PROGRESSIVE SAMPLING AND DEM INTERPOLATION BY FINITE ELEMENTS

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SUMMARY

The method of DEM Interpolation by Finite Elements was first suggested in 1978. Based on this concept the HIFI minicomputer program package was developed and presented at the ISP Congress 1980 in Hamburg. In 1983 the PROSA program for computer supported acquisition of DEM data was written in Munich. It makes use of the method of Progressive Sampling and runs in conjunction with the analytical plotters Zeiss Planicomp. Data acquisition starts with the measurement of break lines and a sparse grid, which subsequently is densified according to the local shape of the terrain and the accuracy requirement.

The paper gives a description of data acquisition with PROSA and DEM interpolation using HIFI. Then examples of the combined use of progressive sampling and DEM interpolation, including derivation of digital contours are presented. The obtained results demonstrate the efficiency of PROSA and HIFI with regard to economy and quality. The paper is concluded with comments on research and future developments.

1. INTRODUCTION AND REVIEW

The paper presented deals with photogrammetric computer-supported DEM data acquisition, successive interpolation of a grid DEM and derivation of further information from this DEM.

Data acquisition is carried out with the PROSA program which was developed in Munich on behalf of Carl Zeiss and was presented first at the photogrammetric week in Stuttgart 1983 /REINHARDT, 1983/. The program is written in FORTRAN and runs in conjunction with the analytical plotters Zeiss Planicomp /RODENAUER, 1983/. Starting with the measurement of break lines and a sparse basic grid the final point density is matched to the terrain conditions and the accuracy requirements. This method was introduced by /MAKAROVIC, 1973, 1977/ under the name "Progressive Sampling" and "Composite Sampling" respectively. Further papers on this topic were published by /RODENAUER, 1980/, /BISHOP, 1981/ and /LEUPIN et al, 1982/.

From the reference points of varying density and the break lines a regular grid DEM can be interpolated with the HIFI program package /EBNER et al, 1980/, using the Finite Element Method. HIFI also allows for derivation of perspective views, orthophoto and stereo orthophoto profiles, contours and slope maps from the DEM.

The paper gives a description of data acquisition with PROSA and DEM interpolation using HIFI. Then examples of the combined use of progressive sampling and DEM interpolation, including derivation of digital contours are presented. The obtained results demonstrate the efficiency of PROSA and HIFI with regard to economy and quality. The paper is conluded with comments on research and future developments.

2. DEM DATA ACQUISITION USING PROSA

DEM data acquisition starts with the measurement of break lines and a basic grid. Then second differences of heights are computed at the grid points in both directions taking into account the break lines. If the two second differences at a grid point are below a pre-chosen threshold value, no further measurement is made in this area. If at least one second difference exceeds the threshold, the basic grid is locally densified to half the original mesh size. This can be repeated until the smallest grid width is reached. With the number of densification steps, however, the risk of overlooking reference points increases. Therefore a restriction to two steps of densification is recommended. The size of the basic grid then is the quadruple of the minimum grid width, which itself is chosen by experience. Principally, it can also be obtained as the result of a separate terrain analysis procedure. See for instance /TEMPFLI, 1982/.

For local densification of the basic grid, the overall area is subdivided into patches of approximately eyepiece image size. Each patch is processed completely with up to two densification steps. The patches are measured in a back-and-forth sequence so that adjacent patches can be reached in the shortest possible time. The floating mark is prepositioned to the densification points in plan and elevation. The elevation is interpolated linearly from adjacent grid or break line points and increased slightly so that the operator can set the floating mark from above. During point densification noticeable delays in time do not occur. If ground visibility is obstructed by trees or houses, deviating from the preset planimetric points is possible. Moreover measurement can be interrupted whenever a patch has been completed with the possibility to continue at next program call with the next patch by entering a code.

For the generation of a high quality DEM and especially for the derivation of digital contours geomorphological information of the terrain should be taken into account besides the reference points. Here break lines are of particular importance. Thereby it is reasonable to collect these data first because they should be considered during progressive sampling. As break lines often separate smooth areas reference points can be saved in these areas by considering the break lines. Figure 1 shows the planimetric position of break lines and reference points acquired using PROSA.

