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EXPERIENCE WITH KINEMATIC GPS DURING AERIAL PHOTOGRAPHY IN NORWAY

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1. INTRODUCTION

The experiment reported in the following makes two assumptions from the start:
- The NAVSTAR Global Positioning System (GPS), if used during aerial photography, may reduce the required number of ground control points.
- The GPS-data are best applied as observations to the projection centres of the camera in a block adjustment.

The GPS is here used in a kinematic mode, with a GPS-receiver onboard the fast moving airplane. The receiver records its raw data to a memory during the photoflight. To obtain the necessary accuracy one has to apply relative positioning, that means also having a second GPS-receiver recording data in a known point on the ground. Post-processing of the data from both receivers gives coordinates of the projection centre of each photograph. These coordinates are then put into the block adjustment.

The goal of our experiment was to gain experience with the method and to demonstrate the usefulness. To do this controlled photoflights with simultaneous GPS data registration were carried out over two test fields in Norway in July 1988. The Continental Shelf and Petroleum Technology Research Institute was in charge of the planning, preparation and realization of the project.

The test flights were performed in combination with aerial triangulations. This serves two purposes:
- Standard aerial triangulation provides coordinates of the projection centres of the camera, which can be used for comparison with positions derived from GPS.
- Block adjustment, including projection centre positions measured with GPS, but with few ground control points, demonstrates the usefulness.

This paper presents parts of the results from the experiment.

2. EQUIPMENT USED

Airplane: Rockwell Turbo Commander, belonging to Fjellanger Widerøe A/S, a norwegian company. The flying speed was 380 km/h. This fairly high speed showed up to be not advantageous.

The GPS-receivers were two Trimble 4000SL receivers. One was used in the airplane, and the other one was used in the reference station on the ground. Both are 5 channel, L1 C/A-code receivers providing pseudorange and carrier phase observations.

During the entire flight observations of pseudorange and carrier phase were carried out and recorded in the internal memory of the receivers. The observation rate was 3 seconds, which was the highest rate possible when receiving data from 5 satellites. The capacity of the internal memory was 1 megabyte, sufficient for 1 hour 42 minutes of observation.

The camera used was a Wild RC10 wide angle camera. The synchronization between the camera and the GPS-receiver in the airplane was done with a separate microcomputer. This computer recorded 1 pulse per second from the GPS-receiver, and

1 pulse per aerial photograph from the camera. When flying the first test field the shutter-pulse from the camera was used. Checks revealed that there is a variable delay between the shutter-pulse and the exposure in the RC10. Before flying the second test field diodes were mounted into the camerabody to give more exactly the moment of exposure.

Other cameras and newer cameras can provide a pulse at the midpoint of the exposure interval. And some new GPS-receivers can record this pulse into the datastream in the internal memory. This will make the synchronization easier to handle. The needed accuracy of the timing is high because the airplane is moving 5-10 centimeters in one milliseccond.

The GPS antenna was placed on top of fuselage of the airplane, with the antenna phase centre 1.86 meters away from the camera projection centre. This off-set was measured before flight.

3. TESTFIELDS AND PHOTOGRAPHY

Two testfields, named Follo and Sperillen, both in the southern part of Norway, were used in the experiment.

The Sperillen area is a small testfield designed for camera calibration. Using an image scale of 1:8000 the field is covered with 4 parallel strips with 60% sidelap, each strip having 6 images with 60% forward overlap. This block can show the accuracy of GPS, but is too small to demonstrate the advantages of using GPS in aerial triangulation. This report will therefore mainly concentrate on the other testfield.

The Follo testfield is a rectangular area of 16 x 13 km. The photography was made on 19.06.1988 under good weather conditions. A standard wide angle camera and panchromatic film was used. The image scale was 1:15000. The block consists of 5 parallel strips, each 16 km long, with 30% sidelap. Each strip was flown in both directions, and the forward overlap was 80%. Up till now only one quarter of these images have been used, namely a block of 5 strips with 60% forward overlap and 30% sidelap. Each strip has 11 models on the average. This kind of overlap is the standard overlap for mapping and for aerial triangulation in Norway and in other countries as well. It is most interesting to demonstrate the usefulness of GPS with this kind of overlap.

In the Follo testfield we have 44 points with known x, y, z coordinates. 39 of these points are signalized, 5 are natural. 39 have known x, y, z; while 2 are known in planimetry and 3 in height only. The coordinates are determined with standard field surveying. The standard deviation of the coordinates is estimated to 3 cm. Six of the points were also measured with GPS to make possible transformations between the ground coordinate system and the satellite coordinate system WGS84.

During photography both GPS-receivers were recording their data at 3 seconds interval, as explained in chapter 2. The time interval between the exposures of each of the used photographs in the strip is 13.1 seconds.

