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GPS TEST FLIGHT FLEVOLAND

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1.Introduction

The terrestrial surveys, necessary to establish ground control for photogrammetric mapping projects is rather time-consuming and are an important factor in the costs of the mapping process. A reduction of ground control is possible when camera positions are measured during the flight. Differential GPS techniques offer a powerfull tool to obtain this information with a very high accuracy.

In june 1987 the Survey Department of Rijkswaterstaat initiated and executed a research project in cooperation with KLM-Aerocarto,the University of Stuttgart and Delft Technical University, aimed at two aspects:

1. to establish the attainable accuracy of camera positions measured during the flight with differential GPS techniques.
2. to establish the attainable reduction of ground control by introducing GPS camera positions in a photogrammetric block adjustment.

Up to now the presented results /6/ were mainly focussed on the first aspect. In this paper first the set-up of the project and its realisation will be discussed and the results obtained concerning the first aspect summarised. Then the attanaible reduction of ground control for the mapping practice at the Survey Department and its consequences will be analysed based on simulation studies and the real data from the testflight.

2. Test Set-up

The set-up of the project can best be described with the help of figure 2.1. An airplane from KLM-Aerocarto was adapted to accomodate a GPS receiver and some peripheral equipment. A second GPS receiver was placed at a known reference point to be used as the differential receiver. Photographs are taken from a specially created testfield, containing numerous accurately surveyed ground control points and signalised tie-points and covering an area of 4*4 kilometres.

With this set-up, differentially corrected GPS positions of the projection centres can be computed and their accuracy can be analysed by comparing them with the results from a photogrammetric blockadjustment (reasearch aspect 1). Furthermore, the GPS projection centres can be integrated in a photogrammetric adjustment program with a minimum amount of ground control points using the other control points as reference points to assess the accuracy of the integrated approach (research aspect 2).

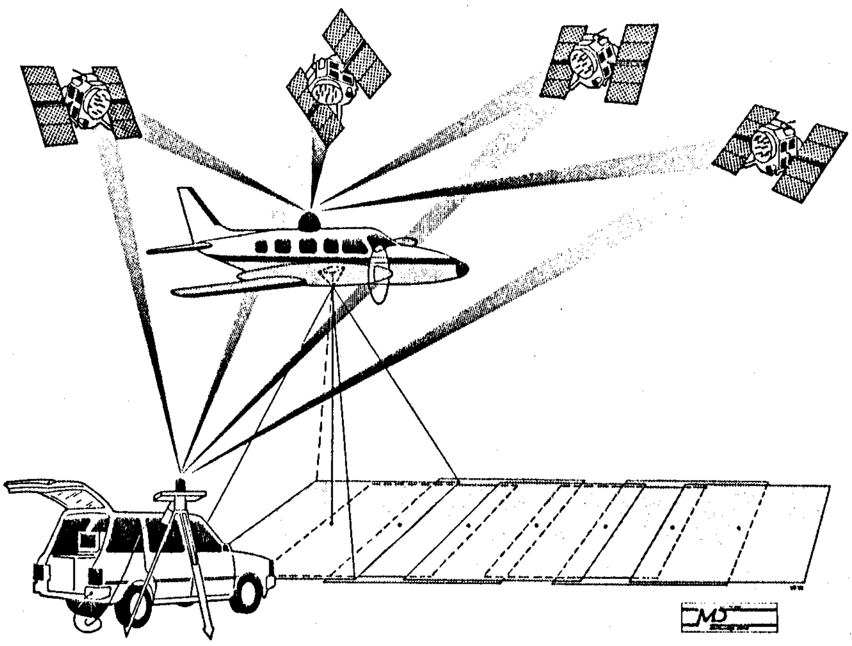

figure 2.1: the Set-up of the "Flevoland" test

2.1 the systemconfiguration in the airplane

In the airplane a Sercel TR5S GPS receiver has been used. This five channel parallel receiver is capable of continuously tracking the signals from up to 5 satellites. It uses a C/A code generator to perform pseudorange and phase measurements on the L1 frequency (1575.42 Mhz). The receiver design permits a measurement rate of 0.6 seconds and simultaneous output of raw data and computed positions on two different RS232 ports at a 0.6 seconds rate. With respect to the precision of the observations, the manufacturer claims a standard deviation of 4 metres for the pseudorange and 3 millimetres for the phase observations (1 sigma), values that have been validated during previous tests. The receiver is operated through a keyboard and video monitor with menu driven software.
In order to minimize the weight and to meet the aeronautical regulations, a portable Grid computer was installed for recording the raw GPS data.
The GPS-antenna was mounted only a few centimetres eccentric to the camera at the top of the airplane. Its position relative to the photo-system has been accurately measured before the flight.