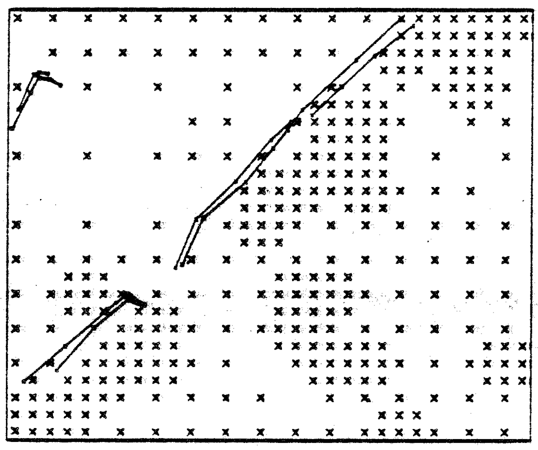

Figure 1: Planimetric position of break lines and reference points acquired using PROSA

The measured break lines and reference points are shown in plan on the graphics CRT screen of the analytical plotter to allow the operator to check that the whole area has been measured. Especially for the break lines supplementary measurements could become necessary. In this case the measurement can be interrupted when the patch has been completed for measuring additional break lines. After that progressive sampling can be continued with the next patch by entering a code.

The second height difference computed from three successive points is used as a criterion for grid densification. This second difference is computed for X and Y direction and is compared with a pre-chosen threshold value. The results of investigations have shown that a threshold value between 1 $^{o}/oo$ and 2 $^{o}/oo$ of the flying height leads to optimum accuracy and economy.

3. DEM INTERPOLATION USING HIFI

DEM interpolation by Finite Elements was first suggested in 1978 /EBNER, 1979/. Based on this concept the HIFI minicomputer program package was developed and presented at the ISP Congress 1980 in Hamburg /EBNER et al, 1980/. Results from representative practical applications have been presented in 1984 /EBNER and REISS, 1984/. The DEM used in HIFI is of grid type. The heights of grid points are interpolated from the heights of arbitrarily distributed reference points and points along break lines using the Finite Element Method.

For terrain description an interpolation surface is defined. It is formed of local surface elements, which are tied together accordingly. If break lines have to be considered, separate bilinear polynomials are defined for the individual grid meshes and continuity along the borders of adjacent elements is guaranteed. The interpolation surface is then determined in such a way, that the weighted sum of squares of the residuals at the reference points and of the second differences of the heights of adjacent grid points is minimized and the given break lines are represented adequately as shown in figure 2. For details see /EBNER et al, 1980/.

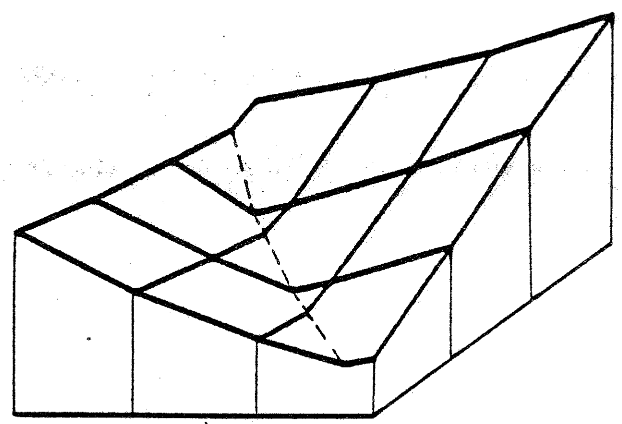

Figure 2: HIFI grid DEM with a break line

The HIFI program package was developed for use with minicomputers and is written in FORTRAN. It is in operation in more than 20 organisations and can be used in conjunction with the analytical plotters Zeiss Planicomp and the analytical orthoprojector Zeiss Orthocomp /FAUST, 1984/. In these cases HIFI runs on a Hewlett-Packard minicomputer HP 1000 or a microcomputer HP 1000 A. Additional HIFI implementations are available for Prime, Digital Equipment- and IBM-computers.

Besides the interpolation of the grid DEM, HIFI allows for derivation of perspective views, orthophoto and stereo orthophoto profiles, contours and slope maps from the DEM.

