GPS CONTROLLED STRIP TRIANGULATION USING GEOMETRIC CONSTRAINTS OF MAN-MADE STRUCTURES

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ABSTRACT:

Conventional block adjustments (bundles or independent models) have been widely used to determine both photogrammetric point coordinates and the exterior orientation parameters of photography for mapping purposes. Ground control points (planimetric points along the perimeter of the block and relatively dense chains of vertical points across the block) are necessary to relate the image coordinate system to the object space coordinate system and to ensure the geometric stability of the conventional block as well as to control the error propagation. The major impact of cost and time consumption for ground control establishment on any mapping project is the primary reason that photogrammetrists have been looking for a replacement for ground control by auxiliary data (e.g. Global Positioning System). This paper describes a new technique for GPS controlled strip triangulation using geometric constraints of man made structures (e.g., high voltage towers, high-rise buildings) located approximately along the flight line. The effects of the different GPS measurement accuracies were also investigated. Both the precision and reliability analysis of the GPS bundle strip adjustment with these constraints were carried out on simulated and real data.

1. INTRODUCTION

Since the launch of the Global Positioning System (GPS) satellites in the early 80s, photogrammetrists have realized the application of GPS for their particular interests (i.e., aerial triangulation). With this technology, the position of the aircraft at the individual exposure moments can be precisely determined. These positions can then be introduced into the combined GPS-Photogrammetric block adjustment as weighted observations for the exposure stations reducing the number of control points to a minimum. Aerial triangulation can even be completed without any control points provided that the satellite signals are not blocked during the flight mission (Lapine, 1992) and as long as datum transformations are known.

However, there are a few problems that require attention in GPS assisted aerial triangulation. These are the GPS antenna offset calibration, interpolation of the exposure time, the initial phase ambiguity resolution, signal interruptions, and datum problems (Ackermann, 1992).

After kinematic processing of GPS observations, coordinates of the antenna phase centres are available in the WGS84 reference frame. Most ground coordinates are defined with respect to a national coordinate system (e.g. UTM). The transformation between these coordinate systems can be based on published formulas (Colomina, 1993) or a set of common reference points available in both systems. Elevations are usually related to the ellipsoid and must be corrected for the geoid undulations.

Ground control points (planimetric points along the perimeter of the block and relatively dense chains of vertical points across the block) are mandatory for relating the image coordinate system to the object coordinate system and to ensure the geometric stability of the conventional block. The minimum control requirement for absolute orientation is three non-collinear points. For GPS-Photogrammetric block, this condition is met by using GPS observations at the perspective centres as control information. Since the GPS observations of the exposure stations are almost collinear for strip triangulation, the above condition is not satisfied and, therefore, the role angle (i.e., around the flight direction) can not be recovered reliably. This makes it necessary to use ground control points to solve for the remaining exterior orientation parameters (Alobaida, 1993).

This paper reviews the concept of the GPS observable used in the precise photogrammetric applications and describes a new technique for GPS controlled strip triangulation using geometric constraints of man-made structures (e.g. high voltage towers and high-rise buildings) located approximately along the flight line. The effects of the accuracies of different GPS measurements were also investigated. A precision and reliability analysis were performed on both simulated and real data. All results were obtained using GAP (General Adjustment Program) developed by the first author at the Department of Geomatics Engineering (Digital Photogrammetry Group).

2. GPS OBSERVABLE USED IN PRECISE PHOTOGRAMMETRIC APPLICATIONS

There are three types of positioning information which can be extracted from GPS satellite signals; pseudorange (code), carrier phase, and phase rate (Doppler Frequency). Due to the high accuracy required for aerotriangulation, GPS phase measurements are needed to meet the accuracy requirement. In order to eliminate the effects of systematic errors introduced by GPS, double difference GPS phase measurements are used. The reason is that most GPS errors affecting GPS accuracy are highly correlated over a certain area and can be eliminated or reduced. The observation equation for DGPS phase measurement is given as (Lachapelle et al., 1992):

$$\nabla\Delta\Phi = \nabla\Delta\rho + \nabla\Delta\, d_\rho + \lambda\nabla\Delta N - \nabla\Delta\, d_{ion} + \nabla\Delta\, d_{trop} + \varepsilon\nabla\Delta\Phi \qquad (1)$$

where

$\nabla\Delta$ is the double difference notation,
Φ is the carrier beat phase measurement in cycles,
ρ is the distance from satellite to the receiver,
d_ρ is the orbital error,
λ is the carrier wave length,
N is the integer carrier beat phase ambiguity,
d_{ion} is the ionospheric error
d_{trop} is the tropospheric error
ε is the receiver noise and multipath.

