GENERATION OF DTM'S WITH SPACE PHOTOGRAPHS

Commission I/II

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0. Abstract

Comparative tests have been carried out with space photographs (MC, LFC, KATE 200, KFA 1000) in order to test their suitability for generation of Digital Terrain Models (DTM's) and contour lines. At first the accuracy of elevations, measured with an analytical plotter, was investigated. Grid measurements with the standard software of the analytical plotter and the method of 'Progressive Sampling' were applied to obtain terrain data for interpolation of DTM's and contour lines. For direct plotting of contour lines, a program was developed which compensates the effect of earth curvature. Finally some experiments were done with the Kern Correlator.

1. Introduction

In many disciplines (e.g. agriculture, transportation) topographic maps at scales 1 : 50 000 up to 1 : 200 000 are basic aids for planning. It is well known that for many parts of the world maps at these scales do not exist. Images from space offer an alternative for fast and economic map production / Doyle 1984 /.

Several authors / e.g. Konecny 1979, Doyle 1981 / suggest systematic or permanent space missions of modified aerial survey cameras as supplement to digital scanners images (e.g. TM, SPOT). The main advantages of space photographs are :

- a high resolution can be achieved,
- evaluation with standard photogrammetric equipment is possible,
- overlapping photos allow stereoscopic viewing and 3-D point determination.

Due to these advantages, aerial survey cameras were tested on NASA's Space Shuttle missions STS-9 (Metric Camera MC, 1983) / Konecny 1984 / and STS-41 G (Large Format Camera LFC, 1984) / Doyle 1985 /. Investigators of different institutions agreed that the planimetric accuracy is sufficient for mapping in 1 : 50 000 / e.g. Engel et al. 1986, Jacobsen & Müller 1987, Togliatti 1987 /. The critical points were above all the identification of details (map features) but also the accuracy of height determination.

Since 1976 the MKF-6 Multispectral Camera is in operation on the Soyuz-Salyut missions / Szangolies 1986 /. In the meantime also other camera systems are used. By support of the Federal Ministry of Research and Technology (BMFT) two short strips of KFA 1000 photos (Hannover, Munich) and a stero pair of KATE 200 photographs over Bavaria could be acquired from SOJUZKARTA. With these photos the investigations concerning the potential for DTM generation and contour line plotting were carried on.

2. Accuracy of Measured Heights

For near vertical photos, the theoretical accuracy of heights can be roughly estimated by :

$$\sigma_z = \frac{h}{f} \cdot \frac{h}{b} \, \sigma_{px}$$

σ_z = standard deviation of heights
h = flying altitude
σ_{px} = standard deviation of x-parallaxes
b = base
f = focal length

Depending on the image quality and the terrain relief, the standard deviation of x-parallaxes varies between 8 and 12 microns. For different cameras and endlaps, the theoretical accuracy is listed in table 1.

Camera	h [km]	f [mm]	endlap [%] 80	70	60	40	20
MC	250	305	54.3	----	27.2	18.1	13.9
LFC	235	306	----	17.0	----	8.5	----
KFA 1000	279	1011	----	----	23.2	----	11.6
KATE 200	279	200	----	----	38.8	----	----

Table 1 : Theoretical Height Accuracy (based on σ_{px}= 10 microns)

The practical investigations were performed with photos of the following test areas :

a) MC : North Germany, Alps
b) LFC : Switzerland, Liechtenstein
c) KFA : Hannover, Munich
d) KATE : Bavaria

In order to get precise ('true') heights for comparison with measured heights, spot points were digitized in maps 1 : 5 000 (North Germany, Hannover), 1 : 10 000 (Alps, Liechtenstein), 1 : 25 000 (all test areas).

The spot points were subdivided into the following terrain categories :

A) flat (terrain slope < 5°)
B) hilly (terrain slope < 15°)
C) mountainous (terrain slope < 25°)
D) steep (terrain slope > 25°)

For measurement with the Zeiss Planicomp C100 a program was developed which enables automatic planimetric precise pointing and approximate z-pointing with a random offset between 0 and e.g. 100 m. Only the precise z-pointing is done by the operator with the right handwheel. At the end of the measurement statistics of the achieved accuracy are printed. The averaged results of measurements by several operators are listed in table 2.