4. EXAMPLES OF THE COMBINED USE OF PROSA AND HIFI

4.1 Example Donauwoerth

Project Data

- one map sheet of the base map of Bavaria at the scale of 1:5000, 2335 x 2335 m^2
- Zeiss RMK A 15/23 photography, photo scale 1:14.400, two models

Data acquisition (Zeiss Planicomp, PROSA)

- preparations, orientations, measurement of break lines (1108 points), 3.5 hours
- measurement of an 80 m basic grid, locally densified to 40 m and 20 m respectively (4141 points), 3.5 hours

Further processing (HIFI, Zeiss DZ 7 tracing table)

- interpolation of a 20 m grid DEM (14157 points)
- derivation of 2.5 m digital contours from the DEM
- contour plotting at the scale of 1:5000

Data acquisition with PROSA was based on a threshold value of 4 m (∿ 2^{0}/oo of the flying height) for the second height differences. The required time of 3.5 hours is only 30 % of the estimated time of 11.5 hours which would have been necessary to measure a full 20 m grid. The total time, including preparatory work is 7 hours or 47 % of a time of 15 hours, estimated for the measurement of a full 20 m grid.

To allow for an evaluation of the economy of progressive sampling and the quality of the final contours a part of 2000 m x 880 m of the total area was investigated in more detail. In that area a full 20 m grid was measured and compared with sub-sets of points of an 80 / 40 / 20 m grid, as would have resulted from data acquisition with PROSA. In this way the problems of separate measurements with different random errors could be avoided. These simulations of PROSA were based on threshold values of 2 m and 4 m.

Figure 3a shows 2.5 m contours obtained with HIFI from 437 points along break lines and 4545 reference points of the full 20 m grid.

Figure 3b represents the corresponding contours, obtained from the same break lines but only 2668 PROSA points, as they result from a threshold value of 2 m (∿ 1 ^{0}/oo of the flying height). Compared with the full 20 m grid the number of reference points is reduced to 59 %, the quality of contours, however, is scarcely affected.

Finally, figure 3c shows the contours, resulting with a threshold value of 4 m (∿ 2 ^{0}/oo of the flying height) and 1125 PROSA points. Compared with the full 20 m grid the number of reference points is now reduced to only 25 %. Although in flat areas the contours are much more smooth, the terrain representation in general is still adequate.

The results of this example demonstrate the efficiency of the combination of PROSA and HIFI with regard to economy and contour quality.

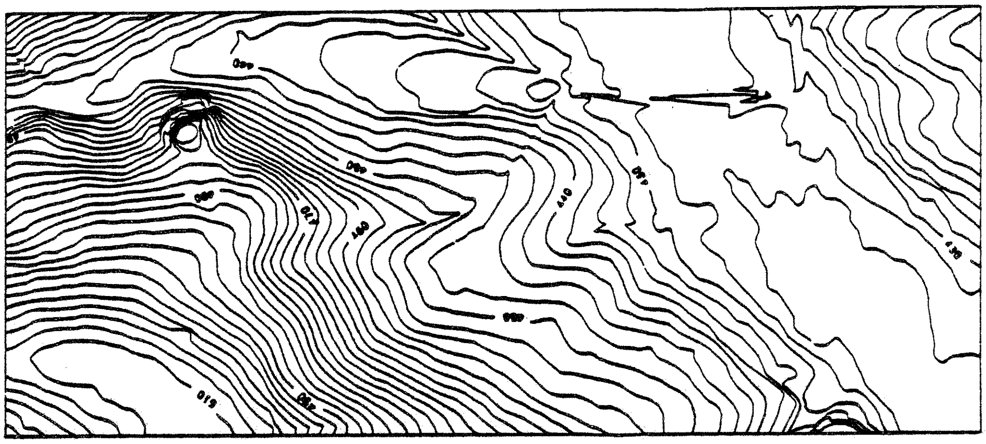

Figure 3a: Example Donauwoerth. 2.5 m contours obtained from 437 break line points and 4545 reference points of a 20 m grid using HIFI

