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EUROPEAN ORGANIZATION FOR EXPERIMENTAL PHOTOGRAMMETRIC RESEARCH

EMPIRICAL RESULTS OF GPS-SUPPORTED BLOCK TRIANGULATION

Report by H. Burman and K. Torlegård

OEEPE

Official Publication Nº 29

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EMPIRICAL RESULTS OF GPS-SUPPORTED BLOCK TRIANGULATION

(with 5 Figures, 3 Tables and 8 Appendices)

Report by H. Burman and K. Torlegård

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ABSTRACT

This OEEPE report on GPS aerial triangulation presents a summary of block adjustment results of GPS-supported blocks executed by six institutions in five European countries. The material was collected and the report was compiled by the pilot centre, Dept. of Geodesy and Photogrammetry at the Royal Institute of Technology, Sweden, on behalf of the OEEPE GPS-working group.

The GPS measurements were all done with relative phase measurements on one or two carrier waves. In most cases there were interruptions in the GPS measurements which were treated by separate sets of GPS drift and shift parameters for every strip or for different parts of the blocks. The phase ambiguity was, in some cases, meant to be determined on the ground and the phase lock to be maintained during the flight. This was achieved only once (the block Rörberg). In the other cases the ambiguity had to be determined with "on-the-fly" techniques. The most common solution was to use pseudo ranging to initialise the ambiguity at the beginning of the strips.

The submitted material differs greatly with regard to flight altitude (500 m - 7500 m) and block size (12 - 264 images).

The à priori precision of the GPS-measurements were estimated to be between 0,03 m and 0,22 m when the observations were corrected for shifts and time dependent drift parameters. However, many of the projects were often among the first of their kind in each country, and many of the problems that occurred, are unlikely to occur again. Still, the reliability of the GPS-measurements is a problem in some cases, mostly connected to the fact that too few projects have been performed, by the different institutions, using the technique. On the other hand there are already regular applications with no apparent problems.

The study shows that in most cases GPS-supported aerial triangulation reaches the required accuracies of the submitted blocks. For small-, medium- and large-scale mapping, the method safely fulfils the accuracy requirements of aerial triangulation, as the GPS-measurements have a precision in the order of 0,10 m or better. If the standard error of the GPS-measurements is in the order of 0,05 m or better, the technique can be used even for large scale mapping, and photogrammetric point determination, although the benefit goes down.

The economic importance of GPS aerial triangulation lies in the drastic saving of conventional control points. For large scale, high precision block adjustment, when sufficient ground control points are often available, the economic advantage may diminish, however.

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Our particular gratitude to prof Dr Ing Fritz Ackermann for encouragement, support and contribution to the compilation and editing of this report.

Helén Burman, Kennert Torlegård

1 INTRODUCTION

The airborne application of the NAVSTAR Global Positioning System (GPS) is capable of providing relative kinematic positioning coordinates of air survey cameras, based on high precision differential GPS carrier phase observations. A particular interesting application concerns the use of GPS data for aerial triangulation, by introducing GPS camera position coordinates into the combined block adjustment with photogrammetric aerial triangulation measurements.

The OEEPE has in May 1993 decided to collect a number of GPS blocks in order to review the status of practical performances and results of GPS supported aerial triangulation. A working group was established under the leadership of professors Fritz Ackermann and Kennert Torlegård. The majority of the blocks in this report come from practical application projects, some are scientific test blocks. They all include at least a certain number of check points for independent accuracy assessments. No attempt is made, in this report, to go deeper into theoretical and methodical questions. The results are displayed as they have been obtained. In this way, this empirical status review demonstrates that GPS aerial triangulation is operational with available equipment and software.

The accuracy of points computed through a traditional block triangulation without GPS depends basically on the image scale, the distribution and photogrammetric measurement of tie points, and on the number and configuration of control points in the block. Attempts to determine the position of the camera at the time of exposure have been done over the years, but few have been as successful as GPS. There already exist operational systems for using the technique. This report is to show that such systems give the expected results and are ready for practical operational applications.

The introduction of GPS-observations and GPS-unknowns in block adjustment programs has been the easy part when implementing GPS-supported block triangulation. Derivation of GPS coordinates is more complicated. Better receivers and the use of a large number of satellites change the conditions. New ways of solving signal interruptions, cycle slips and phase ambiguity are continually being developed.

In this report results from thirteen GPS-supported blocks from five countries will be presented. Hopefully it will show that the method is useful for mapping. A review of blocks and used methods will be given and the parameters influencing the results will be discussed. Some of the participants of the project have submitted cost-benefit aspects. Most of the submitted material is presented in appendices, for closer inspection.

2 A BRIEF DESCRIPTION OF THE GPS TECHNOLOGY

One of the reasons for placing a GPS-receiver in the aircraft is to get the position of an air survey camera at the time of exposure. Other reasons can be navigation and pin-point photography. Receivers are often used for these applications at the same time. When the goal is to get the position of the camera, the requested precision is mostly high, at least for large scale mapping. The most common method is kinematic differential GPS. At least one stationary receiver is placed on a known point on the ground and another receiver is placed in the aircraft (Figure 2.1).

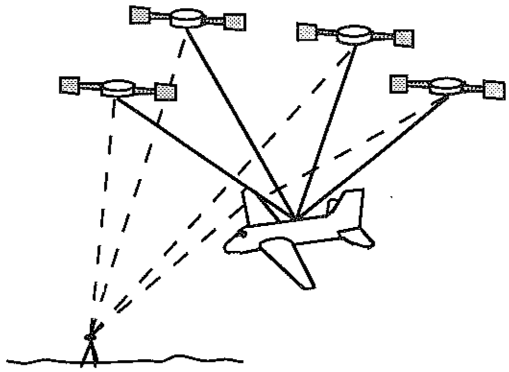

Figure 2.1 The principle of kinematic relative GPS positioning.

2.1 The NAVSTAR GPS

The NAVSTAR GPS is a US military positioning system. Twenty-one operative satellites are placed in polar orbits covering the whole earth. Signals from the satellites are collected by GPS receivers. The oscillator frequency is 10,23 MHz. The modulated signals are [Hofmann-Wellenhof et. al. 1992]:

Carrier frequencies	**L1**	1575,42 MHz (10,23 * 154)
	L2	1227,60 MHz (10,23 * 120)
Binary codes	**P**	10,23 MHz repeated every 266,4 days
	C/A	1,023 MHz (10,23 / 10) repeated every millisecond

Different receivers have different possibilities to handle the received signals. US government has introduced "Selective Availability", which means that a noise on the satellite binary codes decreases the accuracy of the measurement, for non-privileged users.

2.2 Kinematic Differential GPS for Aircraft Positioning

For camera positioning, high precision GPS measurements are necessary. Therefore phase measurements on one or both carrier frequencies (L1 and L2) are used. The phase measurements have much better resolution than the code measurements. If two carrier frequencies are used, atmospheric error effects can be removed. A stationary receiver on a known point on the ground during flying is used in differential GPS for relative positioning of the aircraft. This gives a considerably higher accuracy than without a reference station on the ground, as a number of error effects cancel out.

2.3 Phase Ambiguity

Phase observations have the ambiguity problem, as the integer number of cycles which the L signal has travelled through is unknown. Solution of the phase ambiguity can be found in different ways. One way is a stationary base line solution, i.e. to start the receiver while the aircraft stands still on the ground. When the ambiguity is solved, the aircraft can start its mission, but one has to assure that the receivers keep continuous contact with the satellites all through the flight. Afterwards, post processing of the GPS-measurements is done and coordinates of the photo stations are obtained. The problem with this method is to keep contact with the satellites by continuous recording all through the flight mission. At take-off, landing and turning one has to make sure that the plane does not bank too much, i.e. that signal interruptions are avoided. This leads to longer and more time consuming flights.

Another way to solve the problem of phase ambiguity is to allow for some phase error. New phase correlation is initialised for each new strip. This can be done by using the codes, but then the phase correlation will not be correctly determined. This will lead to shift and time dependent drift along the strip. These are however easy to compensate for in a block triangulation by additional unknowns in the adjustment. Other, more refined methods have come up recently, which solve the phase ambiguity from on-the-fly measurements. The aim with such more refined methods is to restore continuity and possibly do the block adjustment without unknown shift and drift parameters.

2.4 Time Registration of the Exposure

The GPS-receiver collects data continuously, and the positions of the antenna can be derived at certain time intervals, once or twice every second. To derive the position of the antenna at the time of exposure one has to know when the photograph was exposed. The exact time of exposure is hard to define as it takes place over a time period when the plane moves forward. Often the mid time of the exposure is exactly recorded. The registration is done with an electrical pulse that is sent to the GPS receiver for recording. Different types of interpolation methods can be used to get the respective antenna position. The most common one among the projects presented in this report is linear interpolation.

2.5 The Eccentricity of the Antenna

The GPS antenna is placed somewhere on the roof of the aircraft as the radio signals must have an uninterrupted direct path from the satellite to the antenna. For high precision measurements one has to consider this eccentricity between the antenna and the projection centre of the camera. The spatial off-set reduction should refer to the external coordinate system. Hence, in principle, the eccentricity and the aircraft attitude have to be taken into account. The external attitude parameters of camera resp. aircraft can be derived approximately from first block adjustment runs. The eccentricity is geodetically measured beforehand. If the camera is held fixed all through the flight, the eccentricity will be so too, with regard to the aircraft and also the camera coordinate system. If the camera changes its orientation towards the aircraft during the flight, this has to be measured or recorded in one way or another, when high precision measurements are required.

2.6 Coordinate Transformation

The coordinates obtained from GPS measurements will refer to the geocentric coordinate system WGS84. Often, however, the block adjustment shall relate to a local geodetic network. If the transformation parameters between the two systems are known it is possible to just transform the WGS84 coordinates. When drift and shift parameters of the GPS measurements are used, they will take care of the datum transformation, which is provided via ground control points. The transformation between the two systems can be done by a three-dimensional similarity transformation with one scale factor. That means theoretically that two horizontal and three height control points are enough for solving the transformation parameters. In practice, more control is often used which is discussed in a following chapter.

2.7 Block Configuration and Ground Control

The economic reason for using GPS-supported blocks is to considerably decrease the number of ground control points as compared with conventional aerial triangulation. The requested number of ground control points and the block configuration depends on the quality of GPS-measurements. In the following examples the principle of block configuration and ground control is laid out.

GPS positioning refers, in principle, to the 3-dimensional cartesian coordinate system WGS84. If the ambiguity problem is solved correctly and phase lock is maintained all through the flight, then one can be sure that no shifts or drifts afflict the GPS measurement, and one can consider the measurement of every camera station to be absolute in WGS84. In that case no ground control points are necessary provided that a perfect camera calibration is given and that no connection between WGS84 and the ground coordinate system is required. The traditional overlap of 60 % along and 20-30 % between strips would be sufficient. The adjusted block would refer to the WGS84 coordinate system. Thus, in principle, GPS aerial triangulation could do without any conventional photo-control-points. Instead, GPS stations outside the block area would be required.

If an overall datum transformation from WGS84 to a local datum is required, a few ground control points are used to define it. Normally one ground control point in each corner of the block is advisable (figure 2.2). In GPS blocks - contrary to conventional blocks - the ground control points have the only function to provide the datum transformation. Therefore a few ground control points are sufficient.

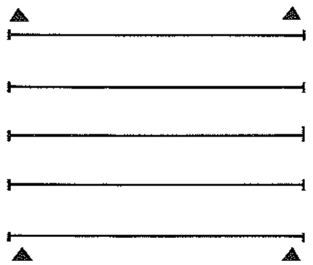

Figure 2.2 *Block configuration with maintained phase lock (continuous GPS trajectory) when an overall datum transformation is required.*

If the ambiguity problem is solved only approximately and maybe separately solved for each strip, then GPS shift and drift is different for each strip. In this case one can stabilise the block with two crossing strips or two height control chains at the ends of the parallel strips. One full control point in each corner of the block will be sufficient. In some methods this is the standard scenario. If a block is highly rectangular or has irregular shape, it is advisable to use three of more cross-strips and also some more control points.

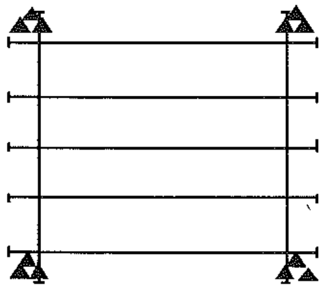

Figure 2.3 *Block configuration with crossing strips for the determination of separate GPS shift and drift parameters in different strips.*

If as few as four control points are used the block will be very sensitive for gross errors in the control points. Therefore it is advisable to signalise two or three control points distinctly in each corner so as to assure reliability (figure 2.3).

3 OEEPE PROJECT PLAN

3.1 Design of the Project

The 81st OEEPE Steering Committee meeting in Bruxelles in November 1992 decided to set up a GPS-project. The aim of the project was to promote application by demonstrating that the technique of using GPS-support in block triangulation is operational and that the expected, highly favourable results are obtained. At the OEEPE Steering Committee meeting in Delft, 12-14 May 1993, the plan for the project was accepted and it was decided to go on with the project. The Department of Geodesy and Photogrammetry at KTH, Stockholm, was assigned as project centre and Prof. Kennert Torlegård as project coordinator.

The members of OEEPE were asked to join the project. The following persons announced their participation:

Fritz Ackermann	Stuttgart, Germany
Øystein Andersen	Ås, Norway
Leif Erik Blankenberg	Ås, Norway
Helén Burman	Stockholm, Sweden
André Flotron	Meiringen, Switzerland
Anton Høgholen	Helsinki, Finland
Jüri Talts	Gävle, Sweden

The participants were asked to submit results of adjusted blocks and information about methods and technology used and statistics from block triangulations that had been calculated in two ways, firstly without GPS and traditional ground control, secondly with GPS and minimum ground control. In cases when check points were available, rms-values were to be calculated. The participants were also asked to deliver cost-benefit assessments if possible.

A draft of the report was presented to the Steering Committee in November 1993 for approval. After changes and amendments, the president of OEEPE, prof Dr Fritz Ackermann, gave final approval for printing and circulation by the OEEPE Publishing Office.

3.2 Requested Information from the Participants

The participants were asked to submit the following information for each block calculated both with and without GPS control.

Method and Technology

- Information on block size, geometry, overlap and flying height
- Map sketch with block lay-out, models, control and check points
- Type of adjustment, independent model or bundle, program name

- GPS information, instrument type, method of data reduction, one or more fixed stations

- Timing between camera and GPS

- Continuous or interrupted GPS recording

- Datum transformation separate from the block or included in the block adjustment

- What type of GPS parameters were used in the adjustment, per block or per strip, drift and shift, transformations between coordinate systems

- Eccentricity between the antenna and the camera, constant or changing (fixed camera or not), eccentricity known or estimated in the adjustment

- How was the phase ambiguity solved

<u>Statistics</u>

- How many tie points typically between models (or images) in the same strip and between strips; were they natural, targeted or PUGged

- Type of control and check points, targeted or natural features, type of targets, what kind of features

- Theoretical or à priori estimates of accuracy of coordinates of
  * geodetic control points
  * geodetic check points
  * photogrammetric image points (or model points)
  * GPS measured camera stations

to be used for à priori weights in the adjustment

- Root mean square (RMS) values of coordinate differences
  * photogrammetry - geodetic ground control points
  * photogrammetry - geodetic check points

- If available (but not necessary) on 3,5" diskette (formatted for MS-DOS) in ASCII files also listings of
  * control point coordinates
  * photogrammetric coordinates of new points
  * check point coordinates
  * coordinate differences
    - photogrammetry - ground control points
    - photogrammetry - check points

- Any other information regarded to be of importance for the aim of the project

4 RECEIVED BLOCKS

This is a summary of the blocks submitted to this project. Further information you can find in the appendices.

Table 4.1 shows an overview of the received blocks. Totally thirteen blocks were submitted and the image scale is between 1:3300 and 1:50000. Two of the blocks (Follo and Sperillen) were calculated with the independent model adjustment method, the rest with bundle adjustment.

All blocks with GPS support had crossing strips, except for four blocks (Eura II, Follo II, Sonvilier II, Sperillen II) that had height control chains instead. All blocks were also adjusted without GPS but with plenty of ground control, mostly more control than would have been necessary for the block. Thus, they do not represent the normal results of equivalent conventional blocks without GPS, but represent, instead, the best possible results obtainable with the material. As some of the blocks adjusted with GPS have several versions, they altogether represent seventeen cases. The most common design for GPS-blocks is to use two crossing strips and six drift parameters per strip.

Most of the blocks were related with practical application, except for Follo, Fredrikstad, Rörberg and Sperillen, that were scientific test blocks.