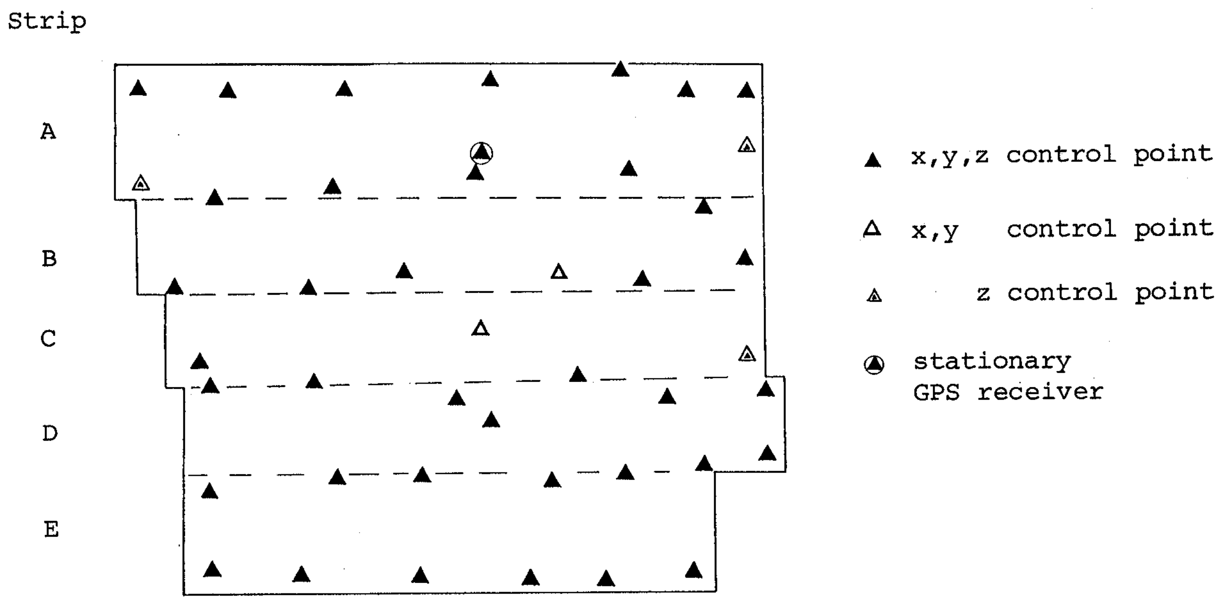

Fig. 1 : Testfield Follo, block configuration

4. MEASUREMENT OF PHOTOGRAPHS

All tie points are natural. Each model has double points in the "von Gruber positions". Tie points from the neighbouring strips, and control points comes in addition, bringing the total number of points up to 13.7 per model on the average.

The main data of the Follo block then is:

size	: 5 strips with a total of 55 models
camera	: Wild RC10, f=152.00 mm
forward overlap	: 60%
side overlap	: 30%
flight altitude	: 2300 m.a.t.
image scale	: 1:15000
number of points	: 44 x,y,z ground control points 281 tiepoints.

The models were oriented and measured in a Planicomp C100. Both photo-coordinates and model-coordinates were stored.

5. GPS COMPUTATIONS

The post-processing of the GPS-observations, which is not the topic of this paper, provides the positions of the antenna phase centre, in our case at 3 seconds intervals. Interpolation, as a function of time, gives the position of the antenna at the moment of exposure. A reduction for the off-set vector finally gives

"GPS-values" for the camera projection centre at the moments of exposure. A transformation from satellite coordinate system to ground coordinate system finalizes this part of the computations.

Coordinates of the projection centres derived from photogrammetry and derived from GPS, show systematic discrepancies. There are several possible sources for this:
- Datum differences between GPS and local ground coordinate system.
- Unmodelled errors in GPS.
- Cycleslips in GPS.
- Unmodelled errors in photogrammetry, imperfect calibration being one of the possibilities.

At the present stage of development it is not possible to eliminate all the sources of systematic errors. The only way at the moment seems to be to compensate for the errors with additional parameters in the block adjustment.

6. BLOCK ADJUSTMENT WITH GPS

Both "independent models" and "bundles" are possible methods for adjustment with GPS. Several others have reported using the bundle method. We did choose the independent models for these reasons:
- It is the mostly applied method in Norway, and in other countries as well.
- A program was at hand.
- The method provides fairly straightforward means to compensate for systematic errors in the GPS data.

Adjustments were performed with the program BLOKK developed at our department. It runs on a microcomputer, IBM AT or compatible. The program provides choice between adjusting all three dimensions in one run (7 parameters per model), or adjusting planimetry (4 parameters) and height (3 parameters) separately. The program also computes weight coefficients and standard deviations for all points.