A Wild RC-10 camera has been used for the test. For computing the projection centre coordinates from the GPS observations, the exact time of exposure of each photograph has to be determined and related to the GPS observations. So some hardware connection between the camera and the GPS receiver had to be realised. The first problem however was the determination of the exact time of exposure of a photograph. The pulse that can be generated with the Wild RC-10 camera proved to be too inaccurate for this purpose, fluctuations in the definition of the time of exposure at the 10-100 millisecond level were found. With a ground speed of 100m/s this would cause errors of 1-10 metres. To overcome this problem, a special photosensor has been installed in the lens cone i.e. between the lens and the focal plane. The sensor generates a pulse at the exact time-instant at which the shutter reaches its maximum aperture. With a pulse length of only 0.2 milliseconds, an accuracy of a few tenth of a millisecond was achieved. To relate this time-instant to the GPS observations the pulse is then sent to the GPS receiver and timed in the receiver timeframe, thus in the same timeframe as the raw GPS observations. This accuracy proved to be better than 0.5 milliseconds. Receiving an external pulse, the receiver sends a special raw data message containing the receiver time of the pulse, which is stored on the logging computer together with the raw GPS observations.

Since the GPS receiver performs measurements with a rate of 0.6 seconds the position of the projection centres had to be interpolated based on the previous and subsequent GPS positions and the known time-instant of the exposure. (figure 2.2)

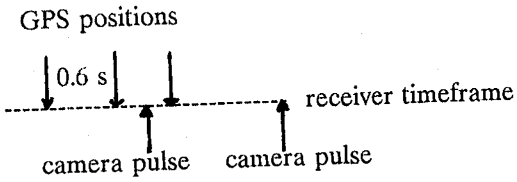

figure 2.2: receiver timeframe with raw GPS data and camera pulse

The camera has been strapped-down during the test in order to avoid a change in the antenna position relative to the camera and thus keeping the excentricity vector between the antenna and the camera constant during the complete flight. This is important when trying to solve for the excentricity as an unknown in the photogrammetric adjustment, it is however a practical limitation.

2.2 the differential receiver.

For the differential station a Sercel Nr52 receiver has been installed on one of the ground control points in the testfield. This receiver is basically the same as the TR5S but has no built in software to compute a realtime position fix and is operated through a portable PC.

2.3 the testfield.

For the project, a special testfield has been created covering an area of approximately 4*4 kilometres. The testfield is situated in Flevoland, a large polder in the center of the country, in open and flat terrain. A total number of 80 ground control points were painted on the roads in a regular grid with mutual distances of approximately 400 metres as shown in figure 2.3. All 80 points were surveyed with conventional geodetic methods (tachymetry and levelling). The northern part of the testfield containing 50 points has been surveyed with GPS too. As shown in /6/ the overall internal precision of these control points proved to be 2-3 centimetres (1 sigma). All coordinates have been computed relative to one basepoint, the same as the reference point for the differential receiver during the flight and are transformed from WGS ` 84 to the Dutch national datum (RD) and to heights above the Bessel ellipsoid.

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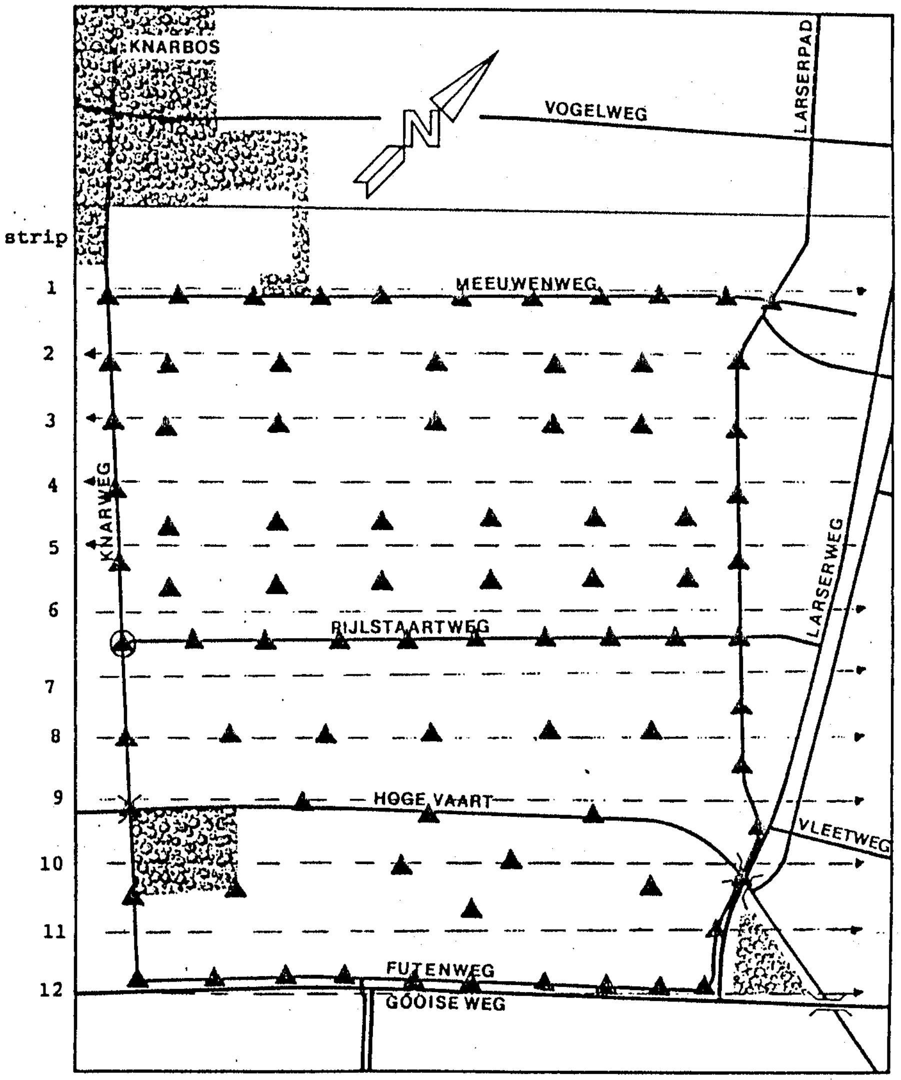


