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GPS-SUPPORTED AEROTRIANGULATION IN FINLAND - THE EURA BLOCK

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Abstract

Two test flights were carried out to gain experience with GPS-supported aerotriangulation in Finland. Only the results of the second flight (the Eura block), which was closely related to practical work, are dealt with in this article. The Eura test flight shows, despite certain problems with the GPS registration, that GPS-supported aerotriangulation has a potential for mapping in scales 1:5000 and smaller in Finland.

1. INTRODUCTION

The determination of the aerial camera position by GPS at the moment of exposure has meant a big step forward in the development of aerotriangulation. The GPS coordinates of the aircraft antenna at exposure time can be introduced as additional observations into a combined block adjustment. The number of ground control points in a block can thus be considerably reduced, both saving time and expenses in the targeting work. Undeveloped countries with very sparse geodetic networks and poor map coverage will benefit enormously by using GPS-supported aerotriangulation, and in many cases it will be the only alternative available. Also in countries with well established geodetic networks the method could be of great importance.

The NAVSTAR Global Positioning System (GPS) is not far from being completed. Today there are 25 satellites available, of which 3 are Block I and 22 Block II satellites. It is expected that the "Initial Operational Capability" will be declared by the end of this year (1993) /7/. "Full Operational Capability" will be declared when there are 24 Block II satellites available, which will, according to the latest launch program, happen in 1994 /7/. Bad observation windows have until these days been a limiting factor for the use of GPS-supported aerotriangulation. From a practical point of view this can not be accepted. A complete GPS satellite program will change the situation.

The first practical test with GPS-supported aerotriangulation was carried out in 1987 /5/. Since then quite a number of test flights have been completed. Some are described in /2/,/3/,/4/,/6/ and /11/. The method is already in use in practical applications, but some research work is still going on. The software and hardware have developed a lot in the last few years, but the software especially still needs development to meet the requirements from the user side. The processing of the GPS data has been quite a time consuming part of the aerotriangulation process so far.

The first test flight in Finland was carried out in August 1991 and will not be described here. The results of this flight, which was of a more experimental character, are published in /8/ and /9/. A second flight was carried out in May 1992. The latter one was a photo flight for the Finnish base map production (1:5000) and covered the municipality of Eura in the south-western part of Finland. The distance between the airport and the area to be photographed is often long in Finland. The flight mission time is often several hours due to the location and the large size of the blocks. This was also the case for the Eura block and thus the effect of this was an important part of the project. The study was a joint project between the Finnish Geodetic Institute (FGI) and the National Board of Survey (NBS).

2. MEASURING PROCEDURE

The classical two-receiver set-up was used, with one GPS receiver on board the aircraft and the other one stationary on the ground (at the airport) working as a reference. The aircraft antenna, a single frequency one, was mounted on top of the aircraft fuselage almost vertically above the aerial camera. The receivers operated at a recording rate of 0.5 seconds. The principle of relative positioning using differences of carrier wave phase observations was used. The initial integer phase ambiguities were solved by stationary recordings before take-off and after returning. Due to the single frequency aircraft antenna, the GPS receivers' dual frequency capability could not be utilised. The processing of the GPS data is therefore based on carrier wave phase measurements on L1 and C/A-code pseudo ranges.

The eccentricity (or offset) between the GPS antenna and the aerial camera was measured using a tacheometer. The horizontal components of the eccentricity are quite small with 0.055 m in X (parallel to the flight direction) and 0.260 m in Y. The vertical component of the eccentricity is 1.425 m (referred to the entrance nodal point of the camera). The crab setting of the camera was not recorded. The camera was rotated but not tilted between strips and the crab setting was not changed during a flight strip. The effect of the crab setting on the eccentricity is more or less compensated for by introducing additional drift parameters into the block adjustment (see Section 3.2). The remaining effect was considered to be of minor interest in this project.

The photogrammetric measurements of the aerial images were carried out on a Kern DSR1 analytical plotter at FGI.

