A COMPARATIVE STUDY OF DYNAMIC POSITIONING BY GPS

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ABSTRACT

The purpose of this study was to compare the positions of the camera exposure stations determined by the GPS-NAVSTAR during the survey flight mission with the corresponding positions determined by accurate aerial triangulation.

For the experimental test, a survey flight mission was carried out of a test area which has a dense and accurate ground control network. The Zeiss RMK A 15/23 camera was equipped with a pulse generator for recording the time of exposures. The camera and the five channel GPS receiver (TR5S-B) were interfaced with a portable computer. The GPS raw data, obtained by a single receiver, were processed in a combined pseudo range-phase mode. A Zeiss C120 Planicomp was used for aerial triangulation and the PAT-B program was used for the bundle block adjustment.

1. INTRODUCTION

For effective social and economic development, administration and management of land, engineering, environment reconnaissance, and a wide variety of other human activities, up-to-date and relevant geo information of sufficient quality is a firm prerequisite. The main source of information is high-quality aerial survey photography with the corresponding control data. The latter are acquired primarily for aerial triangulation (AT), which requires some ground control data (usually high order triangulation/ trilateration network). Establishment of adequate ground control, however, is time consuming and costly. This problem can be largely overcome by using the Global Positioning System (GPS-NAVSTAR)in the survey flight missions.

The main objective of this project was to assess experimentally the feasibility and especially the performance, of the GPS-Navstar positioning system for spatial positioning of the survey camera stations by comparing the spatial positions (X,Y,Z) of the camera stations determined by the GPS with those determined by high precision aerial triangulation using a dense ground control network.

The scope of the experimental test concerned the survey flight mission preparation and its execution with on-board integrated survey camera/ photo sensor, GPS receiver and a computer. The primary data contain the photographs of a block and the corresponding GPS positional data. The second part of the project concerns the aerial triangulation, which provided the positions of the projection centers serving for the comparison with the corresponding GPS data. The last part of the test addressed the comparative analysis of the GPS data with the corresponding aerial triangulation data. This analysis included the accuracy assessment of the discrepancies.

This project required cooperation with several institutions and companies, which demanded efficient project managment and engineering. The participating institutions were:

ITC International Institute for Aerospace Survey and Earth Sciences, (ITC) Enschede, The Netherlands.
FHB Fachhochschule Bochum, Bochum, Germany.
RW Rijkswaterstaat Survey Department, Delft, The Netherlands.
HL Hansa Luftbild Munster German Air Surveys, Germany.
IGI Ingenieur-Gesellschaft fur interfaces-Hilchenbach, Germany.
STU Stuttgart Technical University, Stuttgart, Germany.
LVA Landesvermessungsamt Nordrhein-Westfalen, Bonn/Bad Godesberg, Germany.

This paper addresses the project preparation, ground control, flight mission, processing GPS data, aerial triangulation, comparative analysis, and the assessment of the results.

2. PROJECT PREPARATION

For the experimental test the following equipment was available:

(a) TR5S-B Sercel GPS receiver (Rijkswaterstaat,Delft)

This is a five parallel channel receiver; it can receive and process simultaneously the signals of up to 5 satellites. It uses the C/A-code generator to perform pseudo range and phase measurement on the L1 frequency (1575.42 Mhz). With an internal processor and coprocessor, the receiver computes at an interval of 0.6 second a complete 3D + T position.

The TR5S receiver permits recording messages triggered by external pulses (e.g., a photo sensor pulse). Such a message gives the time of the external event (e.g., camera exposure). The position of this event can be determined by linear interpolation between the positions of the previous and subsequent (0.6s interval) raw data block messages.

- GPS Antenna

To receive the signals from the space segment of the Navstar, the GPS receiver has an antenna installed atop the fuselage. For determining a suitable antenna position, the following items should be considered: - Reflections from the aircraft surface should not be received. - The antenna-camera offset should be minimal, as indicated in [1]. The ideal position is vertically above the camera lens. In practice, however, the actual position is chosen by the mechanical considerations for installation.