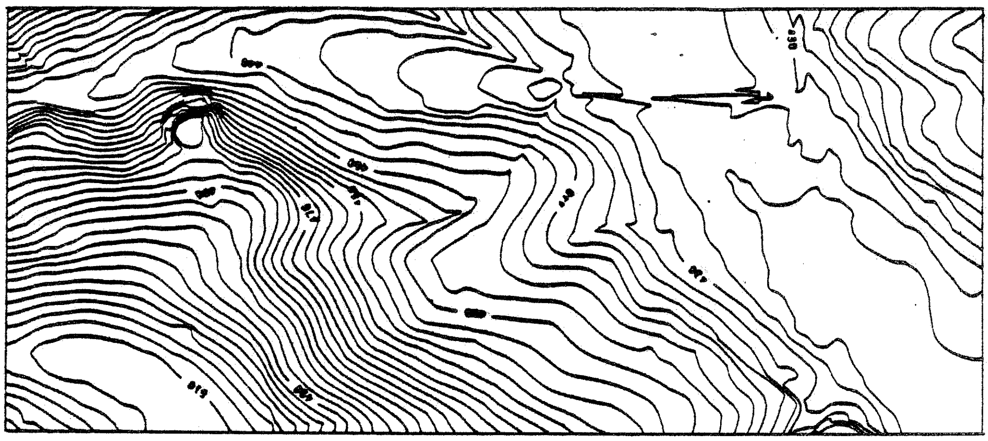

Figure 3b: Example Donauwoerth. 2.5 m contours obtained from 437 break line points and 2668 PROSA points using HIFI

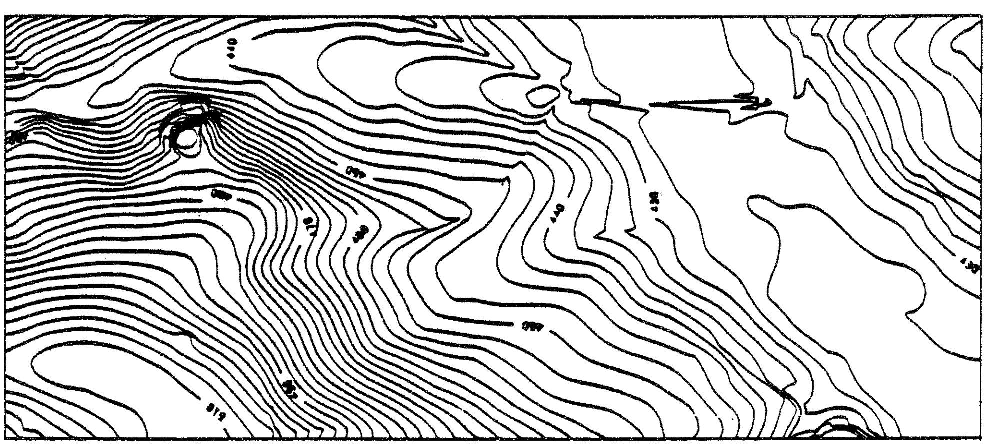

Figure 3c: Example Donauwoerth. 2.5 m contours obtained from 437 break line points and 1125 PROSA points using HIFI

4.2 Example Nordheim

Project Data

- one map sheet of a local map at the scale of 1:2000, 704 x 704 m^2,
- Zeiss RMK A 15/23 photography, photo scale 1:5000, two models

To be able to compare the use of PROSA with the measurement of a full grid in respect of economy and accuracy first a dense 8 m grid was measured from which the following three sub-data sets were derived:

- a full 16 m grid
- a 32 m grid, locally densified to 16 m and 8 m respectively, simulating PROSA with a threshold value of 1.0 m (∿ 1.3 °/oo of the flying height)
- a 64 m grid, locally densified to 32 m and 16 m respectively, simulating PROSA with the same threshold value of 1.0 m

From each of these data sets an 8 m grid DEM was interpolated, using HIFI (7921 points). All points of the measured 8 m grid, not used as reference points, were now used to check the accuracy of the respective grid DEM.

Table 1 represents the number of reference points, the RMS values and the maximum values of the discrepancies at the check points as well as the percentages of discrepancies exeeding 0.50 m for all three data sets.