When including GPS-values for the projection centres into the adjustment, the systematic errors must be modelled. Linear timedependent terms is one possibility:

$$\begin{aligned} \Delta x &= a_0 + a_1 t \\ \Delta y &= b_0 + b_1 t \\ \Delta z &= c_0 + c_1 t \end{aligned} \qquad (1)$$

Our experience so far is that the systematic errors are different from strip to strip. One main reason is that one can not, under operational photography, be sure to avoid cycle slips when the airplane turns from one strip to the next. Then, assuming the x-axis to be along the strip, the time t in (1) will be proportional to x. And then we can rewrite (1) using other symbols:

$$\begin{aligned} \Delta x &= c_x + \Delta m \cdot x \\ \Delta y &= c_y + \Delta \kappa \cdot x \\ \Delta z &= c_z - \Delta \varphi \cdot x \end{aligned} \qquad (2)$$

We have found it convenient to treat the GPS-values as models in the same manner as the regular models in the block, and compensate the systematic errors in this way. We can form one "GPS-model" per strip, containing the GPS-values for the projection centres of that strip. The only difference is that the 7th parameter, the omega-rotation, of the GPS-models, must be constrained to zero.

Following this line of thinking one will find that we need to determine all the unknown parameters in one adjustment including all observations. It is our conclusion that when compensating the systematic GPS-errors in an independent model adjustment, all 7 parameters of the models must be determined in one adjustment. It is no longer possible to separate planimetry and height. For instance I guess that with minor modifications the program PAT-M7 can handle GPS-values, but I doubt that PAT-M43 can do it.

One final point about including corrections for systematic errors in the adjustment: It may have strong influence on the matrix structure. If this is not thought of when designing the program, one is likely to run into surprises.

7. TEST RESULTS, GPS VALUES

The basis for comparison of the GPS-values of the projection centres, is values for the same centres determined by block adjustment without GPS, but with all ground control. The 7-parameter-per-model version was used. The standard deviation of unit weight, sigma naught, was 11 cm, or 7.4 µm in the image at scale 1:15000. The standard deviation of the adjusted coordinates of the projection centres was on the average 22 cm.

When comparing the GPS-values of the projection centres to their "should be"-values, the systematic errors are evident. The means applied to remove these errors are some or all of the 7 parameters in a conformal threedimensional transformation. The tool applied to do it, is once again the adjustmentprogram BLOKK. Putting the "should be"-values into the ground coordinate file, and the GPS-values in one or more model files, the program does what is needed.

Results, using 7 parameters common to the whole GPS-block:
σ_0 planimetry = 0.64 m σ_0 height = 1.12 m
Results, using 7 parameters per GPS-strip:
σ_0 planimetry = 0.35 m σ_0 height = 0.25 m
Results, using 6 parameters per strip, omega constrained to zero:
σ_0 planimetry = 0.35 m σ_0 height = 0.28 m

A plot of the remaining discrepancies reveals a discontinuity in GPS-strip B. A fifth satellite came into view at that moment and changed the geometry of the satellites. In the following GPS-strip B is split in two, B1 and B2.
Results, using 6 parameters per strip, omega constrained to zero, B split:
σ_0 planimetry = 0.34 m σ_0 height = 0.25 m
The improvements in GPS-strip B are more evident on a plot.

Table 1 shows that the scale may be constrained to 1.0 without loss of accuracy, and κ and φ constrained to zero with a modest increase of inaccuracy. In the last case the only remaining active parameters are the shifts c_x, c_y, c_z.

Remaining active parameters	σ_0 planimetry (m)	σ_0 height (m)
c_x c_y c_z scale φ κ	0.34	0.25
c_x c_y c_z φ κ	0.34	0.25
c_x c_y c_z	0.38	0.27

Tab. 1 : Accuracies of GPS-values for the projection centres, after removal of systematic errors.

The values in table 1 contains also the errors in the "should be"-values, formerly estimated to have a standard deviation of 0.22 m.

Conclusions:
- The GPS-values have systematic errors which varies from one strip to the next.
- Abrupt changes may occur within a strip due to sudden change in satellite geometry.
- Shifts c_x, c_y, c_z removes most of the errors.
- An additional modest improvement is obtained with correction terms $\Delta y = \Delta\kappa \cdot x$ (or $\Delta y = b_1 \cdot t$) and $\Delta z = -\Delta\varphi \cdot x$ (or $\Delta z = c_1 \cdot t$).
- There is no evidence of timedependent errors continuing over more than one strip.
- The accuracy of the GPS-values of the projection centres, when sources of errors are removed, is estimated to:

  planimetry 0.25 m
  height 0.12 m

The results from the other test field, Sperillen, show similar results, with two exceptions:
- Each strip need 6 parameters for removing systematic errors. The reason for this must be that in Follo was 6 points measured with GPS on the ground also, thus permitting a good initial transformation from satellite system to ground system. In Sperillen this was not the case. One may draw the conclusion that when none of the ground points are measured with GPS, one should be prepared to use 6 linear correction parameters per strip.
- The estimated reamining accuracy of the GPS-values of the projection centres, when sources of errors are removed, is estimated to:

  planimetry 0.15 m
  height 0.11 m

  For planimetry there is a significant, up till now unexplained, difference between the two fields.

8. BLOCK ADJUSTMENTS WITH GPS

The aim of the following computations is to demonstrate the possibility of reducing the number of ground control points when including GPS-values in the adjustment. The computations are made with the same software, the same images and measurements as earlier in this paper.

