COMBINED BLOCK ADJUSTMENT FOR EVALUATING A GPS/INERTIAL SYSTEM IN A LARGE-SCALE PHOTOGRAMMETRIC PRODUCTION ENVIRONMENT

Remko J. WICHERSON*, Mark R.F. HEINE**, Frank A. VAN DEN HEUVEL**, Pieter W. BRESTERS*
*Survey Department, Rijkswaterstaat, The Netherlands
R.J.Wicherson@mdi.rws.minvenw.nl
P.W.Bresters@mdi.rws.minvenw.nl
**Delft University of Technology
Department of Geodesy
F.A.vandenheuvel@geo.tudelft.nl

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ABSTRACT

The Survey Department (SD), part of Rijkswaterstaat, produces among others highly accurate digital topographical databases of highways and rivers of The Netherlands. At the moment, following aerotriangulation, the aerial photos are georeferenced using signalised ground control points (GCPs). Laying, maintaining, measuring and guarding these markers is time-consuming and expensive. Therefore the SD is looking for methods to reduce the number of GCPs. Such a reduction can be achieved by using an integrated GPS/Inertial system on board of an aircraft. With such a system, the attitude and position of the camera on the aircraft can be established accurately. For a highly accurate and reliable product a low number of GCPs and an aerotriangulation are still necessary.
To answer the question how much GCPs are required and in what configuration, an experiment was set up. An area of 5x6 km was covered by overlapping images in a scale 1:4000, of which the GPS/Inertial system data were gathered with the Applanix POS/DG system. A redundant number of 108 artificial markers were used. The data was analysed with the BLUH-bundle block adjustment software.
The results of the test are promising: comparing projection centre parameters from a triangulation with GPS/INS data yields X, Y, Z differences of 1, 3 and 9 cm respectively and φ, ω, κ differences of 0,0014°, 0,0015° and 0,0039° respectively. A cost-benefit analyses shows that extra costs caused by the use of GPS/Inertial systems are more than compensated by the benefits.

1 INTRODUCTION

1.1 The Survey Department, Rijkswaterstaat

The Department of Public Works (Rijkswaterstaat) ensures that The Netherlands keeps its feet dry, sufficient clean drinking water is available and the country is safely accessible by land and water. In order to fulfil these duties, the Department of Public Works is divided into regional boards which carry out the core tasks on a regional level, and specialised departments to support the regional boards. The Survey Department (SD) is one of these specialised departments.
The duties of the Survey Department comprise:

- producing and supplying geo-information. For example, the SD produces digital topographical databases of highways and rivers and digital elevation models for road construction using photogrammetry and the current Dutch height database (AHN) using laser altimetry;
- acting as a broker in supplying other geo-information;
- providing advice about the use of geo-information;
- carrying out studies in the field of collecting and using geo-information.

1.2 Problem definition

At the moment aerial photos are georeferenced using signalised ground control points. Laying, maintaining and measuring these markers is time-consuming and expensive, reason why the Survey Department (SD) is looking for methods to reduce the number of markers.

Such a reduction can be achieved by using an integrated GPS/Inertial system on board of an aircraft, by which the camera attitude and position can be measured accurately. In principle this means that the directly measured exterior orientation is accurate enough to make the use of ground control points (GCPs) and aerial triangulation obsolete. For a highly accurate and reliable product a low number of GCPs and an triangulation are still necessary.
Gathering dGPS co-ordinates of the camera can already bring a significant reduction in the amount of GCPs (Haala et al., 1998). Because the SD mainly maps elongated objects like highways, the stability of the strip-wise configuration (figure 1) is poor and asks for attitude information of the camera. Inertial systems provide this information.

