Photogrammetric Week '93 Eds. D. Fritsch / D. Hobbie, Wichmann, Karlsruhe, 1993

Block adjustment with GPS - results from test flight FREDRIKSTAD

LEIF ERIK BLANKENBERG and OLA ØVSTEDAL, Aas

ABSTRACT

In the last years, GPS has made it possible to reduce the necessary ground control in block adjustments to a minimum. This paper presents the results from a test flight in Fredrikstad, Norway in 1992. The results demonstrate the efficiency of the method.

1. INTRODUCTION

GPS makes it possible to determine accurately the coordinates of each exposure station during a photo flight. Several experiments (e.g. ANDERSEN 1989, FRIEß 1990 and 1991) show how to reduce the necessary ground control to a minimum when these exposure station coordinates are used in a GPS-supported block adjustment. Systematic errors in the GPS determined coordinates may be treated by introducing additional unknowns in this adjustment. Up to six additional unknowns per strip may be necessary.

In 1988 two test flights were carried out in Norway (ANDERSEN 1989) in photo scales 1:8000 and 1:15000. Both tests showed promising results. Based on the experience gained in these test flights, and similar test flights abroad, a new test flight was set up at the Department of Surveying, NLH in 1992 under the leadership of professor Øystein Andersen. The main goal for this new experiment was to achieve an accuracy that satisfied the demand for large scale mapping (1:1000).

Since the 1992 test flight was carried out with the largest photo scale commonly used in Norway (1:5000), we found it necessary to establish a very accurate and homogeneous test field for this purpose. The following describes the test field, the test flight, the kinematic GPS post processing and the results from the GPS-supported block adjustment.

2. FREDRIKSTAD TEST FIELD

With traditional block adjustment and photo scale 1:5000, it is possible to obtain a theoretical accuracy of 2-3 cm for the adjusted points. GPS supported blocks are expected to have the same accuracy properties, which we would try to confirm empirically with our test flight. The problem when dealing with such high-accuracy blocks, is to find a test field with better accuracy than the block we want to test. For our test flight, we found it necessary to establish a new test field.

The test field is located in Fredrikstad (ca. 100 km south of Oslo) in a fairly flat terrain. The rectangular field covers an area of 6.0 x 4.5 km and contains 52 well distributed points (figure 1). Our initial goal was to achieve a point accuracy better than 1 cm. The network was established by means of traditional static GPS. The achieved coordinate accuracy, in terms of standard deviation, is better than 5 mm for all points of the network.

The planimetric adjustment was carried out in a local Gauss-Krüger coordinate system, while the height adjustment was carried out on the ellipsoid. Both systems are referred to the WGS84 ellipsoid, so no datum transformations is necessary in the later block adjustments. In the network adjustment only one point was fixed.

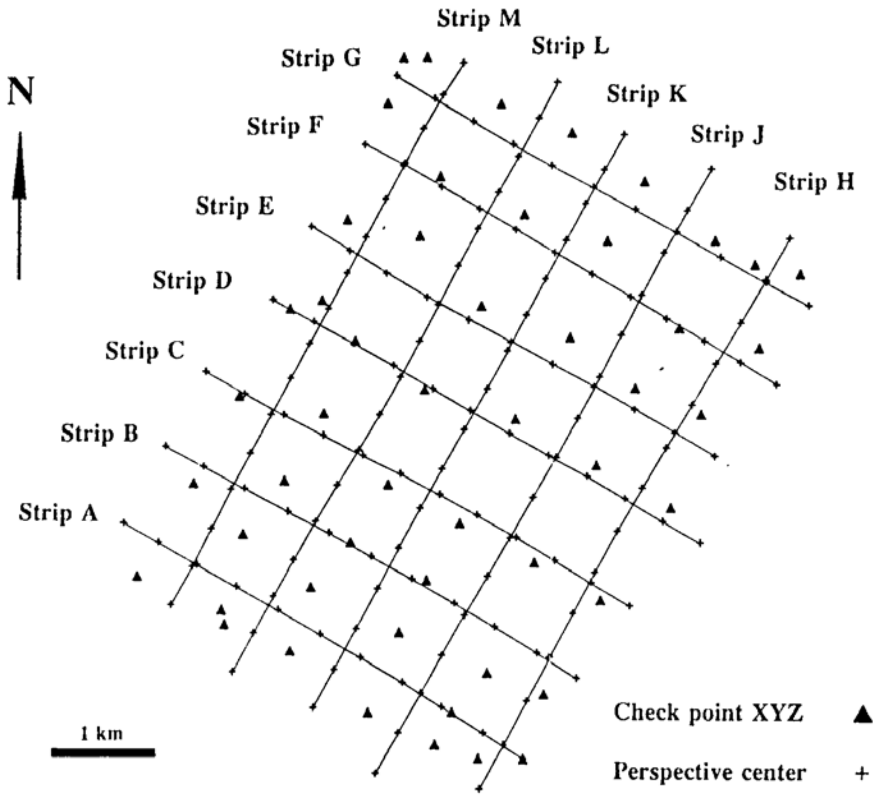

Figure 1: All the strips in test field FREDRIKSTAD 1992.