Table 4.1 *A summary of submitted blocks*

No.	Block name Country	Flying Height Image scale	Block size km^2	Overlap long/lat %	Number of photos Number of strips	Type of adj.	Number of control points XY / Z	Number of GPS-unknowns (parameters)
1.0	Botkyrka I Sweden	800 m 1:5300	3 * 5 km	60/25	37 photos 4 strips	Bundle	32/32	No GPS-support
1.1	Botkyrka II Sweden	800 m 1:5300	3 * 5 km	60/25	50 photos 4 + 2 strips	Bundle	11/11	6 / strip
1.2	Botkyrka III Sweden	800 m 1:5300	3 * 5 km	60/25	50 photos 4 + 2 strips	Bundle	11/11	12 / block
1.3	Botkyrka IV Sweden	800 m 1:5300	3 * 5 km	60/25	50 photos 4 + 2 strips	Bundle	32/32	12 / block
1.4	Botkyrka V Sweden	800 m 1:5300	3 * 5 km	60/25	50 photos 4 + 2 strips	Bundle	151/151	12 / block
2.0	Eura I Finland	3400 m 1:16000	25 * 45 km	60/30	264 photos 10 strips	Bundle	78/209	No GPS-support
2.1	Eura II Finland	3400 m 1:16000	25 * 45 km	60/30	264 photos 10 strips	Bundle	7/19	6 /strip
3.0	Follo I Norway	2250 m 1:15000	16 * 13 km	60/30	60 photos 5 strips	Indep. model	21/29	No GPS-support
3.1	Follo II Norway	2250 m 1:15000	16 * 13 km	60/30	60 photos 5 strips	Indep. model	8/24	6 / strip
4.0	Fredrikstad I Norway	800 m 1:5000	4,5 * 6,0 km	60/20	79 photos 5 strips	Bundle	22/30	No GPS-support
4.1	Fredrikstad II Norway	800 m 1:5000	4,5 * 6,0 km	60/20	80 photos 7 strips	Bundle	22/28	No GPS-support
4.2	Fredrikstad III Norway	800 m 1:5000	4,5 * 6,0 km	60/20	101 photos 5 + 2 strips	Bundle	4/4	3 /strip
4.3	Fredrikstad IV Norway	800 m 1:5000	4,5 * 6,0 km	60/20	110 photos 7 + 2 strips	Bundle	4/4	3 /strip
5.0	Rörberg I Sweden	500 m 1:3300	3 * 3 km	60/20	55 photos 5 strips	Bundle	20/36	No GPS-support
5.1	Rörberg II Sweden	500 m 1:3300	3 * 3 km	60/20	75 photos 5 + 2 strips	Bundle	4/4	6 / strip
6.0	Sonvilier I Switzerland	800 m 1:5000	11 km^2	60/60	114 photos 11 strips	Bundle	43/43	No GPS-support
6.1	Sonvilier II Switzerland	800 m 1:5000	11 km^2	60/60	114 photos 11 strips	Bundle	19/19	6 / strip
7.0	Sperillen I Norway	1215 m 1:8000	3,5 * 3,5 km	60/20 - 70/30	12 photos 2 strips	Indep. model	12/12	No GPS-support
7.1	Sperillen II Norway	1215 m 1:8000	3,5 * 3,5 km	60/20 - 70/30	12 photos 2 strips	Indep. model	6/6	6 / strip
8.0	Inpho Block A I Germany	1120 m 1:7500	5 * 6 km	60/20	50 photos 4 + 2 strips	Bundle	32/32	No GPS-support
8.1	Inpho Block A II Germany	1120 m 1:7500	5 * 6 km	60/20	50 photos 4 + 2 strips	Bundle	4/4	6 / strip

No.	Block name Country	Flying Height Image scale	Block size km^2	Overlap long/lat %	Number of photos Number of strips	Type of adj.	Number of control points XY / Z	Number of GPS-unknowns (parameters)
9.0	**Inpho Block B I** **Germany**	1200 m 1:8000	7 * 7 km	60/20	70 photos 6 + 2 strips	Bundle	43/43	No GPS-support
9.1	**Inpho Block B II** **Germany**	1200 m 1:8000	7 * 7 km	60/20	70 photos 6 + 2 strips	Bundle	4/4	6 / strip
10.0	**Inpho Block C I** **Germany**	1150 m 1:7500	6 * 5,5 k m	60/20	55 photos 4 + 2 strips	Bundle	32/32	No GPS-support
10.1	**Inpho Block C II** **Germany**	1150 m 1:7500	6 * 5,5 k m	60/20	55 photos 4 + 2 strips	Bundle	4/4	6 / strip
11.0	**Inpho Block D I** **Germany**	7500 m 1:50000	133 * 33 k m	60/20	143 photos 4 + 3 strips	Bundle	63/63	No GPS-support
11.1	**Inpho Block D II** **Germany**	7500 m 1:50000	133 * 33 k m	60/20	143 photos 4 + 3 strips	Bundle	6/6	6 / strip
12.0	**Inpho Block E I** **Germany**	7500 m 1:50000	130 * 33 k m	60/20	143 photos 4 + 3 strips	Bundle	65/65	No GPS-support
12.1	**Inpho Block E II** **Germany**	7500 m 1:50000	130 * 33 k m	60/20	143 photos 4 + 3 strips	Bundle	6/6	6 / strip
13.0	**Inpho Block F I** **Germany**	915 m 1:6100	7,6 * 7,6 k m	60/20	154 photos 8 + 2 strips	Bundle	40/40	No GPS-support
13.1	**Inpho Block F II** **Germany**	915 m 1:6100	7,6 * 7,6 k m	60/20	154 photos 8 + 2 strips	Bundle	12/12	6 / strip

5 RESULTS OF ADJUSTED BLOCKS

Many different aspects can be discussed concerning the information given in the submitted material. The following discussion concentrates on the most significant accuracy aspects.

Empirical accuracy is best described by RMS values of differences between photogrammetric and geodetic coordinates of check points. These RMS values in the submitted blocks are listed in table 5.1 and 5.2. , for both traditional blocks and GPS-supported blocks. In some cases no check points existed, then theoretical accuracies are given, as obtained via the inversion of the normal equation matrices, in terms of RMS values of the standard coordinate deviations of all adjusted block points.

5.1 Accuracy Without GPS

Results from traditional blocks without GPS are listed in table 5.1. Further details about the blocks you find in table 4.1 and in the appendices. All blocks were adjusted without crossing strips, except for the six Inpho blocks no. 8 - 13.

Table 5.1 *Accuracy results of blocks without GPS. The blocks 2.0 and 8.0-13.0 give theoretical RMS-values, all others empirical RMS-values from check points.*

Block	σ_0 [μm]	Scale factor = s	$\sigma_0 * s$ [mm]	No. of control points xy / z	No. of check points xy / z	RMS-X [mm]	RMS-Y [mm]	RMS-Z [mm]	RMS-X / $\sigma_0 * s$ [ratio]	RMS-Y / $\sigma_0 * s$ [ratio]	RMS-Z / $\sigma_0 * s$ [ratio]
1.0	3,2	5300	17,0	32 / 32	119/119	44	32	51	2,6	1,9	3,0
2.0	6,4	16000	102,4	82 / 226	- / -	85	97	253	0,8	0,9	2,5
3.0	7,3	15000	110	21 / 29	23 / 15	130	130	220	1,2	1,2	2,0
4.0	3,9	5000	19,5	22 / 30	28 / 20	31	29	49	1,6	1,5	2,5
4.1	3,8	5000	19,0	22 / 28	29 / 23	44	33	65	2,3	1,7	3,4
5.0	4	3300	13,2	20 / 36	8 / 39	16	33	35	1,2	2,5	2,7
6.0	3,8	5000	19,2	43 / 43	- / -	-	-	-	-	-	-
7.0	7,5	8000	60	12 / 12	18 / 18	60	60	120	1,0	1,0	2,0
8.0	4,6	7500	34,5	32 / 32	- / -	14*	14*	41	0,4*	0,4*	1,2
9.0	4,2	8000	33,6	43 / 43	- / -	20*	20*	44	0,6*	0,6*	1,3
10.0	4,4	7500	33,0	32 / 32	- / -	23*	23*	46	0,7*	0,7*	1,4
11.0	6,5	50000	325	63 / 63	- / -	195*	195*	390	0,6*	0,6*	1,2
12.0	6,9	50000	345	65 / 65	- / -	207*	207*	414	0,6*	0,6*	1,2
13.0	6,7	6100	40,9	40 / 40	- / -	29*	29*	53	0,7*	0,7*	1,3

* The RMS-X and the RMS-Y values are identical, calculated as mean horizontal coordinate errors.

As one can see from the resulting standard errors of unit weight (σ_0), all the triangulations are of very good quality. The two blocks that have a standard error above 7 micrometers are adjusted with the independent model method. In that case the σ_0 does not refer to image coordinates but to model coordinates, and its magnitude is theoretically larger. The blocks that have a standard error under 4 micrometers are blocks with mostly signalized tie points. The rest of the blocks have a majority of natural or artificially marked tie points.

The RMS accuracy results of blocks number 2.0 and 8.0-13.0 are based on theoretical error propagation after adjustment. The very good results are obtained because of strong ties and the very large number of control points which were used.

5.2 Accuracy With GPS

Table 5.2 shows the accuracy results of GPS-supported blocks. Most blocks had two crossing strips and six GPS drift parameters per strip. Further information about the blocks can be found in table 4.1 and in the appendices.

On first glance the GPS-supported blocks give larger RMS values in planimetry and height than the traditional blocks in almost all cases. That comparison between the tables 5.2 and 5.1 is misleading, however, as the block adjustments without GPS have made use of (the available) excessive numbers of ground control points. Therefore they are not representative for equivalent practical cases, the errors of which would be about twice as large, in general.

The σ_0 estimates, i.e. the estimated precision of the image coordinate observations are slightly larger in the GPS supported block adjustments. It is an indication that the total error modelling of all observations (GPS included) is not yet in final balance.

***Table 5.2** Accuracy results of GPS blocks*

No.	σ_0 [µm]	Scale factor = s	$\sigma_0 * s$ [mm]	No. of control points xy / z	No. of cross. strips	No. of drift param.	No. of check points xy / z
1.1	3,2	5300	17,0	11/11	2	6 / strip	140/140
1.2	3,6	5300	19,1	11/11	2	12	140/140
1.3	3,7	5300	19,6	32/32	2	12	119/119
1.4	3,7	5300	19,6	151/151	2	12	- / -
2.1	6,4	16000	102,4	7/19	-	6 / strip	71/190
3.1	8,0	15000	120	8/24	-	6 / strip	36/20
4.2	4,1	5000	20,5	4/4	2	3 / strip	47/47
4.3	4,1	5000	20,5	4/4	2	3 / strip	47/47
5.1	4,0	3300	13,2	4/4	2	6 / strip	24/71
6.1	3,8	5000	19,0	19/19	-	6 / strip	24/24
7.1	7,5	8000	60	6/6	-	6 / strip	24/24
8.1	4,9	7500	36,8	4/4	2	6 / strip	28/28
9.1	4,8	8000	38,4	4/4	2	6 / strip	39/39
10.1	4,6	7500	34,5	4/4	2	6 / strip	28/28
11.1	6,4	50000	320	6/6	3	6 / strip	57/57
12.1	7,0	50000	350	6/6	3	6 / strip	59/59
13.1	6,9	6100	42,1	12/12	2	6 / strip	28/28

No.	A priori σGPS [m]	RMS-X [mm]	RMS-Y [mm]	RMS-Z [mm]	RMS-X / $\sigma_0 * s$ [ratio]	RMS-Y / $\sigma_0 * s$ [ratio]	RMS-Z / $\sigma_0 * s$ [ratio]
1.1	0,10	43	56	74	2,5	3,3	4,4
1.2	0,10	43	48	93	2,3	2,5	4,9
1.3	0,10	40	32	71	2,0	1,6	3,6
1.4	0,10	-	-	-	-	-	-
2.1	0,20	180	132	355	1,8	1,3	3,5
3.1	0,22	180	180	230	1,5	1,5	1,9
4.2	0,03	28	51	44	1,4	2,5	2,1
4.3	0,03	55	41	46	2,7	2,0	2,2
5.1	0,08/0,05	30	39	35	2,3	3,0	2,7
6.1	0,05	49	40	143	2,6	2,1	7,5
7.1	0,12	65	65	150	1,1	1,1	2,5
8.1	0,10	66	66	85	1,8*	1,8*	2,3
9.1	0,10	61	61	88	1,6*	1,6*	2,3
10.1	0,10	55	55	83	1,6*	1,6*	2,4
11.1	0,10	352	352	416	1,1*	1,1*	1,3
12.1	0,10	525	525	665	1,5*	1,5*	1,9
13.1	0,10	76	76	80	1,8*	1,8*	1,9

* The RMS-X and the RMS-Y values are identical, calculated as RMS horizontal coordinate errors.

6 DISCUSSION

6.1 General

The method of using GPS-supported block triangulation worked very well in all cases. The main result is that the accuracy of GPS blocks is close to the accuracy obtained with dense control in conventional block triangulation. The accuracy performance of the GPS blocks is equivalent, in general, to high performance aerial triangulation, in spite of minimum control. The stabilizing accuracy effect of GPS camera station observations is clearly demonstrated. The average accuracy of all the blocks is 1,9 ($\sigma_0 * s$) in x and y and 2,7 ($\sigma_0 * s$) in z (excluding Sonvilier's result in height, where errors in the check point heights were found). This result confirms that GPS keeps the propagation of errors in the block within narrow limits.

6.2 Comparison with Theoretical Accuracy Prediction

The theory shows that the accuracy expected for GPS-supported blocks with cross-strips and free drift parameters per strip, assuming $\sigma GPS \leq \sigma_0 * s$, is about 1,5 ($\sigma_0 * s$) in x and y direction and about 2,0 ($\sigma_0 * s$) in z [Ackermann 1992]. For the blocks in this study with the scale 1:6100 or smaller, the average empirical accuracy from check points is 1,6 ($\sigma_0 * s$) in x, y and 2,2 ($\sigma_0 * s$) in z, which fits well to the theoretical accuracy expectation, although the assumed GPS accuracy σGPS is in the order of (2 - 3) $\sigma_0 * s$, except for the excellent small scale blocks 11.1 sand 12.1. For blocks with scale larger than 1:6000, the average accuracy is 2,2 ($\sigma_0 * s$) in x, y and 3,2 ($\sigma_0 * s$) in z. Those results refer to blocks with signalized points. The resulting small magnitudes of σ_0 (3,2 - 4,1 μm) are not quite representative for the vertical block accuracy. Also, the standard GPS errors σGPS are large in comparison with the photogrammetric measuring precision, because of large photo scale, reaching ratios up to 6 $\sigma_0 * s$. If the effects of σGPS are properly considered, then also the accuracy results of the large scale blocks agree very well with the theoretically expectation, as will be shown in the following section 6.3.

6.3 Accuracy as Function of σ_{GPS}

The resulting block accuracies are theoretically expected to be correlated to the precision of the GPS coordinates. In the figures 6.1 and 6.2 the RMS values are plotted against the à priori GPS precision as used in the block adjustments. The empirical relation compares well with the result from a theoretical investigation of expected accuracies of new point coordinates for rectangular blocks with four ground control points and crossing strips. This investigation was presented in [Burman 1992] and similar results were presented in [Ackermann 1992] and [Frieß 1990].

The actual precision of the GPS measurements, expressed in standard errors, is not known in this investigation. The GPS precision was introduced in the photogrammetric block adjustments by the participants as á priori assumption. They have been estimated by some of the participants by comparison between GPS coordinates and resected projection centres derived from traditional adjustment. Other participants have derived estimates of the GPS precision in other ways.