Camera	b : h	number of check points	terrain type flat	hilly	mountainous	steep
MC	0.60	149	---	22.1	---	---
MC	0.45	149	---	25.6	---	---
MC	0.30	307	---	31.3	---	29.2
MC	0.15	307	---	46.9	---	45.4
LFC	0.45	429	6.8	10.5	13.5	14.7
LFC	0.90	317	5.1	7.2	10.0	13.1
KFA	0.23	139	16.5	---	---	---
KFA	0.12	548	18.9	20.8	20.4	25.2
KATE	0.36	388	---	---	17.6	40.4

Table 2 : Root Mean Square Differences between Spot Heights (Map) and Measured Heights (corrected by systematic differences)

3. Generation of DTM's

A DTM can be defined as regular grid of terrain points with known elevations. With an analytical plotter , a DTM can be generated by computer supported direct measurement of the heights of the grid points. The more accurate method is known as 'Progressive Sampling'. A regular basic grid is densified only in difficult areas with rough terrain surface. Both methods were applied to the space photographs.

At the Institute for Photogrammetry and Engineering Surveys (IPI) of the University of Hannover a program package for Progressive Sampling was developed for the Zeiss Planicomp C100. The program system contains modules for :

- definition of a working area and cut-off areas by measurement of polygons,
- measurement and analysis of terrain profiles to find an optimum basic grid spacing,
- measurement of 'break lines' and 'form lines',
- measurement of a basic grid,
- on-line densification of the basic grid or alternatively
- off-line computation of densification points for later measurement,
- finding the optimum densification criteria.

For every measured point of the basic grid a combination of the following criteria can be used for densificaton :

- slope differences to neighbouring points,
- the difference between the measured height and the interpolated height (out of the surrounding points),
- the standard deviation of the interpolated height,
- the terrain curvature.

In a model of MC photos, a regular grid was measured with the standard software of the Planicomp. The 6.3 km x 5.6 km test area 'Josefsthal' is situated near Rottach-Egern in the Bavarian Alps. The spacing of the grid points was 100 m. In addition to 3648 grid points, 208 'break line' points were measured.

The same procedure was applied to LFC photos. The test area 'Zug' contains a steep slope near the lake and a hilly plateau. In total 51 x 61 grid points were measured with a grid spacing of 100 m.

The Progressive Sampling method was tested with KFA 1000 photos. The size of the test area 'Rottach-Egern' is 5.4 km x 6.5 km. A basic grid was measured with a point distance of 125 m. A maximum difference of 20 m between the measured and the interpolated heights was used as the only criterion for densification. In a first densification step 1087 new points were measured. In second step only 73 more points were measured.

In order to test the accuracy of the DTM, also digitized spot points from existing maps were used. The heights of these points were interpolated with the University of Hannover's interpolation program TASH. The number of check points (n) and the root mean square (rms) and maximum (max) differences can be taken from table 3.

Camera	b : h	n	rms	max
MC	0.30	92	42.3	103.5
LFC	0.90	55	20.3	90.4
KFA	0.12	52	24.0	92.5

Table 3 : Accuracy of Generated DTM's

4. Interpolation of Contour Lines

The generated DTM's were used for interpolation of contour lines with the TASH program. The interpolated contours were then compared with those from existing maps 1 : 10 000 resp. 1 : 25 000. This was done by digitizing the map contours and computing the shortest distances between two corresponding contour lines for every point of the interpolated contour line polygon (see fig. 1). With the terrain slope (S mean), the mean planimetric discrepancies D were converted into mean elevation errors (E mean) for the contour lines. The results are listed in table 4.

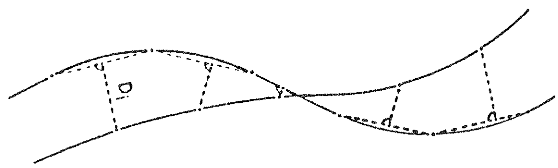


Fig. 1 : Comparison of Map and Interpolated Contours

Camera	S mean [%]	E mean [m]
MC	32	52.0
LFC	19	24.3
KFA	31	43.5

Table 4 : Accuracy of Interpolated Contour Lines

The interpolated contours overlayed with the map contours are shown in fig 2 for test area 'Josefsthal' and in fig. 3 for test area 'Zug'. Fig. 4 shows the interpolated contour lines for test area 'Rottach-Egern' together with the positions of the basic grid points and the densification points.