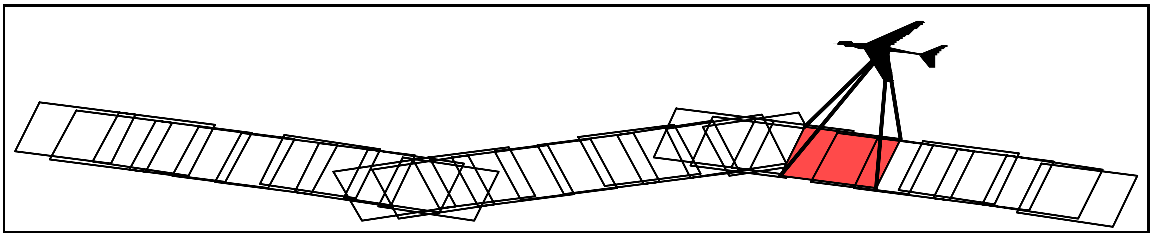

Figure 1: Strip-wise configuration

2 GPS/INERTIAL INTEGRATION

The Global Positioning System (GPS) is used in photogrammetry for determining the camera position for years already (Ackermann et al., 1993). Due to recent improvements of the Inertial Measurement Unit (IMU) direct determination of the full exterior orientation of the camera is feasible. After integration of both systems, the position and attitude data are even better (Cramer,1999).

2.1 GPS

The Global Positioning System (GPS) is a system that measures the position of mobile GPS receivers using the signals broadcasted by the GPS-satellites. If such a system is mounted on an aircraft, it delivers position data of the camera indirectly. Differential GPS (dGPS) means that close to mobile GPS receivers, a master GPS receiver measures simultaneously. Using phase observations, dGPS delivers relative an accuracy at the centimetre level (Fritz et al., 1997).

2.2 Inertial systems

Inertial systems mounted on an aerial camera provide both position and attitude of the camera.
Mostly, *strapdown*-measurement units are used. The axes of these systems are fixed to the platform they are mounted on, for example the camera. An Inertial Measurements Unit (IMU) delivers seven output parameters: time, three spatial angular and three velocity components. These data can be transformed to position, velocity and attitude. The transformed data is called 'Inertial navigation data' or 'INS data'.
The IMU gathers orientation data which is used for repositioning the camera during the triangulation. Therefore, the IMU has to be mounted close to the camera. Normally, the IMU bodyframe is mounted on the camera frame directly, or on a bracket close to the camera. The offset between the IMU and camera projection centre (initial alignment) can be measured tacheometrically.
Besides that, the misalignment, the deviation in orientation, between the IMU bodyframe and the camera system has to be determined by carrying out a calibration flight (see paragraph 4.2).
The IMU axes are defined by the earth gravitation and the earth angular velocity. To get an aligned IMU, an alignment procedure is carried out before the recording. This procedure consists of two steps. First, roll and pitch can be retrieved by flying constantly in a straight line for sufficient time. Second, the heading is defined after making a 360° curve (Fritz et al., 1997).

2.3 GPS/Inertial integration

A typical IMU records with a frequency of 200 Hz changes in angle and velocity. Out of these data, the position can be extracted accurately. However, IMU drifts cause deviations on the long term. Therefore, an IMU is not able to determine an accurate position of the camera on its own.

DGPS measurements are stable in the long term, but collected with a much lower frequency. 'Cycle slips' occur resulting in big errors.
Integration of both systems leads to a combination in which the GPS data correct the drifts of the IMU data and the IMU data detect and correct the cycle-slips in the GPS data.

Kalman filtering is used for prediction, filtering and smoothing of the unknown flightpath parameters. In this procedure the dGPS and IMU data are integrated by processing them simultaneously, resulting in a solution for the camera position and attitude (Lithopoulus, 1999).

3 USE OF GPS/INS IN PHOTOGRAMMETRY

Todays photogrammetric workflow and photogrammetric products of the SD are described first (section 3.1). Next, the integration of a GPS/Inertial system in this workflow is presented (section 3.2).

3.1 Present photogrammetric workflow

The SD produces among others large-scale digital topographical databases of the highways and rivers and digital elevation models for road construction. For this production the SD uses photogrammetry.
The precision of these photogrammetric products is high; depending on the kind of objects, in planimetry between 5 and 15 cm and in height between 6 and 10 cm. To reach such a high precision especially in height, large-scale photographs are used (scale 1:4000) and a 15 cm lens is applied. Artificial markers, white circles with a black rim and a total diameter of about 60 cm, are used as ground control points. Each 800 m a marker is painted or placed, corresponding with one marker for each second model.
The triangulation is a semi-automatic process, using the DPW-770 of LH-systems. After the bundle block adjustment, mapping is carried out on analytical plotters.