The results of each adjustment must be compared to same check values. The ideal is to have an abundant number of precise check points, in addition to the 44 control points. We do not have this ideal situation. In stead we use what we have:
- Check A: The remaining of the 44 control points not used in each adjustment. The number and positions of these point then varies from one adjustment to the other. The points are field-surveyed with good precision.
- Check B: Coordinates of all tie points, not including projection centres, determined with block adjustment using all ground control points. There are 262 such points, and they are the same in all adjustments. Their standard deviation was estimated to 11 cm in planimetry, 13.5 cm in height. The disadvantage of this check set is that it is not independent in stochastic sense from the results they are compared to. But it does give the answer for this block to the question:

  "If we use GPS and few ground control points, how much will the results differ from an adjustment without GPS but with many control points?"

Figure 2 shows the distribution of control points for the first set of adjustments, while figure 3 shows the results for planimetry in graphic form. Three different kinds of adjustment are performed:
- Without GPS.
- With GPS, 7 correction parameters per strip.
- With GPS, 3 correction parameters per strip.

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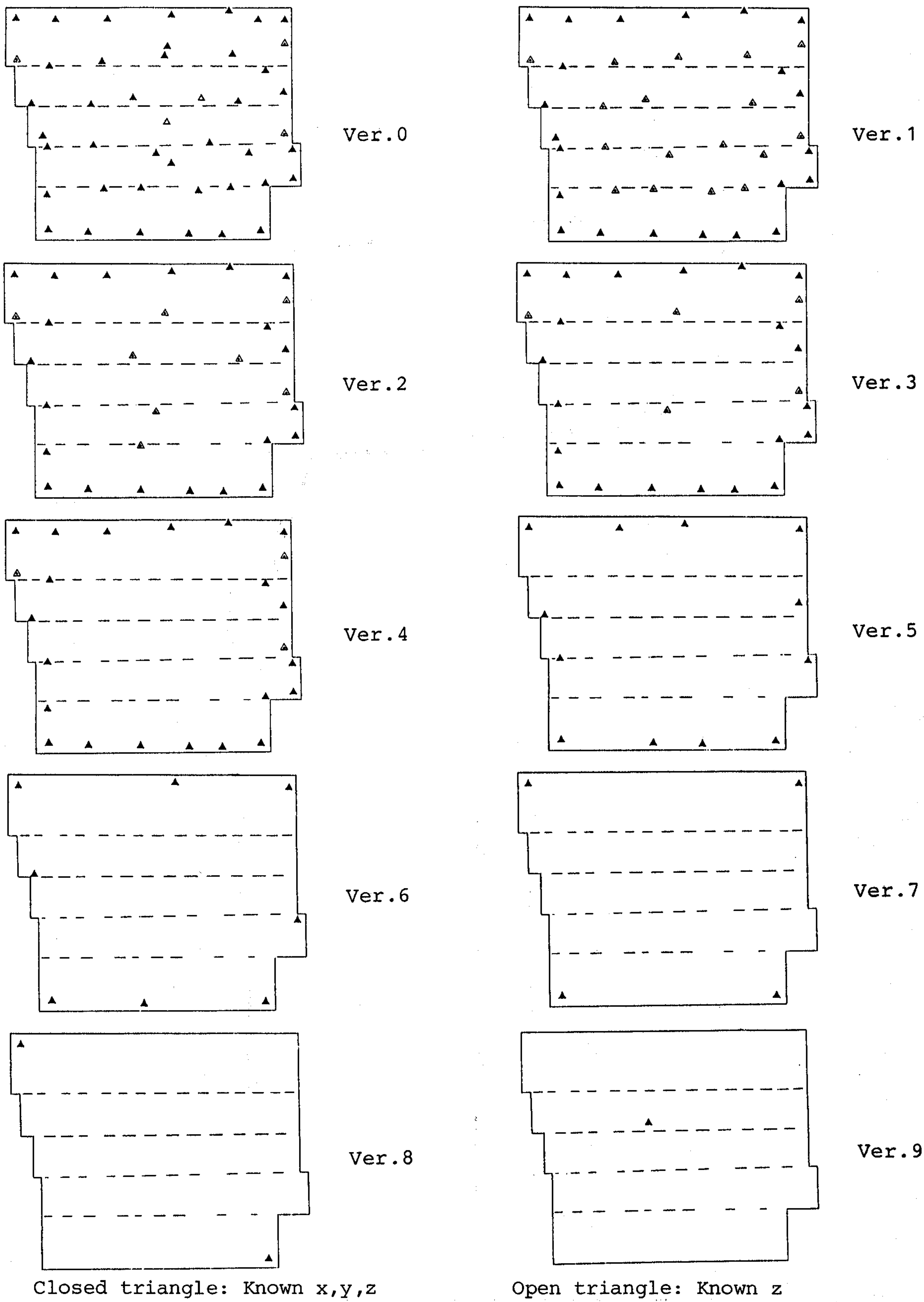


Fig. 2 : Different distributions of control when investigating planimetric accuracy from block adjustment with GPS.