(b) Zeiss RMK 15/23 Survey camera with photosensor (ITC)

To position the camera stations (actually of the antenna) by GPS, the time of the exposures has to be known. In the existing aerial cameras (Zeiss, Wild), the actual instances of exposures are not accurately known. Hence, an improvisation was necessary to carry out the test by installing a photo sensor in the lens cone (between the lens and the focal plane). When light passes through the open shutter of the camera lens (at exposure), the photo sensor generates a pulse. Both the Zeiss and the Wild cameras can be equipped with a similar photo sensor/pulse generator. In this project, a photo sensor with a pulse amplifier was installed in the lens cone of the Zeiss RMK 15/23 aerial camera.

(c) Cessna 404 Titan Ambassador aircraft (Hansa Luftbild)

The size and weight of the equipment, and the corresponding power consumption, require a relatively large (twin-engined) aircraft. An interface between the Zeiss camera photo sensor with the GPS receiver is required for the transfer of the photo sensor pulse signals. The interfaces ensure synchronisation of the signal flows in the integrated system. The integrated system configuration is shown in figure 1.

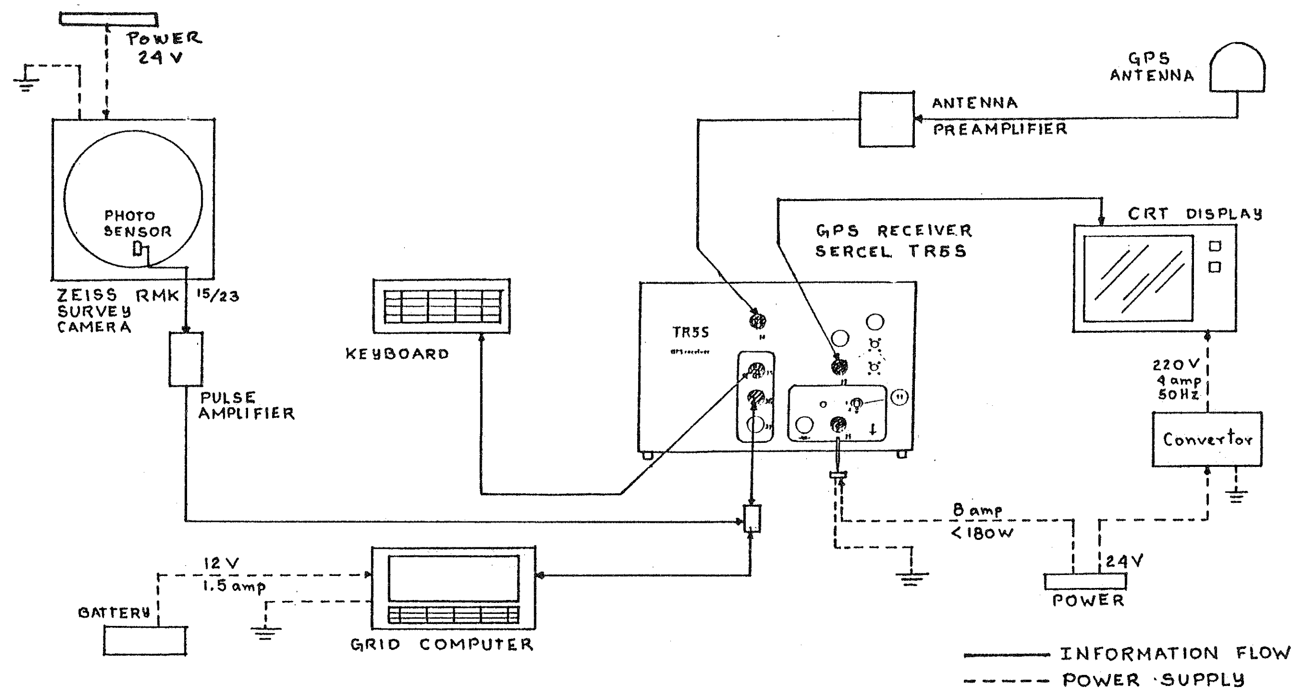

Figure 1. Integrated system configuration.

3. SELECTION OF THE TEST AREA AND FLIGHT PLAN

(a) Selection of the test area.

The following factors influenced the selection of the test area:

- The area should be representative of the normal operational circumstances.
- Availability of a dense (geodetic and/or photogrammetric) ground control network.
- The area should, where possible, be near the airfield.

According to these criteria, an area of 30 km by 8 km (west of Münster, Germany) was selected. Good quality topographic maps at scale 1:5000 are available for the area.

(b) Flight mission parameters.