3.2 Use of GPS/Inertial systems in the photogrammetric workflow

If photographs have a known position and attitude from a GPS/Inertial system, two ways are open to handle this information: a direct versus an indirect approach.
With the direct approach - named direct georeferencing - the GPS/INS data is directly used for reconstructing the photogrammetric stereo model. Only an interior orientation is needed. No ground control points are necessary and thus no adjustment is carried out.
The indirect approach makes use of GCPs and triangulation. GPS/INS data is used for approximation of attitude and position of the camera centre and used in the adjustment as additional observations. GCPs are still required, but their number can be strongly reduced (Cramer, 1999).
The reliability of the indirect approach is much better then that of the direct approach (Colomina, 1999).

4 TEST 'MOERDIJK'

To answer the question how much GCPs are still needed and how these have to be distributed, an experiment named 'test Moerdijk' is set up,.

4.1 Testflight set-up

The test site near Moerdijk had an extension of 5x6 km. Aerial photographs, image scale 1:4000, were captured at a flying height of 600 m. The site was covered by a block of five strips and four cross strips. The photo overlap was 60% and the side overlap 30%. At the northern and the southern side of the block two single strips were flown. In total 140 photographs were taken (figure 2).

The test area was covered with 108 signalised artificial markers. The co-ordinates were measured with dGPS; their planimetric accuracy being between 2 and 3 cm, the height accuracy is a bit worse. In the test field two GPS reference receivers were located and another two receivers were placed at a distance of 20 and 100 km. The GPS/INS data were gathered by Eurosense b.v. with the Applanix POS/DG system. This system showed promising results in earlier tests (Cramer, 1999). A gyro-stabilised camera mount was used, so aircraft movements didn't affect the camera attitude; the main advantage is that the camera records photo's on the chosen location, not displaced by a tilt of the aircraft. On the other hand, the determination of the camera projection centre is less accurate.

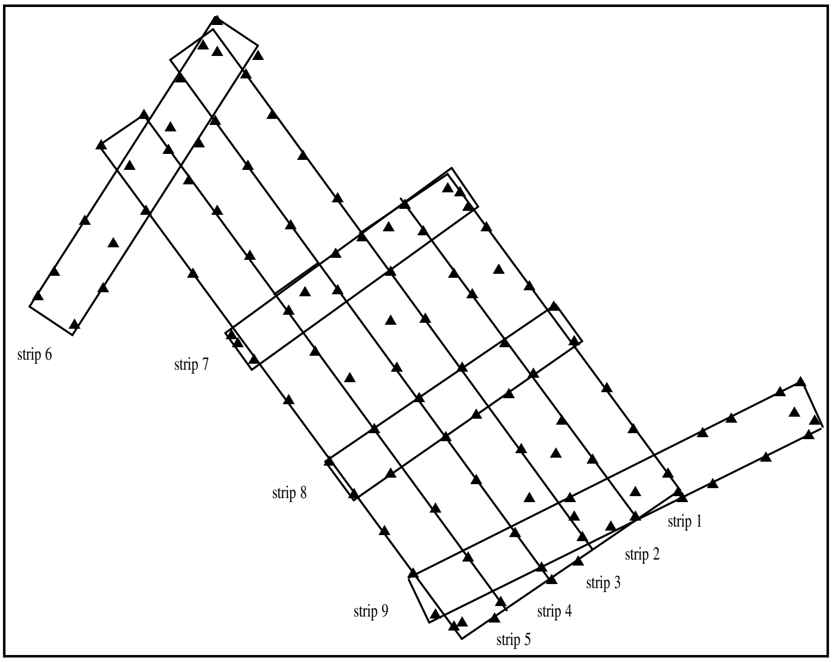

Figure 2: Moerdijk test block. A block of five strips and 4 cross strips; 108 XYZ-GCPs are marked with ▲.

4.2 Data processing

Data processing is subdivided in three parts: system calibration, processing GPS/Inertial system data to GPS/INS data and the photogrammetric processing.