3. FREDRIKSTAD 1992 TEST FLIGHT

The technical data for the test flight are as follows:

GPS receivers	:	2 Ashtech M XII-P and 3 Ashtech LD XII
Data sampling rate	:	0.5 second
Survey aircraft	:	Partenavia P68TC Observer
Ground speed	:	ca 70 m/s
Flight duration	:	65 min
Aerial camera	:	Wild RC20 15/23 (upgraded with EDI), c=152.840 mm
Image scale/ Flight altitude	:	1: 5000 / 800 m
Overlap	:	Forward=60% / Side=25%
Number of photos	:	159
Number of object points	:	670
Number of image points	:	4307
Image points per obj. point	:	6.4
Image points per photo	:	27.1
Available control points	:	51 of originally 52 (one target was missing)

For the test flight we used a setup with five GPS receivers. Three GPS receivers were on board the aircraft. Two of these were connected to one antenna above the fuselage, almost directly above the camera, while the third receiver was connected to an antenna on top of the aircraft's tail-fin. The

fourth and fifth receivers were on the ground, one at the test field, and one at the airport, ca. 20 km from the test field. The receiver in the test field was a P-code receiver.
Usually a two-receiver setup is used, one receiver on board the aircraft and one on the ground. The three spares in our case served as backups. Unfortunately, only two of the five receivers were P-code receivers.
The two Ashtech P-code receivers (one in the test field, the other in the aircraft) collected C/A-, P1- and P2-pseudoranges, P-code derived L1- and L2-carrier phases as well as instantaneous doppler observations on L1 and L2. The three LD-XII receivers (one at the air-port, two in the aircraft) collected C/A-pseudoranges, C/A-code derived L1- carrier phases, L2-squaring carrier phases and instantaneous doppler on L1.
All the receivers operated at a sampling rate of 0.5 second. The data-file from each P-code receiver contained ca. 9 Mbyte, while the C/A-code receivers each had a data file of ca. 6 Mbyte. Because of this large amount of data, we used portable PC's as external data loggers. This resulted in two problems. First, when the P-code receiver on the ground tracked seven or more satellites, block errors occurred during data transmission, resulting in some lost epochs. Second, the battery on one of the PC's on board the aircraft was weak, also resulting in loss of epochs.
The P-code receiver on board the aircraft time-tagged the rising edge of the incoming pulse from the camera at the times of exposure. One complicating factor was that the mid-exposure pulse from the Wild RC20 camera was correct at the falling edge of the pulse (HØGHOLEN 1992). We solved this problem by connecting an invertor to the cable between the camera and the GPS receiver. This invertor changed the mid-exposure pulse from low to high.
The test flight was carried out in May 1992. A wide angle lens was used (15/23). Photo scale was 1:5000, which gave 5 strips along the test field and 7 cross strips. The overlap was 60% within the strips and 25% between strips (figure 1). We initialized the integer ambiguities at the airport before take-off and after returning. The pilot flew flat turns between the strips, to avoid signal interruptions. The camera was fixed to the aircraft during the flight.
Traditional surveying methods were used to determine the eccentricity vector between the GPS antenna and the entrance nodal point of the camera (BLANKENBERG 1992).
In order to achieve the highest accuracy, 75% of the tie points were targeted. Three pairs of tie points were used between models inside the strips. Between strips at least one tie point per model was used. The image points were measured with a Zeiss P3. All tie points in the strips along the test field were measured in the cross strips and vice versa.

4. KINEMATIC GPS POST PROCESSING

4.1 Postprocessing

The binary Ashtech-data were converted to the RINEX-format (Receiver INdependent EXchange format, GURTNER/MADER/MacARTHUR 1989) using the Ashtech supplied routine ASHTORIN. The size of the RINEX observation files were about the same as the size the Ashtech raw data files. The post processing took place in three steps.

4.1.1 Postprocessing with the OMNI-software

During a stay at the National Geodetic Survey (NGS) in USA we processed the data with the NGS software OMNI (MADER et al 1991). The processing revealed lots of problems in the GPS-data. As expected, the data from the C/A-code receivers were worse than the data from the P-code receivers. Since the PC which stored data from the receiver connected to the antenna on the tail of the aircraft, experienced a power failure, we decided to concentrate the processing on the data from

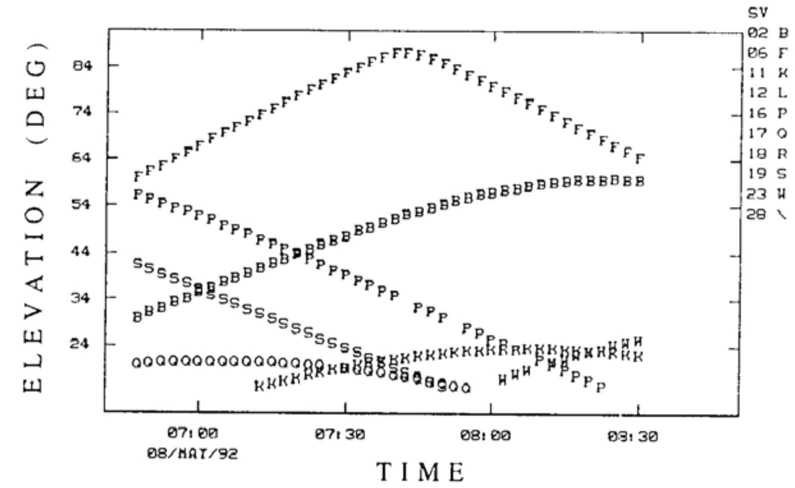

Figure 2: Available satellites.

the two P-code receivers.