figure 2.3: the testfield "Flevoland" with the 16 flight lines

3. Realisation of the testflight.

Two testflights were performed on june 10th and 12th 1987. Both flights were interrupted prematurely due to lowering clouds and turbulence. The flights resulted in 16 parallel strips with 360 photographs with a forward lap of 70% and a sidelap of 50%. The mean flight altitude was 770 metres which resulted with the focal length of 213.67 millimetres in a photoscale of approximately 1:3700. The strips were flown in two alternating directions (SE-NW) and (NE-SW) to be able to trace possible systematic effects in the results (e.g. timing errors). Figure 3 shows the satellite visibility plot for june 11th. Both flights were performed between 1300 and 1400 UTC and the satellites Prn 6,8,9,11 and 12 were tracked. Satellite tracking started before take-off with a 10 minutes receiver calibration. The satellite configuration provided a good geometry with GDOP values well below 5. During the flight the raw GPS-data (C/A-code and carrier phase) are recorded simultaneously in the airplane and at the differential station every 0.6 seconds. A real time solution from the airborne receiver is used for on-line quality control.

```
Station: Lelystad    Date: 11 6 1987    Min. Elevation (deg): 5
Phi (deg): 52.5      Lambda (deg): 5.3      Height (m): 0.0

      13        --------       -----------
      12    ----           -------------
s     11     -------         --------
v      9  -----         --------------
       8  ---------        -------
       6 ----        -------------                --
       3          ------         ------------
        --------------------------------------------
         0 2 4 6 8 10 12 14 16 18 20 22 24
                         time of day
```

figure 3: satellite visibility plot for june 11th 1987.

4. GPS data processing.

From the accuracy requirements for large scale photogrammetry it is obvious that the computations should be based on the use of the carrier-phase observables. However, when using this observable, the problem of the cycle ambiguities has to be solved for. At the Survey Department a GPS processing package has been developped which computes an estimate for the initial cycle ambiguities by averaging the measured pseudoranges and the integrated phase observables over a certain period of time /6,4/. This approach is based on the assumption that at each epoch i the difference between the pseudorange measurement P(i) and the integrated phase observable D(i) is a constant but arbitrary value A. As soon as this value is computed from n measurements P(i) and D(i) at n different epochs, a smoothed pseudorange $\underline{P(i)}$ can be computed for all subsequent epochs from:

$$\underline{P(i)} = A + D(i)$$

The precision of this smoothed pseudorange is determined by the precision of the phase observable D(i) (mm-level) and the estimate for A. Position fixes for the stationary and the moving antenna have been computed with an interval of 0.6 seconds from smoothed pseudoranges. Subsequently the differential corrections obtained from the difference between the known position of the stationary point and the computed solutions have been applied to correct the airplane positions.

4.1. the accuracy of the GPS projection centres.

The accuracy of the interpolated GPS projection centre coordinates has been assessed by comparing them with the results from a photogrammetric adjustment. This adjustment, performed at the University of Stuttgart, incorporated 7 strips (strip 1-7) flown on two different days and covering the northern part of the testfield. The results reported in /6/ indicated a relative coordinate precision for all strips at the 5 cm level. The results also

showed a remaining systematic effect in the GPS positions, resulting in a drift with a maximum magnitude of 0.5 mm/ second and an offset in the vertical component up to 1.4 metres. It was concluded that both drift and offset were probably caused by the GPS processing approach and could be handled either by trying to refine the GPS solution and the measuring procedure or by extending the mathematical model in the photogrammetric adjustment. The overall accuracy however is assumed to be sufficient to cope with small and large scale mapping applications.
In the next paragraph the validity of this assumption for the daily mapping practice at the Survey Department will be studied in some more detail.

5. Combined Adjustment

For the mapping division of the Survey Department, the most interesting research aspect is, of course, the attainable ground control point reduction when introducing the GPS positions in the photogrammetric block adjustment program. This section of the paper will deal with this aspect and will indicate the optimal control point distribution for our mapping activities. The effect of some disturbing factors on the results is shown and options to correct for them are discussed. The analysis is divided in a simulation part and a part in which the real data from the testflight have been used to check the validity of the conclusions from the simulations studies. All computations are performed with the Bingo bundle adjustment program. Since the final aim is to analyse the cost benefits of the combined GPS/Photogrammetric adjustment, the conventional ground control point distribution has been used as a reference.