The system calibration takes two steps. First the shift between the GPS antenna and camera projection centre (GPS offset), as well as the shift between the IMU and the camera is measured tacheometrically. Next the misalignment between the IMU and the camera is determined by carrying out a specially constructed flight of a calibration site close to the test site. This calibration site is covered by 6 strips, 4 parallel and 2 cross-strips. Photo's of the site are captured and photogrammetrically processed to determine the position and attitude of the camera. These data are compared with the simultaneously recorded GPS/INS data. The difference in orientation is equal to the mean misalignment.

To convert the GPS/IMU data to GPS/INS data, first the GPS data is processed. Comparisons between solutions from different GPS reference stations haven't been made, partially because of missing data from one reference station in the test field. Next, dGPS and IMU data are integrated into a GPS/INS solution.

After scanning the photographs with a resolution of 15 µm, all photo's are triangulated strip-wise on the DPW-770. Next the parallel and cross strips are adjusted.
The bundle block adjustment program BLUH is used for connecting the GCPs to the photo block. It should be possible to use GPS/INS data in an adjustment program. However, BLUH is currently not able to process GPS/INS data in a combined adjustment.

5 ANALYSIS AND TEST RESULTS

5.1 Analysis plan

The test block is specially designed for multilateral research possibilities. Due to the redundancy in high accurate GCPs and the presence of four cross-strips it is possible to create accurate and reliable reference data. Since the reference data is used for evaluating different research scenario’s as well as the quality of the POS/DG data, it is important that the block adjustment data is free of errors. For this reason there has been chosen to run the automated aerial triangulation (AAT, Leica Helava System) with all GCPs including blunder detection followed by an additional bundle block adjustment (BLUH). The reference data could be divided in two different data sets: an aerial triangulation (AT) data set with exterior orientation parameters and a set of 3D-co-ordinates of 108 check points.

5.2 Quality description POS/DG data

5.2.1 Comparison with reference data. The simplest way to estimate the quality of the POS/DG data is a comparison between the GPS/INS data and the exterior orientation parameters of the photo perspective centres, derived from a triangulation. The results have shown that the heading parameters of one strip deviate enormously from the reference data. Probably the fine alignment was disturbed during data capturing of this strip and was recovered by flying to the next strip. For the further analysis of the POS/DG data this strip was eliminated. In table 3 the remaining results are shown.

	j [ ]	w [ ]	k [ ]		X_0 [m]	Y_0[m]	Z_0[m]
Mean	0,0014	-0,0015	-0,0039		0,011	-0,030	-0,090
Max. D	0,0234	0,0275	0,0242		0,278	0,369	0,293
RMSE	0,0082	0,0069	0,0079		0,091	0,076	0,045

Table 3: Differences between AT reference data and POS/DG data.

5.2.2 Removal of systematic errors. The integration of GPS/INS comprises 15 additional parameters for modelling position, speed, attitude, gyro drifts and accelerometer errors. This should be enough for eliminating most systematic errors (Cramer, 1999). Remaining errors should be modelled by the initial and misalignment parameters. In spite of these remarks table 3 shows relatively big systematic errors.

Normally, in a combined block adjustment, systematic errors can be estimated by using additional parameters like shift and drift. In the analysis of this test the AT reference data is used to estimate systematic errors per strip by simply comparing the two data sets. Instead of using shift and drift, second and third order polynoms are estimated as well . Figures 4 and 5 show the RMSE values of the position and attitude after removing systematic errors.

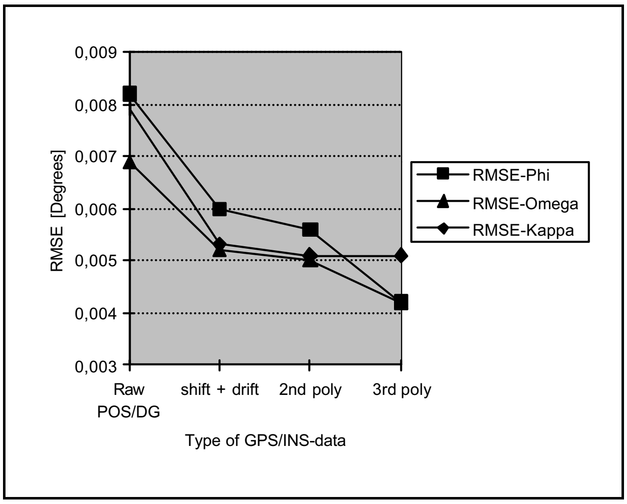

Figure 4: RMSE value of attitude differences between AT reference data and (corrected) POS/DG data.