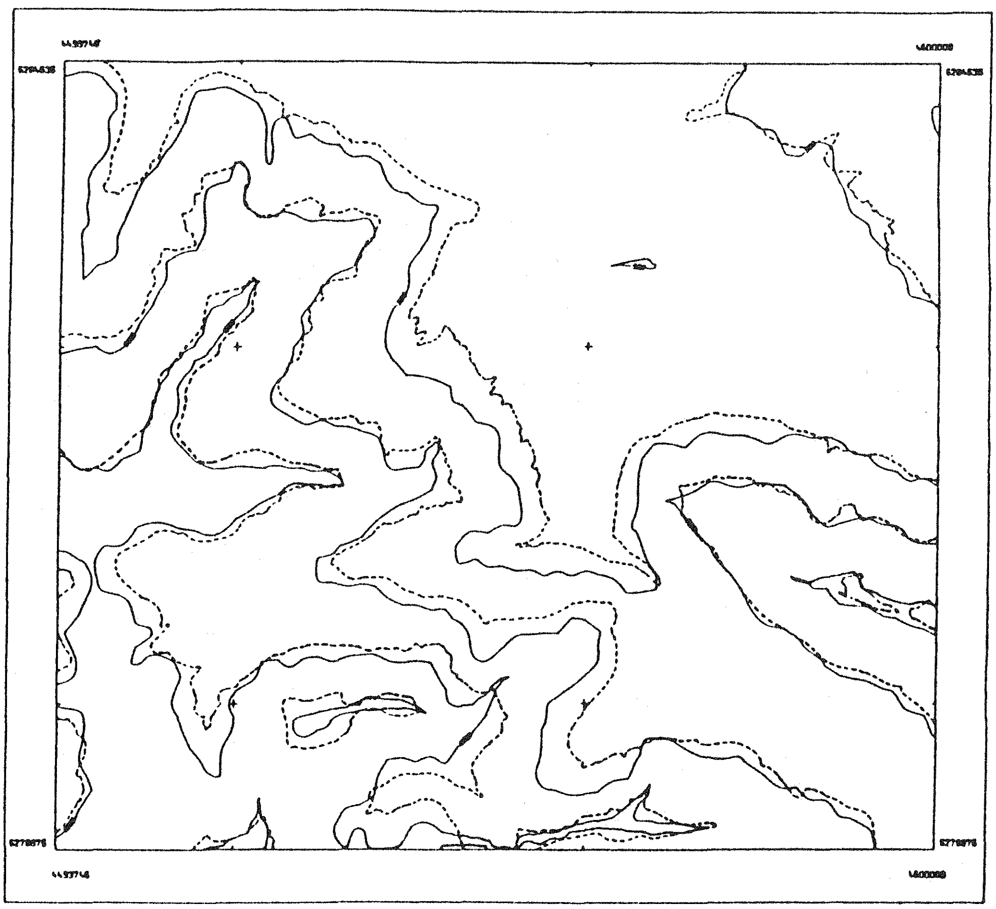


Fig. 2 : Comparison of Interpolated Contours (solid) and Map Contours (dashed) for Test Area 'Josefsthal' (approx. scale 1 : 53 000)