5.1 Simulation studies

For the simulation studies two configurations have been generated:

- a block consisting of 6 strips with 12 models per strip
- a single strip with 12 models.

The terrain is assumed flat, there are 9 regularly distributed points in each photograph, the flight height is constant and the photographs are vertical. The photoscale is 1:4000, the principal distance 15 cm. and the forwardlap and sidelap 60% and 20% respectively. A simple stochastical model without correlation has been used with the following standard deviations:

-ground control points : Sigma(Xcp) = Sigma(Ycp) = Sigma(Zcp) =2cm.
-photo coordinates : Sigma(x) = Sigma(y) = 5um.
-GPS projection centres: Sigma(X) = Sigma(Y) = Sigma(Z) =5cm.

Simulations have been performed to analyse:

1.the precision of the terrain coordinates for a conventional adjustment (the reference situation)
2.the minimum number of control points and their distribution for a combined adjustment (constraint: no degradation in precision)
3.the effect of disturbing factors in GPS and Photogrammetry on the terrain coordinates for the integrated adjustment.

At the Survey Department most photogrammetric mapping is performed at 1:4000 scales. The precision of the terrain points should be at least 5 cm (1 sigma) or better in all three coordinates. To cope with these rather high demands, ground control points (x,y and z) are placed around the perimeter of the block and height control at regular intervals within the block (figure 5.1. configuration B1). For the photogrammetric mapping of the highways single strips are flown with a control point distribution as shown in figure 5.1. configuration S1.
As a first step in the simulation study, the precision of the terraincoordinates has been computed for the conventional ground control point distribution, meaning 20 full and 15 height control points for the block and 7 full and 3 height control points for the strip. The results for the block- (B1) and strip configuration (S1) are shown in table 5.2. Listed are the mean and maximum values for the standard deviations. The results are even slightly better than the practical requirements.
Adding GPS projection centre coordinates to this configuration only slightly improves the results (B1* and S1*) as shown in table 5.2.
To determine the minimum amount of necessary ground control, three other block- and strip configurations have been analysed. The configurations are shown in figure 5.1. and the results are listed in table 5.2.
The results clearly show that 4 full control points in the corners of the block combined with GPS projection centre coordinates (B4*) gives a precision comparable with the conventional configuration with 35 control points (B1).
A strip configuration with only 4 full control points in the corners (S4*) results in relatively large standarddeviations for the Y coordinates of the terrainpoints (the component perpendicular to the flight direction). Adding one full control point in the centre of the strip reduces this effect to an acceptable value (S3*).
The results demonstrate the attainable reduction of ground control in an ideal, errorfree, situation for mapping applications at the Survey Department.

5.1.1. Disturbing effects

In practice there are a number of phenomena which can cause errors in the terraincoordinates obtained from photogrammetry. Introducing GPS observations in the photogrammetric adjustment adds at least two :
-systematic errors in the GPS positions (offset and drift)
-the excentricity between the antenna and camera position.
As indicated in /13/, moving the control from the ground level to the flight level requires a reconsideration of the propagation of errors and the influences of biases on the coordinates of the terrain points. This is especially true for biases in the inner orientation elements, whose effect is rather small in the conventional configuration but very dominant in the case with GPS flight control.
Simulation studies have been performed to investigate the effect of the above mentioned errors on the terraincoordinates, the possibilities to correct for those errors with the options available in the Bingo software package and the consequences of these correction methods for the precision of the terrain coordinates. The block configuration B4* and the strip configuration S3* are used in the simulations.