Analyzes based on range- and ionospheric residuals (MADER et al 1991, ØVSTEDAL 1992) detected as much as 136 cycle slips (figure 3 - right) in the moving receiver. This receiver tracked fewer than four satellites at several occasions. 40 of the cycle slips occurred within the photo strips! The reference receiver on the ground had 7 cycle slips. Both frequencies (L1 and L2) were similarly affected.

Attempts with OMNI to fix all these slips proved to be unsuccessful. Clearly this was due to the noise of the data and the cycle slips being very close to one another in time. Manual editing based on range- and ionospheric residuals did not work either.

4.1.2 Preprocessing with TurboEdit - subsequent processing with OMNI

In the search for good data-editing algorithms we came up with TurboEdit, which is part of the software system GIPSY from JPL, USA (BLEWITT 1990). TurboEdit requires data from GPS receivers that supplies both P1- and P2-pseudoranges as well as L1- and L2- carrier phase observations with full wavelength. By deriving new phase observables (widelane and ionospheric combination), similarly derived P-code observables are used to estimate cycle slips on these observables. Widelane and ionospheric slips are finally converted to L1 and L2 slips. As for the range- and ionospheric residuals, the method is independent of the receiver's movement; the editing is done for one receiver at a time.

TurboEdit did a good job in cleaning up the data, but some slips remained however. OMNI tried to fix these slips in the subsequent processing. But the deviations from antenna coordinates derived from the block adjustment (chapter 5) still showed some discrepancies.

4.1.3 Preprocessing with TurboEdit - subsequent processing with GPSPROG

The Department of Surveying, NLH has been developing the GPS-software GPSPROG since 1991. The software uses pseudoranges for computation of receiver clock offsets. Cycle slip identification and estimation is based on TurboEdit, range- and ionospheric residuals and on time-differencing schemes (LICHTENEGGER/HOFMANN-WELLENHOF 1989). The data editing can be carried out for one receiver at the time, for single-differences and for double differences. The final processing is carried out in the double-difference mode. Any linear combinations of phases and pseudoranges can be processed. We are currently investigating methods for deciding the integer ambiguities while

Photogrammetric Week '93 Eds. D. Fritsch / D. Hobbie, Wichmann, Karlsruhe, 1993

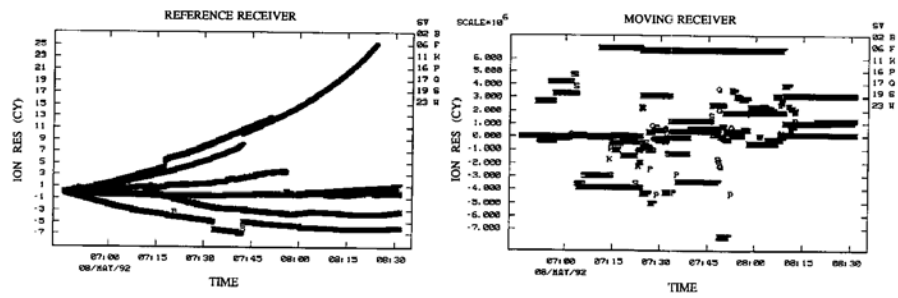

Figure 3: Plot of ionospheric residuals for the reference receiver (left) and the moving receiver (right).

the antenna is moving (On-the-fly ambiguity resolution).
The initial goal of maintaining the continuous phase history of the data from take-off to landing was not achieved. To accommodate photogrammetric needs for antenna coordinates, the following strategy was therefore used.
GPS-data for each strip were extracted and stored in separate sub-directories. Each subset of data was processed independently. We initialized the ambiguities with a double-difference P-code solution in the start of each strip. By constraining the ambiguities to values which probably are incorrect, the calculated coordinates will of course also be incorrect. As shown in chapter 5, this can be handled in the GPS-supported block adjustment. Important however, is that the GPS-derived positions inside each strip are homogenous. This means that besides all the cycle-slips being fixed, no constellation changes are allowed to occur within the strips. If the ambiguities are constrained to wrong numbers, the computed positions can be altered by several cm if a new satellite enters the solution or alternatively if a satellite is discharged.
The results presented in chapter 5 are based on the GPSPROG results.

4.2 Discussion on GPS data-quality

The receivers in the aircraft also experienced numerous cycle slips when the aircraft was flying steadily in the strips. In the following a short discussion is given on possible reasons:

1. The P-code receivers were recently upgraded from C/A-code receivers with L2 squaring to P-code receivers. The receiver used in the aircraft had developed a hardware-error on 6 of the channels. This problem was tried eliminated by forcing the receiver to track the best set of 6 satellites on the remaining 6 seemingly healthy channels. The P-code board on this receiver was changed immediately after the flight.
2. In the compromise between photogrammetry and GPS (favorable sun-angle versus favorable satellite availability), we carried out the test while some of the satellites were well below 20 degrees (figure 2). In the postprocessing we used an elevation cut-off of 15 degrees.
3. The antenna cables were not in accordance with the specifications of the receivers. This may have resulted in loss of signal strength.
4. In order to minimize obstructions from the aircraft, the antenna was mounted ca. 30 cm above the fuselage. This probably resulted in increased multipath.