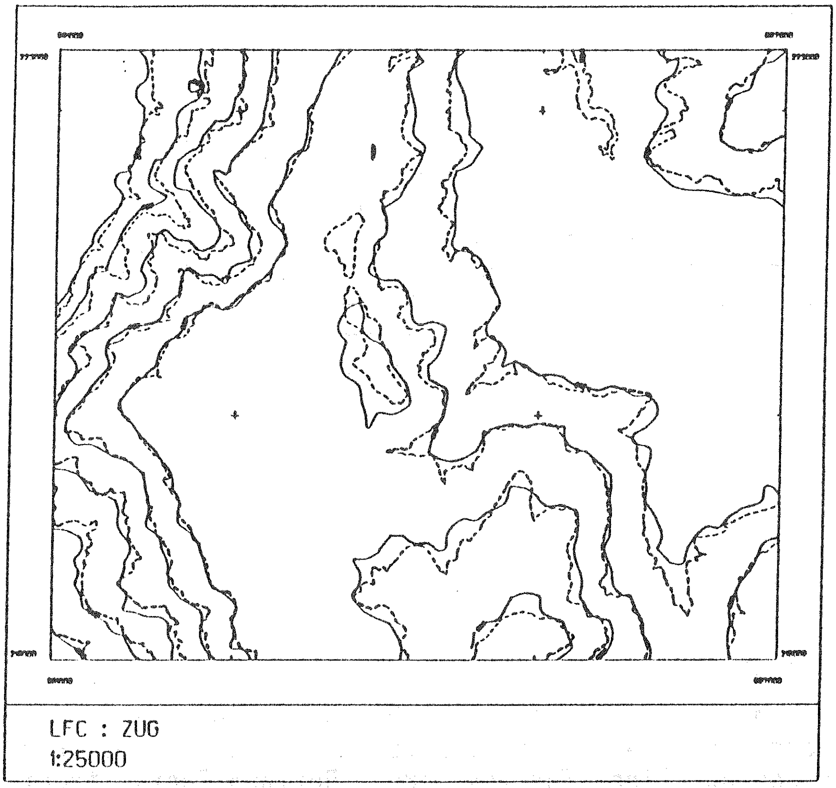
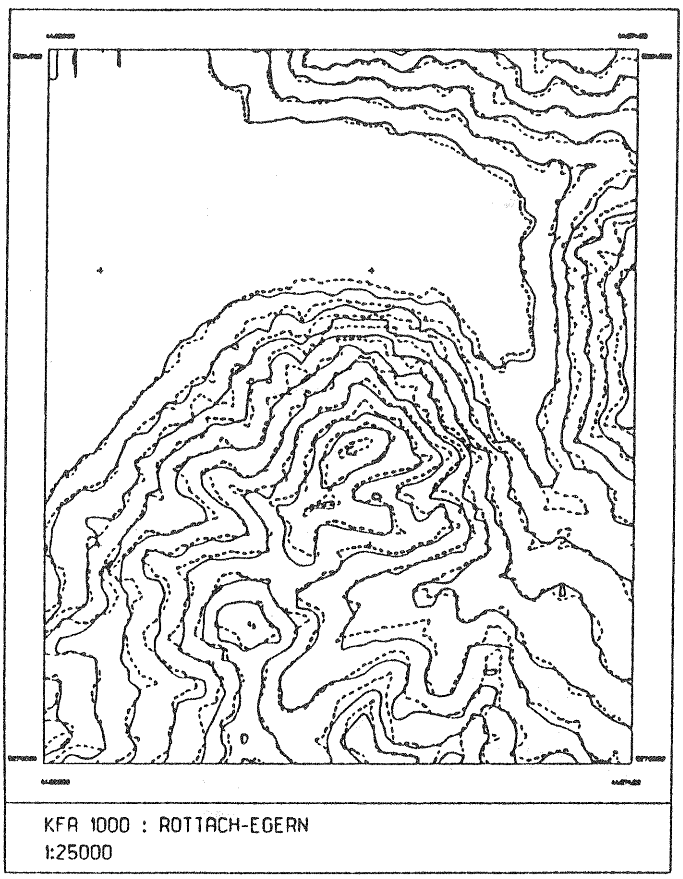


Fig. 3 : Comparison of Interpolated Contours (solid) and Map Contours (dashed) for Test Area 'Zug' (approx. scale 1 : 61 000)