The specified photo scale was 1:12000 for the following reasons:
- It was intended that each photograph would cover a map sheet at scale 1:5000.
- The control points are well identifiable on photographs, i.e., to provide for high accuracy aerial triangulation.

To ensure one photo per map coverage to strengthen the aerial triangulation, and to increase the number of camera stations for the comparative study, the specified forward overlap was 80%.

Other flight parameters were specified as follows;

- 4 lines of 30 km length, direction north-south (from 51 50 latitude north to 52 07 latitude north) line spacing 2 km.
- 2 cross lines 8 km long, direction east-west (from 7 20 longitude east to 7 27 longitude east), 25 km apart.
- Flight altitude 1920 m (wide angle camera).
- 30% side overlap.

4. GROUND CONTROL

The control point coordinates were acquired at the German federal geodetic office ("Landesvermessungsamt Nordrhein - Westfalen") in Bonn/Bad-Godesberg. All the points were distinct corner points of roofs. Hence, these points could be easily identified and marked on the photographs (paper prints).

The accuracy of the control points was (according to LV N-W) for:
- Full (X,Y,Z) points: SXo = SYo = 0.3 m and SZo = 0.5 m
- Height points: SZo = 0.5 m

In total, 302 full control points and 94 height control points were used in aerial triangulation. These points were evenly spread over the whole block. On average, there were five to six double points on each map sheet at scale 1:5000 (hence the same number of control points on average on each photograph). The total test area was covered by 60 map sheets.

5. FLIGHT MISSION EXECUTION

After several unsuccessful trials (due to bad weather conditions), the actual flight mission was accomplished on August 21th between 9:30 and 11:10 (local time). Before take-off, the corresponding satellite configuration was selected and the receiver was calibrated.

The weather conditions on August 21th were good. The sky was cloudless, and the wind was light and without turbulence; because of haze visibility was restricted to 10 or 15 km. The GPS receiver remained locked on to all selected satellites during the entire flight mission, including during aircraft banked turns.

6. PROCESSING OF GPS DATA

Processing of these raw data was carried out by the Rijkswaterstaat, Survey Department and Department for Satellite Systems. Using locally developed software, the two types of observed data were combined, resulting in the "smoothed pseudo range" (PR) [2],[3].

For the coordinate transformation from the WGS-84 to the Gauss-Krugger system, the programs GERSH.FOR and TR.FOR were developed (B.Kunji,ITC). These programs concern the following modules:

- Datum Shift: GERSH module which provides for the shift of the datum between the WGS-84 ellipsoid and the German first order triangulation network (Deutsches Hauptdresecksnetz DHDN).
- Transformation module from DHDN to Gauss-Krugger system:TR, which comprises two stages: first it transforms the coordinates from the DHDN system (cartesian) to the Bessel ellipsoidal system (ϕ, λ, h), and then, in the second stage, from the Bessel to the German Gauss-Krugger system (Transverse Mercator) [4].

7. AERIAL TRIANGULATION

(a) Measurements

To attain homogeneous and accurate observations, the measurements were carried out by an experienced operator on the C120 analytical stereoplotter (Zeiss Oberkochen). The observations were the photo-coordinates of the fiducial marks, control points and tie points.

(b) Block Adjustment

The PATB-S block adjustment program (University of Stuttgart), using bundles, was chosen for the adjustment [5]. One important feature of PATB is the optional output, such as the parameter values of the exterior orientation for each photograph. These include the spatial position (Xo,Yo,Zo) of the projection center (PCat) and the rotation matrix. The positions PCat are needed for the comparison with the corresponding GPS data.

The input and output of the block adjustment are as follows:
- Number of image points: 4560
- Number of photographs: 218
- Number of horizontal control points: 302
- Number of vertical control points: 396
- Standard deviation of the observed photo coordinates so = 8.2
- Standard errors of the: tie Points: sxt = 5.5 ,syt = 7.1
  control Points in photo: sxc = 5.5 ,syc = 7.1.

From the accuracy and density of the ground control network and from the standard deviation of the observed photo coordinates, it could be assumed that the accuracy of the adjusted block was relatively high. Consequently the adjusted projection center positions (PCat) provided a suitable reference for comparison with the corresponding GPS data.