We have in 1993 carried out similar tests with the last generation of "state of the art" receivers, and have seen a significant improvement in data-quality.

5. BLOCK ADJUSTMENTS

All the block adjustments below are calculated with the PC program NLHBUNT. This is a bundle block adjustment program developed at the Department of Surveying. The accuracy investigations have been carried out in two ways. First, GPS antenna coordinates estimated in a traditional block adjustment were compared to the same GPS determined coordinates. This gives a good estimate of the accuracy of the GPS determined positions. Secondly, GPS determined antenna coordinates were used as additional observations in block adjustments with minimum ground control. The empirical accuracy estimates are based on residuals in check points (ground control points not used in the adjustment).
The offset in time between the actual camera exposures and the GPS recordings are resolved by ordinary linear interpolation between the closest GPS-positions.

5.1 Estimation of the accuracy of the GPS positions

In order to determine the accuracy of the GPS determined camera positions, we performed a traditional block adjustment based on all available photos and control points (figure 1). In this adjustment the following accuracy (RMS of the estimated standard deviations) were obtained for the perspective center coordinates:

$$RMS_X = 3.7 \text{ cm} \qquad RMS_Y = 3.7 \text{ cm} \qquad RMS_Z = 1.9 \text{ cm}$$

The image rotations estimated in the block adjustment and the known eccentricity vector, were used to transform these perspective center coordinates into GPS antenna coordinates. Compared to the GPS determined antenna coordinates, stripwise systematic errors were found in the GPS values (figure 4 - left). This was of course expected, since the ambiguity initializations were done stripwise by means of a differential P-code solution at the first epoch in each strip. These systematic errors can easily be modelled in the subsequent GPS-supported block adjustments.
Test flights abroad (e.g. FRIEß 1991) and simulation studies with static GPS data (e.g. SCHADE 1992), showed that these systematic errors (often called drift errors) are time dependent and linear within a limited time span. This means that the drift errors can be modelled by six parameters per strip. If the errors were not time dependent, only three parameters per strip would be sufficient. Figure 5 shows the remaining errors when the systematic part is removed with three and six parameters respectively. Only the Z-coordinate errors are shown, but the situation is similar for the X- and Y-coordinates.
Figure 5 shows that the three parameter solutions are almost as good as the six parameter solutions, meaning that the errors are not time dependent for these data. The reason is probably that all the strips are shorter than 2 minutes duration and the positions used for the ambiguity initializations is close to the true positions (within a few metres). Applying carrier phase smoothing of the pseudoranges and using the newest generation of GPS receivers, will improve the differential code solution further.
Based on these results, we conclude that only three additional unknowns per strip will have to be added to the GPS-supported block adjustments in section 5.2. Up to now, six additional unknowns per strip have been common.
When the stripwise systematic errors have been removed, the overall RMS of the deviations between antenna coordinates from the block adjustment and the GPS processing is:

