AUTOMATIC DIGITAL AERIAL TRIANGULATION

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ABSTRACT

The great progress in aerial triangulation during the past decades has been achieved mainly by the computional methods of block adjustment. Point transfer and measurement of image- or model-coordinates has largely remained conventional. Digital point transfer and point measurement by image matching procedures has opened new possibilities for almost complete automation of aerial triangulation, including point selection, point transfer, point measurement, and block-adjustment. The paper reports on the development of a method and a computer program on automatic digital aerial triangulation. The essential part is the automatic selection and transfer of tie-points, operating with multiple feature based matching, for the time being. The procedure is potentially fully automatic, but allows interactive guidance and interference, whenever necessary. First empirical results demonstrate the accuracy of the method and its economic potential.

1. Progress in aerial triangulation

Aerial triangulation has been a photogrammetric technique for a long time. It has made particular progress during the past 30 years, under the influence of analytical methods and computional tools. Its accuracy and economy performance has made it an indispensable item in modern photogrammetry, and a highly reliable and predictable one. The application has grown beyond the classical task of providing minor control points for stereomapping, aiming at photogrammetric point determination resp. photo-geodesy.

1.1 Block-Adjustment. If we recall the recent development it is noticeable that the progress was accomplished almost exclusively in the adjustment part of aerial triangulation. It was essentially block-adjustment whish pushed aerial triangulation to its present level of performance. In the course of its development the classical first order instruments disappeared from photogrammetry, and the computional adjustment methods evolved operationally to large systems and sophisticated procedures like the refinement by self-calibration, the intergration of auxiliary and other observations data, the consideration of external constraints and the automatic detection of outlier observations.

1.2 Interactive Data Acquisition. By comparison the data acquisition part of aerial triangulation has seen little or no development. There has been some accuracy improvement provided by image quality, camera calibration, and measurement by mono-comparators and analytical plotters, as well as increased operational efficiency and sophisticated data reduction. However, the 3 distinct steps for obtaining aerial triangulation observation data have remained unchanged, in principle :

(1) Selection (identification) and possibly artificial matching of image points,

(2) transfer and possibly artificial matching of image points,

(3) measurement of image coordinates (or model coordinates).

The essential point is here that the 3 tasks have not been subject to any automation. They are, to the present day, handled entirely by the human operator, i.e. executed interactively. The identification and image measurement of control points fits into that scheme, but is not further considered here in any detail. It is recalled that the precision of image coordinate observations is essentially determined by item (2), i.e. by the point transfer.

In the exceptional case that triangulation- and tie-points can de used which are premarked in the terrain, the above scheme of interactive operations remains valid, except that the point transfer does not apply. It is mainly for that reason that this case gives generally the highest accuracy in block-triangulation.

1.3 Automatic Data Acqusition. The new development of digital photogrammetry techniques has opened new possibilities for partly or fully automating hitherto interactive operations. We assume here that all photographs of a block are digitized and the digital image data stored and made accessible in a soft copy workstation. The technical questions especially of storage and fast retrieval of large amounts of image data are becoming solved, at present. They remain outside our considerations here, although they are a prerequisite. We also recall that digital methods of feature extraction and of image matching have been developed and can be considered standard software tools.

On the basis of such technology the digital acquisition of aerial triangulation observation data, especially image coordinates of tie-points, becomes feasible, and has already been realized and implemented in some systems. There are, at present, 2 strategy lines whish can be pursued. They are distinguished by different degrees of interactive and automatic operations.

The first strategy is close to the conventional procedure. It is already in practical use, to some extent. The human operator selects interactively one or several suitable tie-points in each of the overlap areas of an image. The selection takes place under visual observation on the computer screen of a softcopy workstation by placing the measuring mark on the respective image point which means measuring the image cordinates of that point at same time. That image point is transferred by image matching into all other images in which it appears. That point-transfer, which again implies assessment of the respective image coordinates, is automatic but is guided (for sufficient approximation) and controlled interactively. If necessary the transfer can be done interactively, under mono- or stereo-observation. In view of the 3 steps defined above in section 1.2 it can be said that the selection of the tie points is interactive and the point transfer is automatic, under interactive guidance and control. The measurement of image coordinates is implied in the described operations and disappears as a separate item (except for control points).

The second strategy goes one essential step further and attempts a fully automated procedure for selecting, transferring (matching) and measuring aerial triangulation tie-points. In this case also the selection of tie-points is automatic, i.e. executed by the computer on the digital image data. Again, the accessment of image coordinates disappears as a separate item, being implied in the identification of a digital image point. The system also provides interactive help functions, but they are only called upon in case necessary.