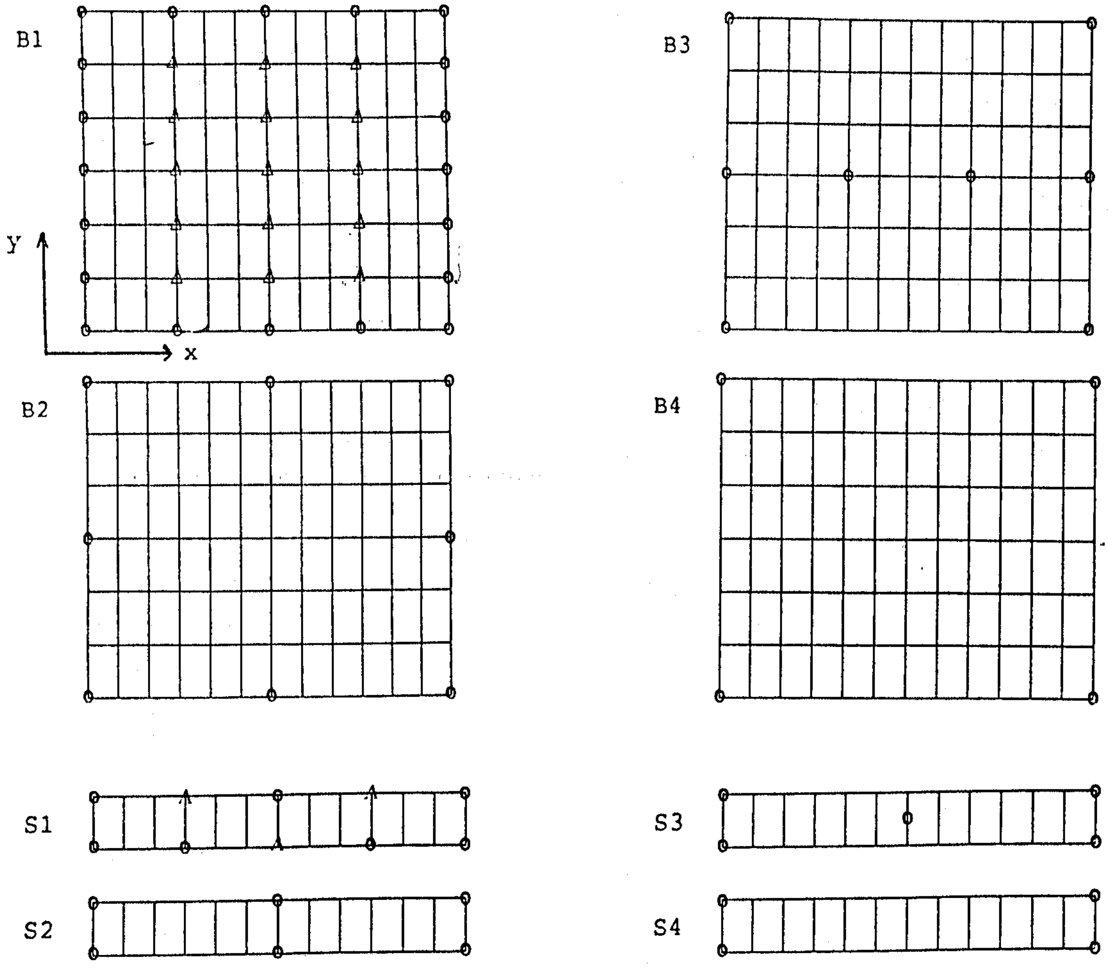


figure 5.3: the block- and strip configurations used in the simulations

configuration	standard deviation of the terrain coordinates (cm)					
	mean			maxima		
	S(X)	S(Y)	S(Z)	S(X)	S(Y)	S(Z)
B1	1.8	2.0	3.4	2.7	3.6	6.0
B1*	1.6	1.6	2.7	2.6	3.1	5.5
B2*	1.8	1.9	3.1	2.8	3.5	5.7
B3*	1.9	2.0	3.2	2.8	3.9	5.7
B4*	2.0	2.1	3.3	3.2	3.9	5.7
B4	10.1	10.6	>200	26.1	27.4	>300
S1	2.6	3.2	4.6	3.3	4.5	6.5
S1*	2.1	2.6	3.6	2.7	3.6	5.6
S2*	2.2	2.9	4.0	2.8	4.1	5.6
S3*	2.4	3.4	4.2	2.8	4.4	5.7
S4*	2.7	4.2	4.7	3.3	6.4	5.7
S4	24.5	50.0	>300	>50	>50	>500

table 5.4 : standard deviations of the terrain coordinates for the different block- and strip configurations

-Systematic effects in the GPS positions and camera/antenna excentricity.

The remaining drift in the GPS positions is timedependent. The maximum value obtained for the testflight Flevoland is of the order of 0.5mm /second. With the Bingo software package it is not possible to solve for this drift. However the camera/antenna excentricity and the systematic offset in the vertical component can be introduced in the adjustment as a combined excentricity vector. Simulations with an apriori standarddeviation of 500cm. for the excentricity vector showed that the components of this vector can be determined in the B4* blockconfiguration with a precision better than 4 centimetres and 7 centimetres in the S3* strip configuration. However the precision of the terraincoordinates decreases when estimating this vector (table 5.3).

configuration	excentricity			terraincoordinates		
	S(x)	S(y)	S(z)	S(X)	S(Y)	S(Z) (cm.)
B4*	3.5	3.9	4.0	4.0	4.3	5.6
S3*	2.5	6.8	2.8	2.9	3.8	5.6

table 5.3 : the precision of the excentricity vector and the terrain coordinates (cm) when solving for the combined camera/antenna and GPS position offset.

