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UTILIZATION OF NAVIGATION DATA FOR AERIAL TRIANGULATION

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Abstract: Camera orientation data, directly recorded, have since long been known to be highly effective as auxiliary data in aerial triangulation. Especially statoscope- and APR-data have been successfully utilized in joint block adjustment procedures.

The modern computer controlled systems for photo flight navigation supply extended auxiliary data the processing of which in joint block adjustment allows considerable reduction of ground control. Simulations and practical results are reviewed which demonstrate the economic and accuracy potential of navigation data for aerial triangulation.

1. Introduction

1.1 The utilization of directly measured camera orientation data as "auxiliary data" for aerial triangulation dates back more than 50 years. In particular statoscope, horizon camera, and solar periscope then provided such data. After some revival during the 1950's and extension to gyroscopes and airborne profile recorder (APR) the interest in auxiliary data subsided, however, to the extent that the topic has almost disappeared from photogrammetric literature. It is only statoscope and APR which survived to some extent in practical application. Still, their application is far too little when compared with the great economic benefits and saving of vertical ground control which they provide |1|.

During the 1950's airborne ranging methods were developed which allowed horizontal positioning of camera stations and which were extended to airborne determination of large geodetic networks (Shoran, Hiran, Shiran, see |2|). They have since disappeared completely, for economy and accuracy reasons. The same fate experienced other attempts to determine directly all 6 parameters of exterior camera orientation accurately enough to make aerial triangulation obsolete (AN USQ 28, |3|). The idea keeps being brought up, as evidently today's technology seems to make it feasible, in principle, |4|.

It is certainly the performance of present day block adjustment and the geodetic developments for ground control determination which lowered the interest in auxiliary data for aerial triangulation. On the other hand the computational methods would just allow easily to make full use of auxiliary data. The successful example of statoscope or APR shows the great potential and therefore can justify an attempt to reconsider the application of auxiliary data in photogrammetry.

1.2 The matter of auxiliary data has recently been brought into discussion again through developments in the field of air-navigation. Systems for survey flight navigation have been proposed the purpose of which is real-time assessment during the photo flight of position (and attitude) of the camera carrier and the camera, respectively. The concept is to display to the pilot actual position, speed and heading of the aircraft in comparison with the prespecified flight plan,and to automatically give signals to the camera in order to obtain pin point photography. The latter is considered of great economic advantage for all subsequent photogrammetric restitution work. Examples of such navigation systems are PICS (Photogrammetric Integrated Control System, |5|) of Litton or the CPNS (Computer Controlled Photo Navigation System) as described in |6|. Whilst PICS operates with an inertial navigation system CPNS is based on the high accuracy Thomson-CSF-Trident III airborne ranging system which is of the aircraft interrogator/ground transponder type. Also, the use of GPS satellites for flight navigation will have to be considered soon.

1.3 The economic justification of such systems, which are not inexpensive, has been based entirely on the aspects of navigation for survey flight missions and on the advantages of ideal overlap and pinpoint photography. It is obvious, however, that such navigation data, if recorded, may in addition be subsequently refined and processed off-line as auxiliary data for photo orientation, in particular in connection with aerial triangulation and block adjustment. The photogrammetric use of such data may distinguish 2 levels:

a) It would be ideal if the processed camera orientation data would be accurate enough for direct use. All photogrammetric restitution work would be greatly simplified. However, the accuracy requirements are very high (about 5 cm - 1 m in position, depending on photo scale, and 0.5 - 2 mgon in attitude) and are, as yet, not met directly. Nevertheless, partial fulfilment of requirements is feasible and will increasingly be applied for certain tasks (rectification, for instance), possibly in connection with simplified block-adjustment procedures.

b) For the time being camera orientation data will be used as additional observations to be jointly processed in combined block adjustment procedures, together with conventional aerial triangulation and ground control data. Based on the most favourable experience with statoscope data it can be anticipated that also horizontal positioning data will be most effective. The navigation data need not be extremely precise, as the combined adjustment will make best use of the relative and absolute error properties of either set of data. In any case considerable reduction of ground control requirements can be expected which is still of economic importance for topographic mapping.

It is known, from former analyses, that auxiliary positioning data (for xy, and/or z) are much more effective than attitude data (ω, ϕ, κ), as the latter still imply a summation (integration) of errors which affect the final coordinate data.