In the following chapters a system for automatic digital aerial triangulation observations is decribed and some results are presented. The method has been developed in the dissertation Tsingas (1992). Additional development and implementation has made it ready for pilot application.

2. The Tsingas method of automatic digital aerial triangulation.

2.1 Overview. The method aims at the automatic selection and transfer (by matching) of multiple tie-points. The total aerial triangulation procedure can be subdivided in 4 main steps, after the complete digital image data have been prepared and stored:

- A decisive first step is the automatic identification and delineation of the overlap areas and the selection of the specific image patches (windows) in which the image tie-points will be chosen.
- The actual tie-point measurement starts with the extraction in the overlap patches of image points which are suited to potentially become tie-points. The image points are obtained by feature extraction with the Foerstner interest operator. The extraction implies pixel coordinates assessment to subpixel precision and represents eventually the measurement of the image coordinates of the respective image points.

- The core of the method concerns the automatic identification resp. correlation of tuples of identical (homologous) tie-points out of the extracted image points, by feature based matching. That part is subdivided in 2 steps. First approximate matching of pairs of points is accomplished by mutual, pairwise matching between overlapping patches in all combinations. Thereafter the final tuples of image tie-points are determined by multiple matching.
- The established tie-points, after transformation to image coordinates, go as observation data into a bundle-blockadjustment, like in all conventional procedures of aerial triangulation. Hence the automatic assessment of observation data has a well defined interface and remains outside the adjustment part of aerial triangulation.

The method provides pixel coordinates of automatically selected and matched multiple tie-points. It covers, in terms of conventional aerial triangulation, the selection, the transfer, and the measurement of image tie-points. The method operates, in principle, fully automatic. The derived tie-points are "natural" tie-points, i.e. neither pre-marked nor artifially marked. The measurement of image coordinates of control-points (premarked or not) is not part of the method. They are to be measured interactively, for the time being. Also the treatment of signalized triangulation- and tie-points is not part of the method. They may identified and measured interactively or automatically by appropriate procedures. The essential image processing operations are feature extraction and feature-based matching.

The accuracy performance of any method of digital aerial triangulation is characterized by 2 parameters:

- The precision of image point extraction (feature extraction, precise to about 0.3 pixel, or point definition by least squares matching, precise to about 0.1 pixel); it shows up in the $\sigma_{\underline{o}}$ estimate for image coordinate observations in the bundle-blockadjustment.
- The number of tie-points; it determines the internal geometrical strength of the image connections, and hence of the block.

Those parameters, together with the control points and the photo-overlaps, determine the resulting accuracy of the adjusted block.

The method which is discussed here is fast enough to operate with many more tie-points, i.e. with much stronger connections than are conventionally used in aerial triangulation. At least 50 - 100 tie-points per image are considered standard. In the example of chapter 3 up to 270 tie-points per image were used. Such strong ties imply high redundancy with all it advantages concerning easy and safe blunder detection and high accuracy of the resulting exterior orientation parameters. For that reason the feature extraction need not be pushed to highest precision, and also small mismatches in the point-transfer may be permitted for easy discovery in the adjustment phase. The Tsingas method operates with feature extraction only, for the time being. Least squares matching has not been implemented, as yet, although it could be superimposed, taking the feature matches as approximations. It will be shown below that the results of the present implementation qualify in any case as high accuracy performance aerial triangulation, even if $\underline{\sigma_o}$ estimates do not reach the highest possible level.

There may be cases, hopefully few, when the automatic point identification and point transfer system will require some interactive guidance and support. This is provided for in the system. However, the support concerns normally only the interactive provision of approximate values, the actual measurements (feature extraction and matching) still remaining automatic.

A major problem in image matching is the provision of sufficently close approximations. In order to solve that problem automatically the system goes step by step through an image pyramid. 3 levels are sufficient, separated by a scale factor of about 4 or 5. Another, most coarse level of the image pyramid is used for the automatic identification of the overlap areas. The image pyramid is prepered and stored together with the original scanned image data.