3. DATA PROCESSING

3.1. GPS data processing

The GPS data was processed using the GPPS program package from Ashtech. The program is capable of treating cycle slips quite effectively. Problems appear if the data is too noisy, which was the case for the Eura block (see Section 4). The computed GPS coordinates were transformed from WGS84 to the Finnish KKJ system (Gauss-Krüger) using a transformation program made by Mr. Matti Ollikainen of FGI. It is a well known fact the WGS84 coordinates can not be transformed precisely enough to a national reference system. For the Eura area the transformation causes a systematic error of about 0.5 m in all three coordinate components. The combined block adjustment program takes care of this datum problem (see Section 3.2). The positions of the GPS aircraft antenna at exposure time were computed using linear interpolation except for a few cases where polynomial interpolation was used (see Section 4).

3.2. Block adjustment

The bundle block adjustment program ESPA (Expert System for Photogrammetric Analysis) /13/ at FGI was extended to treat GPS antenna position coordinates as additional observations in a combined block adjustment. Almost all experimental tests on kinematic GPS positioning have concluded that the GPS antenna coordinates are affected by almost linear time dependent drift errors (e.g. /1/,/2/,/5/,/11/ among others). In addition to the time dependent drift error there is also an offset (shift) for each coordinate. Though Blankenberg and Øvstedal /3/ show that in cases where the strips are very short (under 2 minutes flight time) and the initial phase ambiguities are well fixed, only stripwise offset parameters are needed. The drift parameters (shifts and drifts) are introduced as unknown parameters into the combined block adjustment.

The drift parameters can be treated as common for the whole block provided the GPS trajectory is continuous. Cycle slips are likely though to occur when the aircraft is turning, but not so easily within a strip. It is therefore normally more safe and in many cases necessary to use stripwise drift parameters, despite the fact that the more parameters the weaker the geometry of the block is. Another alternative could be separate drift parameters for parts of the block.

The additional observation equations introduced into the block adjustment have the following form (stripwise drift parameters considered):

$$\begin{bmatrix} X_{A_{GPS}} \\ Y_{A_{GPS}} \\ Z_{A_{GPS}} \end{bmatrix}_i + \begin{bmatrix} v_X \\ v_Y \\ v_Z \end{bmatrix}_i = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}_i + R(\varphi,\omega,\kappa)_i \cdot \begin{bmatrix} x^A_{PC} \\ y^A_{PC} \\ z^A_{PC} \end{bmatrix} + \begin{bmatrix} a_X \\ a_Y \\ a_Z \end{bmatrix}_j + dt \cdot \begin{bmatrix} b_X \\ b_Y \\ b_Z \end{bmatrix}_j$$

$X_{A_{GPS}}, Y_{A_{GPS}}, Z_{A_{GPS}}$ - GPS-antenna coordinates of photo i in the ground coordinate system
v_X, v_Y, v_Z - Residuals in $X_{A_{GPS}}$, $Y_{A_{GPS}}$ and $Z_{A_{GPS}}$
X_0, Y_0, Z_0 - Ground coordinates of perspective centre i
$R(\varphi,\omega,\kappa)$ - Orthogonal rotation matrix for perspective centre i
$x_{PC}{}^A, y_{PC}{}^A, z_{PC}{}^A$ - GPS antenna eccentricity components
a_X, a_Y, a_Z - GPS drift parameters (constant terms) of strip j
b_X, b_Y, b_Z - GPS drift parameters (linear time dependent terms) of strip j
dt - Elapsed time since start of strip j

4. THE EURA BLOCK

The Eura test flight was carried out on the 14th of May 1992. It covered the municipality of Eura about 200 km north-west of Helsinki (see Fig. 1) and it was at the same time a real flight mission for the Finnish base map production (1:5000). Helsinki-Vantaa airport worked as the operating base. An important task of the photography was to measure boundary marks for the numerical boundary map. The photographs are also used to produce ortophotos in the scale 1:5000. Eura was one out of 3 alternative areas to be photographed before the start of the flight. An area north of Helsinki was chosen, but the weather in this area turned out to be too cloudy for air photography. The pilot then headed towards the Eura area where the weather was excellent.

The targeting of the ground control points was based on the existing geodetic network, but in addition some new points were measured using GPS (about 10% of all the control points). Altogether 253 control points (80 XYZ, 7 XY and 166 Z) were targeted. A storm in the area in April 1992 caused some damage, especially to the Z control points. Some of the points were rejected in the block adjustment and a few XYZ points had to be changed to XY points. The final adjustment contains 220 targeted ground control points (67 XYZ, 11 XY and 142 Z). In addition about 220 tacheometric and water surface points were measured in Kern DSR1 to support the vertical control. The tie points were natural points.