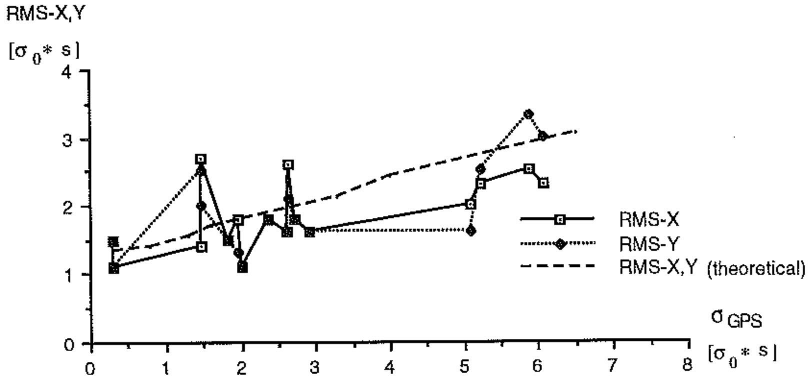

Figure 6.1 *Comparison of empirical RMS values in X and Y with GPS accuracies. The line is the relation between accuracy of GPS camera stations and of new point coordinates for a rectangular block with two crossing strips and four ground control points, derived from a theoretical investigation, [Burman 1992].*

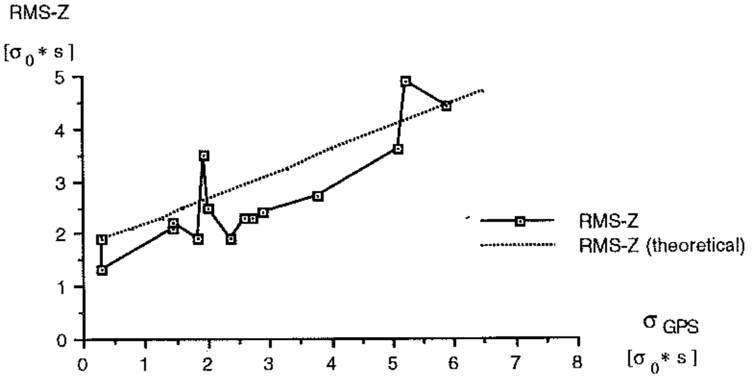

Figure 6.2 *Comparison of empirical RMS values in Z with GPS accuracies. The line is the relation between accuracy of GPS camera stations and of new point coordinates for a rectangular block with two crossing strips and four ground control points, derived from a theoretical investigation [Burman 1992].*

Compared to the correlation curves derived from the theoretical investigation, most of the empirical block results are as good or better than expected. Nevertheless, the expected trend is visible. The accuracy performance of GPS blocks is confirmed to depend on the accuracy of the GPS camera station coordinates. The relation is, however, quite weak. The standard GPS errors have to become 5 to 6 times larger, in z resp. x,y, to increase the RMS block errors by a factor of 2. It means that the GPS block accuracies are not very sensitive against the precision of GPS camera stations. The above quoted theoretical block accuracies of 1,5 σ_0*s (in x,y) and of 2,0 σ_0*s (in z) correspond to the lower ends of the theoretical relations of Figs 6.1 and 6.2. Thus they are confirmed as being highly realistic.

6.4 Effect of Overlap, Block Size, Photo Scale

Overlap is in all blocks approximately 60 % along and 20-30 % between strips, except for the block Sonvilier where the overlap between strips was 60 %. That single case is not conclusive enough. Therefore, the case of blocks with 60 % side lap, which should theoretically be more accurate, is not considered here any further.

The block sizes vary from 12 photos in 2 strips (Sperillen) to 264 photos in 10 strips (Eura). This variation in block sizes did not show any significant influence on the accuracy results, as theoretically expected [Ackermann 1992; Burman 1992].

The photo scales vary from 1:3300 (Rörberg) to 1:50000 (Inpho Blocks D and E). The difference in result is naturally large in absolute values. It simply reflects the projection of photogrammetric image measurements onto the terrain. This effect can however be taken away, e.g. normalized, by expressing the result as a ratio between RMS and (σ_0 * s). This ratio is practically constant, and well suited for comparison of results. It is also useful as a thumb-rule for planning of GPS blocks. As pointed out before, the ratios RMS / σ_0 * s depend to some extent on the accuracy of the GPS camera stations, see Figs. 6.1 and 6.2. The empirical results confirm the theoretical relations very well. It means that the ratios are indeed constant, if $\sigma GPS \leq \sigma_0 * s$.

6.5 Adjustment Method

Two types of adjustment programs were used. All blocks except two were calculated with bundle adjustment programs. The blocks Follo and Sperillen were treated with an independent model adjustment program. The σ_0 values referring to different observations, are slightly higher for these two blocks, as one must expect for theoretical reasons, but otherwise no differences in the result can be found. All the programs included drift parameters for the GPS measurements. Some of them included also correction of GPS antenna eccentricity due to rotation of the aircraft.

6.6 GPS Data

The GPS method of data reduction is the same for all blocks, namely relative phase measurements. Most of the blocks used only one carrier wave, L1, for the solution. Three of the blocks were calculated with two carrier waves. The result was in one case very good (0,03 m, Fredrikstad), for one block it was pretty good (0,05-0,08 m, Rörberg) and for one it was pretty poor (0,11-0,13 m, Botkyrka). From this no valid conclusion can be drawn of how the type of solution influences the result. But other investigations has shown that the capacity of dual frequency measurement is higher than single frequency measurements, especially for detection and correction of atmospheric noise. However, as long as drift parameters/strip are used in the adjustment, single frequency data are evidently highly equivalent and fully satisfactory.

In some of the projects, the intention was to initialise the phase correlation before take-off and to maintain phase-lock during the flight mission. This was in almost all cases not achieved. Instead, code measurements (pseudo-ranging) were in most cases used for re-initialising the ambiguity solution at the beginning of each strip. With the Inpho blocks no attempts were made, deliberately, for any initial ambiguity solution, nor for maintaining signal lock during the flight turns.

As a consequence of the type of ambiguity solutions, most blocks had three shift and three time dependent drift parameters per strip as unknowns in the block adjustment. The only exceptions are some of the block adjustments done on the Botkyrka block, where only two parameter sets were used for the entire block, and the block Fredrikstad, were only three shift parameters were used as unknowns per strip. Only for the Fredrikstad block, the result was better with fewer unknown parameters. Further investigations have to be done to be able to see what influence the number of parameters and the number of parameter sets will have on the result. In other words, the systematic GPS errors and the datum errors warrant closer investigation.

6.7 Eccentricity of Antenna

The eccentricity of the antenna was in most cases known beforehand. However, the attitude of the cameras were often not kept fixed during the entire flight mission. In most cases the crab angle was only fixed within a strip. In one block, the camera attitude was not fixed at all, namely in the Botkyrka block. In that case the effect of rotating the camera was considered to be small (0,02-0,03 m) and of less importance for that project. This may have increased the RMS values a little. The effect of changing the camera position in the aircraft between strips is mostly compensated for by constant correction or by using shift parameters per strip. The antenna is often placed so that the eccentricity is small in x- and y-direction. Changing the camera attitude, often means only a rotation of the κ angle which does not influence the external eccentricity if the antenna is placed above the camera.

6.8 Distance between GPS Ground Station and Block

Normally it is recommended to have the stationary GPS receiver in the block area or close to it, for good cancellation of systematic errors. At 10 of the 13 blocks the receiver was placed accordingly, in or at the block area. However, in three cases (Eura, Sonvilier, Sperillen) the stationary receiver was at a distance of 200 km, 50 km, and 35 km, respectively, without apparent loss of accuracy. The explanation is that large distances between GPS receivers cause systematic errors in the differential mode, which are compensated in the adjustment, however, if drift parameters are applied. It is a major reason for applying such parameters. Another example of 400 km distance is referred to in Appendix 8.

7 COST - BENEFIT

The main justification for GPS supported aerial triangulation is economic: drastic saving of ground control. On the other hand GPS application implies additional efforts and costs. The main extra costs of using GPS-support are mobilization and installation in the aircraft, operation of a GPS-receiver on the ground, processing of the GPS-data, and aerial triangulation measurements and adjustment efforts if crossing strips are used. All these extra costs must be over-compensated by the savings of signalising and field surveying of ground control points, if GPS-supported block triangulation is to perform economically compared to traditional triangulation.

Some of the participants have given comments on cost-benefit. For the Botkyrka block, the additional cost for using GPS is about 50%. The cost would only be balanced if 35 completely measured and signalised control points could be saved. This means that there is no economy in using GPS in this case.

The Eura block could reduce the amount of targeted points to 1/10 of what is normal in Finland today. This means that GPS reduces the costs for the block. However, the block has to be of a certain size. The Eura block is about the average size for base map production in Finland today, and its size is enough for GPS to be cost effective.

For the Fredrikstad block, a time consumption analysis has been made. The analysis shows that GPS-supported block triangulation can mean large savings in time compared to traditional triangulation. For a block with about 80 images one can save about 30% in time with GPS compared with conventional block triangulation. This reduction is related to geodetic measurement and calculation of the ground control point coordinates.

Ackermann (1993) reports from some case studies that the photo flight with GPS, GPS data reduction and GPS aerial triangulation increase total costs by about 25%, if compared with conventional cases, and on the basis of equal accuracy results. The saving of ground control is in the order of 90 % or more, which results all together in a total economical benefit of about 40%. However, this cost reduction is not obtained in case ground control is already available or is cheap. Also with very large scale high precision aerial triangulation the economic advantages of GPS diminish. More research is required to determine how much influence these factors will have on the result.

8 CONCLUSIONS AND RECOMMENDATIONS

The results of this study show that block triangulation with GPS-support works very well under operational conditions. The blocks cover a great variety of different conditions, as far as image scale, block size, GPS receivers, adjustment programs, data reduction are concerned. The accuracy results qualify generally as high precision aerial triangulation (relative to image scale), although the GPS blocks operated with very few ground control points only. The same results could normally, without GPS, be obtained only with numerous horizontal control points and vertical control points in particular.

The empirical results have confirmed the theoretical accuracy expectations for adjusted GPS blocks to a remarkable degree. In particular also the weak dependency on the accuracy of the GPS camera position data has been confirmed. Thus the theoretical expectations are quite realistic and operate at any scale used for mapping.

Today, we can expect GPS camera positioning, derived from differential phase observations to be precise to 0.10 m or 0.05 m. This is enough to fulfil the accuracy requirements of the full range of large-, medium-, and small-scale mapping. In most cases that precision of the GPS coordinates is as good or better than 1,0 ($\sigma_0 * s$) , i.e. the photogrammetric measuring precision. The accuracy of the adjusted blocks then would be approximately 1,5 ($\sigma_0 * s$) in X and Y and 2,0 ($\sigma_0 * s$) in Z. This would be sufficient for all mapping scales. However, it may not be sufficient for high precision photogrammetric point determination, a case which will require further investigation.

The GPS method of data reduction has until now been phase observations mostly on one carrier frequency only. The empirical results show that single frequency observations give highly satisfactory results, if combined with the drift parameter approach of adjustment, Nevertheless, for highest precision two carrier frequency observations are recommended.

The influence of distance from the mapping area to the reference receiver on ground has not been specially investigated in this study. However, some available cases showed that distances up to 450 km or more can be safely handled, if linear drift corrections are applied per strip. Further investigations are suggested to fully establish the influence of distance between the mapping area and the reference receiver [Ackermann 1993].

The blocks in this study have confirmed that continuous GPS phase measurements during the whole flight mission are hard to achieve. From an operational point of view it is therefore safer and sufficient to keep contact with the satellites only during flying of individual strips. This will lead to shorter and less time consuming flights. It does require, however, adjustment procedures with drift parameters per strip. All participants have used such programs. New "on the fly" techniques to solve the phase ambiguities may ease the problem in the future.

For high precision GPS-measurements, the eccentricity between the camera and the antenna must be known for each exposure. If the antenna is placed right above the camera, the camera can be rotated in κ to compensate for the crab angle without changing the eccentricity.

The remarks from the participants concerning cost-benefit show that many people believe in strongly reduced costs in aerial triangulation, when using GPS-support, but also that it is questionable for large scale mapping with small blocks. For large scale mapping many control points often already exist. The costs of using GPS is not always compensated for by the savings of ground control points. However, there exist numerous cases where GPS-supported aerial triangulation truly yields considerable economic benefits. It is up to each user to evaluate the cost and benefit of GPS-supported and of traditional block triangulation under his own operational circumstances.

In conclusion it can be summarized that the results of this study highly recommend the practical application of GPS aerial triangulation as a regular procedure. The method has proven to be operational, although some participants had initial difficulties. On the other hand there are companies which regularly apply the method without problems. The method can be applied for the full range of image scales which are used in aerial surveys. There is a large class of cases where GPS aerial triangulation has great economic advantages.

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APPENDICES

Appendix 1 : Block Botkyrka
Appendix 2 : Block Eura
Appendix 3 : Block Follo
Appendix 4 : Block Fredrikstad
Appendix 5 : Block Rörberg
Appendix 6 : Block Sonvilier
Appendix 7 : Block Sperillen
Appendix 8 : Inpho blocks A - F

Block Botkyrka

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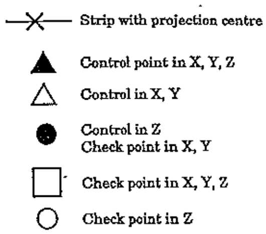
Block sketches



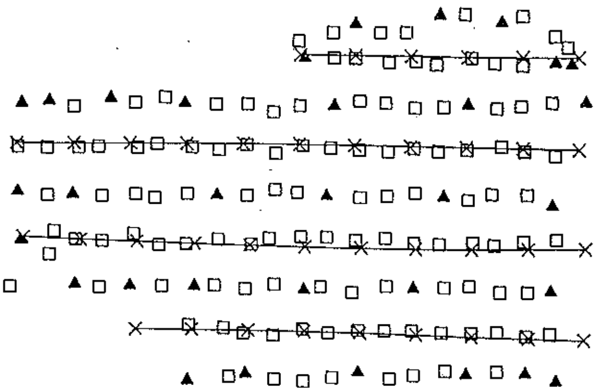


Image scale 1:5300

Fig a1.1. Botkyrka I, without GPS.

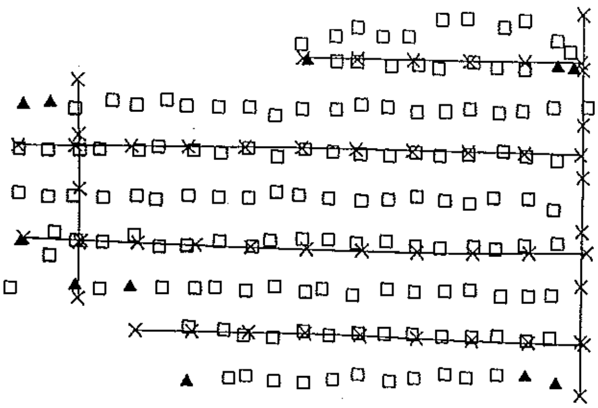


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Fig a1.2. Botkyrka II and Botkyrka III, with GPS.

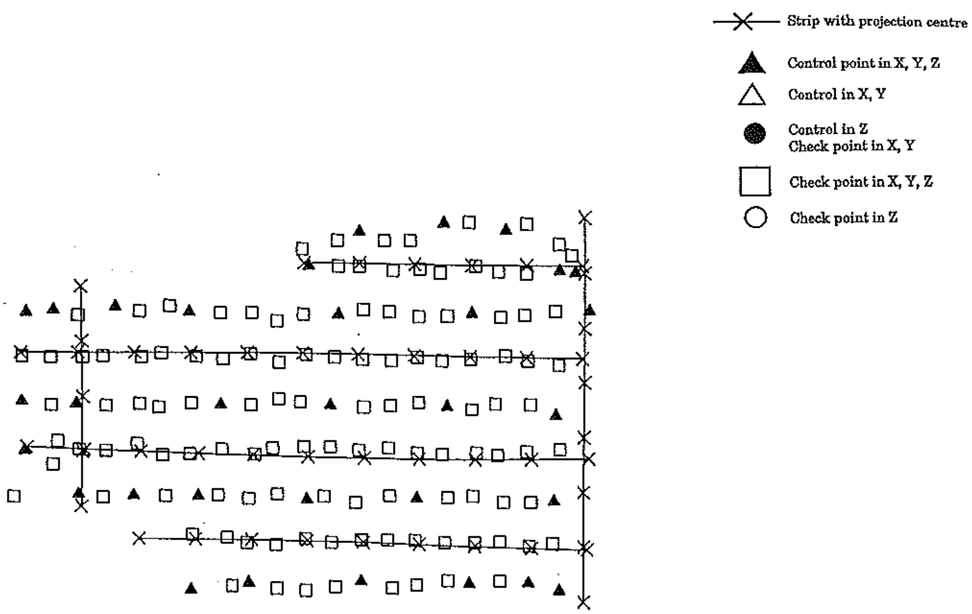

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Fig a1.3. Botkyrka IV, with GPS.

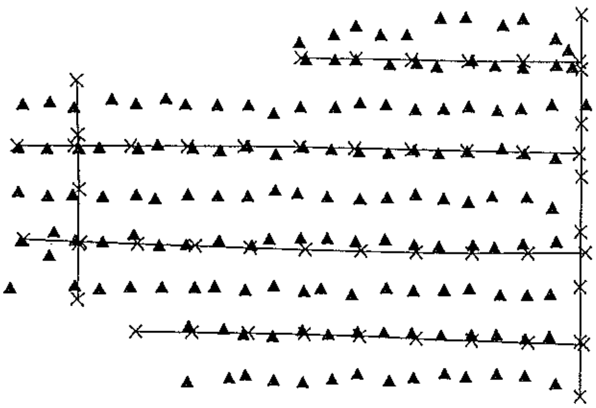

Image scale 1:5300

Fig a1.4. Botkyrka V, with GPS.