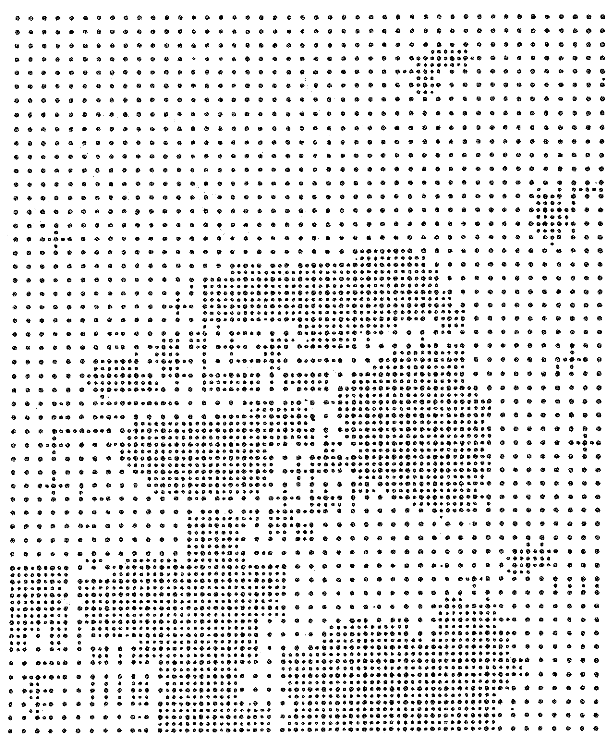


Fig. 4 : Comparison of Interpolated Contours (solid) and Map Contours for Test Area 'Rottach-Egern' (approx. scale 1 : 68 000)
Basic Grid Points (thick) and Densification Points (thin)

5. Direct Plotting of Contour Lines

The mathematic model of the central perspective projection requires a 3-D cartesian object coordinates system. However the results of the photogrammetric evaluations are expected in separate national coordinate systems for planimetry and heights, which do not meet the above mentioned requirements. In the case of small scale space photographs, the deviations cannot be neglected or compensated by standard 'earth curvature corrections'.

At the IPI a program has been developed for the Zeiss Planicomp C100 which enables a nearly strict solution for direct plotting of contour lines. A local cartesian coordinate system has to be used for model orientation. Every 0.5 sec the program calculates corrections for the photo carriage coordinates by strict transformations between the local coordinate system and the national map projection system (e.g. UTM). This cycle is fast and accurate enough since the floating mark is being moved slowly.

At first some selected contour lines were measured several times in order to check the internal accuray. Then contours were drawn for the whole test area with intervals of 50 m (LFC) resp. 100 m (MC, KATE 200). The accuracy of the contours was checked in the same way like for the interpolated contours. The results are listed in table 5. It should be mentioned that expecially in the MC and LFC photos some parts of the terrain were hardly visible because of shadows. For test area 'Vaduz', fig. 5 shows some of the repeatedly measured contours and fig. 6 shows the contour lines for the whole test area. Overlays of directly plotted contour lines and map contours are shown in fig. 7 for test area 'Zug' and in fig. 8 for test area 'Rottach-Egern'.

Camera	test area	b : h	S mean [%]	E mean [m] (internal)	E mean [m] (external)
MC	Josefsthal	0.30	32	25.6	54.5
MC	Karwendelgeb.	0.30	26	21.9	----
LFC	Zug	0.90	19	17.8	24.7
LFC	Vaduz	0.45	33	22.5	31.6
KATE	Rottach-Egern	0.36	31	47.3	69.4