2. Auxiliary data and joint block adjustment

2.1 There is considerable experience available for statoscope- (and APR-) data which constitute a special class of auxiliary data, referring to vertical camera positioning and vertical positioning of terrain points, respectively, see |7|, |8|. It is not the subject of this paper, to delve into that field. It may be recalled, however, that with such data vertical accuracies of blocks down to the order of 1 m or better can be maintained for long bridging distances. The economic effect by saving vertical control and the related cost-benefit ratio is most favourable. Even application in medium and large scale mapping can be most advantageous, see |9|. It is difficult to understand why such easily available and effective auxiliary data are not used more in practice. The potential of airborne barometric measurements has not yet been fully exploited. Further development of statoscopes is suggested.

Vertical auxiliary data have also set the example that joint adjustment can solve for unknown orientation parameters (for the isobaric surface) and systematic errors and thus make the method extremely flexible and efficient. The joint adjustment can improve the accuracy results by a factor 2, as compared with previous methods of independent utilization of data (for instance orientation per strip).

2.2 It can be expected that the use of auxiliary horizontal positioning data will be effective in a similar way as vertical data have been shown to be. This has been confirmed by a series of computer simulations at the Photogrammetric Institute of Stuttgart University. The simulations are part of a thesis and will be published in detail elsewhere. It can be summarized, however, that an internal precision of 2 - 5 m of auxiliary horizontal positioning data will be sufficient to give horizontal accuracies of jointly adjusted blocks of 1 - 2 m, even with 4 horizontal ground control points only. Thus the application to topographic mapping seems most feasible. Of course, the datum reference of the navigation data and systematic errors (drift) have to be mathematically modelled by a sufficient number of parameters and taken into account during the adjustment.

It is even conceivable to utilize horizontal navigation data for block adjustment without any horizontal ground control points in the area. This is possible if the orientation of the auxiliary data with regard to the geodetic coordinate system is established in a suitable way outside the area (or, if it may not be required at all).

The effect of attitude data on the joint block adjustment has not yet been investigated closer. Their effect will be less marked, but an overall solution will have to include them.

2.3 The method of integrating auxiliary camera orientation data into the photogrammetric block adjustment is basicly simple. In particular it does not create serious numerical problems. The auxiliary data give rise to additional observation equations, properly weighted, which interconnect with the photogrammetric block data via common unknowns. For example, the statoscope- or APR-data are used in the PAT-M block adjustment program in the following way:

$$z_j^{stat} + v_j^{stat} + (a_o + a_1 x_j) = Z_j^{PC}$$

$$z_i^{APR} + v_i^{APR} + (b_o + b_1 x_i) = Z_i$$

Here, the observations z_j^{stat} and z_i^{APR} of camera stations j or terrain points i , respectively, are given appropriate weights, with respect to the photogrammetric observations of unit weight (σ_o). The unknown parameters a_o, a_1 and b_o, b_1, respectively, take care, per strip, of the unknown orientation of the isobaric surface with regard to the Z-datum. The unknown parameters are solved in the joint least squares adjustment. The observational equations tie together with the photogrammetric block via the common unknowns Z_j^{PC} and Z_i relating to the camera stations j and to terrain points i, respectively. The structure of the normal equations is not affected at all by the additional observation equations, except that the unknown parameters give rise to a bordered matrix. The datum problems are taken care of by control points (possibly in combination with cross strips or cross profiles) and thus do not constitute particular difficulties.

In a very similar way auxiliary positioning data for perspective centers can be introduced into the block adjustment:

$$x_j^{nav} + v_j + (a_o + a_1 x + \ldots) = X_j^{PC}$$

$$y_j^{nav} + v_j + (b_o + b_1 x + \ldots) = Y_j^{PC}$$

Again, the observed auxiliary data X_j, Y_j are to be weighted appropriately. Also, they may not necessarily be treated as independent. More general stochastic behaviour may be considered, resulting in correlation between all auxiliary observations X and Y of a flight line. Also the additional orientation parameters a_o, b_o..., which establish the connection with the XY datum and which also take care of systematic errors such as drift effects may represent more general transformations than indicated here. In case non-linear terms are required configuration defects have to be watched in order to prevent break down or poor reliability of the solution. The basic structure of the resulting banded-bordered normal equation system will be the same as in the case of statoscope data and thus will not present particular problems. Even complete correlation of auxiliary data within a strip will be manageable.