Technical data

Date of flight	April 28th, 1993
Flight altitude	800 m
Scale	1:5 300
Block size	3 * 5 km
Overlap	p = 60 %, q = 25 %
Camera	Zeiss LMK 014A
Camera constant	ca 152 mm
Type of adjustment	Bundle block
Adjustment program	PATB-RSG
Type of tie points	Targeted (control and check points) + 3 artificially marked / image
Type of control points	Targeted (white 40 * 40 cm)
Type of check points	Targeted (white 40 * 40 cm)

GPS data

GPS instrument in aircraft	Ashtech P-XII
GPS instrument on ground	Ashtech P-XII
Number of ground stations	One
Distance between ground station and test field	10 km
GPS recording continuous or interrupted	Continuous
Fixed camera or not	Not fixed
Known eccentricity or not	Known
Interpolation method	Linear
GPS-parameters in adjustment	Three shift and three time dependent 1 parameter set /strip (Botkyrka II) or 2 parameter sets /block (Botkyrka III-V)

À priori estimates

Control points	0,04 m	0,04 m	0,06 m
Check points	0,04 m	0,04 m	0,06 m
GPS-measurements	0,10 m	0,10 m	0,10 m
Photogrammetric measurements	5 µm		

Botkyrka I (4 strips East - West, without GPS)

Number of photos	37		
Available control points			
- Ground Control Points (GCP)	32 in X and Y / 32 in Z		
- Check Points (C P)	119 in X and Y / 119 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,028 m	0,029 m	0,024 m
- Photogrammetry - C P	0,044 m	0,032 m	0,051 m
À posteriori σ_0	3,2 µm		

Botkyrka II (4 strips East-West + 2 crossing strips, with GPS)

Number of photos	50		
Number of drift and shift parameter sets	6		
Available control points			
- Ground Control Points (GCP)	11 in X and Y / 11 in Z		
- Check Points (C P)	140 in X and Y / 140 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,026 m	0,026 m	0,017 m
- Photogrammetry - C P	0,043 m	0,056 m	0,074 m
À posteriori σ_0	3,2 µm		

Botkyrka III (4 strips East-West + 2 crossing strips, with GPS)

Number of photos	50		
Number of drift and shift parameter sets	2		
Available control points			
- Ground Control Points (GCP)	11 in X and Y / 11 in Z		
- Check Points (C P)	140 in X and Y / 140 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,029 m	0,035 m	0,036 m
- Photogrammetry - C P	0,043 m	0,048 m	0,093 m
À posteriori σ_0	3,6 µm		

Botkyrka IV (4 strips East-West + 2 crossing strips, with GPS)

Number of photos	50		
Number of drift and shift parameter sets	2		
Available control points			
- Ground Control Points (GCP)	32 in X and Y / 32 in Z		
- Check Points (C P)	119 in X and Y / 119 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,030 m	0,041 m	0,049 m
- Photogrammetry - C P	0,040 m	0,032 m	0,071 m
À posteriori σ_0	3,7 µm		

Botkyrka V (4 strips East-West + 2 crossing strips, with GPS)

Number of photos	50		
Number of drift and shift parameter sets	2		
Available control points			
- Ground Control Points (GCP)	151 in X and Y / 151 in Z		
- Check Points (C P)	-		
Resulting RMS of differences			
- Photogrammetry - GCP	0,026 m	0,027 m	0,030 m
- Photogrammetry - C P	-		
À posteriori σ_0	3,7 µm		

GPS-method of data reduction

In the calculations both observations on the carrier waves (both frequencies) and on the codes (P and C/A) were used. The program used was PNAV (Ashtech).

Solution of phase ambiguity

The integer ambiguity was determined by using the observations of phase measurements on two carrier waves and code measurements. These observations were made when the aircraft was in the air.

Eccentricity of antenna

The location of the GPS antenna in relation to the projection centre was known and introduced in the calculations. In no instance was the eccentricity determined in the solution of the block adjustment. The antenna was 18 cm behind, 18 cm to the left and 1,43 metres above the projection centre. The camera was not fixed meaning that rotations influence the real eccentricity of the antenna. However, these errors are in the order of 2-3 cm. In relation to the rather poor accuracy of the GPS observations these errors are disregarded here.

Timing GPS and camera

Time marks from the mid-exposure pulse (from the camera) were stored in the GPS-receiver.

Transformation between ground coordinate system and WGS84

The transformation parameters between the ground coordinate system and WGS84 were known and the GPS observations were transformed to the ground coordinate system before the bundle adjustment was done. If there are discrepancies between the systems they would be compensated for by the drift and shift parameters of the GPS observations.

Comments

The à priori standard errors of control points were assumed to be 4 cm in X and Y and 6 cm in Z and the GPS-measurements were assumed to have a standard error of 10 cm in X, Y and Z in the adjustment. The standard errors of the control points could have been lower (2 cm in X, Y and Z) and higher (13 cm in X, 11 cm in Y, 11 cm in Z) for the GPS observations. The standard errors of GPS observations were estimated by comparing photogrammetrically determined co-ordinates of the projection centres and GPS observations corrected for eccentricity. The differences were adjusted for drifts and offsets.

It turned out that when 12 additional parameters describing image deformation were included in the block adjustment, the σ_0 was reduced drastically. It was a bit astonishing that the the residual systematic errors were so large even if they were corrected with help of the fiducial marks. The residual systematic errors were up to 10 µm in the image scale. This indicates disturbances on the image geometry. All blocks were calculated with 12 additional parameters.

The block with GPS-support, 4+2 strips, 11 control points and 6 parameters per strip (Botkyrka II) showed relatively good results. However, the maximum residuals in the check points were 0,14-0,18 metres in planimetry and up to 0,24 metres in elevation. Therefore the block could not be used for its intended purpose. The same goes for the similar block with 2 parameter sets (Botkyrka III). To get a better result in elevation, 21 control points were added (Botkyrka IV). This block still shows large residuals in elevation and can not compete with the traditionally performed block (Botkyrka I). The last adjustment (Botkyrka V) shows the high accuracy potential of the block when GPS and all control points are used.

Cost / Benefit

The conventional block for this area would have been four strips with together 37 images. The alternative with GPS would have been six strips with 50 images.

GPS supported aerial photography and block triangulation will be more expensive. There will be more images, more equipment involved and more calculations. The increase in the cost is about 50 percent. For break-even this increased cost most be compensated with increased accuracy or with reduced number of control points. In this case there is no increase in accuracy with GPS. The best results were obtained without GPS. Instead of using GPS supported triangulation, in this case 35 additional completely determined control points could be measured for the same amount of money.

A more detailed account for the cost is the following:

Botkyrka without GPS

Aerial photography - 4 strips	4300 ECU
Diapositives, measurements and calculation of block - 37 images	2750 ECU
Sum	**7050 ECU**

Botkyrka with GPS

Aerial photography - 6 strips	6100 ECU
Calculations of GPS observations	1100 ECU
Diapositives, measurements and calculation of block - 50 images	3700 ECU
Sum	**10900 ECU**

Discussion

A block with large scale photography (1:5300) which was photographed with GPS observations of the projection centres, has been calculated in different ways. One conclusion is that minimum control according to theoretical studies is not sufficient for practical large scale applications.

Another conclusion is that the value of GPS for large scale blocks is very questionable. The accuracy of the GPS co-ordinates is relatively low and can not help to produce high-accuracy co-ordinates in the block. A change can not be expected until the GPS co-ordinates are much better determined.

A normal block triangulation, without GPS but with about one control point per image gave in this block results which can be used for the large scale mapping. The photography and the block triangulation was in that case 35 percent cheaper than the block with GPS support. This reduced cost could i.e. be used to measure additionally 35 completely determined control points. So there is no economy for GPS supported large block triangulation.

Acknowledgements

Many people have been involved in this experiment and contributed with their professionalism. Botkyrka community has signalised and measured control points and acted as host for this experiment. Aircraft crews, photographers, geodesists, photogrammetrists and other people within the National Land Survey have contributed with their knowledge and skill. I would like to thank them all for their contribution.

Reference

Talts, J. (1993) : Aerial triangulation with GPS over Botkyrka.

Block Eura

Submitted by :

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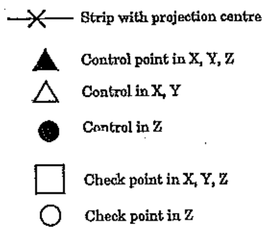


Block sketches

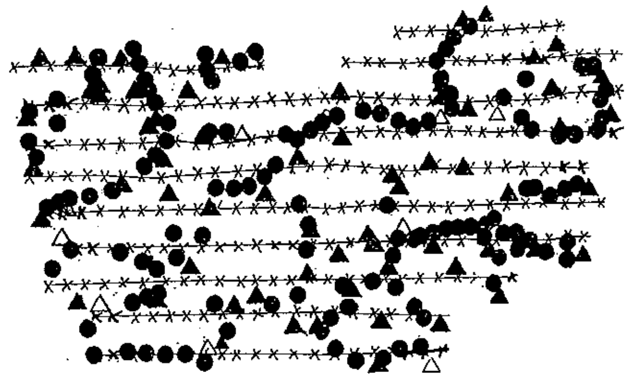


Image scale 1:16 000

Fig a2.1 Eura I, without GPS.

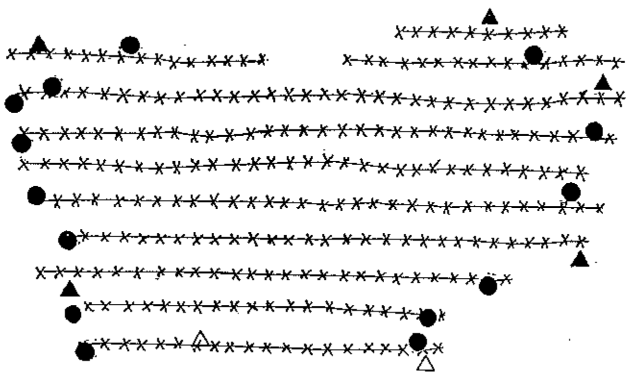


Image scale 1:16 000

Fig a2.2. Eura II with GPS. The points used for control in Eura I are used as check points in Eura II.

Technical data

Date of flight	May 14th, 1992
Flight altitude	3400 m
Scale	1:16 000
Block size	25*45 km
Overlap	p=60% q=30%
Number of tie points	21/image in strip, 6/image between strips
Camera	Wild RC20
Camera constant	214,10 mm
Type of adjustment	Bundle block
Adjustment program	ESPA (by Tapani Sarjakoski)
Type of tie points	Natural
Type of control points	Targeted
Type of check points	Targeted

GPS data

GPS instrument in aircraft	Ashtech MD-XII
GPS instrument on ground	Ashtech MD-XII
Number of ground stations	One
Distance between ground station and aircraft	About 200 km
GPS recording continuous or interrupted	Continuous
Fixed camera or not	Fixed in strip (the crab angle that was changed between strips)
Known eccentricity or not	Known
Interpolation method	Linear except for a few positions based on polynomial interpolation
GPS-parameters in adjustment	Three shift and three linear drift param. per strip

À priori estimates and weights

Control points	0,05 m	0,05 m	0,05 m
Check points	0,05 m	0,05 m	0,05 m
GPS-measurements	0,20 m	0,20 m	0,20 m
Photogrammetric measurements	5 µm		

Eura I (10 strips, without GPS,)

Number of photos	264		
Available control points			
- Ground Control Points (GCP)	78 in X and Y / 209 in Z		
- Check Points (C P)	-		
Theoretical accuracies of new points	0,085 m	0,097 m	0,253 m
Resulting RMS of differences			
- Photogrammetry - GCP	0,049 m	0,046 m	0,024 m
- Photogrammetry - C P	-		
À posteriori σ_0	6,4 µm		

Eura II (10 strips, with GPS)

Number of photos	264		
Available control points			
- Ground Control Points (GCP)	7 in X and Y / 19 in Z		
- Check Points (C P)	71 in X and Y / 190 in Z		
Theoretical accuracies of new points	0,134 m	0,149 m	0,348 m
Resulting RMS of differences			
- Photogrammetry - GCP	0,024 m	0,029 m	0,009 m
- Photogrammetry - C P	0,180 m	0,132 m	0,355 m
À posteriori σ_0	6,4 µm		

GPS-method of data reduction

The GPS aircraft antenna was of single frequency type, which meant that only L1 observations were available even though the GPS receivers were capable of receiving on both frequencies. The principle of differential GPS carrier phase observations was used to compute the antenna positions at the time of exposures. The GPPS program by Ashtech was used.

Solution of phase ambiguity

The GPS receivers registered continuously from before take-off till after landing. The starting position of the aircraft with respect to the reference point was determined by GPS baseline determination. This made it possible to solve the initial phase ambiguity. The same procedure was repeated after landing.

Datum transformation

The WGS84 coordinates were transformed into the Finnish KKJ coordinate system (the geoid was modelled). This transformation is not exact. The remaining part of the datum problem was solved in the block adjustment. Separate shift and linear drift parameters for each strip were included and solved for.

Timing GPS and camera

A signal was sent automatically from the camera to the GPS receiver and recorded on the GPS time scale each time the shutter was released. This signal represented the mid-exposure time.

Eccentricity of the antenna

The eccentricity between the antenna and the camera was measured by tachymetric ground survey. The components of the eccentricity vector were given as input to the adjustment. The effect of eccentricity on each photo was then simply computed using the rotation matrix in an iterative process. The camera was rotated between flight strips, but not tilted, to compensate the crab angle. The crab setting was not recorded because it was considered to be of less importance in this project. The horizontal components of the eccentricity are small (-0,055 m and 0,260 m).

Problems with the GPS observations

The GPS observations are not of the best quality as there were some problems with the registration of the data. Epoches are missing due to error blocks. This was probably caused by some problems with the data logger program. The more satellites visible, the more critical the recording became. As much as 12% of the observations are missing on the stationary receiver compared to 4% on the airborne receiver. There also exist some gaps in the registrations inside some strips which also affected the interpolation of the antenna coordinates for a few photographs (interpolation time interval 1,0 - 3,5 seconds).

The GPS data also contains a lot of cycle slips. The GPPS program recovered most of them, but during one turn of the aircraft the computation broke down. The data therefore had to be computed both forwards and backwards to cover the whole flight mission. Only a 20 seconds period during a turn remained uncomputed. Another problem was that both the memory of the airborne computer and the airborne receiver went full just some 40-50 seconds after the aircraft had returned. This means that the integer phase ambiguities are not very reliable. 8 strips had to be based on backward computation.

Comments

Large savings can be achieved in the targeting work when using GPS supported aerotriangulation. The amount of targeted points can quite safely be reduced to 1/10 of what is normal today for the Finnish base map production. It must though be said that there is a tendency in Finland to overtarget the blocks. The price of equipment needs of course to be taken into account, but the extra expense per flight due to the GPS equipment is certainly smaller than the savings. The block has however to be of a certain size. The Eura block is of average size for the Finnish base map production.

The results of the Eura block are satisfying despite the technical problems and the reduced quality of data. It shows a great potential of GPS-supported aerotriangulation. The equipment and the software develop rapidly and many problems that occured during the first years of experiments are not likely to occur today. Among all the introduction of the "On The Fly"-techniques was a big step forward. The problem with poor observation windows is slowly disappearing and will be history in 1994.

It has however to be considered that GPS-supported block aerotriangulation is not fully developed. The processing of the data is still time consuming and demanding.

Literature on the same project

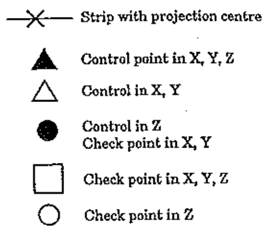
Høgholen, A. (1993) : Kinematic GPS in aerotriangulation in Finland. Reports of the Finnish Geodetic Institute 93:5.

Høgholen, A. (1993) : GPS-supported aerotriangulation in Finland - The Eura block. The Photogrammetric Journal of Finland, Vol. 13, No. 2. To be published in December 1993.