8. COMPARATIVE ANALYSIS OF THE GPS AND AT DATA

The analysis concerned the discrepancies between the projection center (antenna) locations determined by GPS (PCgps) and aerial triangulation (PCat). To gain a differentiated insight, the discrepancies were calculated both directly and after fitting polynomials. After each polynomial fit the discrepancies were computed separately per strip.

(a) Raw Differences

The direct differences = PCgps - PCat were calculated by the ADC.FOR program (B.Kunji, ITC). For the analysis of these differences and thus to avoid misinterpretation, consideration should be given to the:

- Offset: The discrepancies between PCat and PCgps contain the constant antenna offset (approximately 1.5m).
- Gross errors: 22 stations have a constant error of about 10m, in the flight direction (Y). The most probable source is a constant delay in the pulse amplifier of the photo sensor, which occurs randomly at the camera exposures. As noted above, the photo sensor and amplifier had to be improvised, and their operation was not thoroughly tested. All 22 erroneous stations were removed from the GPS observations prior to the polynomial fit.
- Change of the satellite configuration: Two different satellite configurations had to be used during the flight mission. For the first three flight lines (1,2 and 3), only four satellites were used for positioning. Before flying the last line, a different configuration had to be used; an additional satellite entered into it. Table 1 shows the effect of the change in the satellite configuration on the shift in GPS positional data.

	ΔXmean	ΔYmean	ΔZmean	(μΔ mean)
Line 1,2 and 3	-7.7	-5.5	24.6	(source table 2)
Line 4	-18.2	-1.9	3.3	

Table 1 Shift of GPS positional data (in meters)

(b) Polynomial fit

After removing the gross errors, the GPS data (PCgps) and the AT data (PCat) were processed individually per flight line by the STRTR.FOR program (B.Kunji, ITC). For each flight line three polynomial fits were calculated (STRTR.FOR), i.e., the zero, first, and second degree polynomials, by the least-squares method. The corresponding error statistics are based on the remaining discrepancies (residuals) [6].

After applying a polynomial fit, the standard error was computed per strip:

$$S = \sqrt{\frac{\Sigma v^2}{n-u}}$$

where:

S = standard error (in meters)
v = residuals (in meters)
n = number of stations
u = number of unknowns

(b.1) Zero degree polynomial

The unknown parameters were the shifts in X,Y and Z. These shifts were computed separately for each strip (table 2). Lines 1,2,3 are related to the 4 satellite reference system whereas line 4 is related to the 5 satellite reference system.

	ΔXmean	ΔYmean	ΔZmean
Line 1	-8.76	-7.56	26.03
Line 2	-9.02	-5.94	23.53
Line 3	-5.47	-2.85	24.19
Line 4	-18.23	-1.90	3.26

Table 2 Shift components per line (in meters).

After applying the shifts, the corresponding residuals were calculated. The corresponding standard errors per line and their mean values are presented in table 3

	SX	SY	SZ
Line 1	0.80	0.70	0.47
Line 2	0.59	0.59	0.39
Line 3	0.65	0.71	0.67
Line 4	0.68	0.46	0.42
μv (0)	0.68	0.62	0.49

Table 3 Standard errors after fitting zero degree polynomial (in meters)

By analysing the tables and graphs (appendix A) of the residuals after fitting the zero order polynomial, a more or less pronounced linear and quadratic trend could be identified.

(b.2) First degree polynomial

By applying a first degree polynomial least squares fit, a significant reduction of the residuals was obtained. The standard errors per line and their mean value are presented in table 4

	SX	SY	SZ
Line 1	0.42	0.46	0.47
Line 2	0.50	0.56	0.39
Line 3	0.45	0.51	0.34
Line 4	0.36	0.46	0.36
μv (1)	0.43	0.50	0.39

Table 4 Standard errors after fitting the first degree polynomial(in meters)

(b.3) Second degree polynomial

After fitting the second degree polynomial, virtually all the systematic error component was removed. Hence the remaining discrepancies were nearly random.

The magnitude of the residuals was obviously smaller than in the previous case. In all four strips, 90% of the stations had residuals smaller than one meter, nine points had residuals between 1 and 1.5m, and only one point (station 104 in line 2) had a residual of 2m. The standard errors per line and their mean value are presented in table 5.