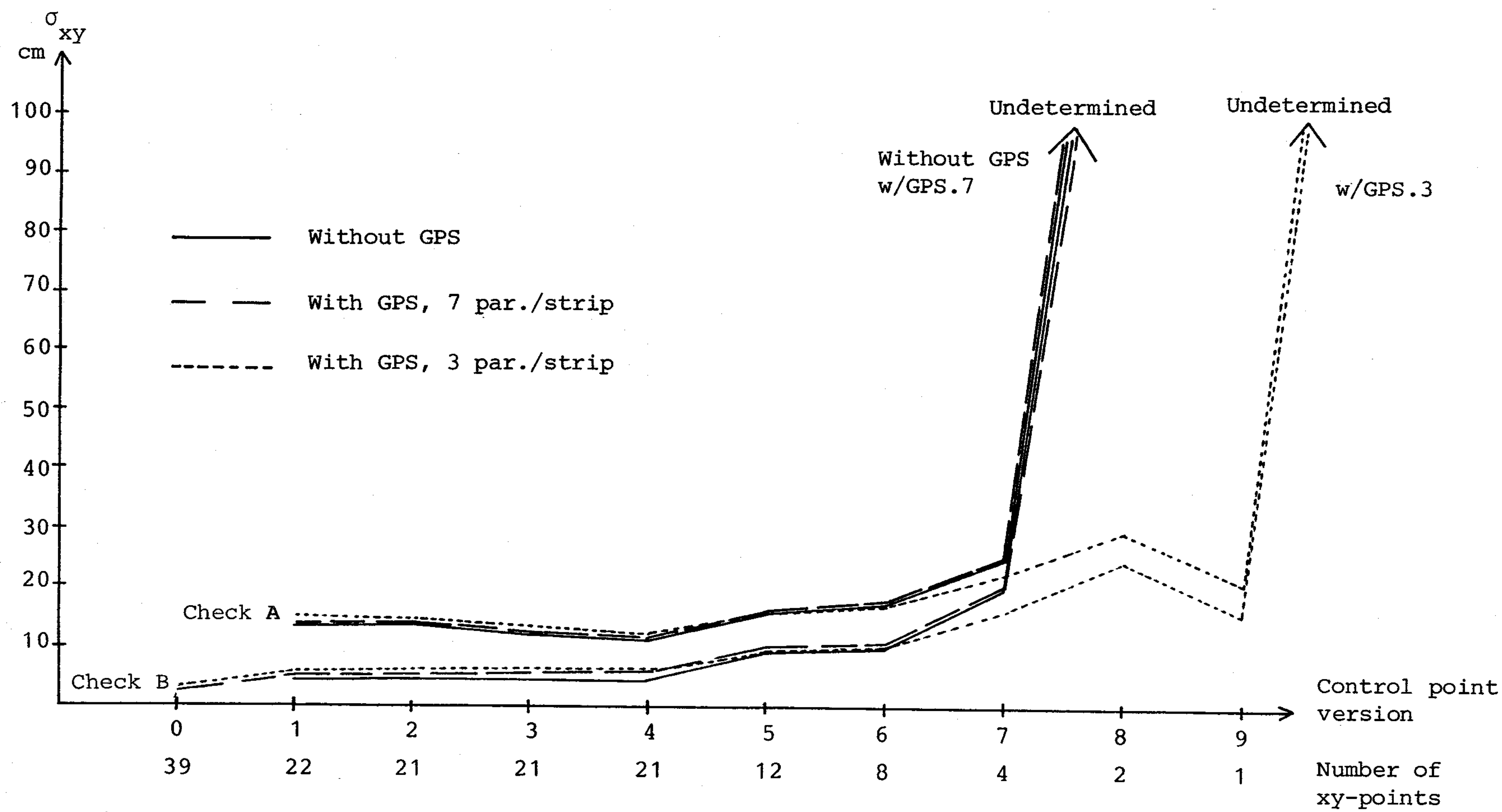


Fig. 3 : Results of block adjustment with GPS compared to checks. Showing r.m.s. accuracy of coordinates in planimetry, depending on the number of control points.

The result shows for planimetry that the accuracy is fairly invariant for 8 control points along the block perimeter, or more control points. The r.m.s. accuracy of coordinates is 11-17 cm. GPS has very little influence on planimetry when this amount of control is used.

With 4 control points, one in each corner, adjustment with GPS gives better result (23 cm) than without GPS (25 cm). Using only 2 or 1 control points gives no solution without GPS. Adjustment with GPS and 3 correction parameters per strip gives satisfactory results with r.m.s. accuracy of coordinates of 25 cm also in these extreme cases.

The "textbook"-solution in this case is full perimeter control, 21 control points. The alternative solution with GPS and a few control points produces a result with r.m.s. deviation from Check B of 10 cm with 12 and 8 control points, 17 cm with 1 point in each corner, and slightly more than 20 cm when using 2 or 1 control points.