The technical data of the flight:

Date of flight : May 14th, 1992
Size of area : 25 x 45 km
GPS receivers : 2 Ashtech MD-XII
GPS aircraft antenna : Sensor Systems / L1 only
Recording rate : 0.5 sec
Aircraft : Turbo Commander 690A
Camera : Wild RC20
Focal length : 214.10 mm
Average speed : 400 km/h
Flying height : 3400 m
Photo scale : 1:16000
Overlap : p = 60%, q = 30%
Duration of flight mission : 3 hours 45 min
Flight time per strip : 2 - 6 1/2 min
Number of photos : 264 (in ten strips)
Antenna-camera offset : $e_X = -0.055$m, $e_Y = -0.260$m, $e_Z = 1.425$m
Number of targeted control points : 220 (67 XYZ, 11 XY and 142 Z) in final adjustment out of a total of 253

The Eura block is of particular interest because of the long distance between the airport and the flight mission area (160-200 km) and because of the long duration of the flight (almost 4 hours). In Finland this is rather a normal case than an exception, but it has not yet been much investigated /1/. Though in Canada a project has been carried out where the distance between the stationary receiver and the flight mission area was about 450 km /10/, and it proved to be very successful, but the strips were very short (less than 2 minutes flight time). Another project with a distance of about 150 km between the reference receiver and the moving

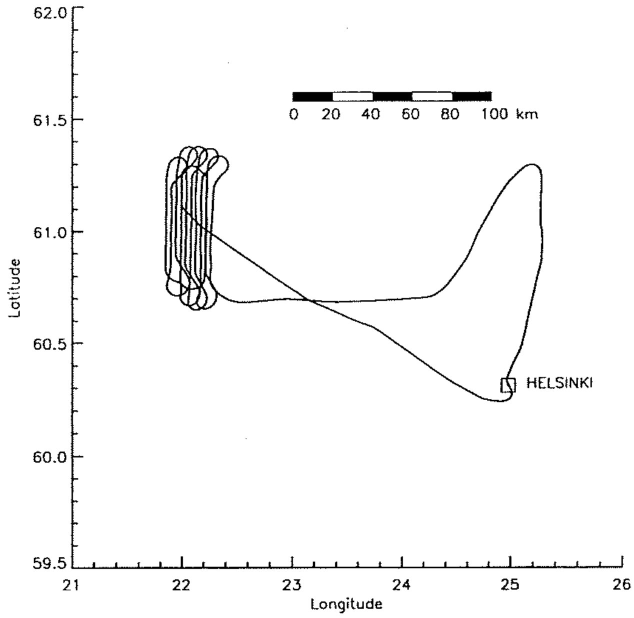


Figure 1. Flight path Eura.

receiver, with quite long strips (up to 16 minutes flight time) also showed good results /10/. Single frequency receivers were used in both projects.

It was well known before take-off that a bad observation window could not be avoided during the flight, and it resulted in poor geometry for a part of the trajectory. The GPS receivers kept track on 4-8 satellites throughout the flight.

The receivers were connected to portable PC's for external datalogging due to the huge amount of data. The data logging program did not work properly resulting in quite a lot of error blocks, which can be seen as missing epochs in the data. On the reference receiver as much as 12% of the epochs are missing compared to 4% on the airborne receiver. A few flight strips were also affected. As a result some of the GPS aircraft antenna positions had to be interpolated over a longer time interval (1.0 - 3.5 seconds).

The receivers each collected more than 18 Mbytes of data. The portable computers had a hard disk storage capacity of only 20 Mbytes which turned out to be rather critical. The reference receiver managed to store all observations on the hard disk, but the moving receiver's hard disk became full and the last part of the data had to be stored in the receiver's memory. About one minute after the return to the airport the memory also became full. The initial phase ambiguities for backward computation are therefore quite questionable (see below).

The data contained a lot of cycle slips. The GPPS program could not recover all of them, which meant that the data had to be processed forward in time as well as backward in time. Quite a number of observations had to be rejected and it was necessary to set the elevation cut-off angle to 0. The processing of the data was really a time consuming part of the project. The most critical point was one flight turn. Finally only a short gap of about 20 seconds remained uncomputed.