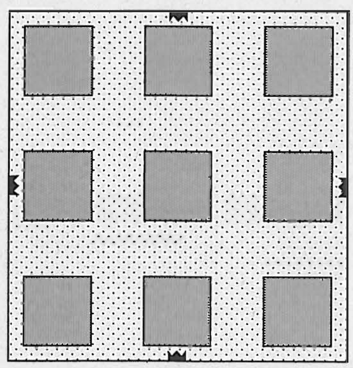

Fig. 1

2.2 <u>Overlap areas, homologous image patches</u>. After the initial preparation of the image data and the image pyramid the operations start with the delineation of the overlap areas of the images, in order to get the first approximation for the homologous image patches. It is particulary essential that this part is automatic. It operates on the highest, coarce level of the image pyramid, with pixel siye of about $(2mm)^2$, a full image being covered by about 115 x 115 pixel. Only some general pre-knowledge about the overlap conditions is required, i.e. 60% forward and 25 % side overlap. With GPS flight navigation the pre/knowledge about overlap areas could be more specific right from the beginning.

In the expected overlap areas feature points are extracted, and with feature matching homologous point pairs are identified in each overlap between adjacent images. It means that the same technical precedure is applied as will be used for the actual tie-point assessment. As a result the areas of mutual image overlap are pairwise identified and clearly delineated.

Within the general overlap areas local homologous patches are then defined within which the tie-points will be selected. These initial patches have an extension of about 4cm x 4cm (100 x 100 pixel on the second level). They are normally located more or less at the 9 standard positions within an image at the tie-points are ideally positioned, see Fig. 1, but also irregular overlaps can be accomodated, as shown in Fig. 6. These overlap patches have homologous correspondences in the adjacent, overlapping images. In case of regular photo-overlap, as obtainable with GPS flight navigation, the image patches form quite a regular pattern.

Once the homologous image patches have been identified the actual process of image point selection and the feature based matching of tie-points will start on the next lower, i.e. 3rd level of the image pyramid. That process is subsequently repeated throgh the remainig 2 levels of the image pyramid. Any selected point serves as an approximate center for defining the respective image patch on the next lower level within which again image points are selected. The size of the subsequent patches can be chosen by the program. It is in the order of 100 x 100 pixel. And the agreement of homologous patches is expected to be within about 10 pixel. Any previous point is not carried through to the next level, i.e. it is not used as an image point again, see Fig. 2.

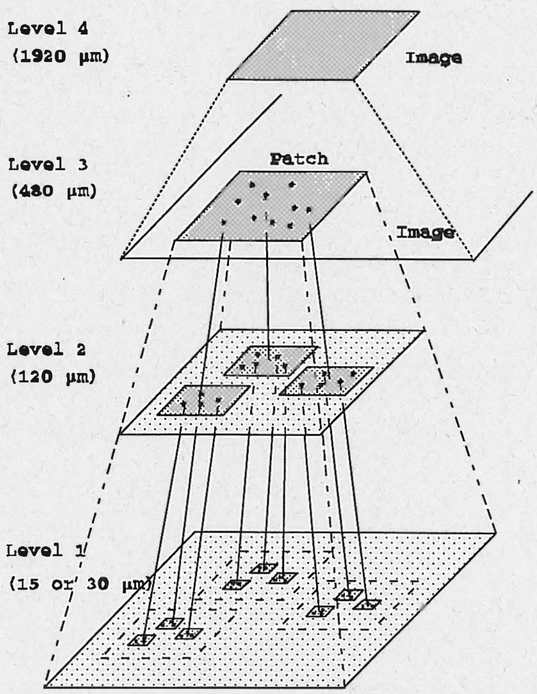

Fig. 2

With regard to the number of patches and of selected points different strategies can be pursued. In case of good image texture it is sufficient to use only one node point per patch on the pyramid levels 3 and 2 and select a certain number of points on the lowest level 1 only, see Fig. 3. If on the lowest level perhaps 10 tie-points per patch are obtained then in 9 patches altogether 90 tie-points per image are accomplished, which is certainly a sufficient number.

On the other hand on level 3 three node points may be chosen per patch, for instance, which will give 3 related patches on the next level 2. If in each of them 2 points would be chosen there wuold be 6 related patches on level 1. And if in each of the for instance 5 tie-points within the area of the original patch on level (see Fig. 4) or about 270 tie-points per image. These strategies can be monitored and adapted automatically. Thus the method is quite flexible with regard to the number and reliability of the identified tie-points, as the condinions may require.

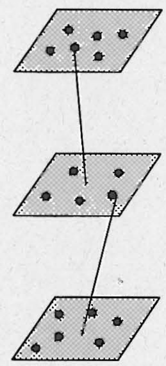

Fig. 3

2.3 Feature extraction and feature matching. On each of the 3 levels of the image pyramid the full program of the feature extraction and multiple tie-point identification is executed. It starts by running a window of 7 x 7 picel over each of the predetermined image patches, applying the Foestner interest operator. That efficient operator selects image points which are particularly suited for image matching, see Foerstner (1986). Within each patch a number of feature points are extracted and located in terms of pixel coordinates, to subpixel precision. The number of points can be monitored by thresholding the parameters q_i and w_i which describe the quality of the selected feature point in terms of roundness and siye of the associated error ellipse :

q

w

(The 2x2 matrices N and $Q = N^{-1}$ refer to the Foerstner operator.)
The accepted points are numbered and listed, per patch.