An alternative way of estimating accuracy is the standard deviations derived from the weight coefficients of unknown coordinates. This is computed for 231 tie points, and the quadratic means of these are shown in figure 4. The results for planimetry are very good, also with few control points, assuming GPS is used.
Standard deviation of coordinates:

8 or more control points:		11-15 cm
4 control points	:	approx. 20 cm
2 or 1 control points	:	approx. 25 cm

The estimated values in figure 4 are pleasingly alike the real results shown in figure 3.

Most of the control point configurations examined so far are not good for heights. Height control is needed in the interior of the block. Figure 5 shows a new set of control used to examine the heights. In these cases we have chosen to study the squared mean of the standard deviations computed from weight coefficients.

The results are shown in figure 6. Control point versions H1 - H4 shows that the key to good height accuracy is bands of control points across the strips (as usual). Versions H4 to H7 shows that with one full control point in each corner, only one additional height band is required. Version H8 shows that in the band the outermost point on each end may be omitted. But trying to omitting even more points causes the inaccuracies to blow up.

The computations so far have used GPS with 3 correction parameters (shifts) for each strip. We assume that this is the best obtainable today under operational photography. In this case version H8 is an optimal point configuration for both planimetry and height, providing standard deviations in height of 0.09 $^0/_{00}$ of the flying height.

The far right end of figure 6 shows what <u>may</u> be possible in future <u>if</u> one can master the cycleslips. In that case, one control point may be sufficient.

One final warning remark: In this paper only accuracy, or more correctly precision, has been investigated. Reliability is not touched upon at all.