Photogrammetric Week '93 Eds. D. Fritsch / D. Hobbie, Wichmann, Karlsruhe, 1993

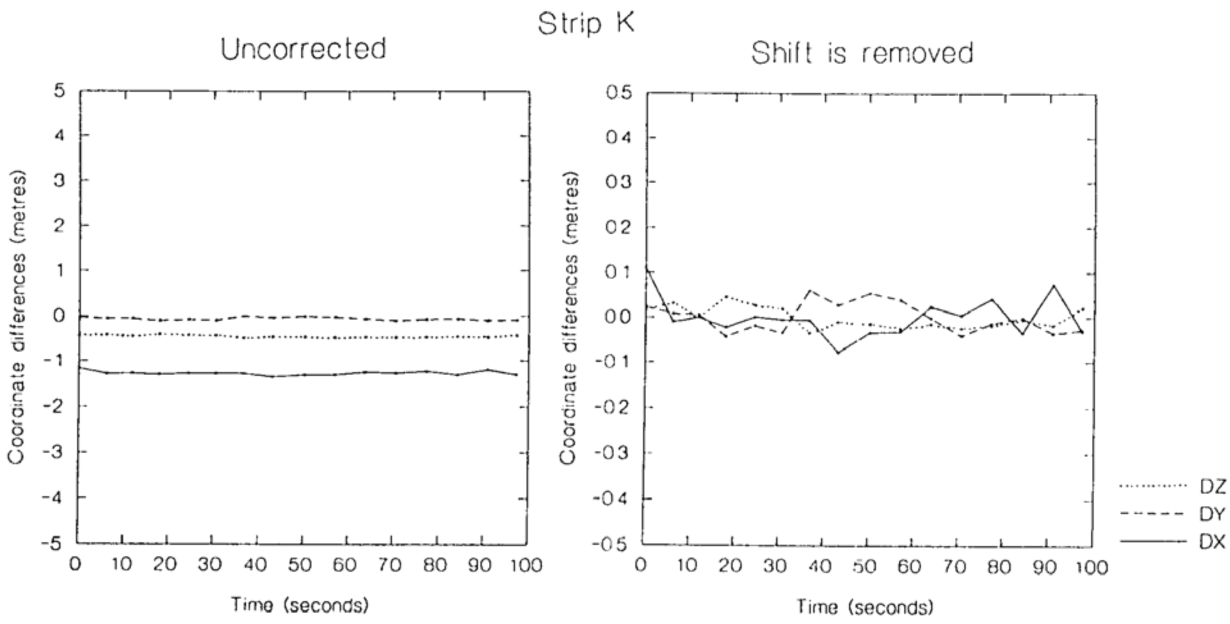

Figure 4: Left: Errors of GPS determined antenna coordinates for one strip. Right: Remaining errors when the constant coordinate offsets are removed. The situation is similar for the other strips.

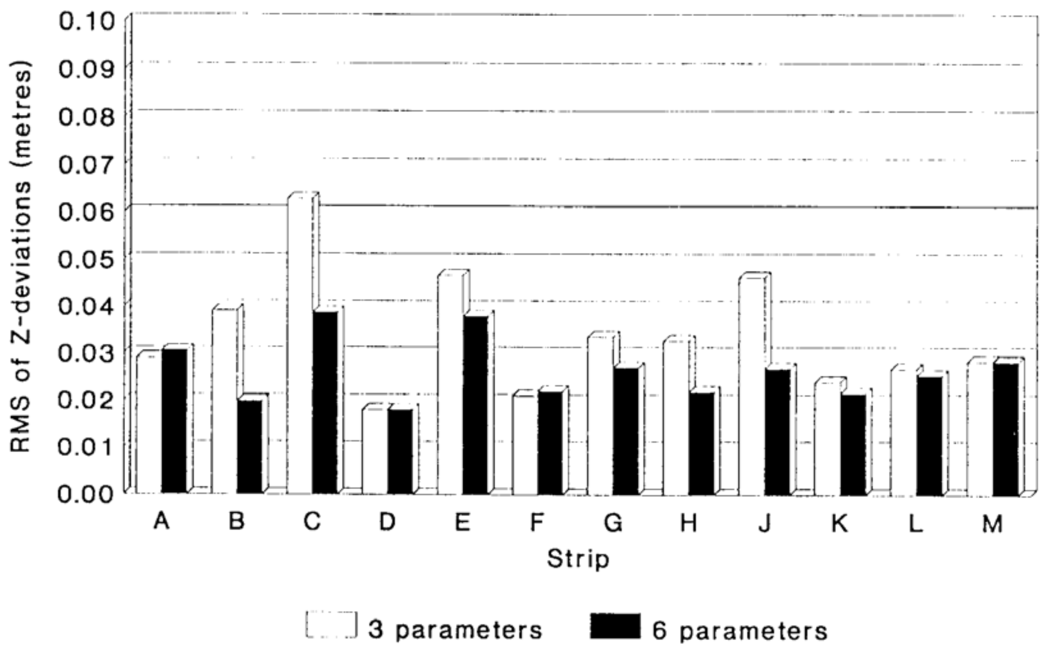

Figure 5: RMS of deviations between GPS determined antenna Z-coordinates and antenna Z-coordinates estimated in a conventional block adjustment, when stripwise systematic errors have been removed.

$RMS_{FIT,X}$ = 4.5 cm $RMS_{FIT,Y}$ = 4.9 cm $RMS_{FIT,Z}$ = 2.7 cm

These accuracy measures are based on deviations between antenna coordinates from the block adjustment and the GPS processing. Both solutions contain random errors. If we assume that the errors from these two adjustments are independent, we can compute the relative accuracy of the GPS determined antenna coordinates as:

$$RMS_{GPS} = \sqrt{RMS_{FIT}^2 - RMS_{BLOCK}^2} \tag{2}$$

RMS_{GPS},	The relative accuracy of the GPS determined antenna coordinates, when the systematic part is removed.
RMS_{FIT},	An accuracy measure based on deviations between antenna coordinates from the block adjustment and the GPS processing.
RMS_{BLOCK},	The accuracy of the antenna coordinates estimated in the block adjustment.

We then get this accuracy of the GPS determined antenna coordinates:

$RMS_{GPS,X} = 2.6$ cm $RMS_{GPS,Y} = 3.2$ cm $RMS_{GPS,Z} = 1.9$ cm

The errors caused by the interpolation are still present in these figures.

5.2 Results from the GPS supported block adjustments

The GPS determined antenna coordinates were treated as additional observations in the GPS supported blocks. *A priori* standard deviations for these coordinates were set to 5 cm. For the ground control points, 1 cm was used. The eccentricity vector between the antenna phase center and the entrance nodal point of the camera, was treated as known in the adjustment.