The main problem is then the identification of homologous points in homologous patches, i.e. the recognition of identical tie-points out of the independently extracted feature points. That task is accomplished in 2 steps. In the first step only preliminary pairs of matched points are determined, in all compinations of pairs. In each pair of patches the contained feature points are tentatively matched in all combinations and evaluated (weighted) on the basis of the correlation coefficient and a similarity measure w_{ij} :

w ij

where ρ is the correlation coefficient, n is the number of pixels involved, σ_p the point error, w the weight accordin to (2), and σ_g the gradient variation of the gray values. Certain bounds are applied to keep the number of point combinations limited. All paired point combinations with $w_{ij} > 0.5$ are kept as weighted candidates for further proccessing. That list of pairs of homologous points can still contain wrong or double

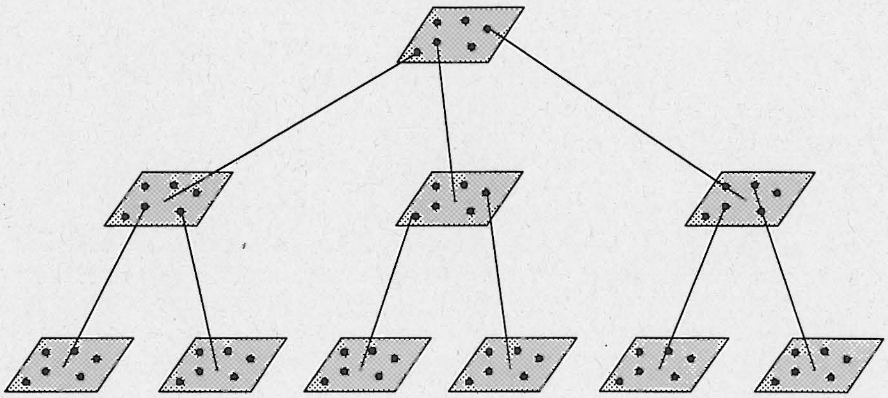

Fig. 4

valued matchings. The preliminary accepted pairs of points are therfore tested against the mathematical model of a robust affine relation between the pairs of points resp. the homologous patches. The affine relations are local approximations to the perpective relationships.

That acceptance test concludes the preliminary pairwise identification of tie-points. In the following second step the still remaining mismatches are to be eliminated and subsets of correct multiple matches identified which will finaly quakify as multiple tie-points. For that purpose the preliminarily matched pairs of points go through a simultaneous robust least squares adjustment of all affine relationships involved by which erroneous matches are recognized and eliminated. The remaining multiple matchings must be analyzed and evaluated for complete and best combinations. They are represented by a topological graph based on which an iterative heuristic search procedure identifies, by binary optimisation, subsets (n-tuples) of multiple tie-points for sufficient or best agreement, see Fig. 5. By a final repetition of the affine transformations adjustment the chosen set of multiple tie-points is issued and its internal accuracy assessed, in terms of residual errors against the combined affine modell.

It may be noted that the procedure applied is aquivalent to complete point transfer and its simultaneous adjustment in all combinations. A 6-fold overlap has 15 transfer combinations, rather than only 5. This is basic difference against the conventionsal