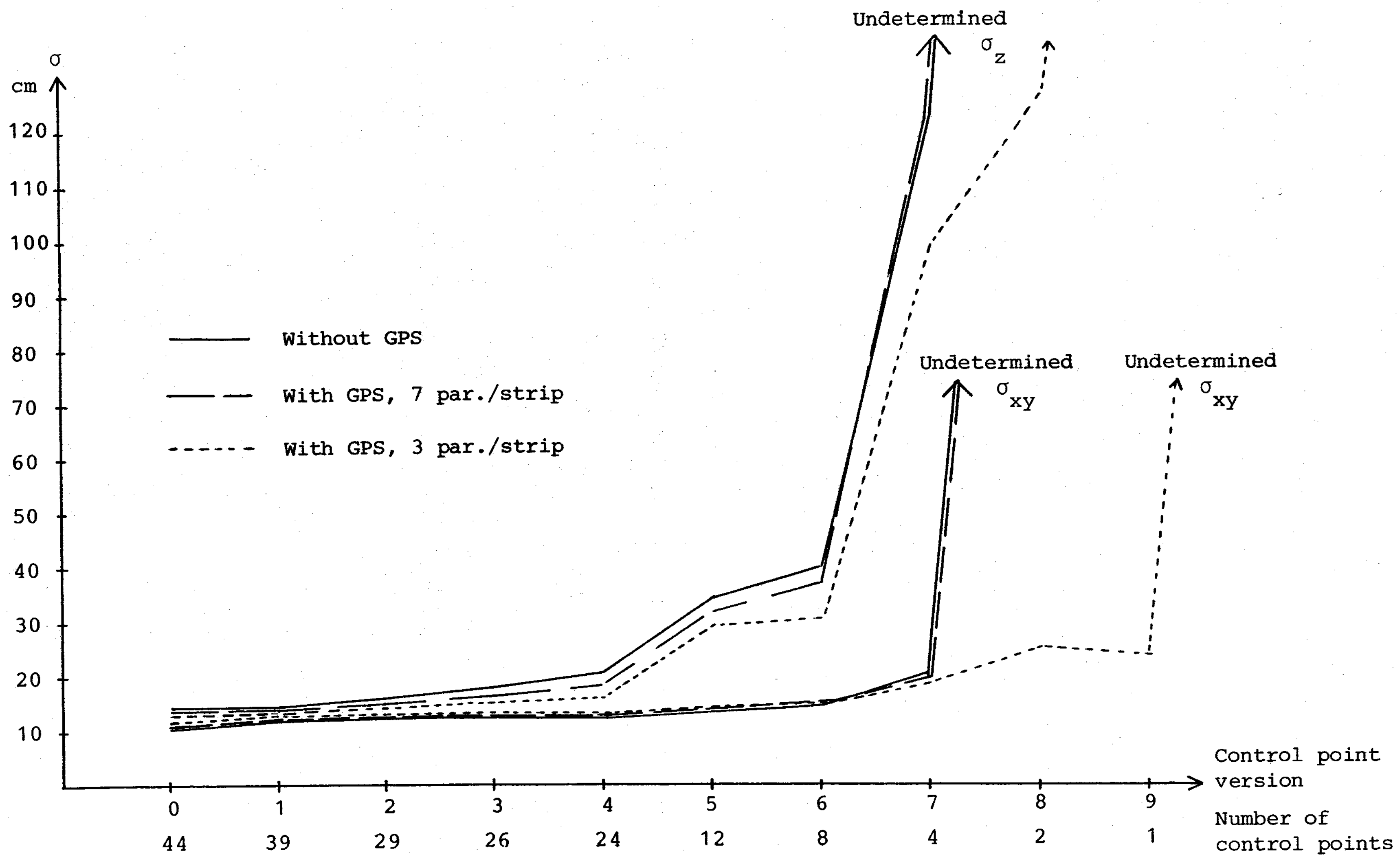
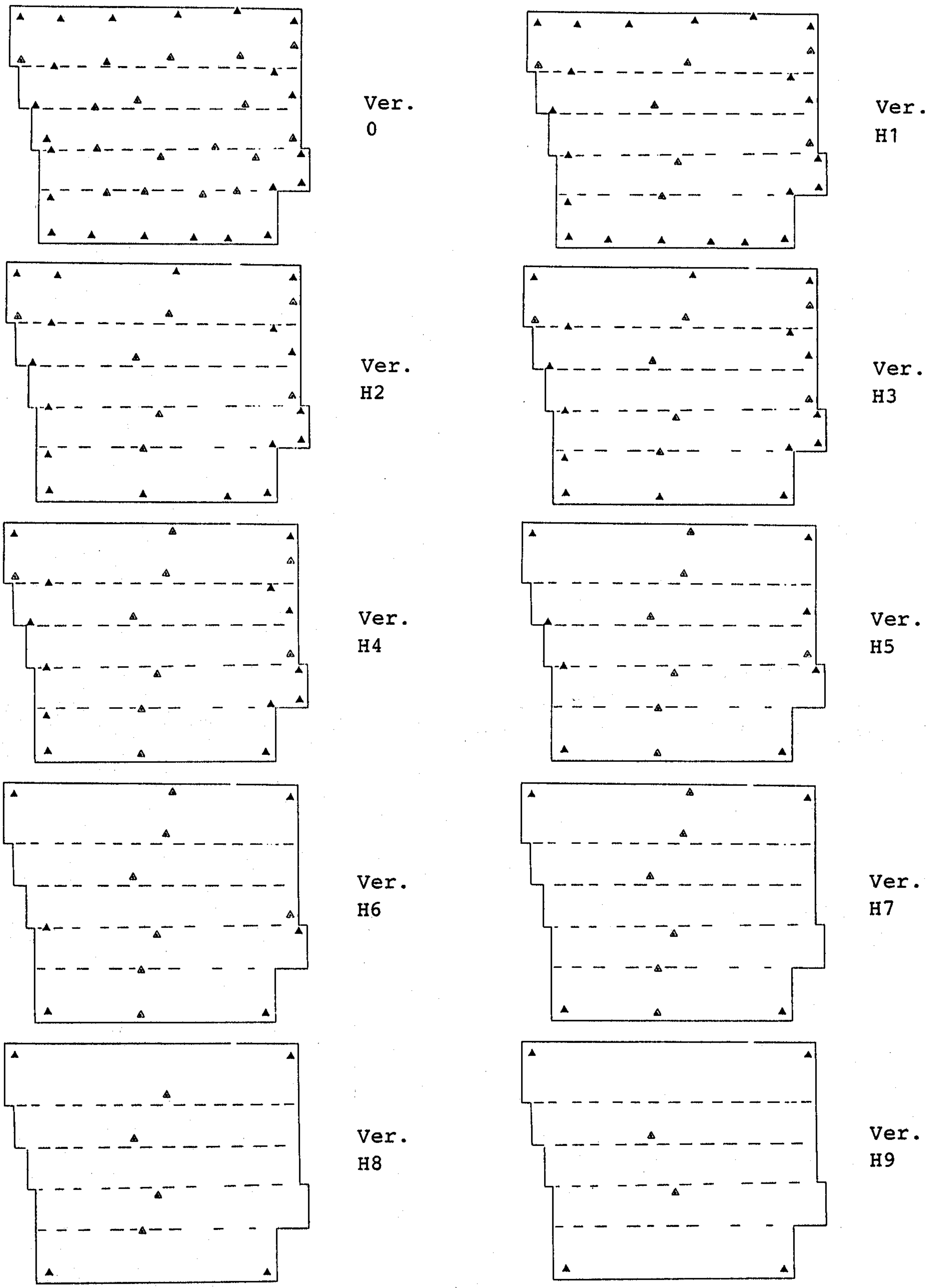


Fig. 4 : Results from block adjustment with GPS and different number of control points. The figure show the squared means of standard deviations derived from weight coefficients.



Closed triangle: Known x,y,z   Open triangle: Known z

Fig. 5 : Different distributions of control when investigating height accuracy from block adjustment with GPS.