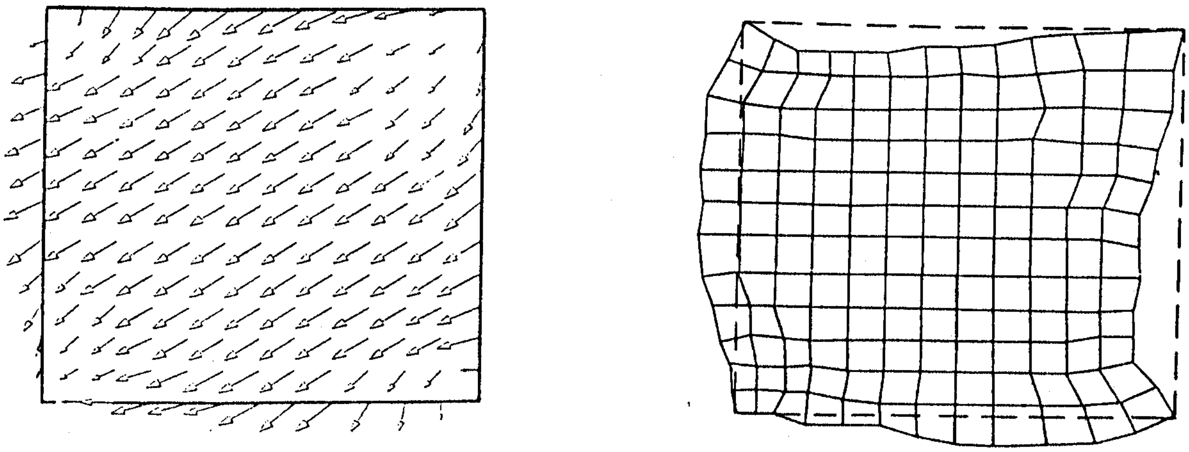
- Biases in the inner orientation elements.

To investigate the effect of biases in the inner orientation elements for the block- and strip configuration (B4* and S3*), biases are introduced in the position of the principal point (dxh,dyh) and the principal distance (dc). In figure 5.4. the introduced errors and the resulting planimetric blockdeformation is shown. Errors of 20 um in the position of the principal point can result in maximum errors of 11 cm for terrainpoints when all strips are flown parallel and in the same direction (fig. 5.4.a). The same 20 um position error causes however errors in the terrain points up to 25 cm when the strips are flown parallel,but in alternating directions as the previous one. In the height component even maximum errors up to 70 centimetres occur (figure 5.4b).

The results for the strip configuration S3* are shown in figure 5.4c. Errors of 20 um in the principal point position cause terraindeformations up to 6 cm in planimetry and 7 cm in the vertical component. Errors in the principal distance have only a minor influence on the planimetry but result in errors for the vertical components as large as dc * scale (with dc the error in the principal distance).

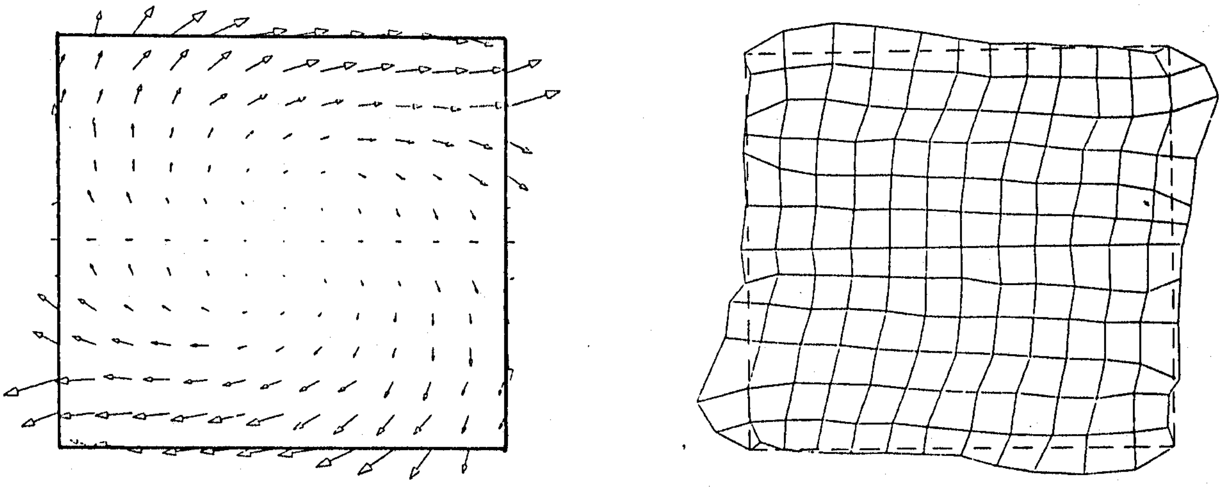
It is obvious that the errors in the inner orientation elements have a large impact on the resulting terraincoordinates. The errors can be eliminated by applying a selfcalibration. For the B4* and S3* configuration the inner orientation elements can be determined with a precision of respectively 8,7,8 and 6,5,15 um. for Sigma(c),Sigma(xh) and Sigma(yh). The impact on the precision of the terraincoordinates is neglictable.

The results obtained clearly demonstrate the neccessity to use a proper calibrated camera and/or to apply selfcalibration methods when GPS camera positions are introduced in the photogrammetric adjustment.