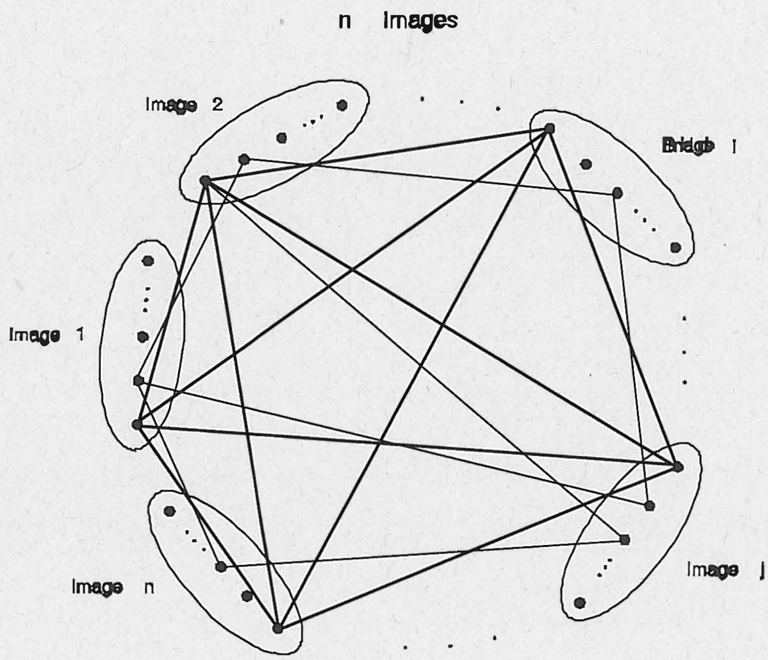

Fig. 5

method of point transfer and also against the digital interactive transfer.

It is evident that the heuristic search procedures are quite involved, and care had to be taken to avoid exponential increase of the computational efforts involved. The programming has succeeded to keep the computation time within quite acceptable bounds. _____ see Fig. 6.

Finally the accepted image tie-points are numbered and the complete list of tie-points is established, still expessed in pixel coordinates relating to the initial feature extraction on level 1 of the image pyramid which essentially represent the image "observations". Together with the interactively measured pixel coordinates of the control points or any other additional points they are transformed to image coordinates and constitute in that form the input observations for the subsequent block-adjustment. For those transformations the fiducial marks have to be captured from the original digital image data which may be done automatically, by mask matching, or interactively. The block-adjustment is entirely conventional, from there on, and may be executed in any of the standard versions, possibly with selfcalibration, combined adjustment with GPS camera station data, or with blunder detection algorithmus.

3. Empirical Example

3.1 Some previous results. Before presenting a complete example for the automatic digital aerial triangulation observations it is recalled that in Ackerman/Schneider (1986) an example of semiautomatic point transfer was given which demonstrated at that time already the high accuracy potential of digital aerial triangulation. The image coordinate precision of automatically transferred natural tie-points reached 4 μm in image scale which is very close to the analytical accuracy with pre-marked points.

With the Tsingas method there have been 2 preliminary tests in 1992 which were still handled in a non-integrated way. They did demonstrate, nebertheless, that the automatic methods works and that very good accuracy results can be expected.

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The method was applied to real aerial photographs. 21 black and white photographs of scale 1:7800 of the 20 years old test block Appenweier were digitized with the Yeiss-Intergraph Scanner PS 1, with 15 μm pixel size. Again, the method was applied with some interactive support, giving 2236 automatically determined image tie-points. The block-adjustment gave an image coordinate precision (σ_0) of 7.9 μm or 0.53 Pixel, and the absolute accuracy of the adjusted block reached 7,5 cm in x, 10.5 cm in y and 12.5 cm in z. The accuracy results were not further investigated. But the results confirmed that the method worked, even under difficult conditions. The execution was then quite lengthy (about 50 minutes per image computational time), as all operations were run on a VAX 3500 machine. In the meantime additional developments and experiments have brought the method on a quasi-operational level, and the test described in the following has now a much representative character.

3.2 OEEPE test block Finnland, procedure and observations. Very recently the OEEPE (European Organisation for Experimental Photogrammetric Research) has established a Working Group for digital aerial triangulation which has provided digital test material. The Institute for Photogrammetry of Stuttgart University has participated in the test, applying the Tsingas updated method and program. The test was run on the Silicon Graphics IRIS/Indigo workstation. It has a MIPS-R3000 processor and a 32 MByte RAM. The station was equipped with a 5 GByte hard disc. It was sufficient capacity for storing the complete block of 28 digital images (including the image pyramid) with 30 μm pixel resolution. On the 15 μm level of pixel size the disc could store 12 images simultaneously. The workstation had been made available by the Deutsche Forschungsgemeinschaft which had supported some previous methodical investigation.