Block Follo

Submitted by :

Øystein Andersen
Dept.of Surveying, NLH
Ås, Norway



Block sketches

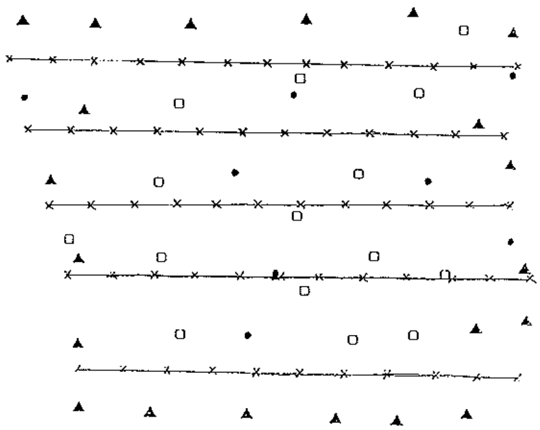


Image scale 1:15 000

Fig a3.1. Follo I, without GPS.

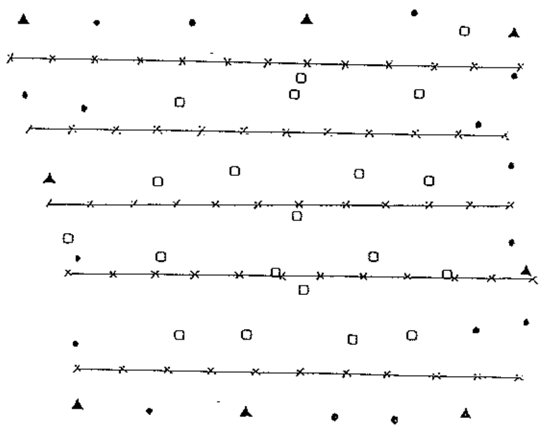


Image scale 1:15 000

Fig a3.2. Follo II, with GPS.

Technical data

Date of flight	June 9th, 1988
Flight altitude	2250 m
Scale	1:15 000
Block size	16*13 km
Overlap	p=60% q=30%
Number of tie points	6/model in strip, 4/model between strips
Camera	Wild RC10
Camera constant	152,00 mm
Type of adjustment	Independent model
Type of tie points	Natural
Type of control points	39 targeted (white 60*60 cm) and 5 natural
Type of check points	39 targeted (white 60*60 cm) and 5 natural

GPS data

GPS instrument in aircraft	Trimble 4000SL
GPS instrument on ground	Trimble 4000SL
Number of ground stations	One
Distance between ground station and test field	Ground station in test field
GPS recording continuous or interrupted	Interrupted
Fixed camera or not	Not fixed
Known eccentricity or not	Known
Interpolation method	Second degree interpolation
GPS-parameters in adjustment	Three shift and three time dependent parameters

À priori estimates and weights

Control points	0,03 m	0,03 m	0,03 m
Check points	0,03 m	0,03 m	0,03 m
GPS-measurements	0,22 m	0,22 m	0,22 m
Photogrammetric measurements	7,4 μm		

Follo I (5 strips, without GPS)

Number of models	55		
Number of object points	275		
Number of model points	754		
Available control points	44		
- Ground Control Points (GCP)	21 in X and Y / 29 in Z		
- Check Points (C P)	23 in X and Y / 15 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,04 m	0,04 m	0,05 m
- Photogrammetry - C P	0,13 m	0,13 m	0,22 m
À posteriori σ_0	0,11 m		

Follo II (5 strips, with GPS)

Number of models	55		
Number of object points	275		
Number of image points	754		
Available control points	44		
- Ground Control Points (GCP)	8 in X and Y / 24 in Z		
- Check Points (C P)	36 in X and Y / 20 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,03 m	0,03 m	0,05 m
- Photogrammetry - C P	0,18 m	0,18 m	0,23 m
À posteriori σ_0	0,12 m		

GPS-method of data reduction

The GPS processing was performed by the "Institutt for kontinentalsokkelundersøkelser og petroliumteknologi AS", with their software KINPOS. This software uses pseudorange, Doppler and carrier phase data for determination of GPS positions.

Solution of phase ambiguity

The phase ambiguity was solved by filtering the difference between pseudo-distance and phase.

Eccentricity of antenna

The camera was aligned before the start of each strip. The pilot adjusted the flight direction inside the strip if deemed necessary. The photography was thus performed according to conventional procedures. The antenna eccentricity to the camera was known (x:-1,630, y:-0,379, z:-0,813 metre) and the GPS positions were reduced for the eccentricity before the block adjustment, using the average direction of each strip as orientation.

Timing GPS and camera

A portable PC in the aircraft logged both time marks from the camera and 1 PPS (1 Pulse Per Second) from the GPS receiver. The shutter release pulse in the camera was used as time marks.

Transformation between coordinate systems

The coordinates of the points in the test field are referred to the local coordinate system. The positions of the camera, determined with GPS, were transformed to the local ground coordinate system, with the help of transformations determined from GPS-measurements in the test field.

Problems

The original plan was to maintain phase-lock to the satellites during the flight. The integer ambiguities were initialized at the airport (30 km from the testfield) before take-off. However, phase-lock was lost during take-off and there were also interruptions in the turns between strips. In addition to this, the receiver stopped recording before landing due to exceeded storage capacity (1 Mbyte).

Comments

Some of the lessons learned in the project were:

- new GPS-receivers are needed, which have sufficient storage capacity, which have capacity of recording on more than 5 channels, which has the ability to record the camera exposure pulse, which has a sampling rate of 1 sec or faster

- a camera that can emit a mid-exposure-pulse is needed

- the aircraft should not fly too fast, preferably 80 m/s or slower

- better software for processing of GPS observations needed

- block adjustment software that can use the GPS observations in a better way, for instance should the eccentricity vector be treated in a way that allows it to be rotated by the orientation matrix

- the satellite geometry should be considered, it is necessary to have 5 or more satellites with good geometry

This project is fairly old (1987-1988) and improvements of the GPS-receivers, the data recording system, the algorithms for processing the GPS-data and the methods for block adjustment have been done. This implies that the result would be better if the test was made today.

In a practical job one might expect less blunders when using GPS-support since less ground control points are used and blunders often occur during surveying of these points in field and during identification in the images. In addition, the GPS-data is expected to stabilize the block, making it somewhat easier to detect blunders in ground control points and photogrammetric measurements.

The next important steps in the development of GPS for photogrammetric applications are:

- to gain experience of different distances to the reference GPS receiver on the ground

- to minimize the additional unknowns in the block adjustment (by phase-lock through the flight mission or by development of "on the fly ambiguity resolution")

- to add some kind of recording of the drift-angle of the camera, to allow the crew to adjust the camera for drift inside a flight line

- to try to exploit the extra information gained from kept phase-lock, as better equipment now allows kept phase-lock during a mission

To those who have not yet begun with GPS-supported block adjustment , the recommendation is to use qualified people, both for the GPS processing and for the block adjustment. The technique is not developed so far that you can say "just push a button and get the answer". It is necessary to understand the underlaying theory.

Block Fredrikstad

Submitted by :

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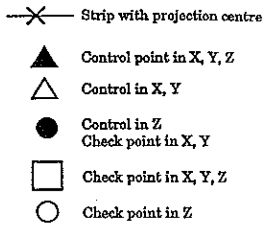
Norway

Block sketches



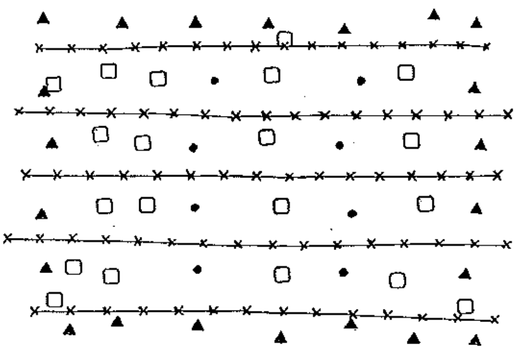


Image scale 1:5000

Fig a4.1 Fredrikstad I, without GPS.

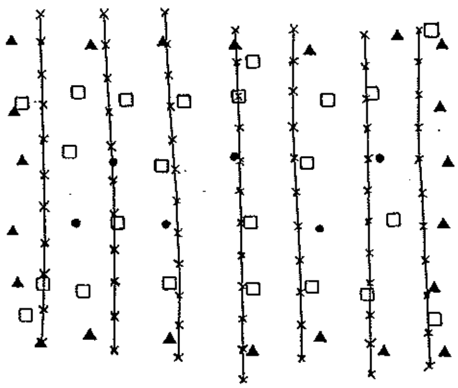
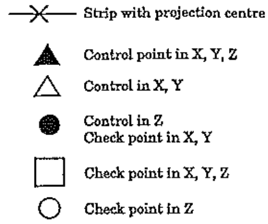


Image scale 1:5000

Fig a4.2 Fredrikstad II, without GPS.



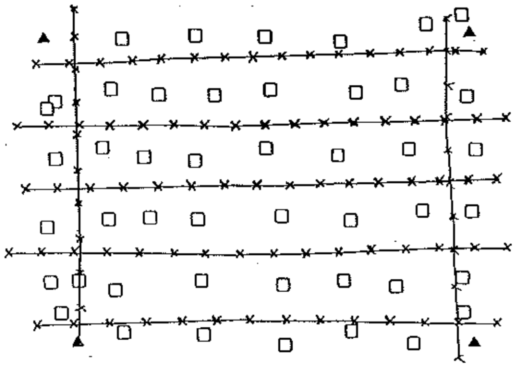


Image scale 1:5000

Fig a4.3 Fredrikstad III, with GPS.

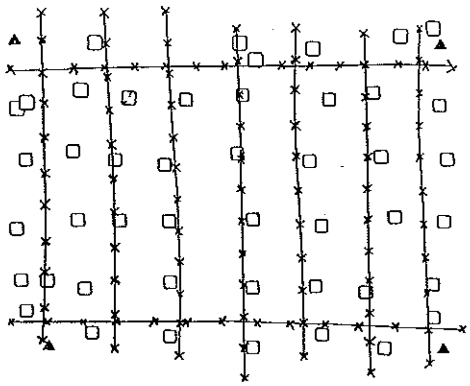


Image scale 1:5000

Fig a3.4 Fredrikstad IV, with GPS.

Technical data

Date of flight	1992
Flight altitude	800 m
Scale	1:5 000
Block size	4,5*6,0 km
Overlap	p=60% q=20%
Number of tie points	18/image in strip, 3/image between strips
Camera	Wild RC20 15/23 (upgraded with EDI)
Camera constant	152,84 mm
Type of adjustment	Bundle block
Adjustment program	NLHBUNT (from the dept. of surveying, NLH)
Type of tie points	75% targeted, 25% natural
Type of control points	Targeted (Yellow 27*27 cm + 30 cm black border)
Type of check points	Targeted (Yellow 27*27 cm + 30 cm black border)

GPS data

GPS instrument in aircraft	Ashtech MXII-P
GPS instrument on ground	Ashtech MXII-P
Number of ground stations	One
Distance between ground station and test field	Ground station in test field
GPS recording continuous or interrupted	Interrupted
Fixed camera or not	Fixed
Known eccentricity or not	Known
Interpolation method	Linear
GPS-parameters in adjustment	Three shift parameters

À priori estimates and weights

Control points	0,01 m	0,01 m	0,01 m
Check points	0,01 m	0,01 m	0,01 m
GPS-measurements	0,03 m	0,03 m	0,03 m
Photogrammetric measurements	4 μm		

Fredrikstad I (5 strips North-South, without GPS)

Number of photos	79		
Number of object points	624		
Number of image points	2125		
Available control points	50		
- Ground Control Points (GCP)	22 in X and Y / 30 in Z		
- Check Points (C P)	28 in X and Y / 20 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,011 m	0,013 m	0,003 m
- Photogrammetry - C P	0,031 m	0,029 m	0,049 m
À posteriori σ_0	3,9 μm		

Fredrikstad II (7 strips East-West, without GPS)

Number of photos	80		
Number of object points	622		
Number of image points	2166		
Available control points	51		
- Ground Control Points (GCP)	22 in X and Y / 28 in Z		
- Check Points (C P)	29 in X and Y / 23 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,012 m	0,015 m	0,003 m
- Photogrammetry - C P	0,044 m	0,033 m	0,065 m
À posteriori σ_0	3,8 μm		

Fredrikstad III (5 strips North-South + 2 crossing strips, with GPS)

Number of photos	101		
Number of object points	639		
Number of image points	2727		
Available control points	51		
- Ground Control Points (GCP)	4 in X, Y and Z		
- Check Points (C P)	47 in X, Y and Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,007 m	0,009 m	0,006 m
- Photogrammetry - C P	0,028 m	0,051 m	0,044 m
À posteriori σ_0	4,1 μm		

Fredrikstad IV (7 strips East-West + 2 crossing strips, with GPS)

Number of photos	110		
Number of object points	628		
Number of image points	2952		
Available control points	51		
- Ground Control Points (GCP)	4 in X, Y and Z		
- Check Points (C P)	47 in X, Y and Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,012 m	0,009 m	0,004 m
- Photogrammetry - C P	0,055 m	0,041 m	0,046 m
À posteriori σ_0	4,1 μm		

GPS-method of Data Reduction

The GPS-data was downloaded to portable PC's in real time. The GPS processing was done at the Department of Surveying, NLH, with the PC program GPSPROG (developed at the department). This software uses pseudoranges for computation of receiver clock offsets. Cycle slips identification and estimation is based on TurboEdit (part of the software system GIPSY from JPL, USA), range- and ionospheric residuals and on time-differencing schemes. The data editing can be carried out for one receiver at the time, for single-differences and for double-differences. The final processing was carried out in the double-difference mode.

Solution of Phase Ambiguity

As the initial goal to maintain phase-lock to the satellites during flight was not achieved, the phase ambiguity could not be solved by initializing the integer ambiguities at the airport before take-off and after returning. Instead the ambiguities were initialized with a double difference P-code solution in the beginning of each strip. No constellation changes were allowed to occur within the strips as the computed positions can be altered several cm if a new satellite enters or if a satellite is discharged.

Eccentricity of Antenna

The camera was fixed to the aircraft during the whole flight. The eccentricity vector between the antenna phase centre and the entrance nodal point of the camera was treated as known in the adjustment.

Timing GPS and Camera

Time marks from the mid-exposure pulse (from the camera) were stored in the GPS-receiver.

Transformation Between Ground Coordinate System and WGS84

The coordinates of the points in the testfield are referred to the WGS84-ellipsoid, so no datum transformations were necessary.

Cost-Benefit

Based on the the test flight described in this report and similar test flights this year (1993), the department of Surveying at NLH claims that they have a pre-operational system. The cost-benefit analyses below are based on both experiences gained in test flights and information from private Norwegian surveying companies.

Time consumption for the different parts of a job:

-planning a block	4-8 hours (as for traditional job)
-installation/ mobilization in the aircraft	
# first time	10 hours
# repeating	0,5 hour
-targeting of ground control points (GCP)	1,5 hour per point
-measuring and calculations of GCP	4 hours per point
-operation of one fixed GPS-receiver	2-8 hours
-processing of the GPS-data	1 hour per strip
-measurements of additional images	2 hours per model

For a block like Fredrikstad, the following calculations can be done:

	Traditional block	GPS block
Targeting of GCP (30/4)	45,0 hours	6,0 hours
Measuring and calculations of GCP	120,0 hours	16,0 hours
Mobilization in the aircraft		0,5 hours
Operation of the fixed receiver		5,5 hours
GPS-processing (7 strips)		7,0 hours
Measuring of cross strips (20 models)		40,0 hours
Total	165,0 hours	75,0 hours

From these calculations one can say that using GPS in this case , means saving of 90 hours.

Comments

If the block adjustment was made easier or less blunders occured, is difficult to say, since this test was done under well controlled conditions. In a practical job, we might expect less blunders, since we are dealing with less ground control points. Blunders often occur during surveying of these points in the field and during identification in the images.

The next important steps in the development of GPS for photogrammetric applications are, as we see it, to gain experience on different distances to the reference GPS receiver on the ground, and to minimize the necessary additional unknowns in the block adjustment. The latter can only be done if the systematic errors in the GPS determined camera stations do not vary between strips, or if the systematic errors are totally eliminated. Development of "on the fly ambiguity resolution" techniques are therefore important.

To those who have not yet begun with GPS-supported block adjustment, we have the following recommendation: Use qualified people, both for the GPS processing and for the block adjustment. The technique is not developed so far that you can " just push a button and get the answer". It is necessary to understand the underlaying theory.

Reference

Blankenberg, L.E., Øvstedal, O. (1993) : Block Adjustment with GPS - Results from test flight Fredrikstad. PhoWo Proceedings, 1993.