Table 5 : Internal and External Accuracy of Directly Plotted Contour Lines

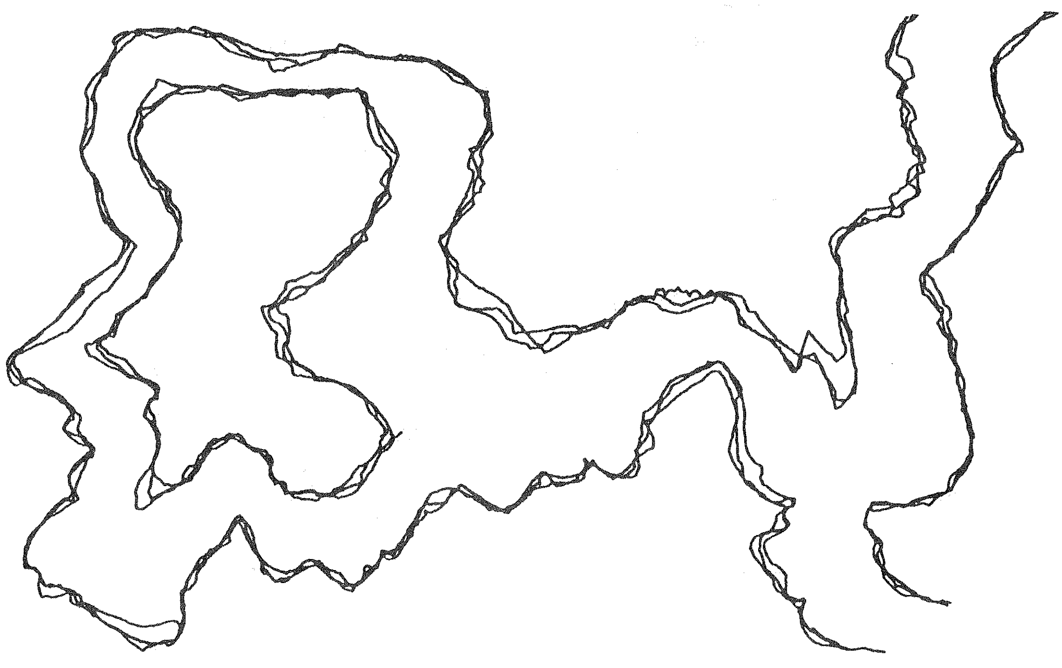


Fig. 5 : Test Area 'Vaduz' - Repeatedly Measured Contours (scale 1 : 25 000)

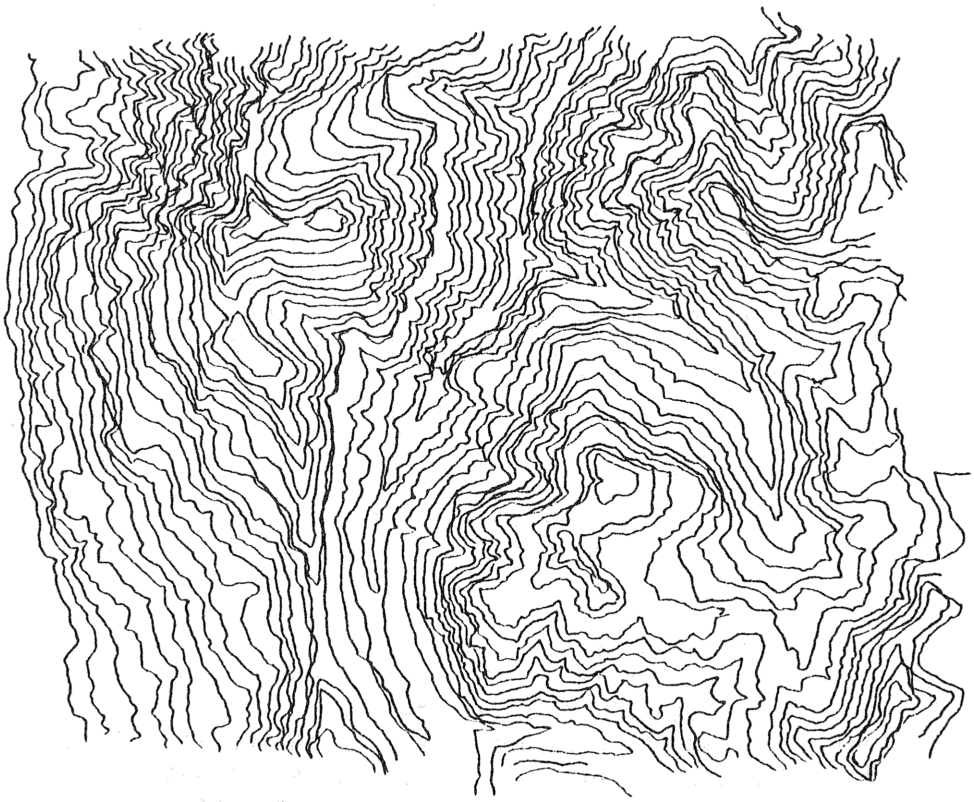


Fig. 6 : Test Area 'Vaduz' - Directly Plotted Contours
(50 m interval, approx. scale 1 : 61 000)