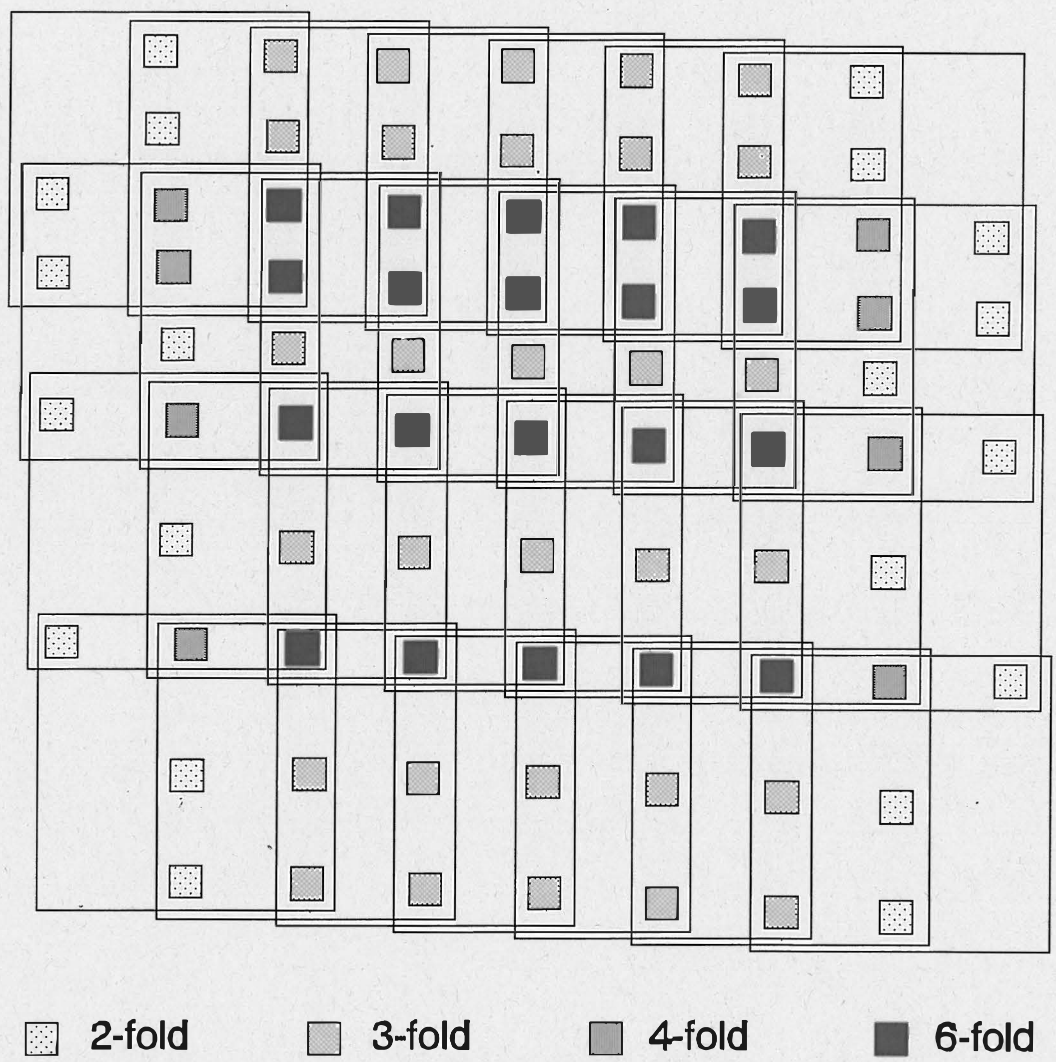

Fig. 6

The OEEPE block coprised 28 aerial photographs, of scale 1:4000, forming a block of 4 strips, with 60% forward overlap. The side overlap was less regular, varying from about 40% between strips 1 and 2 to about 15% between strips 2 and 3 resp. 3 and 4, see Fig. 8. The original color diapositives were digitized on the PS 1 with 15 μm pixel size, amounting altogether to about 7 GByte of image data.

From the original image data of 15 μm pixel size a second set was derived, with 30 μm pixel size. Both data sets were treated separately, providing two (almost) independent test cases. Above these data sets, each representing for its case level 1 of the respective image pyramid, the pyramid levels 2 and 3 were constructed with pixel sizes of 120 μm and 480 μm, respectively. They were maintained in both cases, although the transition from 15 μm to 120 μm represents a scale factor of 8 (which caused no apparent problems). The 4th level of the image pyramid, used only for establishing the overlap areas, had pixel size 1920 μm.

Two different patch strategies were applied for going through the image pyramid. With the 30 μm image data the simpler strategy of Fig. 3 was pursued. The data set with 15 μm pixel size had a higher noise level. Anticipating some problem areas the safer strategy according to Fig. 4 was used, resulting in a considerably larger number of tie-points.