Block Rörberg

Submitted by :

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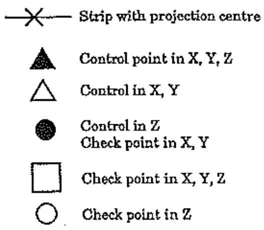

Block sketches

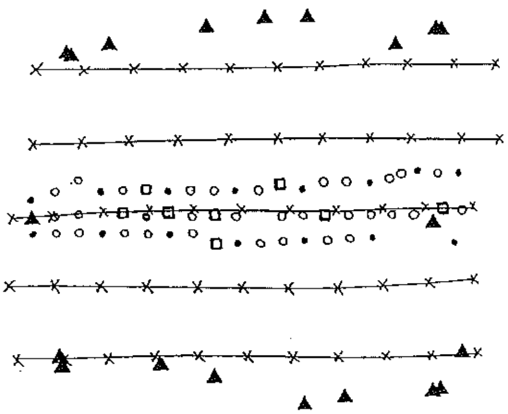

Image scale 1:3300

Fig a5.1 Rörberg I, without GPS.

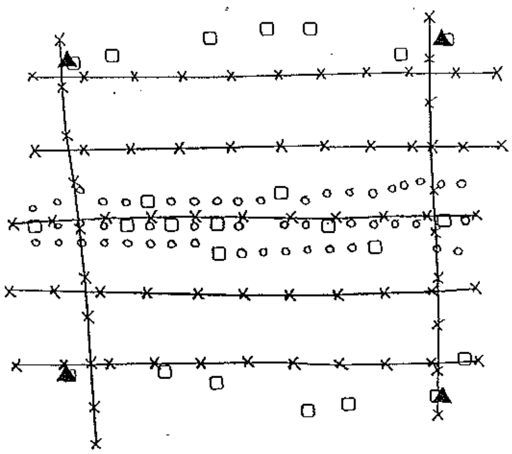

Image scale 1:3300

Fig a5.2. Rörberg II, with GPS.

Technical data

Date of flight	August, 1992
Flight altitude	500 m
Scale	1:3 300
Block size	3*3 km
Overlap	p=60% q=20%
Number of tie points	3/model in strip, 2/model between strips
Camera constant	ca 150 mm
Type of adjustment	Bundle block
Adjustment program	GENTRI
Type of tie points	PUGged
Type of control points	Targeted
Type of check points	Targeted

GPS data

GPS instrument in aircraft	Ashtech MXII-P
GPS instrument on ground	Ashtech MXII-P
Number of ground stations	One
Distance between ground station and test field	Ground station in test field
GPS recording continuous or interrupted	Continuous
Fixed camera or not	Fixed
Known eccentricity or not	Known
Interpolation method	Linear
GPS-parameters in adjustment	Three shift and three time dependent per strip

À priori estimates and weights

Control points	0,015 m	0,015 m	0,022 m
Check points	0,015 m	0,015 m	0,022 m
GPS-measurements	0,10 m	0,10 m	0,10 m
Photogrammetric measurements	5 µm		

Rörberg I (5 strips East-West, without GPS)

Number of photos	55		
Available control points			
- Ground Control Points (GCP)	20 in X and Y / 36 in Z		
- Check Points (C P)	8 in X and Y / 39 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,010 m	0,008 m	0,007 m
- Photogrammetry - C P	0,016 m	0,033 m	0,035 m
À posteriori σ_0	4 µm		

Rörberg II (5 strips East-West + 2 crossing strips, with GPS)

Number of photos	75		
Available control points			
- Ground Control Points (GCP)	4 in X and Y / 4 in Z		
- Check Points (C P)	24 in X and Y / 71 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,004 m	0,005 m	0,008 m
- Photogrammetry - C P	0,030 m	0,039 m	0,035 m
À posteriori σ_0	4 μm		

GPS-method of data reduction

The GPS processing was done at the National Land Survey in Sweden. The program used was PNAV (Ashtech). The method used was relative kinematic differential GPS on two carrier waves. Also code measurements were done. All the observations were used in the calculations.

Solution of phase ambiguity

The phase ambiguity was fixed at the airport by using all observations (codes and carrier waves). The contact with the satellites were then kept during the flight.

Eccentricity of antenna

The eccentricity of the antenna was known in the camera coordinate system beforehand and fixed relativily to the aircraft during the flight. In the bundle adjustment program the eccentricity was rotated with the rotation matrix to get the eccentricity in ground coordinates. The relation between the projection centre and the GPS measurements could in that way be established.

Timing GPS and camera

Time marks from the mid-exposure pulse (from the camera) were stored in the GPS-receiver.

Transformation between ground coordinate system and WGS84

The transformation parameters between the ground coordinate system and WGS84 were known and the GPS observations were transformed to the ground coordinate system before the bundle adjustment was done. If discrepancies between the systems would remain they would be compensated for by the drift and shift parameters of the GPS observations.

Comments

This test to use GPS-supported aerial triangulation was the first in Sweden. The block was planned as a GPS-block and not as a traditional block. The traditional block calculated here is therefore not representative for how a traditional block would be performed in Sweden for this flight altitude. Most likely it would contain more ground control points and a better result would be obtained.

Other GPS-calculations were done than the one presented here, for example "on-the-fly" techniques to determine the phase ambiguity. The result from the bundle adjustment was very much the same for all these tests.

Acknowledgement

I would like to thank the National Land Survey of Sweden, who delivered all the geodetic and photogrammetric data. Without their support, this project would have been impossible to carry out.

Block Sonvilier

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Technical information :

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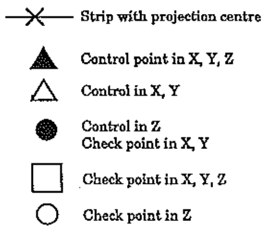

Block sketches

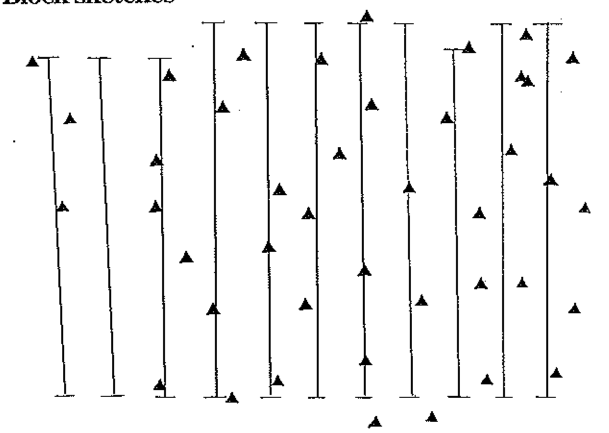

Image scale 1:5000

Fig a6.1 Sonvilier I, without GPS.

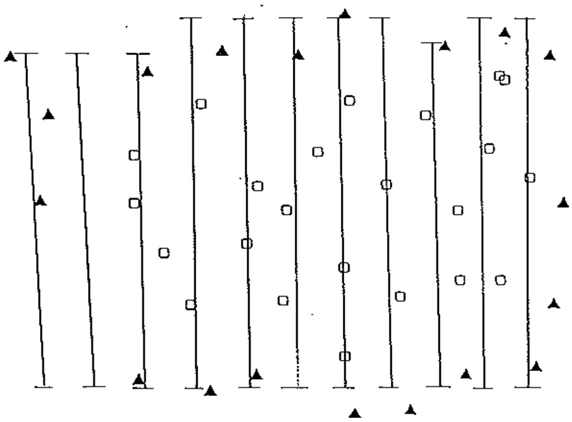

Image scale 1:5000

Fig a6.2 Sonvilier II, with GPS.

Technical data

Date of flight	April 9th, 1993
Flight altitude	800 m
Scale	1:5 000
Block size	11 km^2
Overlap	p=60% q=60%
Camera	Wild RC30
Camera constant	152,92 mm
Type of adjustment	Bundle block
Adjustment program	PAT-B-RS-GPS
Type of tie points	66 targeted, 41 natural
Type of control points	Targeted
Type of check points	Targeted

GPS data

GPS instrument in aircraft	TRIMBLE 4000 SSE
GPS instrument on ground	TRIMBLE 4000 SSE
Number of ground stations	One
Distance between ground station and test field	50 km
GPS recording continuous or interrupted	Interrupted
Fixed camera or not	Fixed
Known eccentricity or not	Not known, estimated in the block adj.
Interpolation method	2nd order polynomial
GPS-parameters in adjustment	Three shift and three linear drift / strip

À priori estimates

Control points	0,05 m in planimetry	0,05 m in height
Check points	0,05 m in planimetry	0,05 m in height
GPS-measurements	0,05 m in planimetry	0,05 m in height
Photogrammetric measurements	4 µm	

Sonvilier I (11 strips East-West, without GPS)

Number of photos	114		
Number of object points	489		
Number of image points	3498		
Available control points	43		
- Ground Control Points (GCP)	43 in X and Y / 43 in Z		
- Check Points (C P)	-		
Resulting RMS of differences			
- Photogrammetry - GCP	0,038 m	0,034 m	0,031 m
- Photogrammetry - C P	-		
À posteriori σ_0	3,84 µm		

Sonvilier II (11 strips East-West, with GPS)

Number of photos	114		
Number of object points	489		
Number of image points	3498		
Available control points	43		
- Ground Control Points (GCP)	19 in X and Y / 19 in Z		
- Check Points (C P)	24 in X and Y / 24 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,038 m	0,031 m	0,053 m
- Photogrammetry - C P	0,049 m	0,040 m	0,143 m
À posteriori σ_0	3,82 µm		

GPS-method of data reduction

The method used for calculating the GPS-coordinates was relative phase measurements on one carrier wave (L1).

Solution of phase ambiguity

For the approximate computations of the ambiguities a pseudo range solution was computed. The remaining error effects of incorrect cycle ambiguities are corrected by the shift and drift parameters in the block adjustment.

Eccentricity of antenna

The eccentricity of the antenna was not known, but estimated in the combined block adjustment. The camera was fixed to the aircraft during the flight which means that the eccentricity was constant in the camera coordinate system.

Timing GPS and camera

The synchronization of the GPS receiver and the Wild RC30 camera was guaranteed by the emitted pulse of the RC30 and the photogrammetric input of the receiver.

Transformation between ground coordinate system and WGS84

The datum transformation of the GPS observations was done within the block adjustment with shift and drift parameters per strip.

Comments

In a previous run of the block using 12 parameters for self calibration, the residuals at the control points showed a systematic block deformation in height of about 0,20 m. The residuals at the planimetric control points showed no systematical error but were larger than expected. There seem to be tensions in the geodetic network used for control, which are responsible for these effects. To fit the block as good as possible to the geodetic ground control coordinates, 44 parameters for self calibration were used. When using 44 parameters for self calibration the residuals at the height control points showed no significant systematic pattern.

Questions of Costs and Cost-benefit

Signalization of Ground Control Points and Tie Points

The total costs of signalization is sfr 18 000.-, representing 25 man-days. With GPS the saving of ground control points would amount to only sfr 1500.- or 2 man-days, which is insignificant as compared with the total effort for the signalisation of all tie-points.

Blunder detection

Normally, targeted points are used as tie points, therefore few problems with blunders occurs.

GPS installation

There exists a platform for installing the GPS instrument in the aircraft. The GPS registration during the flight can be monitored by the camera operator. Therefore the additional amount of costs for the GPS registration are not high.

Expected Benefits in the Future

The trigonometric fourth order network in this region of Switzerland is about 50 years old. In the mountainous areas, there is often movements of the soil, up to 0,05 m in a year. Although the reliability of these points is quit low. It would be of great advantage if photogrammetric blocks could be oriented only with points of the higher order trigonometric network (these points are normally well established in stable regions) and few additional GPS ground control points.

Block Sperillen

Submitted by :

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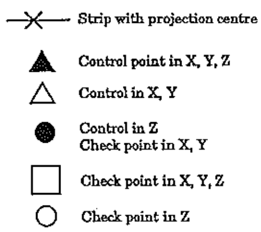
Ås, Norway



Block sketches

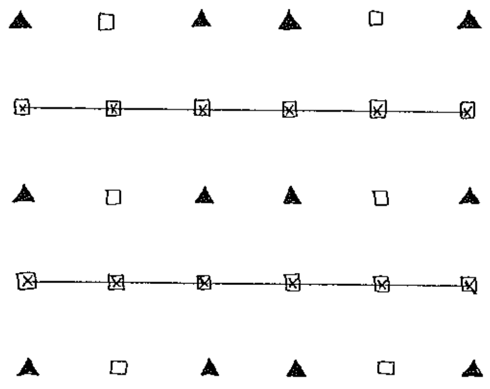


Image scale 1:8000

Fig a7.1 Schematic sketch of Sperillen I, without GPS.

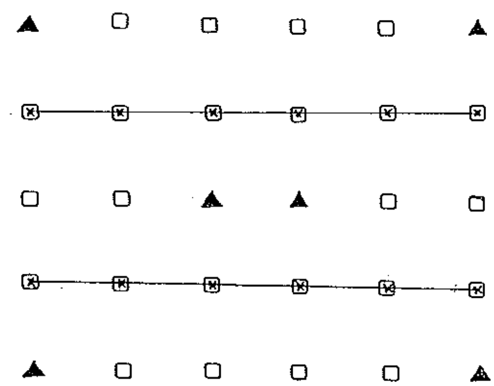


Image scale 1:8000

Fig a7.2 Schematic sketch of Sperillen II, with GPS.

Technical data

Date of flight	June 13th, 1988
Flight altitude	1215 m
Scale	1:8 000
Block size	3,5*3,5 km
Overlap	p=60-70% q=20-30%
Number of tie points	6/model in strip, 4/model between strips
Camera	Wild RC10
Camera constant	152,00 mm
Type of adjustment	Independent model
Type of tie points	Natural
Type of control points	Targeted (Yellow 40*40 cm + black border)
Type of check points	Targeted (Yellow 40*40 cm + black border)

GPS data

GPS instrument in aircraft	Trimble 4000SL
GPS instrument on ground	Trimble 4000SL
Number of ground stations	One
Distance between ground station and testfield	35 km
GPS recording continuous or interrupted	Interrupted
Fixed camera or not	Fixed
Known eccentricity or not	Known
Interpolation method	Second degree interpolation
GPS-parameters in adjustment	Three shift and three time dependent

À priori estimates

Control points	0,02 m	in X, Y and Z
Check points	0,02 m	in X, Y and Z
GPS-measurements	0,12 m	in X, Y and Z
Photogrammetric new points	8 μm = 0,064 m	

Sperillen I (2 strips, without GPS)

Number of models	10		
Number of object points	61		
Number of model points	124		
Available control points	30		
- Ground Control Points (GCP)	12 in X and Y / 12 in Z		
- Check Points (C P)	18 in X and Y / 18 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,021 m	0,021 m	0,037 m
- Photogrammetry - C P	0,060 m	0,060 m	0,120 m
À posteriori s_0	6 cm		

Sperillen II (2 strips, with GPS)

Number of models	10		
Number of object points	61		
Number of model points	124		
Available control points	30		
- Ground Control Points (GCP)	6 in X and Y / 6 in Z		
- Check Points (C P)	24 in X and Y / 24 in Z		
Resulting RMS of differences			
- Photogrammetry - GCP	0,015 m	0,015 m	0,027 m
- Photogrammetry - C P	0,065 m	0,065 m	0,150 m
À posteriori σ_0	0,060 m		

GPS-method of data reduction

The GPS processing was performed by the "Institutt for kontinentalsokkelundersøkelser og petroliumteknologi AS", with their software KINPOS. This software uses pseudorange, Doppler and carrier phase data for determination of GPS positions.

Solution of phase ambiguity

The phase ambiguity was solved by filtering the difference between pseudo-distance and phase.

Eccentricity of antenna

The camera was kept in a locked position relatively to the airplane. The GPS positions were reduced for the eccentricity before the block adjustment using the average direction of each strip as orientation.

Timing GPS and camera

A portable PC in the aircraft logged both time marks from the camera and 1 PPS (1 Pulse Per Second) from the GPS receiver. The shutter release pulse in the camera was used as time marks.

Transformation between coordinate systems

The coordinates of the points in the test field are referred to a local coordinate system. The transformation of the positions of the camera in WGS84, to the local ground coordinate system, was only roughly known.

Problems

The original plan was to maintain phase-lock to the satellites during the flight. The integer ambiguities were initialized at the airport (30 km from the testfield) before take-off. However, phase-lock was lost during take-off and there were also interruptions in the turns between strips. In addition to this, the receiver stopped recording before landing due to exceeded storage capacity (1 Mbyte).

Comments

Four strips with 60 % side overlap were photographed. The strips were grouped in two blocks with 20 % side overlap each. The results represent the average of the two different blocks, both for traditional and for GPS-supported block triangulation.