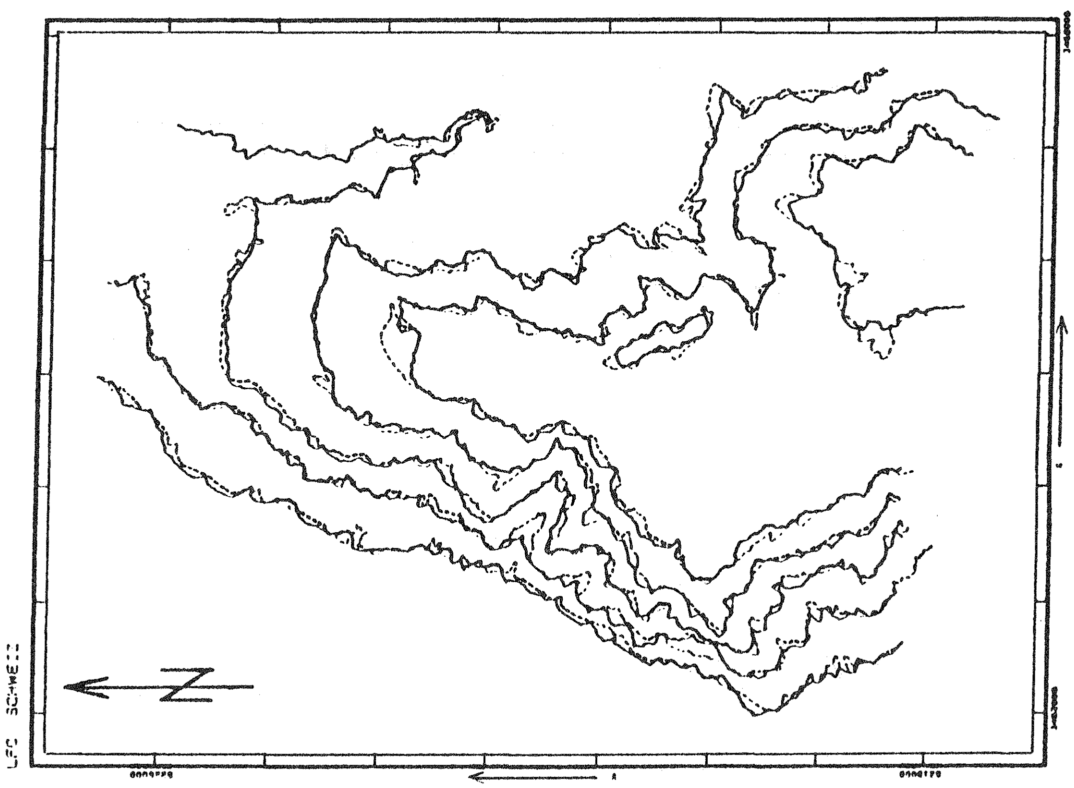


Fig. 7 : Comparison of Directly Plotted Contours (solid) and Map Contours
(dashed) for Test Area 'Zug' (approx. scale 1 : 68 000)

Fig. 8 : Comparison of Directly Plotted Contours (solid) and Map Contours (dashed) for Test Area 'Rottach-Egern' (approx. scale 1 : 61 000)

6. Experiments with the Kern Correlator

Further tests for generation of DTM's were performed with the Kern Correlator / Cogan & Hunter 1984 / using MC and LFC photos. For correlation, the following aspects are of interest :

- accuracy of heights,
- number of correlation failures,
- correlation speed.

With respect to these criteria, different parameter sets were tested. Since the interaction of the operator was required in case of a correlation failure, the main objective was to find parameter sets with a minimum number of failures and acceptable height accuracy. The average speed for correlation of one point varied between 3.5 and 22 seconds (using a DEC PDP 11/73). Only parameter sets with a speed better than 10 seconds were used.