After those preparetions and parameter specifications the program run through both image data sets without serious obstacles nor major problems, delivering the required lists of multiple tie-points, as decribed in chapter 2. As far as the final output is concerned some options can be applied. Normally not all identified tie-points are issued, as the total number of points could be very large and also poorer matches and incomplete multiple tuples would be included. Instead, only subsets of the 10 or 20 best points per original patch are actually edited, selected according to the residual errors at the final affine transformation adjustment. However, with the 30 μm data set also the complete set of identified tie-points aws issued, for sake of interest. Thus altogether 3 sets of tie-points were obtained, to enter into the block-adjustment.

The OEEPE test block contained a number of premarked points in the terrain which were to be used as control points and check points. The automatic procedure was not intended to capture those image points. They were measured interactively, on the mono-screen of the work station, independently for both sets of image data. Some of the points were difficult to measure, because of low contranst.

The statistical summary of table 1 shows that the number of issued tie-points was quite large in each of the 3 sets of results, amounting to 131 and 237 resp. 272 image tie-points per image.

Interactive support of the automatic process was required in 6.4% of all image patches, for both sets of image data and both patch strategies. The 30 μm data set, with the strategy of Fig. 3, produced altogether (on all 3 levels of the image pyramid) 234 hornologes overlap patches, out of which 15 (=6.4%) required support. The 15 μm data set, with the strategy of Fig. 4, gave altogether 780 homologous overlap patches, out which 50 (=6.4%) needed support. The trouble areas related mostly to small side overlap between the strips. There the automatic approch did not allways succeed directly to identify matched points. It is interesting to note further that 6% resp. 1.6% and 0.7% of the delivered image points were discarded as (small) outliers in the final block-adjustment. This rate of errors seems quite acceptable, as the high redundancy permits safe and complete detection. In that sence the block-adjustment checks the provided lists of tie-points and forms an intergral part of the procedure.

DIGITAL AERIAL TRIANGULATION - OEEPE BLOCK FINNLAND						
pixel size	15 µm [0]		30 µm (case A[1])		30 µm (case B[2])	
number of: image points (per photo) terrain points outliers in adj. (image points)	 7643 (272) 3403 6%		 6641 (237) 2991 1.6%		 3686 (131) 1526 0.7%	
ground control points	14 XY 14 Z	4 XY 8 Z	14 XY 14 Z	4 XY 8 Z	14 XY 14 Z	4 XY 8 Z
$\hat{\sigma}_0$ [µm] [pixel]	6.2 0.41	6.2 0.41	11.8 0.39	11.7 0.39	10.7 0.36	10.7 0.36
Empirical Accuracy (RMS)						
number of check points	81 XY 71 Z	90 XY 76 Z	81 XY 71 Z	90 XY 76 Z	81 XY 71 Z	90 XY 76 Z
μ_x[cm] μ_y[cm] μ_z[cm]	3.6 3.9 5.3	4.2 5.1 7.1	5.0 5.5 9.4	6.5 8.0 11.5	4.3 5.1 8.1	5.7 7.3 9.2
Theoretical Accuracy (RMS)						
block points σ_x[cm] σ_y[cm] σ_z[cm]	2.5 2.7 5.9	3.0 3.4 6.3	4.6 4.9 10.8	5.5 6.3 11.5	4.2 4.4 9.9	5.2 5.9 10.7
orientation parameters σ_ω[mgon] σ_φ[mgon] σ_k[mgon]	3.3 2.7 1.0	4.0 2.8 1.3	6.6 5.4 2.0	8.2 5.7 2.5	6.6 5.7 2.1	8.1 6.1 2.6
σ_{X_0} [cm] σ_{Y_0} [cm] σ_{Z_0} [cm]	3.0 3.7 2.5	3.6 5.3 3.0	5.9 7.4 4.6	7.0 10.6 5.7	6.2 7.3 4.4	7.3 10.5 5.6

0) 6 patches per overlap area, 10 best points per patch (Fig. 3)
1) 1 patch per overlap area, all points of patch (Fig. 4)
2) 1 patch per overlap area, 20 best points per patch (Fig. 4)

It is not zet possible to give a full economic assessment of the automatic digital aerial triangulation, as the system has not been completely implemented, as far as initial data handling and data storage is concerned, which depends on hardware. Also the original digitization of the photographs constitutes a major cost factor. Nevertheless, some interesting figures can be quoted. With the image data of 30 μm pixel size the net processing time for feature extraction and feature matching took 47 min or 1.7 min per image, referring to 6641 image points. The corresponding net processing time with the image data of 15 μm pixel size amounted to 150 min or 5.3 min per image, referring to 7643 image points and the special strategy according to Fig. 4. Those computing times exclude the block adjustment and the image transformation for the interior orientation. The also exclude the interactive measurements of the control- and check-points, the interactive support, and preparation and storage of the image data and of the image pyramid. Nevertheless the figures are extremely promising in view of a highly competive cost situation.

