15 $\mu$ m) 6m (30 $\mu$ m)	5m (15 $\mu$ m) 10m (30 $\mu$ m)	5m (15 $\mu$ m) 10m (30 $\mu$ m)	10m (15 $\mu$ m) 20m (30 $\mu$ m)	14m (15 $\mu$ m) 28m (30 $\mu$ m)
area description:	plain agricultural dH = 5m residential area	same as project 1	slightly hilly agricultural dH = 45m residential area	hilly smooth dH = 180m several villages	mountainous rough, rocky dH = 600m terrain breaks
interest points (left and right):	2.9 10 <sup>6</sup> (15 $\mu$ m) 0.7 10 <sup>6</sup> (30 $\mu$ m)	0.6 10 <sup>6</sup> (15 $\mu$ m) 0.15 10 <sup>6</sup> (30 $\mu$ m)	3.6 10 <sup>6</sup> (15 $\mu$ m) 0.9 10 <sup>6</sup> (30 $\mu$ m)	3.5 10 <sup>6</sup> (15 $\mu$ m) 0.9 10 <sup>6</sup> (30 $\mu$ m)	6.0 10 <sup>6</sup> (15 $\mu$ m) 1.5 10 <sup>6</sup> (30 $\mu$ m)
measured terrain points:	499005 (3m) 187120 (6m)	148771 (3m) 49275 (6m)	758658 (3m) 300346 (6m)	714997 (3m) 393356 (6m)	876425 (3m) 443159 (6m)
grid points:	75712 (3m) 18928 (6m)	23976 (3m) 5994 (6m)	122511 (3m) 30806 (6m)	87400 (3m) 21850 (6m)	97821 (3m) 24455 (6m)
points per mesh	6 (15 $\mu$ m) 6 (30 $\mu$ m)	6 (15 $\mu$ m) 8 (30 $\mu$ m)	6 (15 $\mu$ m) 9 (30 $\mu$ m)	8 (15 $\mu$ m) 16 (30 $\mu$ m)	8 (15 $\mu$ m) 16 (30 $\mu$ m)
# check points: (photogrammetric)	2123	1847	4375	3292	1778
# check points: (tacheometric)	135	135	-	-	-

Table 1 Geometrical and statistical parameters of the DEM test projects (values in brackets indicate the pixel resolution and the grid width, respectively)

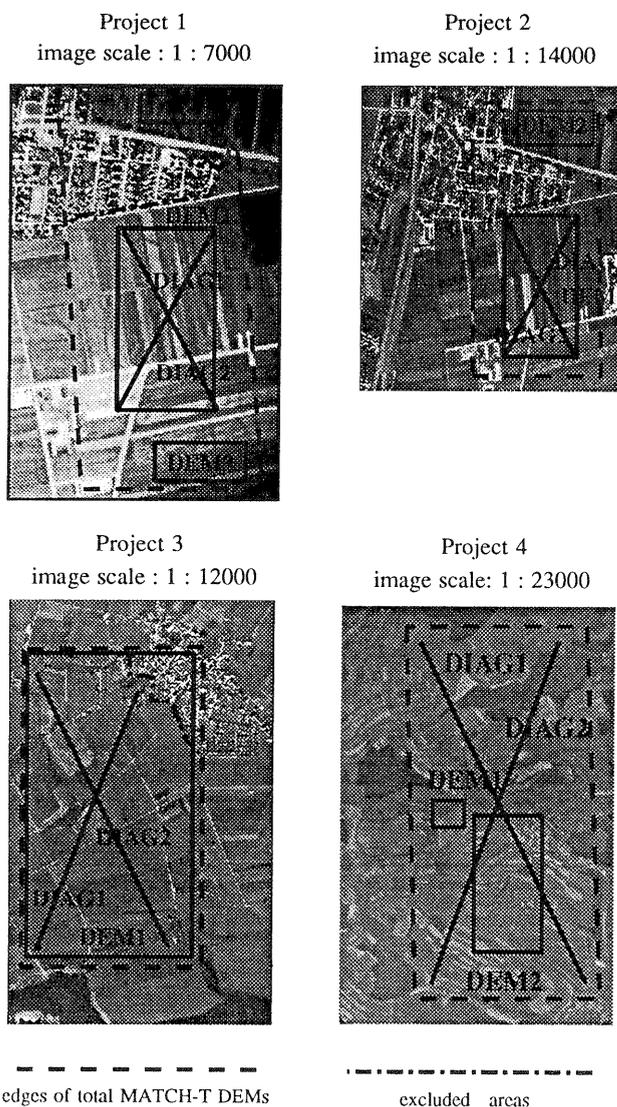


Figure 1: Image and test areas of projects 1 - 4.