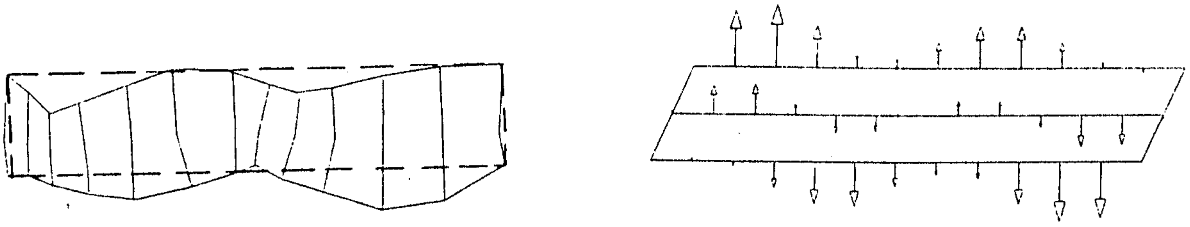
error(mm)	effect on terrain coordinates (cm)					
	mean			maximum		
dx,dy	dX	dY	dZ	dX	dY	dZ
0.02	7.2	7.1	1.4	10	11	5.5

figure 5.4a: the planimetric blockdeformation due to errors in the position of the principal point (blockconfiguration B4*),parallel flight lines same direction.



error(mm)	effect on terrain coordinates (cm)					
	mean			maximum		
dx,dy	dX	dY	dZ	dX	dY	dZ
0.02	2.7	2.9	8.1	24	18	70

figure 5.6 : the planimetric blockdeformation due to errors in the position of the principal point (configuration B4*),parallel flight lines, alternating direction.



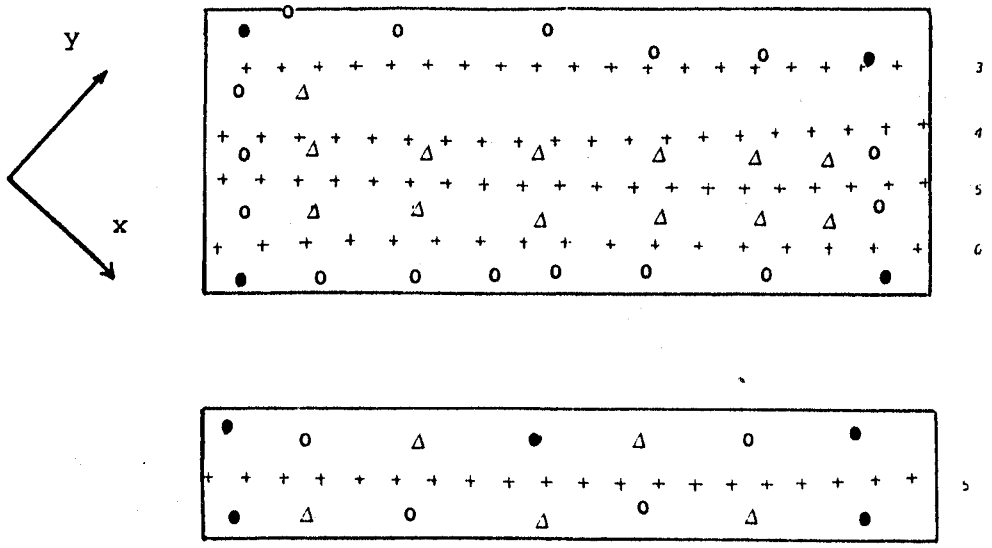
error(mm)	effect on terrain coordinates (cm)					
	mean			maximum		
dx,dy	dX	dY	dZ	dX	dY	dZ
0.02	3.8	2.0	2.7	6.0	5.0	7.6

figure 5.4c : the planimetric and vertical stripdeformation due to errors in the position of the principal point (configuration S3*).