3.3 <u>OEEPE test block, accuracy results</u>. The automatic tie-point extraction had given 3 separate lists of data for block-adjustment. Each of them was processed separately through 4 different block-adjustments, as there were 2 different cases of ground control to be treated, 14 perimeter control points in the first case, and a minimum case of 4 horizontal and 8 vertical control points. In addition, each adjustment was carried out with and without selfcalibration. The ground control points were introduced in the adjustment with the assumed a priori standard deviation of 2 cm.

In table 1 only the 6 cases are quoted which refer to the standard bundle-adjustment without self calibration. The self-calibration had actually very little effect on the adjustment. The σ_o estimates were not affected at all. The resulting horizontal accuracy of the blocks improved by about 12%, whilst the vertical accuracy deteriorated consistently by about 19%.

The first item of major interest concerns the estimated magnitudes of σ_o. That parameter stands for the total image coordinate precision. It concerns in first instance the precision of the feature point extraction and the feature matching. It describes, in other words, the image coordinate precision of the automatic digital procedure and can be compared with the conventional values obtained by traditional point marking and point transfer resp. with the precision of signalized triangulation points. The parameter σ_o is the ____ one, as everything else is a matter of propagation of errors.

Table 1 shows that the σ_o estimates amount to 6.2 μm with the 15 μm image data, and to 11.7 μm resp. 10.6 μm with the 30 μm image data. Those figures .... which is characteristic for the conventional aerial triangulation with point transfer and artificial point marking. Thus, the image obtained coordinate precision is directly comparable with standard conventional aerial triangulation. While those σ_o values are

___ highly acceptable from the practical application point of view the must in reality be evaluated in terms of the respective pixel units. On both levels of pixel size the estimates are consistently close to 0.4 pixel, reaching in the best case 0.35 pixel. These results are not in full agreement with the theoretical precision of feature extraction, but they are comfortably close.

Finally the absolute accuracy results of table 1 demonstrate a remarkable ___ accuracy of the digital aerial triangulation, especially on the 15 μm level of image data, and the empirical results are quite close to the theoretical expectation. The results show the fovourable effect of the strong block-geometry, comed by the large number of tie points. This is a very special feature of the automatic digital procedure which has no equivalent in conventional aerial triangulation procedures, because of economy and cost restraints.

The coordinate accuracy of blocks, as assessed from check points, after adjustment with 14 control points, reached 3.6 cm in X, Y and 5.7 cm in Z, with the 15 μm image data. There are very good results, in conventional terms, with 1:4000 photo scale. The amount to about 1.4 σ_o in X, Y and to 2.3 σ_o in Z. The minimum control point ___ ___, respectively 4.5 cm = 1.8 σ_o in X, Y and 7.7 cm = 3.1 σ_o in Z. With the 30 μm image data the accuracy results are not poorer by a factor 2, as might have been expected. Instead, 4.4 cm = 1.0 σ_o in X, Y and 7.6 cm = 1.8 σ_o in Z are reached. These results are poorer by only 23% (X,Y) resp. 25% (Z) in absolute terms, and are better by 40% resp 28% in relation to σ_o. Those results still qualify as very good, with regard to the photo-scale of 1:4000. Similar ratios are obtained with the minimum control ___. Table 1 also quotes the theoretical accuracy results of the adjusted blocks, as obtained through the inversion of the normal equation coefficient matrices. It is interesting to note that the empirical coordinate accuracies are close to the theoretical results, differing only by 21% in X, Y and by 6% in Z, average over all cases.

Table 1 also shows the theoretical accuracy of the exterior orientation parameters of images after block adjustment. Here the redundancy effects become fully vidible. In the best case the photo tilts (omega, phi) are accurate to 2 mgon and kappa to even 1 mgon. These standard errors are better than could be obtained in a conventional analytical block with signalized points.

It can be concluded in general that the digital aerial triangulation, with image data of 15 μm pixel size, gave excellent accuracy results, which qualify as high precision aerial triangulation. Even with image data of 30 μm pixel size the results would still meet the mapping specification of, in this case, 1:1000 map scale.

Summarizing the empirical test it can be stated that the results are extremely promising in every respect. Automatic digital aerial triangulation will not only more accurate than comparable conventional aerial triangulation. Once properly implemented it can be expected to be very fast (a block in a few days) and less expensive. A high economic and accuracy performance is certainly anticipated.

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