The computation of the positions of the GPS aircraft antenna at exposure time was based on linear interpolation. However a few antenna positions were computed using polynomial interpolation (see /12/) based on a preliminary check of the GPS coordinates.

5. ANALYSIS OF THE BLOCK ADJUSTMENTS

The GPS data was not of the best quality as a result of all the cycle slips and the missing epochs. On the base of this it was necessary to look closely at the GPS coordinates. The method used was to examine the speed of the aircraft computed from the GPS coordinates. In addition to a certain zigzag behaviour of the GPS antenna positions a few jumps (shifts) of up to 10-15 cm were found in the position inside part of the strips (maximum one per strip). The strip is considered to be the smallest unit in practice when thinking about drift parameters. The data in the Eura case may suggest that a few of the strips should have been split up in two parts with separate drift parameters. This was not done, because the geometry of the block will weaken with more additional parameters in the block adjustment and the jumps are not considered to be crucial in this project.

The control point configuration of the block is shown in Fig. 2. All the targeted points used in the final block adjustment (with full control) and the water surface points (used for vertical control, accuracy ±10 cm) are shown. In addition quite a large number of additional points of poorer accuracy (±50 cm) were measured and used to support the vertical control in the block adjustment with full control.

Stripwise drift parameters are chosen in the cases with GPS support as a result of the poor quality of the data. The à priori accuracy of the photogrammetric image coordinates is set to $\sigma_{obs} = \pm 5$ µm. The à priori accuracy of all the targeted ground control points is set to $\sigma_{GC} = \pm 5$ cm. The GPS coordinates of the aircraft antenna are given the moderate à priori accuracy of $\sigma_{GPS} = \pm 20$ cm. There were no separate check points established for this project. The check points referred to in the analysis are therefore identical with the targeted control points not used in the adjustment. The X coordinate is northing and the Y coordinate easting.

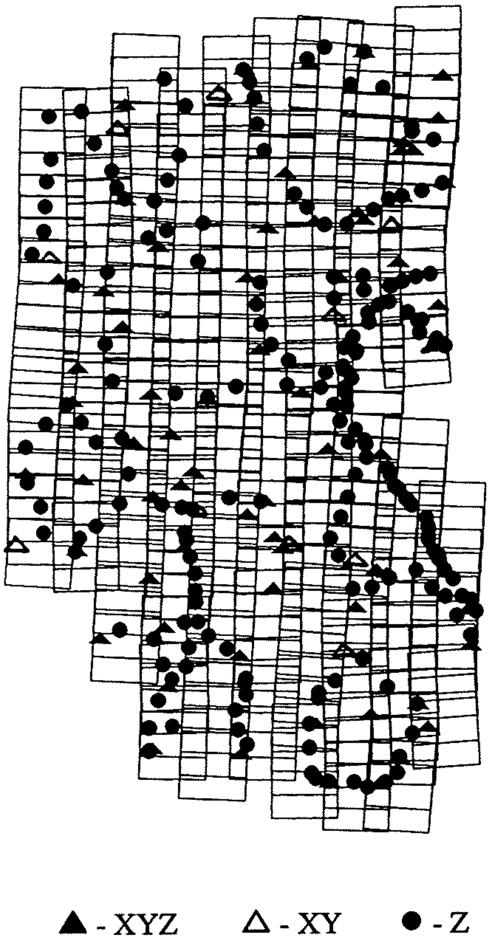
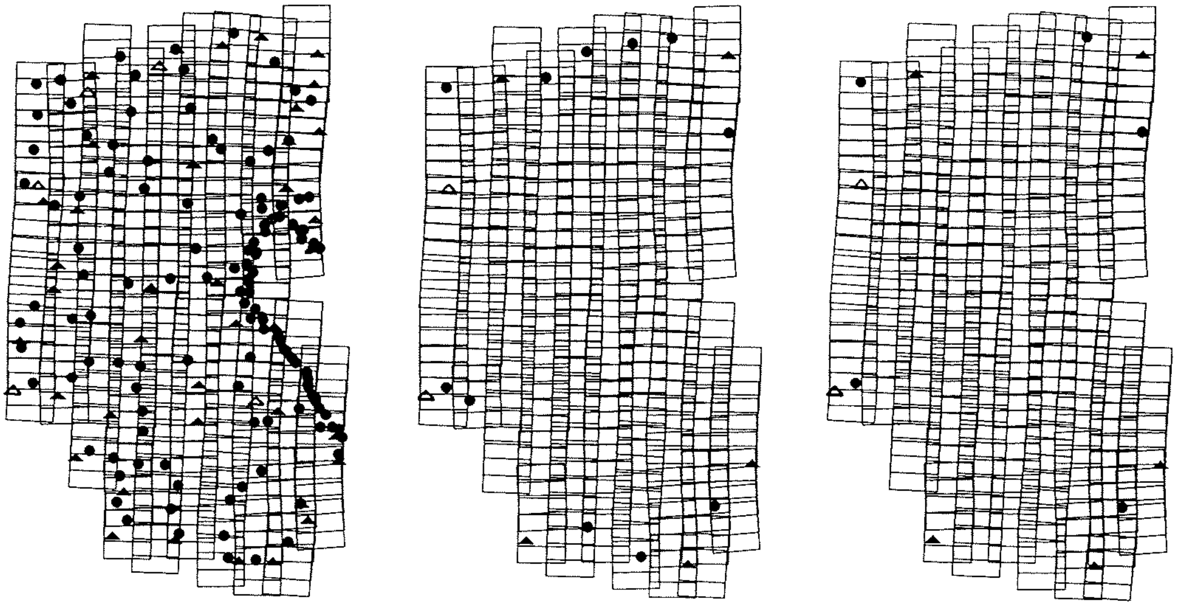