For the introduction of attitude data basicly the same approach as above may be maintained. For instance:

$$\omega_j^{nav} + v_j^{\omega} + (a_o + a_1 x) = \omega_j$$

and similarly for ϕ and κ. Again datum and drift relations can be taken into account by unknown parameters per strip. The connection with the photogrammetric block is provided via the common unknown camera orientation parameters ω_j, ϕ_j, κ_j. The above type of observational equations may be obtainable only after preliminary transformation and linearization. Also general correlation may be taken into account. The general structure of normal equations, as established above, will be maintained, and no particular numerical difficulties are anticipated.

The described approach for joint block adjustment with auxiliary orientation data can be adapted to both independent models and bundle adjustment.

3. Experimental results from CPNS flight "Bodensee 1982"

3.1 There was an opportunity to test some of the above considerations directly in an experiment, during 1982/83. The experiment refers to the CPNS navigation system |6| which is based on the Thomson CSF Trident III radiolocation system, |12|. It operates with several ground beacons to be positioned at distances within 200 km outside the area in question. The beacons re-emit the signals received from the interrogator in the aeroplane. Interrogator and transponders transmit signals of 1219 MHz, or in the 420 - 450 MHz band, or at 232.8 and 272.8 MHz. The signals returning to the survey aircraft are identified and continuously processed for slant ranges which in turn are processed by trilateration to give continuously position data of the aircraft in real-time. The coordinates of the actual camera positions are derived separately by post processing. They refer to the coordinate system as defined by the beacon stations.

In 1982 Grimm/Heimes organized a test flight with the CPNS system. A block of 5 strips in the Bodensee area (Lake of Constance) was flown without visual navigation reference. It covered an area of 480 km² by 240 Wild RC 10 A wide angle photographs of 1 : 16 000 scale. The navigation referred to 4 beacon stations, up to 200 km away from the area, see |10|, |11|. The prime purpose of the experiment was to test the navigation system. However, the navigation data were subsequently used as auxiliary data for aerial triangulation, in order to test and demonstrate the performance of such auxiliary data through joint block adjustment.

We obtained the xy-positions of the camera stations, as derived by post processing of the navigation data. The trilateration adjustment had revealed an average range precision of about 1 m. The air stations were derived from range measurements to 2, 3, or 4 beacons. The data, of which only the horizontal positioning was used, were subsequently analyzed and treated as auxiliary camera position data in a joint block adjustment.

From the total block only a subblock of three strips with 15, 22, and 19 pairs of photographs, respectively, was triangulated, as only in that area 34 signalized planimetric control- and check points as well as 380 natural vertical ground control points were available (see tables 1 and 2). The area also had signalized tie points, about 10 per model. The photogrammetric block was measured with the Zeiss Planicomp C 100, in the stereocomparator mode. The image coordinates were processed to independent models. For the subsequent block adjustments (with and without auxiliary data) the program PAT-M-43 (block adjustment with independent models) was used.

The investigation clearly distinguishes 2 separate aspects, as laid down in the following chapters:

3.2 Accuracy of the navigation data

The accuracy analysis of the positional navigation data is based on a conventional block adjustment in which all available ground control points were used. In this way quasi-true xy-coordinates of the camera stations are obtained which can be compared with the corresponding data from the CPNS navigation system.

The internal accuracy figures of the block adjustment confirm that the block had a good quality level. Referring to model coordinates the following σ_o-estimates were obtained for the planimetric and the vertical adjustment:

$$\sigma_{o_{plan}} = 0.11 \text{ m} \;\hat{=}\; 7\ \mu\text{m in photoscale}$$

$$\sigma_{o_{vert}} = 0.20 \text{ m} = 0.07\ ‰ h \;\hat{=}\; 12\ \mu\text{m in photo scale}$$

The r.m.s. values of the internal residuals at the photogrammetric coordinates of the perspective centres were

$$\bar{v}_x = 0.22 \text{ m}, \quad \bar{v}_y = 0.26 \text{ m}, \quad \bar{v}_z = 0.09 \text{ m} .$$

Also those values are in agreement with expectation. From them an absolute accuracy of the adjusted horizontal camera station position of about 0.4 m to 0.5 m can be estimated.

The quasi-true camera stations from the block adjustment were directly compared with the camera station coordinates as obtained from the CPNS system. The comparison is summarized in tables 3 and 4. In the analysis a distinction is made between well determined stations (with 3 - 4 distances each, group a) and stations of poorer geometric configuration (group b).