	SX	SY	SZ
Line 1	0.35	0.44	0.34
Line 2	0.45	0.56	0.29
Line 3	0.33	0.50	0.27
Line 4	0.34	0.44	0.32
μv (Q)	0.37	0.49	0.31

Table 5 Standard errors after fitting the second degree polynomial (in meters)

9. ASSESSMENT OF TEST RESULTS

To assess the accuracy of the GPS data, we should have a priori knowledge about the accuracy of the projection centers obtained with aerial triangulation. According to the law of error propagation, the variance of the discrepancies μv^2 contains two components, i.e, the variance of the aerial triangulation (Sat^2) and the variance of the GPS ($Sgps^2$):

$$\mu v^2 = Sat^2 + Sgps^2$$

If Sat is known, the variance $Sgps^2$ is:

$$Sgps^2 = \mu v^2 - Sat^2$$

Based on experience in aerial triangulation, and taking into account the:

- great overdetermination because of dense control network,
- accuracy of the photogrammetric ground control; SXo=SYo=0.3m, SZo=0.5m,
- accuracy of the observations so = 8.2 μm, the standard error of the projection centers Sat (estimated intuitively) was approximately:

$$Satx = Saty = 0.4m \quad \text{and} \quad Satz = 0.3m$$

Hence for

$$Sgpsx^2 = \mu v^2 - 0.16 \text{ m}$$
$$Sgpsy^2 = \mu v^2 - 0.16 \text{ m}$$
$$Sgpsz^2 = \mu v^2 - 0.09 \text{ m}$$

By substituting the mean standard errors μv estimated experimentally and of Sat, estimated subjectively, the corresponding estimate of Sgps can be computed;

DERIVED GPS POSITIONING ACCURACY (in meters)

Polyniomial	X		Y		Z	
	v	Sgpsx	v	Sgpsy	v	Sgpsz
Zero degree	0.68	0.55	0.62	0.47	0.49	0.39
First degree	0.43	0.16	0.50	0.30	0.39	0.25
Second degree	0.37	0.00	0.49	0.28	0.31	0.08

These results indicate very high relative accuracy of the GPS data after their postprocessing.

These estimates are relative; by altering the value of Sat, estimated subjectively, the values of Sgps change accordingly.

A more rigurous assessment of the standard error Sat of the projection centers is possible by applying the law of error propagation, i.e., by computing the covariance matrix at block adjustment.

10. CONCLUSION

(a) After appropriate post-processing of the GPS data, the attained accuracy was higher than initially anticipated. It meets fully the requirement for the application to aerial triangulation block adjustment with strongly reduced ground control.
(b) According to Ackermann and Friess [7],[8], the attained GPS accuracy may allow a reduction of ground control in aerial triangulation to a minimum of four points in the corners of a block.
(c) The accuracy required to use GPS data in aerial triangulation can be obtained potentially only with a combined pseudo-range and phase measurement.
(d) When using the absolute GPS positioning mode, a change in the satellite configuration causes a discontinuity (shift) in the GPS positional data.
(e) These results of the test are valid for the specific GPS receiver, which provides a continuous tracking of maximum 5 satellites via 5 separate physical channels, recording the position at a constant interval of 0.6s, and an internal time record activated by an external pulse.
(f) GPS positioning should preferably be by the differential mode rather than by the absolute mode.
(g) If only one GPS receiver is available the pseudo-differential mode can be applied. In this mode the position of a known geodetic point (e.g., in the airfield) is determined by the GPS receiver the day before the survey flight and the day after it. These GPS measurements should be carried out during the same period of time and using the same satellite configuration as at the flight mission. The mean values of these two sets of GPS measurements are then used in differential mode as a substitute of the GPS receiver on ground during the mission.
(h) In survey flight missions with GPS positioning in absolute mode, the following precautions should be taken:
    i) Do not change the satellite configuration during a flight line;
    ii) Use, if possible, the same configuration of satellites; any change produces a discontinuity in the GPS data (in differential mode it is compensated).
    iii) If a change of the satellite configuration is unavoidable, apply it during the turn of the airplane from one line to the next.
    iv) If the flight mission cannot be completed in one day, use (if possible) the same satellite configuration in the next flight(s).
(i) In order to link the World Geodetic System 84 with the local coordinate system, it is recommended to measure at least one ground control point with the same GPS receiver as used in the flight mission.
(j) When the block to be surveyed is not very large, a similarity transformation can be applied instead of a more rigurous geodetic coordinate transformation.

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