## 2.2 Accuracy tests

Objective assessment of accuracy performance requires independent checks on the results. Here, the DEM results are compared with independent measurements as obtained by tacheometric field survey and, for most parts, by conventional photogrammetric measurements with an analytical plotter. The tacheometric checks refer only to projects 1 and 2. The field measurements of 135 check points were compared with the corresponding heights which were interpolated from the DEM. The photogrammetric check measurements referred directly to the grid points of the DEM.

The photogrammetric accuracy checks do not cover the complete DEM areas. Instead, representative smaller areas were selected, and diagonal profiles were measured in addition. Nevertheless, the tests can be considered quite comprehensive as they comprise in each project several thousand check points.

The photogrammetric check measurements were done with the same original photographs the digital data were scanned from (except for project 2 for which the check measurements of project 1 could be used, because of common overlap). This implies the difficulty that the photogrammetric check measurements are not more precise than the DEM heights to be checked. In fact, they have about the same accuracy, or may be even poorer.

The empirical accuracy evaluation is based on the r.m.s. height differences between the DEM heights and check heights. From these differences an estimate  $\sigma_{emp}$  is derived for the height accuracy of the automatically generated DEM, by taking the variance estimates of both components into account. If the digitally derived DEM heights and the photogrammetric check measurements are equally accurate, the DEM estimate comes down to dividing the r.m.s. height difference by  $\sqrt{2}$ .

The comparison is always made on two levels of pixel resolution, for 15  $\mu\text{m}$  and for 30  $\mu\text{m}$  pixel size. The digital images of the projects 1, 2 and 3 with 30  $\mu\text{m}$  pixel size were derived from the 15  $\mu\text{m}$ -imagery by applying a Gauss-filter, and processed separately. The respective results of the projects 4 and 5 are related to the last and next to last level of the DEM pyramid. Thus, they are not entirely independent.

The accuracy investigation presented here is restricted to DEMs without consideration of break lines. They will have to be studied in more detail in future.

The results of the empirical accuracy tests are listed below, for each project separately. The tables include several accuracy parameters and distinguish 15  $\mu\text{m}$  and 30  $\mu\text{m}$  pixel size.

$\sigma_{\text{int}}$ : the internal accuracy indicator, as obtained from the DEM generation, in m

r.m.s.d.: r.m.s. difference between DEM heights and check heights, in m

$\sigma_{\text{emp}}$ : empirical height accuracy of the DEM, as estimated from the r.m.s.d.. in m and in relative height accuracy

# points: the number of check points involved in the comparison

Project 1 (1:7000, h = 1000 m)

15 $\mu\text{m}$	DEM1	DEM2	DIAG1	DIAG2
$\sigma_{\text{int}}$	0.05	0.06	0.05	0.05
r.m.s.d.	0.10	0.13	0.10	0.11
$\sigma_{\text{emp}}$	0.04 0.04 ‰ h	0.06 0.06 ‰ h	0.05 0.05 ‰ h	0.05 0.05 ‰ h
30 $\mu\text{m}$	DEM1	DEM2	DIAG1	DIAG2
$\sigma_{\text{int}}$	0.06	0.09	0.06	0.06
r.m.s.d.	0.13	0.14	0.10	0.13
$\sigma_{\text{emp}}$	0.07 0.07 ‰ h	0.10 0.10 ‰ h	0.05 0.05 ‰ h	0.07 0.07 ‰ h
# points	2200	1092	200	152

Project 2 (1:14000, h = 2100m)

15 $\mu\text{m}$	DEM1	DEM2	DIAG1	DIAG2
$\sigma_{\text{int}}$	0.11	0.10	0.11	0.11
r.m.s.d.	0.15	0.11	0.18	0.20
$\sigma_{\text{emp}}$	0.11 0.06 ‰ h	0.08 0.04 ‰ h	0.13 0.06 ‰ h	0.14 0.07 ‰ h
30 $\mu\text{m}$	DEM1	DEM2	DIAG1	DIAG2
$\sigma_{\text{int}}$	0.17	0.18	0.18	0.18
r.m.s.d.	0.20	0.14	0.18	0.22
$\sigma_{\text{emp}}$	0.17 0.08 ‰ h	0.12 0.06 ‰ h	0.15 0.07 ‰ h	0.19 0.09 ‰ h
# points	1428	198	122	122

Project 3 (1:22600, h = 3200 m)