The first and direct comparison showed average point position errors of the CPNS derived camera stations of 17.9 m. The vector diagram (table 3) shows clearly that there is in first instance a large constant error in y-direction, and secondly a marked systematic error in x-direction the sign of which changes with the flight direction. Further investigations made it very likely that those errors are circumstantial and by no means system inherent. It turned out that the beacon positions had only been taken graphically from the topographic map. The systematic error in x-direction is partly due to the linear distance between camera and antenna in the aeroplane which had not been calibrated. There may also be other constant errors in the electronic system. Such errors could in practical application be taken care of by appropriate system calibration.

It seemed justified, therefore, to remove the observed systematic errors, by similarity transformation of the CPNS coordinates onto the "true" camera station coordinates. The remaining average CPNS positioning errors amounted to 3.6 m (groups a and b). Omitting the poorly determined stations the average errors reduced to 2.6 m.

These results can be interpreted as the internal horizontal precision of the CPNS camera station determination, valid under the conditions of the test, and after removal of all constant errors. The figures may be considered representative for a calibrated CPNS camera system. It should be noted, that in this test no previous experience with the system was available nor that any refinement of processing was applied. As no further information was available it was not possible to push the analysis of the data any further.

3.3 Utilization of positional navigation data as auxiliary data in a joint block adjustment

The previous investigation had given an assessment of the accuracy of camera stations as derived from CPNS navigation data. The results confirmed that the data may successfully be used as auxiliary data in aerial triangulation to the effect that horizontal ground control could substantially be reduced. The second part of the investigation attempted to demonstrate this effect empirically, with the same test block material.

For that purpose the block was adjusted (with the PAT-M-43 program) in an application configuration, based with regard to planimetry on

- only 4 horizontal ground control points, and
- the CPNS position coordinates of 53 camera stations (omitting point 1120), weighted according to the results of the previous investigation (3.2), and after removal of the systematic errors
- and all observed tie points, as previously.

The remaining 30 known ground points served as check points for the independent assessment of the resulting accuracy of the joint block adjustment.

The r.m.s. differences of the block adjustment coordinates of 30 check points against their "true" geodetic coordinates represent sufficiently the average accuracy of the jointly adjusted block. The values amounted to:

$$\mu_x = 0.23 \text{ m}, \quad \mu_y = 0.34 \text{ m} \quad .$$

This empirical accuracy values could, at face value, be taken as a good confirmation of the expected contribution of navigation data to the block adjustment with minimum horizontal ground control (4 points). In fact, the result is a confirmation. However, the evaluation has to consider, that this block is small and that the photo scale is quite large. It means that the gap in precision between auxiliary data and photogrammetric block data is quite considerable. This block cannot, therefore, demonstrate fully the effects of auxiliary data. The full potential of them would show up at large topographic blocks at medium or small scales. Indeed, if this test block was adjusted conventionally, with the 4 ground control points only, and omitting all auxiliary data, the average accuracy, assessed again from the check points, turned out to be

$$\mu'_x = 0.25 \text{ m}, \quad \mu'_y = 0.42 \text{ m}$$

It is evident, that in this case the contribution of the navigation data to the block accuracy were only marginal, as expected. Nevertheless, taking circumstances into account, the results of this particular experiment can be interpreted as confirming the expected effectiveness of CPNS camera station positioning data in the joint block adjustment.

The main feature of auxiliary positioning data is that they are, to some extent, a substitute for horizontal ground control. This can eventually be be pushed to the point that no ground control at all is required. In order to demonstrate the possibility the test block was once more adjusted without any horizontal groundcontrol. The joint blockadjustment was, with regard to planimetry, based only on the 53 CPNS camera station coordinates (corrected for constant errors) and on the photogrammetric tie points.

The resulting absolute accuracy of the adjusted block, expressed in r.m.s. coordinate errors of 34 check points, was in this case:

$$\mu_x = 0.36 \text{ m} , \quad \mu_y = 0.53 \text{ m} .$$

This result is highly interesting, when compared with the coordinate precision of the auxiliary camera stations of 2,2 m. Although ground control points can only be deleted completely when constant or systematic errors of the auxiliary data are negligible or are calibrated otherwise, the example demonstrates convincingly the effectiveness of auxiliary positioning data and the success of joint adjustment.

4. Conclusion

The experiment "Bodensee 1982" with the CPNS navigation system has given an indication of the high precision of the camera positioning capability of the system. It was also demonstrated that utilization of such auxiliary data in joint block adjustment is highly effective. With such data the control requirements for horizontal control can be substantially reduced in small scale mapping projects.