The first tests / Konieczny 1987 / were done by a guest student from the University of Warsaw, Poland. A stereo pair of MC photos over China (60% overlap, CIR) was used. In order to find optimized parameter sets, small grids (c. 30 points) with different terrain characteristics were measured manually and with the correlator. The internal accuracy of manually measured heights was between +/- 15 m and +/- 18 m (from double measurements). The final accuracy checks were done with larger point grids of 240 - 300 points. The number of points (n), the systematic difference (bias) against manually measured heights, the root mean square difference (rms), the maximum differences (max) and the number of correlation failures are listed in table 6.

terrain type	n	bias	rms	max	failures
a) frozen lake	240	-15.6	55.1	161.6	0
b) flat dessert	250	-42.8	98.4	305.7	2
c) hilly	300	-5.2	52.4	170.3	0
d) mountainous	240	-10.4	50.9	205.5	0
e) mixed of a) - d)	300	-11.7	54.7	215.4	1

Table 6 : Correlation Results for MC China

The operational application was tested by generating a DTM (48.4 km x 37.6 km, point distance 400 m, elevations from 4480 m - 5510 m) for orthophoto production. The test area contained all terrain types of table 6. Therefore the total area was split into 9 subareas. Only two different parameter sets were used. The first 250 points of each subarea were remeasured manually. The root mean square of the differences was 58.6 m . The correlation procedure failed only for two points.

A second test with MC photos was done with b/w images of the Alps (80% overlap). Again small grids were used to find suitable parameter sets. Table 7 shows the results for different terrain types.

terrain type	n	bias	rms	max	failures
a) flat	110	11.1	48.0	108.8	3
b) hilly	110	-18.8	39.4	115.3	0
c) mountain (south side)	98	-31.7	42.3	99.1	0
d) mountain (north side)	108	99.1	147.7	487.9	9
e) mixed of a) - d)	98	21.6	81.6	307.5	0

Table 7 : Correlation Results for MC Alps

The same points were also correlated in a model with 40% overlap. Now the frequency of correlation failures varied from 10% to 33%. Also the root mean square difference increased approximately 15%. This may be due to different contrasts in the left and the right image and longer shadows than in the MC China photos. Also in general the optical density of the photos was too high. An image analyser was used to adjust the illumination of the photos. However, this can be done once before starting the correlator and it is not possible to make the adjustment for every point.

With the LFC photos of Switzerland small grids were correlated in all three possible models (70% resp. 40% overlap). The correlation results are listed in table 8. Only in the flat terrain (model 1281/82) the correlation failed for two points.

terrain type	model	n	bias	rms	max
flat	1280/82	117	-5.3	42.3	93.4
	1280/81		14.4	76.8	165.9
	1281/82		-2.0	68.8	218.3
hilly	1280/82	105	0.0	38.8	103.9
	1280/81		21.1	87.3	215.4
	1281/82		18.3	80.3	185.4
mountain (south side)	1280/82	99	-14.4	55.5	121.0
	1280/81		-47.7	96.6	210.5
	1281/82		-15.4	89.4	189.7
mountain (north side)	1280/82	143	59.9	128.2	341.6
	1280/81		65.7	163.6	387.6
	1281/82		84.8	175.0	413.7

Table 8 : Correlation Results for LFC Switzerland

In some cases better results (up to 25%) were achieved with other parameter sets and other correlation strategies, but at the same time the number of correlation failures was growing. In the meantime Kern has improved the soft- and hardware of the correlator. If the correlation fails, the program continues without interaction of the operator. That means that the accuracy of the correlated heights now has the highest priority. It can be assumed that with the new equipment, using accuracy optimized parameter sets, considerably better results can be obtained.

7. Conclusions

The results have shown that DTM's, generated from manual point measurements with analytical plotters, have always a sufficient accuracy for orthophoto production. On easy terms this is also the case if the Kern Correlator is used. Contour lines can be interpolated or directly plotted. Both methods yield approximately the same accuracy. However, direct plotting of contour lines is nearly tree times faster. Depending on the image quality, with the best base/height ratios the following contour intervals seem to be possible :

Metric Camera	75 - 125 m
Large Format Camera	25 - 50 m
KFA 1000	50 - 100 m
KATE 200	75 - 125 m

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