Input data set	reference points		discrepancies at check points		
	number	%	RMS	maximum	> 0.5m(%)
full 16 m grid	2025	100	0.15	1.56	0.83
32/16/8m grid	1749	86	0.14	0.75	0.45
64/32/16m grid	1137	56	0.16	1.45	0.90

Table 1: Example Nordheim. Comparison of a full grid with two PROSA grids in respect of economy and accuracy

Compared with the full 16 m grid, the 32 / 16 / 8 m PROSA grid reduces the number of required reference points slightly to 86 %, but leads to a better DEM accuracy. A closer look at the results shows that the maximum value of the discrepancies at the check points and the percentage of discrepancies exceeding 0.5 m become considerably smaller, when PROSA is used. This is due to the fact that the 32 / 16 / 8 m grid allows for a higher density of points in areas of rough terrain, than the full 16 m grid does.

The 64 / 32 / 16 m PROSA grid reduces the number of reference points to 56 % of the full 16 m grid, without significant loss of accuracy. Figure 4 shows the corresponding reference points and the interpolated DEM in a perspective view.

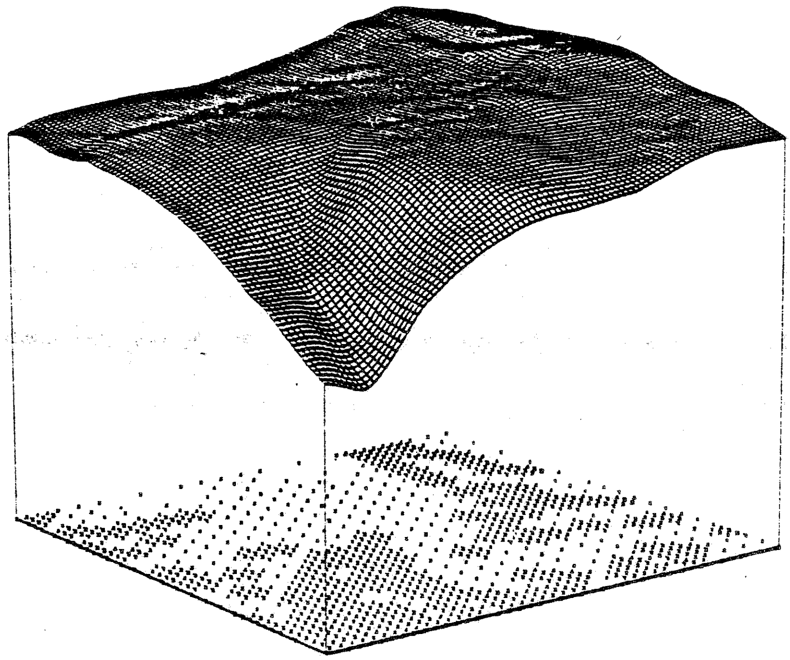

Figure 4: Example Nordheim. Perspective view of an 8 m DEM, interpolated from a 64 / 32 / 16 m PROSA grid using HIFI

The obtained results demonstrate that the use of PROSA instead of the measurement of a full grid leads to better accuracy or better economy. To which of both priority is given depends on the given facts of the respective project.

5. RESEARCH AND FUTURE DEVELOPMENTS

The examples presented have shown that two major parameters have to be preset with the application of progressive sampling using PROSA

- the width of the basic grid, which is the quadruple of the minimum grid size
- the threshold value for the second differences of adjacent grid heights.

Both parameters are presently chosen by experience. More objectively they can be obtained as the result of a terrain analysis procedure, performed prior to the actual data acquisition. This analysis procedure can be based on measurements of dense profiles or better of a dense grid in a representative subarea.

With data acquisition it may occur that inside certain pre-defined cut out areas no height information is required. In this case it would be advantageous to omit all height measurements within the concerned areas. The same cut outs then could be considered with DEM interpolation and derivation of digital contours.

If a DEM of high geomorphological quality is to be generated, break lines, skeleton lines and characteristic points have to be measured. This can be successfully combined with progressive sampling using PROSA. The interpolation of a grid DEM then has to consider this geomorphological information, as well as the fact that the terrain is neither homogeneous nor isotropic. Basically DEM interpolation by finite elements is able to meet these requirements. In /EBNER, 1983/ it is shown, that inhomogeneity and anisotropy of the terrain can be considered by assigning adequate weights to the second differences of heights, which are used in the minimum function, mentioned in section 3. The weights themselves are derived from the heights of measured reference points. If the reference points are measured by progressive sampling the derivation of these weights becomes rather simple.

Research concerning the topics mentioned in this section is in progress and will lead to corresponding future extensions of PROSA and HIFI.

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