Figure 2. The ground control of the Eura block.

Three different ground control configurations were studied (see block sketches in Fig.3) in addition to the case with full ground control. Practically all geodetic points of some importance were targeted for the flight (including supplementary points measured using GPS), which is the routine normally used by NBS. In this way NBS wants to ensure that the blocks have sufficient ground control. Fig. 2 shows that the control point net is rather dense. According to theory, a more sparse control point coverage would be sufficient. Alternative I in Fig. 3 represents the block with more than 90 targeted ground control points less than in Fig. 2. It is expected to be more than enough for a conventional bundle block adjustment.

The ground control in alternative II (see Fig. 3) is assumed to be sufficient for GPS-supported block adjustment. Two chains of vertical control points, running across the block at either end, have been added in addition to the classical XYZ control points at the corners of the block. This is necessary because no cross strips were flown (e.g. /1/). In alternative III the ground control is further reduced compared to case II.

The results of the bundle block adjustments are presented in Table 1. The theoretical accuracy of the photogrammetric new points after adjustment is derived from standard deviations estimated in the block adjustment. The empirical accuracy is computed from the differences of the adjusted coordinates and the given coordinates of the check points.



I II III

Figure 3. Different ground control configurations used in the adjustment.

The results of block adjustment using ground control configuration I show that the ground control is sufficient for computation in the conventional way without any GPS support. The empirical accuracy of the check point coordinates is close to the theoretical accuracy. The combined block adjustment with GPS support looks slightly better, but the difference is not significant.

Alternative II and combined block adjustment with GPS is slightly poorer than alternative I both in empirical and theoretical accuracy. This is somewhat expected because the introduction of additional drift parameters into the adjustment weakens the geometry of the block. The Eura block case with two chains of vertical control points, running across the block at either end, is considered to be poorer in accuracy than a case with two cross-strips /1/. What is important is that the empirical accuracy of the check points corresponds well to the theoretical accuracy. The results are satisfactory when looking at the requirements and considering the rather poor quality of the GPS data. NBS expects the accuracy of the coordinates (X and Y) of the targeted boundary marks to be ±20 cm or better. The conventional block adjustment is clearly poorer than the combined block adjustment, but it is surprisingly good in X and Y.

Alternative III is not supposed to contain enough ground control for the combined block adjustment with GPS when using strip wise drift parameters. Table 1 though shows that the results are at least as good as in case II. One possible reason could be that instead of separate drift parameters for each strip, common drift parameters for 2 or 3 strips exist. The drift parameters presented in Table 2 though, do not indicate any common drift parameters for 2 or more strips. There seems to be no clear explanation for the good performance of ground control configuration III.

Table 1. Results of bundle block adjustment.