15 $\mu\text{m}$	DEM	DIAG1	DIAG2
$\sigma_{\text{int}}$	0.10	0.10	0.10
r.m.s.d.	0.22	0.20	0.21
$\sigma_{\text{emp}}$	0.10 0.05 ‰ h	0.09 0.05 ‰ h	0.09 0.05 ‰ h
30 $\mu\text{m}$	DEM	DIAG1	DIAG2
$\sigma_{\text{int}}$	0.18	0.19	0.18
r.m.s.d.	0.24	0.25	0.24
$\sigma_{\text{emp}}$	0.17 0.09 ‰ h	0.18 0.10 ‰ h	0.17 0.08 ‰ h
# points	4119	122	134

Project 4 (1:22600, h = 3200 m)

15 $\mu\text{m}$	DEM1	DEM2	DIAG1	DIAG2
$\sigma_{\text{int}}$	0.28	0.28	0.28	0.28
r.m.s.d.	0.56	0.65	0.55	0.57
$\sigma_{\text{emp}}$	0.37 0.11 ‰ h	0.43 0.13 ‰ h	0.37 0.11 ‰ h	0.38 0.12 ‰ h
30 $\mu\text{m}$	DEM1	DEM2	DIAG1	DIAG2
$\sigma_{\text{int}}$	0.37	0.37	0.37	0.37
r.m.s.d.	0.65	0.67	0.58	0.58
$\sigma_{\text{emp}}$	0.50 0.16 ‰ h	0.52 0.16 ‰ h	0.50 0.14 ‰ h	0.50 0.14 ‰ h
# points	2200	1092	200	152

The accuracy analysis of project 5 has unfortunately not been completed at the time of writing. (It is nevertheless included in this paper, as it does contribute to the computing time statistic below. It also is worth mentioning that the automatic DEM generation run through, although it was extremely difficult terrain).

The above results speak for themselves. They can be summarized in some statements:

- In smooth terrain the accuracy of the automatically generated DEM is extremely good, well below the threshold of 0.1 ‰ of flying height. In steeper terrain and with larger grid units the accuracy deteriorates somewhat, but is still considerably better than conventional DEMs.
- The pixel size of 30  $\mu\text{m}$  gives, in smooth terrain, practically the same accuracy as 15  $\mu\text{m}$  pixel size.
- The internal accuracy indicator  $\sigma_{\text{int}}$  seems to represent the DEM accuracy quite well. The discrepancy appearing in project 4 will have to be investigated.
- Although not shown here in detail, it can be reported that the DEM generation succeeded very well in eliminating 3D obstacles like trees or houses, and was even acceptable for most parts of the built-up areas.

The test results presented here demonstrate a surprisingly high DEM accuracy which the automatic DEM generation is capable of providing, and which is not reached by conventional photogrammetric DEM generation. This result is almost exclusively based on the high density of point measurements in the automated system. How far the test projects can be

considered representative remains to be seen. There are certainly more investigations to come in which the performance of the MATCH-T system with rugged terrain, and in relation with break lines, will be studied.

### 3. Time Performance

The test models implied the execution of the complete digital processing related to the automatic DEM generation, starting from reading the digital image data. The models were processed in batch mode on the Silicon Graphics 4D35 workstation which is a 33 MIPS, 6 MFLOPS machine. The time performance is quoted here with regard to this machine, because all models were run on it, although the program is operating on other workstations as well. The quoted computation times include all digital operations, except the absolute orientation and the measurement of border lines which were taken over from the analytical plotter.

Project #	pixel size : 15 $\mu\text{m}$	pixel size : 30 $\mu\text{m}$	remark
1	5.3 <sup>h</sup>	1.6 <sup>h</sup>	1991
2	2.1 <sup>h 1)</sup>	0.65 <sup>h 1)</sup>	1991
3	6 <sup>h</sup>	1.9 <sup>h</sup>	1991
4	3.2 <sup>h</sup>	1.1 <sup>h 2)</sup>	1992
5	3.2 <sup>h</sup>	1.1 <sup>h 2)</sup>	1992

1) part of the model 2)estimated

Table 2: Total computation times for automatic DEM generation (Silicon Graphics 4D35)

The table shows that the program version of 1991 took roughly six hours of computing time per model, with 15  $\mu\text{m}$  pixel size. With 30  $\mu\text{m}$  pixel size the computing time was reduced to less

than two hours. In the meantime the computing performance has been increased by a factor 2. At present one model takes about three hours at 15  $\mu\text{m}$  pixel resolution, and about one hour at 30  $\mu\text{m}$  pixel resolution. The further break-down of computing time gives the interesting result, for the time being, that the DEM generation module takes up 43 % of the total computing time. 67 % are used by the pre-processing modules, concerning the image normalization, the image pyramids, and the extraction of the interest points. The total system has certainly reached a high level of economic processing performance.

### 4 References

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