The observation equations for the antenna coordinates in the bundle block adjustment are as follows:

$$\begin{bmatrix} X_{A_{GPS}} \\ Y_{A_{GPS}} \\ Z_{A_{GPS}} \end{bmatrix}_j + \begin{bmatrix} v_X \\ v_Y \\ v_Z \end{bmatrix}_j = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}_j + R(\varphi,\omega,\kappa)_j \cdot \begin{bmatrix} x_{PC}^A \\ y_{PC}^A \\ z_{PC}^A \end{bmatrix} + \begin{bmatrix} a_X \\ a_Y \\ a_Z \end{bmatrix}_k + dt \cdot \begin{bmatrix} b_X \\ b_Y \\ b_Z \end{bmatrix}_k \tag{3}$$

$X_{A_{GPS}}, Y_{A_{GPS}}, Z_{A_{GPS}}$,	GPS-antenna coordinates of image j in the ground coordinate system.
v_X, v_Y, v_Z,	Residuals in $X_{A_{GPS}}$, $Y_{A_{GPS}}$ and $Z_{A_{GPS}}$.
X_0, Y_0, Z_0,	Coordinates of perspective center PC_j in the ground coordinate system.
$R(\varphi,\omega,\kappa)_j$,	Orthogonal rotation matrix composed of non-linear functions of the three angles $\varphi_j, \omega_j, \kappa_j$.
$x_{PC}^A, y_{PC}^A, z_{PC}^A$,	GPS-antenna coordinates in the image coordinate system.
a_X, a_Y, a_Z,	Time independent corrections of GPS values in strip k.
b_X, b_Y, b_Z,	Time dependent corrections of GPS values in strip k.
dt,	Elapsed time since start of strip k.

The estimation of the drift parameters in the block adjustment will weaken the geometry of the block. To avoid singularity problems, it is necessary to have some ground control points (e.g. points in the block corners). New block configurations may also be a solution. Simulation studies (e.g. ACKERMAN 1992) show that ground control points in the block corners combined with one cross strip at each block-end, gives a satisfactory accuracy even with six drift parameters per strip. The

Photogrammetric Week '93 Eds. D. Fritsch / D. Hobbie, Wichmann, Karlsruhe, 1993

simulation studies also shows that these cross strips may be substituted by two chains of height control points, but with some loss of accuracy in the tiepoints.