STD - conventional bundle block adjustment
GPS - combined bundle block adjustment with GPS
X - northing
Y - easting

Ground cont.	Block . adjustm method	No. of check pts.		Empirical accuracy of adjusted check point coord. R.m.s. [m]			Theoretical accuracy of the photogr. new points after adjustment [m]		
		XY	Z	X	Y	Z	X	Y	Z
All	STD	-	-	-	-	-	±0.085	±0.097	±0.253
	GPS			-	-	-	±0.080	±0.094	±0.242
I	STD	33	88	±0.122	±0.111	±0.305	±0.088	±0.100	±0.265
	GPS			±0.112	±0.108	±0.265	±0.083	±0.096	±0.249
II	STD	71	191	±0.280	±0.161	±0.730	±0.182	±0.192	±0.737
	GPS			±0.180	±0.132	±0.355	±0.134	±0.149	±0.348
III	STD	71	197	±0.288	±0.161	±0.939	±0.184	±0.193	±0.843
	GPS			±0.180	±0.132	±0.331	±0.135	±0.149	±0.441

Table 2. Drift parameters after combined block adjustment.

Strip	No. of photos	Drift parameters		
		X	Y	Z
1	20	0.913m - 0.00324m/s	-1.100m + 0.00527m/s	7.268m - 0.00110m/s
2	20	0.221m + 0.00227m/s	-1.669m + 0.00247m/s	6.865m + 0.00446m/s
3	26	-0.789m + 0.00149m/s	-1.093m + 0.00263m/s	6.215m + 0.00064m/s
4	29	-2.442m + 0.00057m/s	-2.262m + 0.00267m/s	7.160m + 0.00291m/s
5	31	-1.813m - 0.00104m/s	-2.594m + 0.00153m/s	8.093m - 0.00260m/s
6	31	0.287m - 0.00087m/s	-1.428m + 0.00165m/s	4.567m - 0.00159m/s
7	33	0.258m - 0.00266m/s	-0.135m - 0.00123m/s	2.166m - 0.00249m/s
8	33	0.924m + 0.00221m/s	-4.977m + 0.00032m/s	3.802m + 0.00462m/s
9	31	1.186m + 0.00014m/s	-0.525m + 0.00107m/s	7.481m - 0.00163m/s
10	10	0.578m - 0.00662m/s	-3.065m - 0.01435m/s	0.494m + 0.00386m/s

6. CONCLUSIONS

The Eura flight is a typical example of an average block for the Finnish base map production. The block is of average size (or slightly smaller) and the distance between the airport and the flight mission area is rather typical (160-200 km). The reference receiver should be kept at the airport, because of the uncertainty of which area to photograph before take-off. During longer flights up to 5 hours, the weather can change dramatically, and parts of two or more areas may be photographed during the same flight.

The Eura block shows the potential for GPS-supported aerotriangulation in Finland. The rather poor quality of the GPS data (a lot of cycle slips) together with difficult processing of the data did not affect the result too badly. The linear drift parameter model used (stripwise drift parameters) in the block adjustment is clearly capable of handling long distances between the reference receiver and the moving receiver. The accuracy requirements are fulfilled with one XYZ ground control point in each corner of the block plus two chains of vertical control points at either end. Whether to fly cross strips or not is a matter of cost and benefit. The cross strips increase the cost of the photo flight mission and the additional photos cause more photogrammetric measurements. On the other hand, with no cross strips additional vertical control points have to be targeted. Both methods may be used in the future.

The need for ground control will be drastically reduced with GPS-supported aerotriangulation. 10% of the normal amount of ground control points is certainly enough, and still this includes a safety margin. The blocks for the Finnish base map production normally contain more targeted ground control points than are needed for the conventional block adjustment. Even compared to a reduced targeting plan the number of control points needed for a combined block adjustment with GPS is dramatically smaller. The extra expenses with the new technique are considered to be smaller than the savings in the targeting work.

Many problems experienced with the Eura block no longer exist. The NAVSTAR Global Positioning System is close to being fully operational which means that problems with poor observation windows will almost disappear. The equipment is getting better and better and the GPS data processing programs are developing all the time. The introduction of fast ambiguity fixing techniques ("On-The-Fly") has increased the reliability, because only serious signal interruptions within a strip are critical. The technique of GPS-supported aerotriangulation has still a bit of development to go through before it can be said to be a streamlined process. Considered as a fully developed technique, GPS-supported aerotriangulation should be well suited for mapping in scale 1:5000 and smaller in Finland if the block is of some size.

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