Although the experiments refer to a small testblock only, the results allow general conclusions as to the high potential of utilizing survey flight navigation data as auxiliary data for block-triangulation. The positive experience gained previously with statoscope and APR concerning vertical auxiliary data can certainly be extended to horizontal camera positioning data. Further research is required, expecially when extending to inertial or GPS navigation systems and to attitude data. Such research is encouraged. It is expected to complete and widen the economic and operational range of aerial triangulation.

REFERENCES

|1| F. Ackermann: Progress in aerial triangulation for medium-scale and small-scale topographic mapping; 8th UN Regional Cartographic Conference for Asia and the Far East, Bangkok, 1973;

J.M. Zarzycki: The use of auxiliary data in aerial triangulation; Invited Paper, Comm. III, ISP Congress Ottawa, 1972, 24 p.;

W. Faig: Independent model triangulation with auxiliary vertical control; Presented Paper, Comm. III, ISP Congress Helsinki, 1976.

|2| F.L. Corten: Survey navigation and determination of camera orientation elements; Photogrammetria, 1959/1960, 4, p. 251 - 281.

|3| C. di Carlo, N. Eakin: Mapping and survey system geodetic AN/USQ-28, Int. Archives of Photogrammetry, 15(1965), 3.

|4| F.L. Corten, F.J. Heimes: Integrated flight and navigation system; Invited Paper, Comm. I, ISP Congress Helsinki, 1976.

|5| R.V. Bruland: Integrated air survey navigation; proceedings 38th Photogrammetric Week, Institute of Photogrammetry, Stuttgart 1982, Heft 8, p. 59 - 72.

|6| J. Beumelberg, A. Grimm, F.J. Heimes: CPNS computer controlled photo navigation system; ISP Comm. I Symposium Canberra, 1982.

|7| H. Klein: Genauigkeit von Höhenblöcken mit gemeinsamer Ausgleichung von Statoskop- oder APR-Hilfsdaten; proceedings Numerische Photogrammetrie (III), Institute of Photogrammetry, Stuttgart 1976, Heft 1, p. 5 - 16.

|8| J. Kure: APR-experience and application; ITC Journal, 1973-4, p. 618 - 639.

|9| F. Ackermann, W. Schneider: Neue Ergebnisse zur Aerotriangulation mit Statoskop-Daten; Bildmessung und Luftbildwesen, 1, 1983, p. 21 - 37.

|10| J. Beumelburg, A. Grimm, F.J. Heimes: CPNS-Computer controlled photo navigation system - new aspects in aerial surveying: proceedings workshop on computer controlled survey navigation, 1983, p. 1 - 27.

|11| F. Ackermann: Use and benefits of X, Y, ΔZ auxiliary data for aerial triangulation; proceedings workshop on computer controlled survey navigation, 1983, p. 28 - 41.

|12| H. Balsan, B. Dumas: Trident III Radio Location System; proceedings workshop on computer controlled survey navigation, 1983, p. 50 - 54.

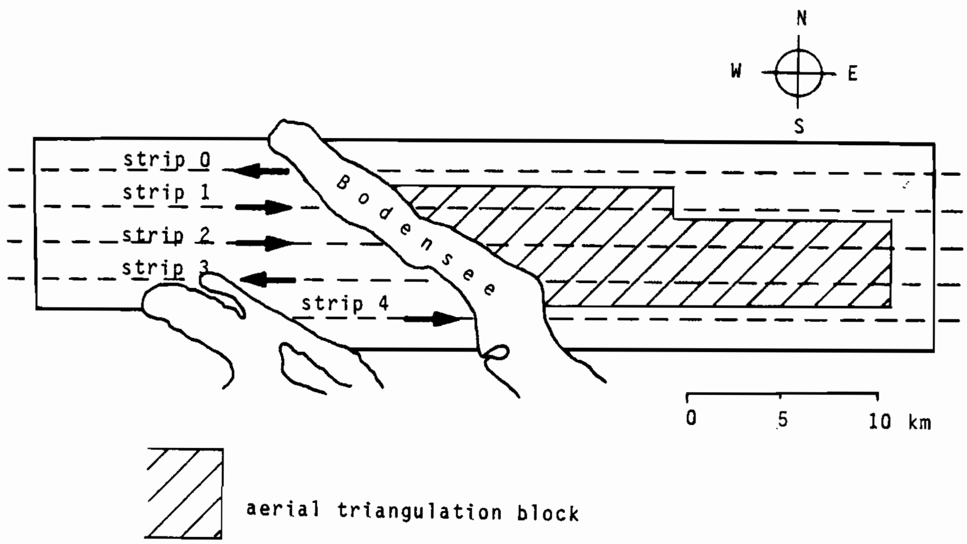


Table 1 : CPNS-Test "Bodensee 1982"; 5 strips, 223 photos, Wild RC 10A, photo scale 1 : 16.000