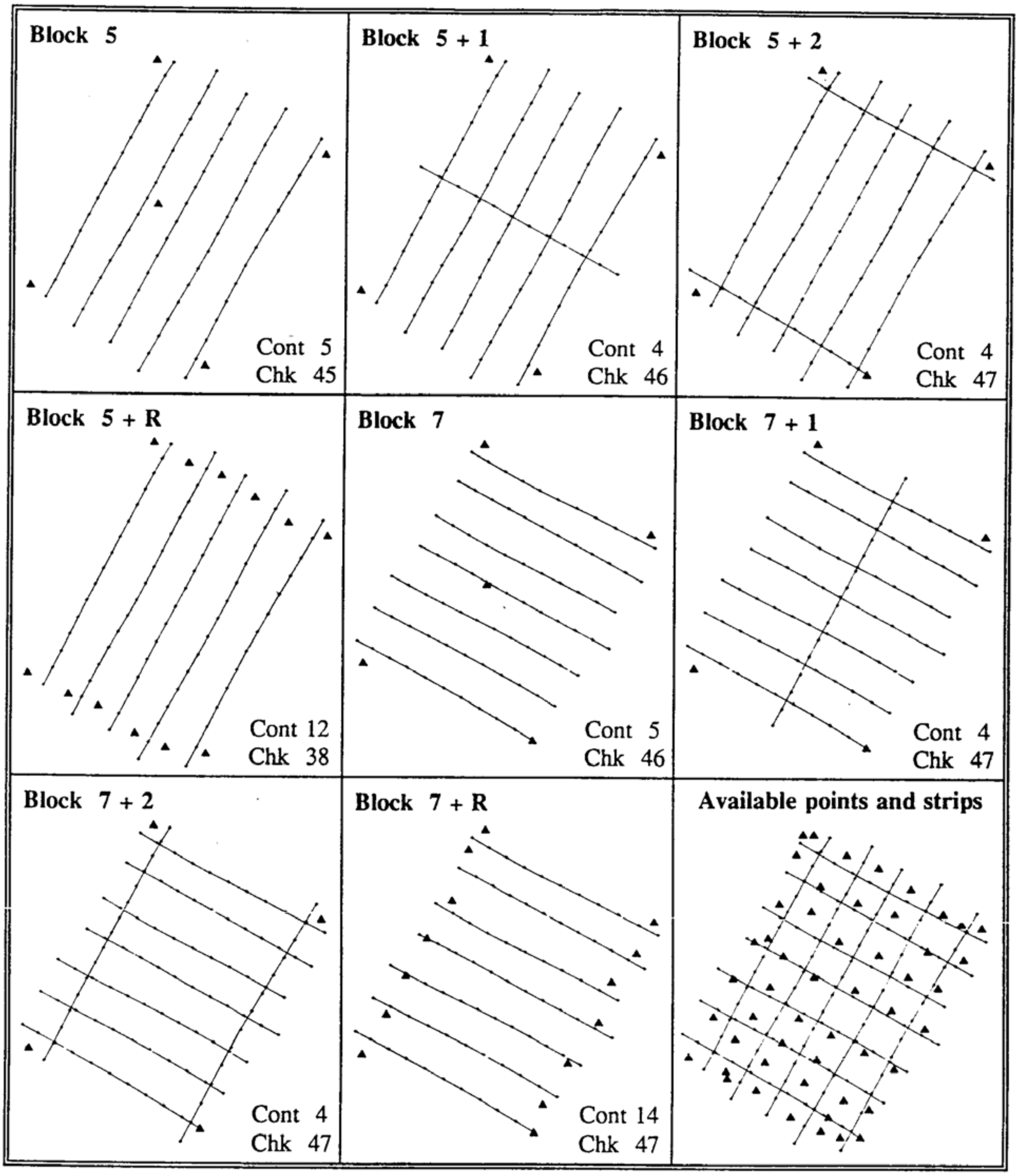

Figure 6: Different block configurations from FREDRIKSTAD 1992.
(Cont = number of ground control points. Chk = number of check points)

Figure 6 shows the different blocks which were calculated in test flight FREDRIKSTAD 1992. All these blocks were calculated with both three and six drift parameters per strip. And for the sake of completeness, all the blocks have also been calculated without the GPS determined antenna

Photogrammetric Week '93 Eds. D. Fritsch / D. Hobbie, Wichmann, Karlsruhe, 1993

coordinates. The results from these adjustments are summarized in table 1. The standard deviation of unit weight (σ_0) varied between 3.4 and 4.1 μm for the solutions.

Block configuration (see figures above) FREDRIKSTAD 1992	Empirical Accuracy From residuals in Check Points RMS (m)			Theoretical Accuracy From standard deviations estimated in the adjustment Check Points RMS (m)			Tie Points RMS (m)		
	X	Y	Z	X	Y	Z	X	Y	Z
5 - no GPS	0.080	0.049	0.113	0.024	0.026	0.081	0.025	0.027	0.081
- GPS and 3 par. pr. st.	0.027	0.064	0.070	0.019	0.021	0.057	0.021	0.022	0.058
- GPS and 6 par. pr. st.	0.063	0.045	0.057	0.022	0.023	0.064	0.023	0.024	0.064
5 + 1 - no GPS	0.071	0.051	0.169	0.033	0.037	0.105	0.035	0.038	0.109
- GPS and 3 par. pr. st.	0.046	0.051	0.070	0.024	0.025	0.047	0.025	0.027	0.052
- GPS and 6 par. pr. st.	0.064	0.036	0.068	0.027	0.029	0.060	0.028	0.031	0.063
5 + 2 - no GPS	0.069	0.080	0.147	0.028	0.030	0.091	0.029	0.031	0.094
- GPS and 3 par. pr. st.	0.031	0.052	0.040	0.021	0.022	0.040	0.022	0.023	0.043
- GPS and 6 par. pr. st.	0.050	0.049	0.058	0.023	0.024	0.045	0.024	0.025	0.048
5 + R - no GPS	0.038	0.081	0.189	0.020	0.022	0.077	0.021	0.022	0.074
- GPS and 3 par. pr. st.	0.028	0.068	0.064	0.017	0.019	0.036	0.018	0.020	0.039
- GPS and 6 par. pr. st.	0.028	0.067	0.064	0.018	0.019	0.037	0.018	0.020	0.040
7 - no GPS	0.054	0.087	0.133	0.024	0.023	0.070	0.024	0.023	0.071
- GPS and 3 par. pr. st.	0.071	0.047	0.088	0.021	0.020	0.057	0.021	0.020	0.057
- GPS and 6 par. pr. st.	0.049	0.086	0.109	0.023	0.022	0.062	0.023	0.022	0.063
7 + 1 - no GPS	0.065	0.090	0.064	0.033	0.033	0.106	0.034	0.034	0.110
- GPS and 3 par. pr. st.	0.057	0.053	0.056	0.025	0.024	0.051	0.026	0.025	0.052
- GPS and 6 par. pr. st.	0.050	0.078	0.074	0.029	0.029	0.061	0.030	0.029	0.062
7 + 2 - no GPS	0.039	0.068	0.075	0.027	0.027	0.087	0.028	0.028	0.092
- GPS and 3 par. pr. st.	0.052	0.045	0.046	0.021	0.021	0.039	0.022	0.021	0.042
- GPS and 6 par. pr. st.	0.043	0.057	0.054	0.023	0.023	0.043	0.024	0.023	0.046
7 + R - no GPS	0.120	0.050	0.133	0.019	0.018	0.058	0.019	0.018	0.055
- GPS and 3 par. pr. st.	0.105	0.041	0.085	0.018	0.017	0.041	0.018	0.017	0.040
- GPS and 6 par. pr. st.	0.107	0.043	0.086	0.019	0.017	0.043	0.018	0.017	0.041

Table 1: Results from the block adjustments from FREDRIKSTAD 1992.

From these results we can see that the block configurations with four ground control points and two cross strips give the best empirical results. In the 7+2 block we get good results, even without GPS data! The most likely explanation for this is that the two cross strips covers a large part of the block. However, it is clearly demonstrated how much cross strips improve the block geometry. Also other block configurations give acceptable results, e.g. four ground control points and only one cross strip.