Some of the lessons learned in the project were:

- new GPS-receivers are needed, which have sufficient storage capacity, which have capacity of recording on more than 5 channels, which has the ability to record the camera exposure pulse, which has a sampling rate of 1 sec or faster

- a camera that can emit a mid-exposure-pulse is needed

- the aircraft should not fly too fast, preferably 80 m/s or slower

- better software for processing of GPS observations needed

- block adjustment software that can use the GPS observations in a better way, for instance should the eccentricity vector be treated in a way that allows it to be rotated by the orientation matrix

- the satellite geometry should be considered, it is necessary to have 5 or more satellites with good geometry

This project is fairly old (1987-1988) and improvements of the GPS-receivers, the data recording system, the algorithms for processing the GPS-data and the methods for block adjustment have been done. This implies that the result would be better if the test was made today.

In a practical job one might expect less blunders when using GPS-support since less ground control points are used and blunders often occur during surveying of these points in field and during identification in the images. In addition, the GPS-data is expected to stabilize the block, making it somewhat easier to detect blunders in ground control points and photogrammetric measurements.

The next important steps in the development of GPS for photogrammetric applications are :

- to gain experience of different distances to the reference GPS receiver on the ground

- to minimize the additional unknowns in the block adjustment (by phase-lock through the flight mission or by development of "on the fly ambiguity resolution")

- to add some kind of recording of the drift-angle of the camera, to allow the crew to adjust the camera for drift inside a flight line

- to try to exploit the extra information gained from kept phase-lock, as better equipment now allows kept phase-lock during a mission

To those who have not yet begun with GPS-supported block adjustment , the recommendation is to use qualified people, both for the GPS processing and for the block adjustment. The technique is not developed so far that you can say "just push a button and get the answer". It is necessary to understand the underlaying theory.

Inpho Blocks A - F

Submitted by :

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Method and technology

	Block A	Block B	Block C	Block D	Block E	Block F
Flying	Terra Bildmeßflug Germany	Terra Bildmeßflug Germany	Terra Bildmeßflug Germany	Hansa Luftbild Middle East	Hansa Luftbild Middle East	Airsat Inc. Canada
Block size	50 photos 5 * 6 km	70 photos 7 * 7 km	55 photos 6 * 5,5 km	143 photos 133 * 33 km	136 photos 130 * 30 km	154 photos 7,6 * 7,6 km
Strips	7 (5+2)	6 (4+2)	8 (6+2)	7 (4+3)	7 (4+3)	10 (8+2)
Overlap	60/20	60/20	60/20	60/20	60/20	60/20
Flying height	1120 m	1200 m	1150 m	7500 m	7500 m	915 m
Image scale	1:7500	1:8000	1:7500	1:50 000	1:50 000	1:6100
Focal length	150 mm	150 mm	150 mm	150 mm	150 mm	150 mm
GPS receiver	Sercel 1 ref. stn	Sercel 1 ref. stn	Sercel 1 ref. stn	Ashtech 1 ref. stn	Ashtech 1 ref. stn	Ashtech 1 ref. stn
Interrupted ot continous GPS record.	Interrupted	Interrupted	Interrupted	Interrupted	Interrupted	Interrupted
Excen-tricity / Fixed camera	Constant excentr. / Camera fixed in strip	Constant excentr. / Camera fixed in strip	Constant excentr. / Camera fixed in strip	Constant excentr. / Camera fixed in strip	Constant excentr. / Camera fixed in strip	Constant excentr. / Camera fixed in strip
Solution of phase ambiguity	Approximate by pseudo ranging	Approximate by pseudo ranging	Approximate by pseudo ranging	Approximate by pseudo ranging	Approximate by pseudo ranging	Approximate by pseudo ranging

The GPS data processing was made at TOPSCAN in Stuttgart with the program SKIP. The block adjustments were made at INPHO GmbH in Stuttgart with the bundle adjustment program PATB-RS.

Statistics of blocks without GPS, conventional aerial triangulation

	Block A	Block B	Block C	BlockD	Block E	Block F
Number of tie points / photo	10 pugged	10 pugged	10 pugged	15 pugged	15 pugged	15 pugged
Number of control points	32 targeted	43 targeted	32 targeted	63 targeted	65 targeted	40 targeted
A priori standard deviation of image co-ordinates	7 µm	7 µm	7 µm	6 µm	6 µm	7 µm
A priori standard deviation of control points	0,02 m	0,02 m	0,02 m	0,20 m	0,20 m	0,02 m
σ_0	4,6 µm	4,2 µm	4,4 µm	6,5 µm	6,9 µm	6,7 µm
Theoretical accuracy of photogrammetric new points	x/y 0,4 σ_0 z 1,2 σ_0	x/y 0,6 σ_0 z 1,3 σ_0	x/y 0,7 σ_0 z 1,4 σ_0	x/y 0,6 σ_0 z 1,2 σ_0	x/y 0,6 σ_0 z 1,2 σ_0	x/y 0,7 σ_0 z 1,3 σ_0

Statistics of blocks with GPS

	Block A	Block B	Block C	BlockD	Block E	Block F
Number of tie points / photo	10 pugged	10 pugged	10 pugged	15 pugged	15 pugged	15 pugged
Number of control points	4 targeted	4 targeted	4 targeted	6 targeted	6 targeted	12 targeted
Number of check points	28 targeted	39 targeted	28 targeted	57 targeted	59 targeted	28 targeted
A priori standard deviation of image co-ordinates	7 µm	7 µm	7 µm	6 µm	6 µm	7 µm
A priori standard deviation of control points	0,001 m	0,001 m	0,001 m	0,001 m	0,001 m	0,001 m
A priori standard deviation of GPS record.	0,10 m	0,10 m	0,10 m	0,10 m	0,10 m	0,10 m
σ_0	4,9 µm	4,8 µm	4,6 µm	6,4 µm	7,0 µm	6,9 µm
Theoretical accuracy of photogrammetric new points	x/y 1,3 σ_0 z 2,5 σ_0	x/y 1,2 σ_0 z 2,6 σ_0	x/y 1,2 σ_0 z 2,6 σ_0	x/y 0,8 σ_0 z 1,4 σ_0	x/y 0,8 σ_0 z 1,6 σ_0	x/y 0,9 σ_0 z 1,6 σ_0
Theoretical accuracy of check points	x/y 1,2 σ_0 z 2,2 σ_0	x/y 1,4 σ_0 z 2,3 σ_0	x/y 1,3 σ_0 z 2,2 σ_0	x/y 1,1 σ_0 z 1,4 σ_0	x/y 1,0 σ_0 z 1,7 σ_0	x/y 0,9 σ_0 z 1,5 σ_0
Empirical accuracy of check points	x/y 1,8 σ_0 z 2,3 σ_0	x/y 1,6 σ_0 z 2,3 σ_0	x/y 1,6 σ_0 z 2,4 σ_0	x/y 1,1 σ_0 z 1,3 σ_0	x/y 1,5 σ_0 z 1,9 σ_0	x/y 1,8 σ_0 z 1,9 σ_0