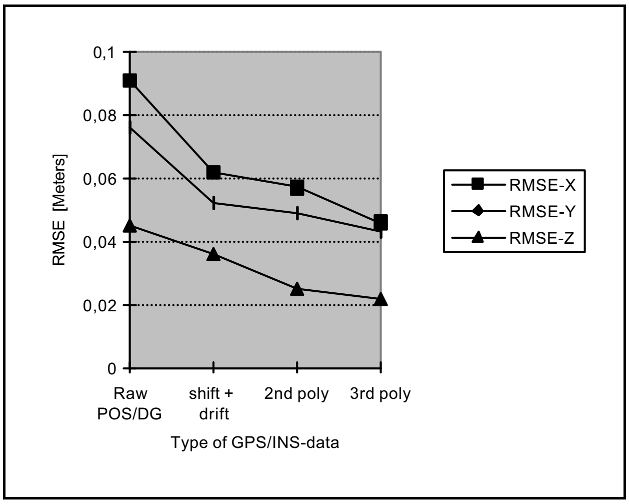

Figure 5: RMSE value of position differences between AT reference data and (corrected) POS/DG data.

5.2.3 Direct georeferencing. Direct geo-referencing gives an alternative, independent way to estimate the quality of POS/DG data. It can be used to directly set the exterior orientation of aerial photographs. Only an interior orientation is necessary. The object co-ordinates of tiepoints and GCPs are calculated by bundle ray intersection.

The calculated co-ordinates of GCPs are compared with the reference co-ordinates of GCPs that were measured by dGPS in advance (check

	X [m]	Y [m]	Z [m]
# Check points	74	74	74
Mean	0,003	-0,055	-0,063
Max. D	0,178	0,138	0,233
RMSE	0,055	0,072	0,085

Table 6: Differences in checkpoints after direct georeferencing.

points). Results of the differences in the checkpoints for a block configuration are given in table 6.

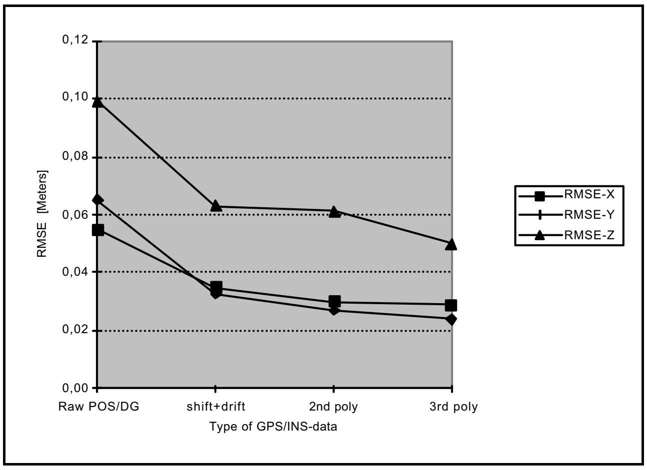

Figure 7: RMSE values of the checkpoint differences after direct geo-referencing with (corrected) GPS/INS data.

To stress out the influence of systematic errors on the checkpoints, the direct georeferencing is also done for the corrected POS/DG data. Figure 7 shows the importance of elimination systematic errors. At least a shift and drift correction should be made which is impossible without reference data and a combined adjustment with additional parameters.

5.3 Use of POS/DG data in different configurations

Integration of automatic AT with directly measured GPS/INS data including a combined block adjustment is probably the most powerful method for high accurate and reliable geocoding (Cramer, 1999). Computer programmes for a combined adjustment with GPS/INS data are still under development. Especially the way of using additional parameters together with GPS/INS data need more research.