5.2. Results obtained with the "Flevoland" data

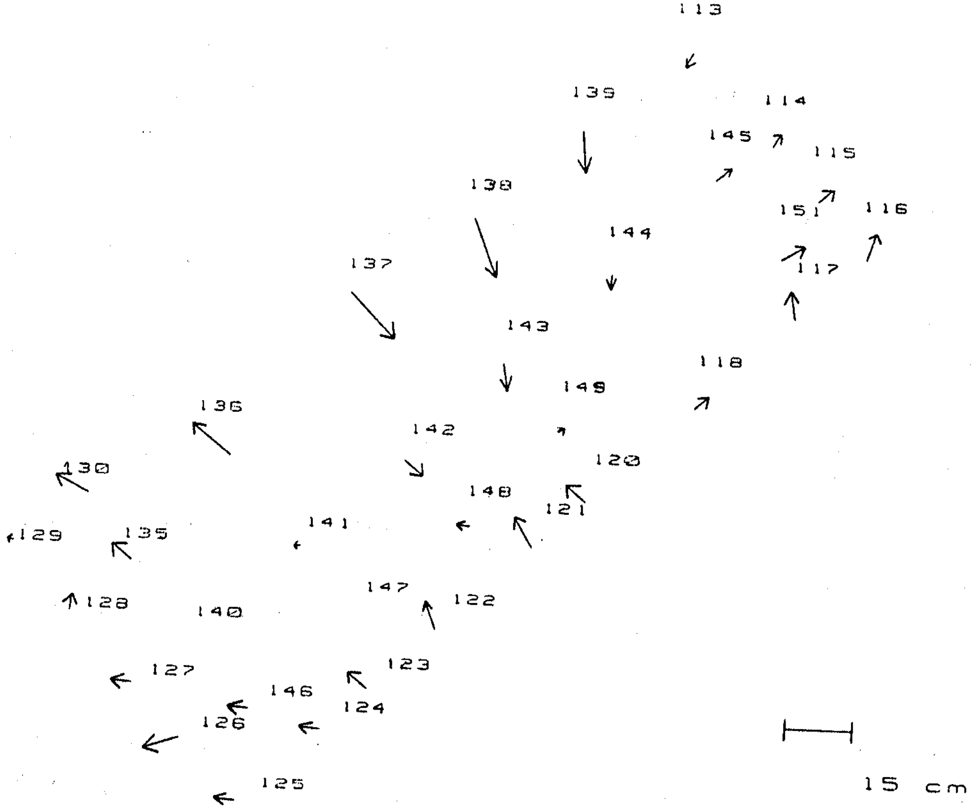
The simulations have indicated the amount of reduction in ground control feasible for the mapping practice at the Survey Department and the important error sources which need to be kept an eye upon.
The data from the testflight "Flevoland" has been used to verify the results from the simulations and to prove the feasibility of the concept in practice.
For the computations with the actual data the blocksize was limited to a maximum of 4 strips, caused by some limitations in the version of the Bingo package available. The strips 3,4,5 and 6 are used for the block computations and strip 5 for the single strip computations.
The distribution of the ground control points in the block- and strip is shown in figure 5.5.
For the combined adjustment a configuration comparable with B4* and S3* in the simulations have been used, with ground control as indicated in figure 5.5. The control points that are not used in this adjustment are used as checkpoints to validate the accuracy of the results. The block contained 29 checkpoints, the strip 11.
For the combined adjustment of the block the offset and the drift of the GPS projection centre coordinates have been removed before the adjustment. The corrections have been computed from the differences between the p.c.-coordinates obtained from the GPS observations and the results from a standard bundle adjustment with all available ground control points.

To evaluate the accuracy of the results obtained with the combined adjustment, the resulting terrain coordinates of the checkpoints are compared with the known coordinates. Figure 5.8 shows a vectorplot of the differences. The largest difference is 14 centimetres. The overall standard deviation,computed for the differences is less than 5 centimetres in all coordinates (figure 5.8).
These results prove the feasibility to minimize the ground control to 4 full control points in the block corners for mapping practice at the Survey Department when GPS drift can be eliminated. The conventional approach would require at least 25 ground control points.



o : full control points
● : full control points used in the combined adjustment
Δ : height control points

figure 5.5: the block- and strip configuration formed with the Flevoland data



mean coordinate differences and standarddeviations in cm.

dX	SdX	dY	SdY	dZ	SdZ
0.7	4.7	-0.4	4.6	1.5	4.2

figure 5.8 : coordinate differences between the known terrestrial coordinates and the results obtained from a combined block adjustment with Flevoland data (strips 3,4,5,6).

The results for a strip are shown in table 5.9. These results also confirm the results from the simulation studies. Here too a drastic reduction of ground control is possible when introducing drift corrected GPS projection centre coordinates.

The excentricity vector determined in the combined strip adjustment differt less than 4 centimetres from the actual value.

mean coordinate differences and standarddeviations in cm.

dX	SdX	dY	SdY	dZ	SdZ
1.0	3.1	-1.5	2.8	3.1	5.1

table 5.9 : coordinate differences between the known terrestrial coordinates and the results obtained from a combined strip adjustment with Flevoland data (strips 5).

6. Conclusions

The presented results demonstrate that drastical minimisation of the amount of ground control points is possible when introducing drift corrected GPS camera positions in the photogrammetric bundle adjustment. For the photogrammetric mapping applications at the Survey Department a configuration with 5 full ground control points for a striplength of at 16-20 models proved feasible. For blockconfigurations with 4 strips and 16-20 models per strip only 4 full control points are necessary. The systematic camera/antenna excentricity can be estimated in combination with a systematic offset in the GPS positions at the cost of some loss in precision. Errors in the inner orientation elements,which cause large deformations in the terraincoordinates, can be corrected by selfcalibration. In order to obtain an operational system a further refinement of the bundle adjustment software to correct for linear drift in the GPS positions is necessary. Further research at the Survey Department is aimed at this aspect.

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Abstract

The paper presents the set-up, realisation and the results from a testflight performed to analyse the attainable reduction of ground control points when integrating GPS observation in the photogrammetric bundle adjustment. The optimal control point distribution for large scale mapping applications at the Survey Department is discussed. Highlighted are the consequences of the combined approach in respect to the propagation of systematic errors and the possibilities to correct for these errors in the Bingo bundle adjustment program. The computations performed with the data from the testproject "Flevoland" prove the feasibility and present limitations of the concept for the mapping practice at the Survey Department.

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