Block sketches

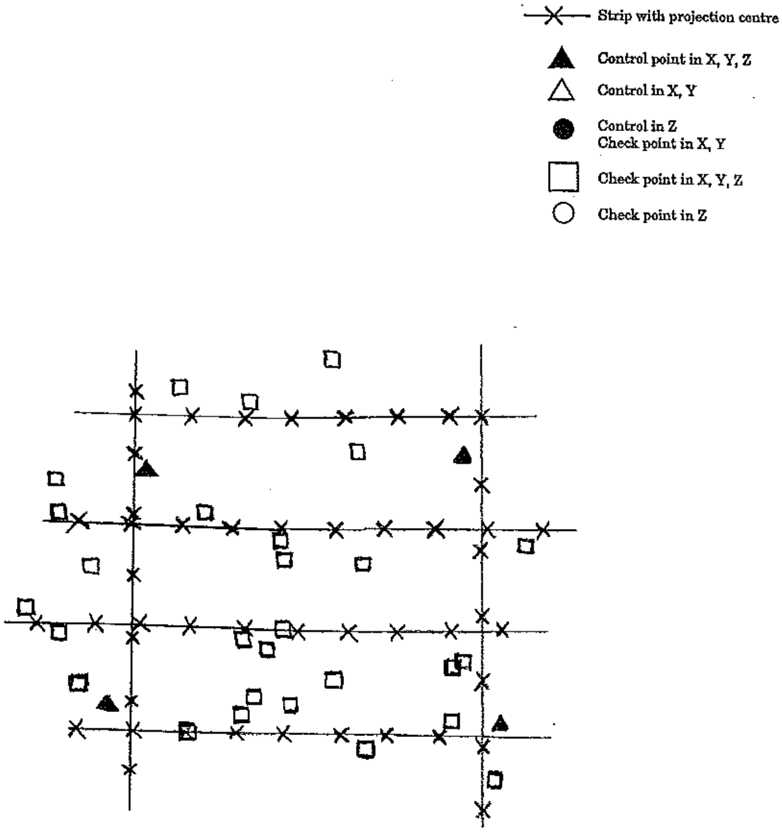

Image scale 1:7500

Fig a8.1. Inpho block A, with GPS

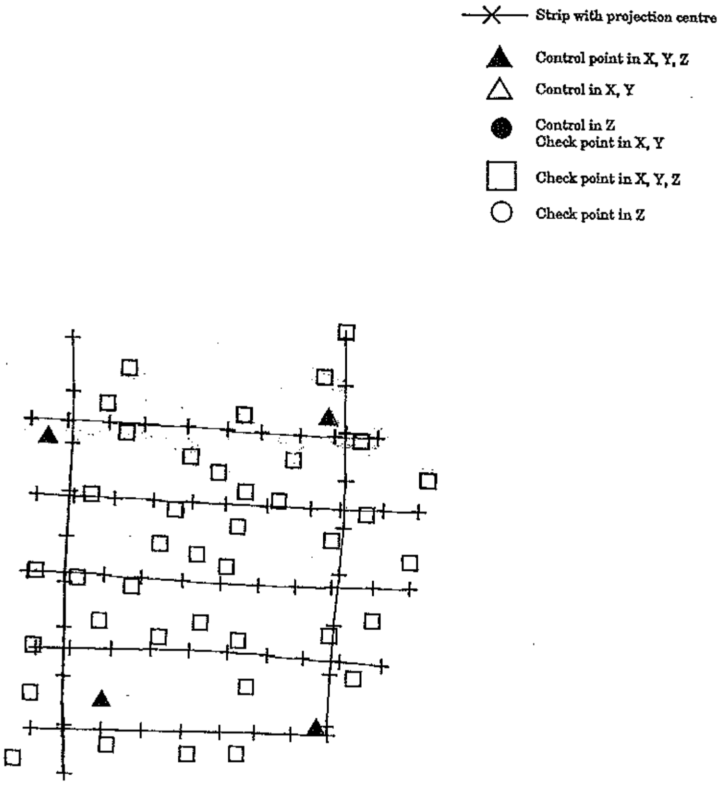

Image scale 1:8000

***Fig a8.2.** Inpho block B, with GPS*

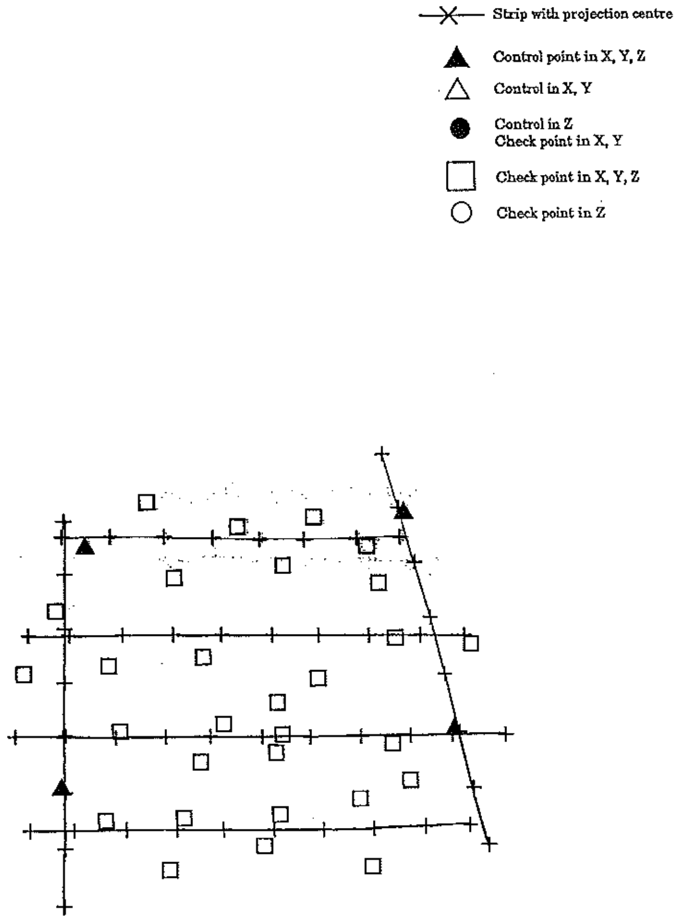

Image scale 1:7500

Fig a8.3. Inpho block C, with GPS

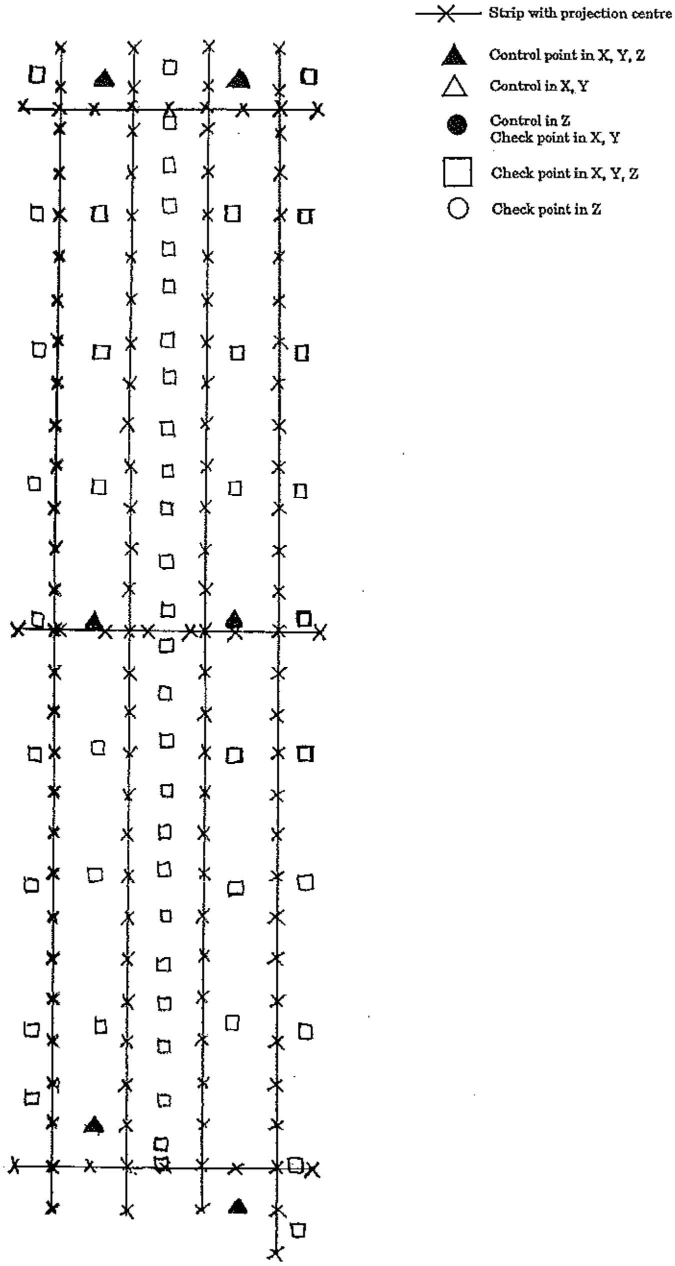

Image scale 1:50 000

***Fig a8.4.** Inpho block D, with GPS*

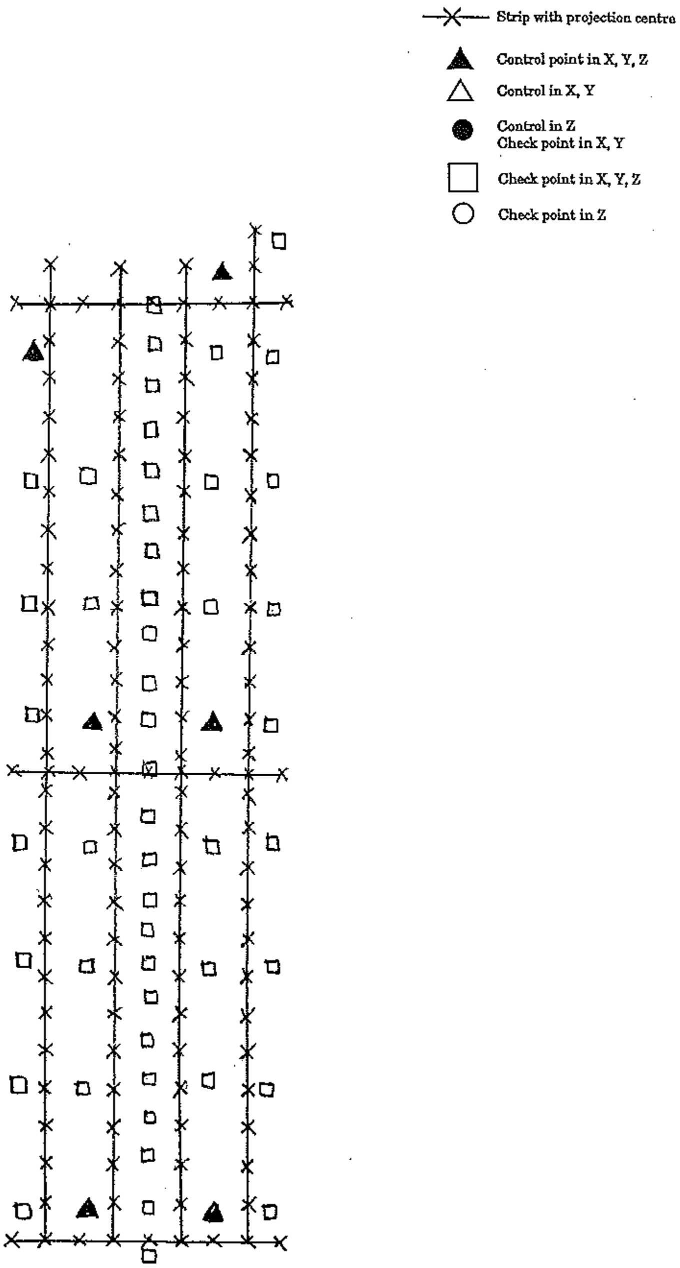

Image scale 1:50 000

Fig a8.5. Inpho block E, with GPS

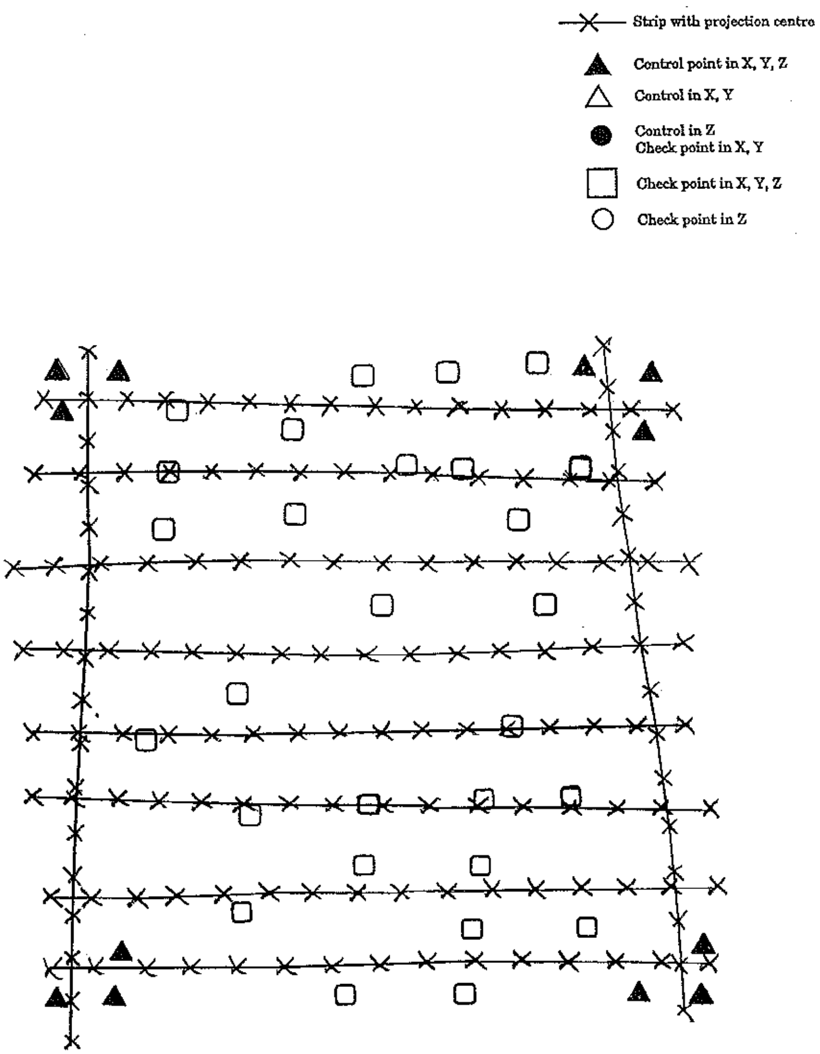

Image scale 1:6100

Fig a8.6. Inpho block F, with GPS

Remarks

1.
All 6 blocks were flown and treated in 1992/93. They all refer to practical application in commercial projects, run by photogrammetric companies and offices. In all cases additional check points were made available, for evaluation purposes. The photogrammetric triangulation observations (image coordinates) as well as the ground control data were submitted by the companies to Inpho company for combined adjustment.

2.
The GPS observations are differential phase observations of the L1 signals and C/A code pseudo range observations. Only one stationary receiver was used on the ground, located in or near the mission area.

3.
The exact time of camera exposure was related, by an electronic pulse, to the GPS time scale and recorded by the GPS receiver in the air-craft. The interpolation of the camera exposure into the GPS recordings by the SKIP program is of 3rd degree, as 4 adjacent GPS recordings are taken into account.

4.
GPS recording in the air-craft (and partly on the ground) have been discontinuous by intention. There was no initialisation before take-off, no recording during the flight to the area, and no recording during the flight turns between strips. This is considered highly advantageous, from an operational point of view, as the flying does not have to pay attention to the GPS part of the mission.

5.
Because of #4 the ambiguity solutions have to be restored for each strip separately. The solutions are approximate only, being based on the first pseudo range position of each strip.

6.
Because of #5 the ambiguity solutions are biased, which leads to off-sets and time dependent drift errors in the subsequent GPS position computations. However, the drift effects are constant or linear for some time, in first approximation. Hence, they are compensated by linear correction terms applied in the combined block adjustment.

7.
The GPS antenna eccentricity is measured on the ground and calculated with respect to the image coordinate system (fiducial marks) of the camera in 0-position. During data processing the off-set corrections were treated as constant per strip or per part of a strip, if the crab setting had been changed during the flight. Treating the off-set corrections as constants is sufficient in most cases, especially if the GPS antenna is mounted approximately vertical above the camera. Our software programs can apply off-set corrections individually for each photo, if desired. In that case the attitude data are derived from the initial block adjustment runs.

8.
The initial GPS camera position coordinates are approximately transformed into the national or local geodetic coordinate system resp. map projection, before being introduced into the combined block adjustment. The final datum transformation is determined and performed by the combined block adjustment, via the drift parameters.

9.
The PAT-B adjustment program prints out the theoretical standard deviations of all unknowns of the adjustment (including the unknown drift parameters). The previous tables contain the theoretical RMS accuracies of all adjusted block points. Also the subset of check points is presented separately, as the results are different, occasionally, depending on the number and location of the check points.

10.
Block F has been treated twice, with reference to two different stationary GPS receivers, one located in the mission area, the other 400 km away. The first case is contained in the above tables. With the data from the second stationary receiver and a different version of the first one, the combined block adjustment was repeated (with the same image and control data). The two cases compare as listed below. The results are virtually identical, although the drift parameters are quite different in both cases. It can be concluded that the stationary receiver can be placed very far from the mission area, 500 km or more, which is of great operational and economic importance. For instance, the stationary receiver may be placed on the home office, without requiring permanent attendance. If the distance to the mission area is large, then the systematic GPS errors may increase, but the principle of drift parameter correction still removes them safely. This is a second major reason for applying that principle. It even seems so work safely for large scale, high precision applications (Block F had photo scale 1:6100).

Distance to receiver	***some km***	***400 km***
σ_0 (1:6100)	6,8μm = 0,040 m	6,9 μm = 0,041 m
Empirical accuracy from 18 XYZ check points		
RMS-X	0,088 m = 2,2 σ_0 * s	0,090 m = 2,2 σ_0 * s
RMS-Y	0,075 m = 1,9 σ_0 * s	0,074 m = 1,8 σ_0 * s
RMS-Z	0,087 m = 2,3 σ_0 * s	0,061 m = 1,5 σ_0 * s
Theoretical accuracy, rms of 787 points		
σ_X	0,036 m = 0,9 σ_0 * s	0,046 m = 1,1 σ_0 * s
σ_Y	0,035 m = 0,9 σ_0 * s	0,046 m = 1,1 σ_0 * s
σ_Z	0,065 m = 1,6 σ_0 * s	0,089 m = 2,2 σ_0 * s

11.
Inpho company has treated about 25 GPS triangulation blocks over the past 2 years, with no failures and no serious problems. The principle of discontinuous GPS recordings and of applying cross-strips, minimum ground control, and combined block adjustment with unknown drift parameters per strip is consistently applied. From practical experience we consider the method fully developed, fully operational, and safely applicable in practice. The accuracy performance and the economic benefits of GPS aerial triangulation are totally convincing to suggest regular application in all air survey mapping projects.

Reference:

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LIST OF THE OEEPE PUBLICATIONS

State – May 1994

A. Official publications

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2 *Neumaier, K.:* „Essais d'interprétation de »Bedford« et de »Waterbury«. Rapport commun établi par les Centres de la Commission E de l'OEEPE ayant participé aux tests" – „The Interpretation Tests of »Bedford« and »Waterbury«. Common Report Established by all Participating Centres of Commission E of OEEPE" – „Essais de restitution »Bloc Suisse«. Rapport commun établi par les Centres de la Commission E de l'OEEPE ayant participé aux tests" – „Test »Schweizer Block«. Joint Report of all Centres of Commission E of OEEPE." – Frankfurt a. M. 1966, 60 pages with 44 annexes.

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Ackermann, F.: „On Statistical Investigation into the Accuracy of Aerial Triangulation. The Test Project Oberschwaben" – „Recherches statistiques sur la précision de l'aérotriangulation. Le champ d'essai Oberschwaben" – *Belzner, H.:* „The Planning. Establishing and Flying of the Test Field Oberschwaben" – *Stark, E.:* Testblock Oberschwaben, Programme I. Results of Strip Adjustments" – *Ackermann, F.:* „Testblock Oberschwaben, Program I. Results of Block-Adjustment by Independent Models" – *Ebner, H.:* Comparison of Different Methods of Block Adjustment" – *Wiser, P.:* „Propositions pour le traitement des erreurs non-accidentelles" – *Camps, F.:* „Résultats obtenus dans le cadre du project Oberschwaben 2A" – *Cunietti, M.; Vanossi, A.:* „Etude statistique expérimentale des erreurs d'enchaînement des photogrammes" – *Kupfer, G.:* „Image Geometry as Obtained from Rheidt Test Area Photography" – *Förstner, R.:* „The Signal-Field of Baustetten. A Short Report" – *Visser, J.; Leberl, F.; Kure, J.:* „OEEPE Oberschwaben Reseau Investigations" – *Bauer, H.:* „Compensation of Systematic Errors by Analytical Block Adjustment with Common Image Deformation Parameters." – Frankfurt a. M. 1973, 350 pages with 119 figures, 68 tables and 1 annex.

9 *Beck, W.:* „The Production of Topographic Maps at 1 : 10,000 by Photogrammetric Methods. – With statistical evaluations, reproductions, style sheet and sample fragments by Landesvermessungsamt Baden-Württemberg Stuttgart." – Frankfurt a. M. 1976, 89 pages with 10 figures, 20 tables and 20 annexes.

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Hárry, H.: „Mesure de points de terrain non signalisés dans le champ d'essai d'«Oberriet» – Measurements of Non-Signalized Points in the Test Field «Oberriet» (Abstract)" – *Stickler, A.; Waldhäusl, P.:* „Restitution graphique des points et des lignes non signalisés et leur comparaison avec des résultats de mesures sur le terrain dans le champ d'essai d'«Oberriet» – Graphical Plotting of Non-Signalized Points and Lines, and Comparison with Terrestrial Surveys in the Test Field «Oberriet»" – *Förstner, R.:* „Résultats complémentaires des transformations de coordonnées de l'essai d'«Oberriet» de la Commission C de l'OEEPE – Further Results from Co-ordinate Transformations of the Test «Oberriet» of Commission C of the OEEPE" – *Schürer, K.:* „Comparaison des distances d'«Oberriet» – Comparison of Distances of «Oberriet» (Abstract)." – Frankfurt a. M. 1975, 158 pages with 22 figures and 26 tables.

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18 *Förstner, W.:* Final Report on the Joint Test on Gross Error Detection of OEEPE and ISP WG III/1. – Frankfurt a. M. 1986, 97 pages with 27 tables and 20 figures.

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22 *Rollin, J.; Dowman, I. J.:* Map Compilation and Revision in Developing Areas – Test of Large Format Camera Imagery. – Frankfurt a. M. 1988, 35 pages with 3 figures, 9 tables and 3 appendices.

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25 *Ducher, G.:* Test on Orthophoto and Stereo-Orthophoto Accuracy. – Frankfurt a. M. 1991, 227 pages with 16 figures and 44 tables.

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B. Special publications

- Special Publications O.E.E.P.E. – Number I

  Solaini, L.; Trombetti, C.: Relation sur les travaux préliminaires de la Commission A (Triangulation aérienne aux petites et aux moyennes échelles) de l'Organisation Européenne d'Etudes Photogrammétriques Expérimentales (O.E.E.P.E.). I^{ère} Partie: Programme et organisation du travail. – *Solaini, L.; Belfiore, P.:* Travaux préliminaires de la Commission B de l'Organisation Européenne d'Etudes Photogrammétriques Expérimentales (O.E.E.P.E.) (Triangulations aériennes aux grandes échelles). – *Solaini, L.; Trombetti, C.; Belfiore, P.:* Rapport sur les travaux expérimentaux de triangulation aérienne exécutés par l'Organisation Européenne d'Etudes Photogrammétriques Expérimentales (Commission A et B). – *Lehmann, G.:* Compte rendu des travaux de la Commission C de l'O.E.E.P.E. effectués jusqu'à présent. – *Gotthardt, E.:* O.E.E.P.E. Commission C. Compte-rendu de la restitution à la Technischen Hochschule, Stuttgart, des vols d'essai du groupe I du terrain d'Oberriet. – *Brucklacher, W.:* Compte-rendu du centre «Zeiss-Aerotopograph» sur les restitutions pour la Commission C de l'O.E.E.P.E. (Restitution de la bande de vol, groupe I, vol. No. 5). – *Förstner, R.:* O.E.E.P.E. Commission C. Rapport sur la restitution effectuée dans l'Institut für Angewandte Geodäsie, Francfort sur le Main. Terrain d'essai d'Oberriet les vols No. 1 et 3 (groupe I). – I.T.C., Delft: Commission C, O.E.E.P.E. Déroulement chronologique des observations. – Photogrammetria XII (1955–1956) 3, Amsterdam 1956, pp. 79–199 with 12 figures and 11 tables.

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- „OEEPE – Sonderveröffentlichung Nr. 1"

  Gigas, E.: „Beitrag zur Geschichte der Europäischen Organisation für photogrammetrische experimentelle Untersuchungen" – *N. N.:* „Vereinbarung über die Gründung einer Europäischen Organisation für photogrammetrische experimentelle Untersuchungen" – „Zusatzprotokoll" – *Gigas, E.:* „Der Sechserausschuß" – *Brucklacher, W.:* „Kurzbericht über die Arbeiten in der Kommission A der OEEPE" – *Cunietti, M.:* „Kurzbericht des Präsidenten der Kommission B über die gegenwärtigen Versuche und Untersuchungen" – *Förstner, R.:* „Kurzbericht über die Arbeiten in der Kommission B der OEEPE" – „Kurzbericht über die Arbeiten in der Kommission C der OEEPE" – *Belzner, H.:* „Kurzbericht über die Arbeiten in der Kommission E der OEEPE" – *Schwidefsky, K.:* „Kurzbericht über die Arbeiten in der Kommission F der OEEPE" – *Meier, H.-K.:* „Kurzbericht über die Tätigkeit der Untergruppe „Numerische Verfahren" in der Kommission F der OEEPE" – *Belzner, H.:* „Versuchsfelder für internationale Versuchs- und Forschungsarbeiten." – Nachr. Kt.- u. Vermesss.-wes., R. V, Nr. 2, Frankfurt a. M. 1962, 41 pages with 3 tables and 7 annexes.

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