The SD calculated different research scenario's with a limited amount of GCPs in different configurations. Due to restrictions of the block adjustment programme the SD concentrated on a combined block adjustment with only additional GPS. Results show that the presence of control points is essential for estimating additional parameters. Especially when shift and drift parameters are modelled, at least four GCPs per strip are necessary. Expectations are that this problem decreases by using INS data in the combined adjustment as well.
In block configurations the number of control points probably will decrease more when INS data is submitted. But the main advantage is that the estimation of systematic errors will be more effective. A minimum number of GCPs remains necessary for the reliability.
The Survey Department is especially interested in strip-wise configurations because the Rijkswaterstaat management areas are mainly elongated (highways and river area's). Inertial data in a combined block adjustment has a particular surplus value in the configurations presented because the attitude data stabilises the strips. Also in this configuration sufficient GCPs are necessary for reliability purposes as well as the estimation of systematic errors.

6 COST ANALYSIS

GPS systems have already proven to be useful for reducing the amount of markers needed for photogrammetric photo flights. The question arises if the benefits of an inertial system added to the GPS receiver is cost-effective or profitable in another way.

For the near future the photogrammetric process using GPS/INS data will still be based on triangulation and bundle block adjustment. Gain of GPS/INS data is delivered by applying an automatic triangulation process which is less time-consuming then the current semi-automatic approach. Above all the smaller amount of artificial markers needed is profitable. For securing reliability and accuracy a few artificial markers will always be necessary. But a reduction of 80 to 90 % of the markers needed can be expected (Wicherson et al., 2000).

The SD subcontracts flying companies for the photo flights. Currently most photo flights do not involve the use of GPS or GPS/Inertial systems. Most companies will have to purchase such a system.
Next to the purchase of a GPS/Inertial system, extra costs come with:

- the tacheometric measurement of the GPS, IMU and camera set-up;
- determination of the misalignment by carrying out a misalignment flight and subsequent analysis;
- placing and guarding the GPS master stations. Besides the extra costs involved, an operational problem arises: for flexible planning purposes numerous receivers, which are hardly available, have to be positioned in advance;
- transforming GPS/IMU data to dGPS/INS data.

The extra benefits are less than the extra costs so it seems to be efficient to use GPS/Inertial systems for photogrammetric production of the SD (Wicherson et al., 2000).

Furthermore, using GPS/Inertial systems are an answer to the problem of inhomogeneous photo block accuracy that arises in projects where large terrain area's are inaccessible (reserves, rivers, lakes) thus unsuited for laying out markers.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The most important conclusions of the GPS/INS test are:

- Comparison between GPS/INS data and the exterior orientation parameters of the photo perspective centres derived from a triangulation gives, after removal of one deviating strip, good results: mean differences are for X, Y, Z 1, 3 and 9 cm respectively and for φ, ω, κ 0,0014°, 0,0015° and 0,0039° respectively;
- Direct geo-referencing, comparing the calculated co-ordinates of GCPs with the reference co-ordinates of GCPs deliver mean differences for X, Y, Z are 0, 6 and 6 cm respectively;
- GPS/INS results are not reliable to use in a production environment without using GCPs as the presence of the deviating strip has shown. Probably the fine alignment was disturbed during data capturing;
- Computer programmes for a combined adjustment with GPS/INS data are still under development. Therefore the reduction of required GCPs for attaining sufficient accuracy can not yet be determined;

The cost benefit analysis provided the following conclusions:

- Extra costs caused by the use of GPS/Inertial systems - purchase of GPS/Inertial system, tacheometric measurements, misalignment flight, using reference GPS receivers and processing of GPS/IMU data - seem to be more than compensated by the benefits: an 80 to 90% reduction of GCPs and a less time-consuming triangulation process;
- Inhomogeneous photo block accuracy caused by the inaccessibility of terrains (reserves, river area's), and thus unsuited for placing markers, can become more homogeneous by using a GPS/Inertial system.

7.2 Recommendations

Future research will be focused on carrying out a combined block adjustment with GPS and INS data. So, the number and configuration of required artificial markers can be estimated. For eliminating systematic errors, GCPs are needed as well.
The Applanix Kalman filtering is a 'black-box' procedure. Insight is needed in the influence of IMU data on GPS results and the parameter setting.

Given proper GPS/INS data, the workflow for map revision has to be re-organised. A match between GPS/INS oriented actual photo's and old databases won't give a geometric fit; a second form of fitting the actual georeferenced photo's in the old databases will be a solution instead.

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