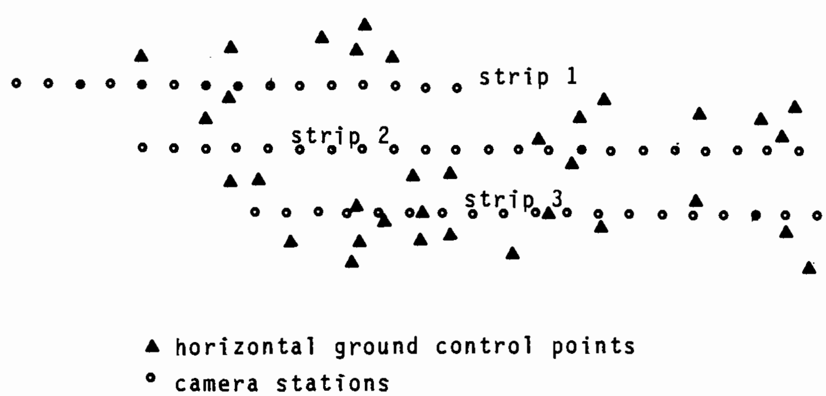
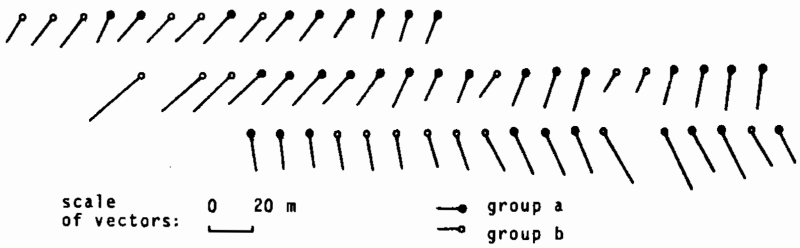
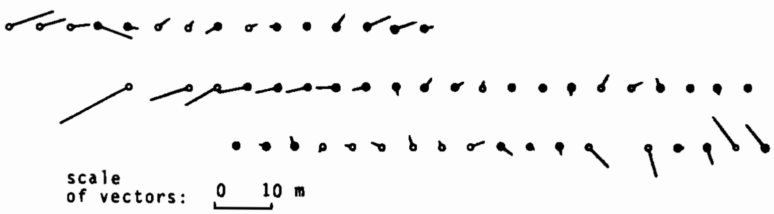


Table 2 : CPNS-Test "Bodensee 1982"; aerotriangulation with a subblock of 53 models

1. CPNS - coordinates derived from trilateration adjustment and distance intersections



2. CPNS - coordinates, constant errors removed (by 4-parametertransformation)



3. CPNS - coordinates, constant errors removed (by 4-parametertransformation), point 1120 omitted

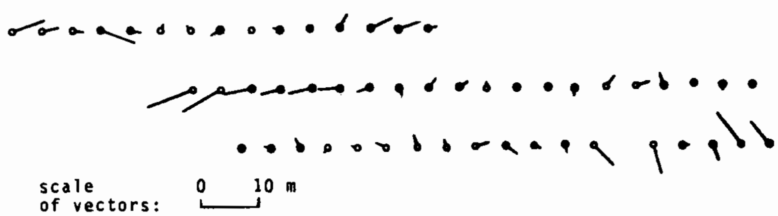


Table 3 : CPNS-Test "Bodensee 1982"; accuracy of CPNS positioning data

CPNS - coordinates	group	rms. values of the differences in meter			number
		μ_x	μ_y	$\mu_s = \sqrt{\mu_x^2 + \mu_y^2}$	
from trilateration and distance intersections	a	8.14	14.97	17.05	32
	b	10.78	15.81	19.14	22
	a+b	9.31	15.32	17.93	54
constant errors removed by 4-parameter transformation	a	2.27	1.34	2.64	32
	b	3.95	2.51	4.68	22
	a+b	3.07	1.91	3.62	54
const. errors removed by 4-par. transf. point 1120 omitt.	a	2.27	1.34	2.64	32
	b	2.99	2.17	3.69	21
	a+b	2.58	1.72	3.10	53

Table 4 : CPNS-Test "Bodensee 1982"; comparison of horizontal coordinates of perspective centres, from CPNS data against photogrammetric values obtained by blockadjustment with PAT-M 43 program