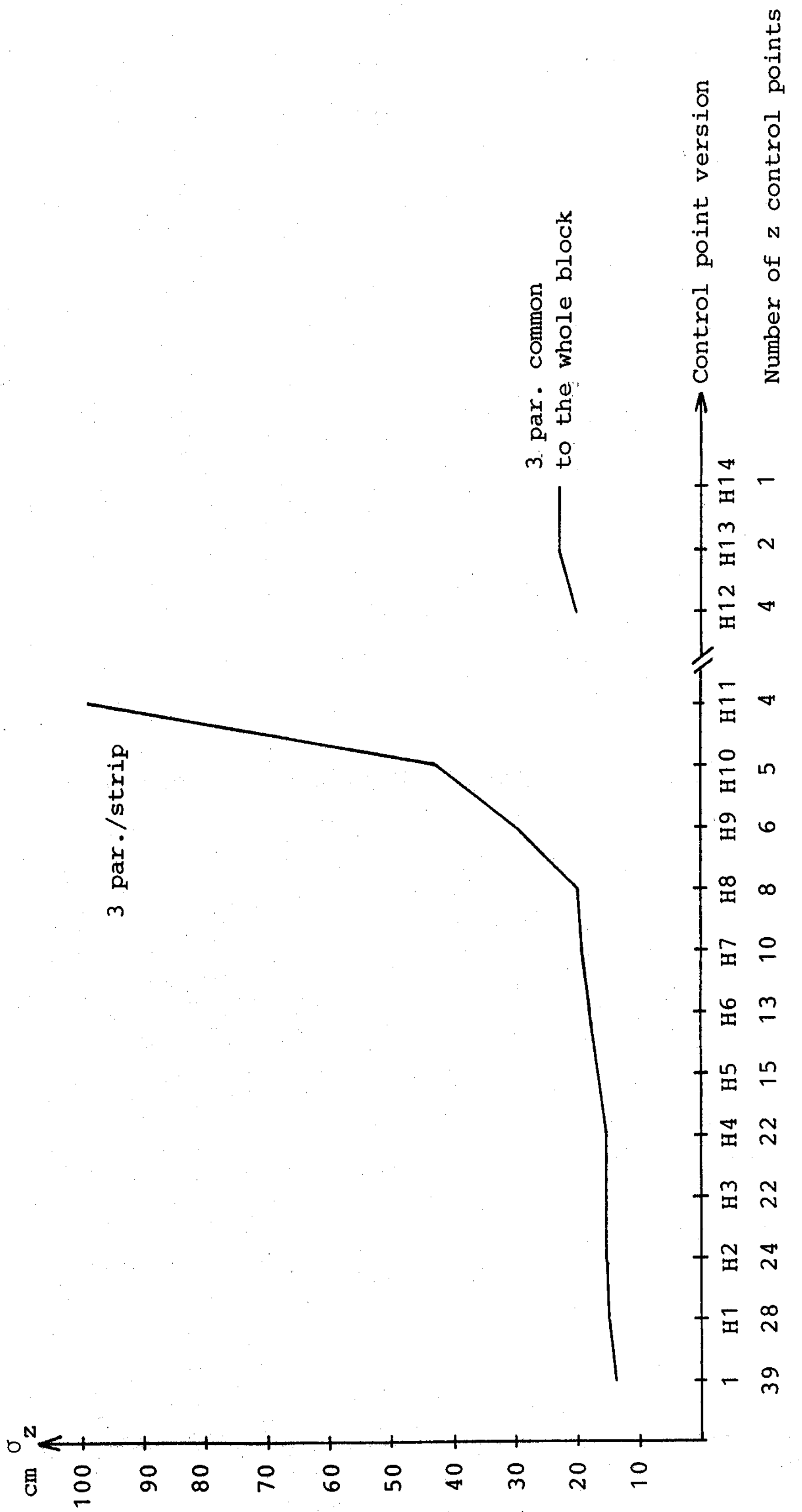


Fig. 6 : Results from block adjustment with GPS and different number of control points. The figure show the squared means of standard deviations in height, derived from weight coefficients.

9. CONCLUSIONS

The experiment has demonstrated the usefulness of GPS during aerial photography and block adjustment. An accuracy of 10-20 cm was obtained in the position of the camera projection centre, and better accuracies are possible.

A bottleneck is the data rate. A high data rate requires high memory capacity. But the high data rate is necessary to avoid too high interpolation errors when interpolating from the basic GPS recordings to the position of camera at the moment of exposure.

Efforts should be put into finding methods to avoid or master cycleslips. Without cycleslips one control point in each corner of the block is sufficient. If cycleslips do occur additional control or photography will be necessary.

Systematic discrepancies will exist between the coordinate systems in question. But they may be effectively removed with linear additional parameters in the block adjustment.

10. ACKNOWLEDGEMENTS

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ABSTRACT

This paper presents the results from an experiment using GPS observations in aerial photography and block adjustment. Photography with simultaneous GPS observations over two test fields was performed in July 1988. The method of block adjustment used is the independent models. Methods for introducing the GPS data into the adjustment are discussed.

The accuracy of the GPS values of the camera projection centres is examined. Studies of the necessary number of control points are reported. The needed amount of control depend on wether cycleslips do occur or not.

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