The block adjustment results also revealed that the solutions with three drift parameters per strip are slightly better than the six parameter solutions. This is expected, since we have already seen that time dependent errors hardly exist (section 5.1), and less additional parameters in the adjustment means improved geometry. We also can see that for all the north-south blocks (5, 5+1, 5+2 and 5+R), $s_X < s_Y$ when three drift parameters are used, and $s_X > s_Y$ with six parameters (the

X-direction is north). For the east-west blocks the situation is reversed. The reason to this is difficult to explain.
For all the calculated blocks we see that the empirical accuracy is not as good as the theoretical accuracy. The empirical accuracy measure is based on residuals in the independent check points, and the theoretical accuracy is based on standard deviations estimated in the adjustments. The situation is worst for the block 7+R (seven strips with chains of ground control points in the beginning and the end of the strips). Investigations of the residuals in the check points for this block and the other blocks, clearly showed that block deformations are present. Further research will hopefully explain the reason for these deformations. If we only look at the theoretical accuracy, we see that 5+R and 7+R are better than 5+2 and 7+2.

6. CONCLUSIONS

The combined block adjustment gave an empirical accuracy, in terms of standard deviation, of $s_X \approx s_Y \approx$ 3-5 cm and $s_Z \approx$ 4-5 cm, using 4 ground control points (Traditional block adjustments gave an accuracy of $s_X \approx s_Y \approx$ 2.0-3.5 cm and $s_Z \approx$ 3.5-4.8 cm, estimated from residuals in 20-21 check points, using 30 ground control points). The accuracy of the interpolated GPS coordinates have a relative accuracy of approximately 2.5 cm. The presented results clearly show that GPS-supported aerial triangulation meets the accuracy requirements for large-scale mapping.
With today's GPS-receiver technology and processing techniques, one can not guarantee that the ambiguities for each strip are constrained to their correct values. The method of modelling drift parameters for each strip seems to be a reliable way of mitigating this problem. For relatively short strips, it is demonstrated that in this case, three offset parameters per strip gives the best result.
It is quite clear however, that the ultimate goal is to eliminate these nuisance parameters. This gives better block geometry and the cross strips will no longer be necessary. Only a minimum of ground control points will be needed for the datum shift. Methods for initializing the integer ambiguities while moving (on-the-fly ambiguity resolution) shows promising results (e.g. EULER/LANDAU 1992). The problem so far has been the reliability of these techniques.

7. REFERENCES

Ackermann, F. (1992) : Operational rules and accuracy models for GPS-aerotriangulation. ISPRS (Commission III), Washington DC, Vol.XXIX, Part B3, pp. 691-700.

Andersen, Ø. (1989) : Experience with kinematic GPS during aerial photography in Norway.Proceedings of the 42nd Photogrammetric Week, Stuttgart, pp. 299-312.

Blankenberg, L.E. (1992) : GPS-supported aerial triangulation - state of the art. The Photogrammetric Journal of Finland, Vol. 13, No.1, pp. 4-16.

Blewitt, G. (1990) : An Automated Editing Algorithm for GPS Data. Journal of Geophysical Research, Vol.17, No.3, pp 199-202.

Euler, H.J., Landau, H. (1992), : Fast GPS Ambiguity Resolution On-The-Fly for Real-time Applications. Proceedings of the Sixth International Geodetic Symposium on Satellite Positioning, Columbos, Ohio, pp. 650-659.

Frieß, P. (1990) : Kinematische Positionsbestimmung für die Aerotriangulation mit dem NAVSTAR Global Positioning System. DGK Serie C, Publication Nr. 359, 1990.

Frieß, P. (1991) : GPS Supported Aerial Triangulation - Empirical Results. Presented paper at the Second International Workshop on High Precision Navigation, November 12th-15th, 1991, Freudenstadt.

Photogrammetric Week '93 Eds. D. Fritsch / D. Hobbie, Wichmann, Karlsruhe, 1993

Gurtner, G., Mader, G., MacArthur, D. (1989): A Common Exchange Format for GPS DATA. Proceedings of the Fifth International Geodetic Symposium on Satellite Positioning, Las Cruces, New Mexico, pp 920-931.

Høgholen, A. (1992): Kinematic GPS in aerotriangulation in Finland. The Photogrammetric Journal of Finland, Vol. 13, No.1, pp. 14-26.

Lichtenegger H., Hofmann-Wellenhof, B. (1989): GPS Data Processing for Cycle-slip Detection. Global Positioning System: an overview, Proceedings of IAGU Symposium No. 102, Edinburgh, Scotland, pp 57-68.

Mader, G.L., Schenewerk, M.S., Chin, M.M. (1991): OMNI 2.00 User's Guide. National Geodetic Survey, Rockville Maryland.

Schade, H. (1992): Reduction of systematic errors in GPS-based photogrammetry by fast ambiguity resolution techniques. ISPRS (Commission I), Washington DC, Vol.XXIX, Part B1, pp. 223-228.

Øvstedal, O. (1992): Adjustment techniques for the Global Positioning System; From static to kinematic mode. The Photogrammetric Journal of Finland, Vol. 13, No.1, pp 38-51.