The terms $\nabla\Delta\, d_\rho$, $\nabla\Delta\, d_{ion}$, and $\nabla\Delta\, d_{trop}$ are generally small or negligible for short monitor-remote distances (e.g. <10-20 km). However, the term $\nabla\Delta d_\rho$ has become more significant due to Selective Availability (SA) and may have some negative effects on integer carrier ambiguity recovery. The satellite and receiver clock errors are eliminated using DGPS method but the receiver noise is amplified by a factor of 2. The phase observable is used extensively in kinematic mode where the initial ambiguity resolution can be achieved using static initialization or " On The Fly " methods. Accuracy at the centimeter level can be obtained if cycle slips can be detected and recovered (Cannon, 1990). The accuracy of kinematic DGPS is a function of the following factors (Lachapelle, 1992):

- Separation between the monitor and the remote station
- The effect of Selective Availability
- The receiver characteristics and ionospheric conditions

3. GPS SUPPORTED AEROTRIANGULATION

The main purpose of aerial triangulation (AT) is the determination of ground coordinates for a large number of terrain points and the exterior orientation parameters of aerial photographs using as few control points as possible. The best scenario in mapping projects is to have the exterior orientation parameters accurate enough so that the AT can be neglected. The GPS accuracy for attitude parameters is about 15 arc minutes and still far from what could be obtained from a conventional block adjustment. Therefore, aerial triangulation is still one of the important steps in mapping and can not be avoided.

The integration of GPS measurements with photogrammetric blocks allows for the accurate determination of the coordinates of the exposure stations resulting in a reduction of the number of ground control points to a minimum. The combined adjustment of photogrammetric data and GPS observations can be carried out by introducing GPS observation equations to the conventional block adjustment (Ebadi and Chapman, 1995). Empirical investigations (Frieβ , 1991) showed that, in addition to the high internal accuracy of GPS aircraft positions, (σ=2 cm) drift errors may occur due to the ionospheric and tropospheric errors, satellite orbital errors, and uncertainty of the initial ambiguity. Out of the mentioned remaining errors, incorrect carrier phase ambiguities contribute the majority of the drift errors to the exposure station position.

4. GPS CONTROLLED STRIP TRIANGULATION WITH GEOMETRIC CONSTRAINTS OF MAN-MADE STRUCTURES

The inherent geometry of a block and the common tie points in consecutive strips make it possible to recover all three rotation angles in the combined block adjustment. Unfortunately, this method can not be used for a single strip, since the GPS coordinates of the exposure stations do not recover the roll angle of the aircraft. As a consequence, control introduced by airborne-GPS leaves an ill-conditioned, if not singular system of normal equations. Ground control points can be used along the flight line to overcome this problem.

A new technique for GPS controlled strip triangulation was developed based on geometric constraints of man-made structures (e.g. high voltage towers, high-rise buildings) located along the flight line. The observation equations for these constraints with proper weight are introduced to the combined strip adjustment. The constraint observation equation for a high voltage tower is written as:

$$\begin{bmatrix} X_j \\ Y_j \end{bmatrix} - \begin{bmatrix} X_i \\ Y_i \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \end{bmatrix} \qquad (2)$$

where

(X_j, Y_j) are the horizontal coordinates of the top of the structure,
(X_i, Y_i) are the horizontal coordinates of the bottom of the structure.

The weights for these equations should be appropriately chosen because the top and the bottom of the structure must have the same horizontal coordinates. However, the absolute ground coordinates of the structure are not required since the top and the bottom of the structure are similar to horizontal pass points. The main idea is to use a number of towers along the flight line in order to recover the roll angle of the aircraft and use these constraints to minimize the number of ground control points.

4. 1. Precision and Reliability Measures

The covariance matrix of object points, $C_X = \sigma_0^2 Q_{XX}$, is generally taken as the measure of theoretical precision. The average theoretical precision of n object points is given as:

$$\overline{m} = \sigma_0 \sqrt{tr(Q_{xx}) / 3n} \tag{3}$$

The average practical precision of object points for simulated or check point data is:

$$\overline{\mu} = \sqrt{\Sigma(\Delta X^2 + \Delta Y^2 + \Delta Z^2) / 3n} \tag{4}$$

where $\Delta X, \Delta Y$, and ΔZ are differences between the adjusted and known coordinates of an object point. Similarly, $\overline{m}_x$, $\overline{m}_y$, $\overline{m}_z$, and $\overline{\mu}_x$, $\overline{\mu}_y$, $\overline{\mu}_z$ are the average theoretical and practical precision of object points in the X, Y, and Z directions, respectively.

Reliability analysis includes internal and external reliabilities. The ability to discover blunders in one particular observation is referred by the internal reliability and the effect of an undetected blunder in the observation on unknown parameters is measured by external reliability. For the reliability analysis, the local redundancy numbers, $r_i = (Q_{vv'}P)_{ii}$, need to be determined, where $Q_{vv'}$ is the cofactor matrix of residuals and P is the weight matrix of observations. A single blunder is generally assumed to exist for the application of this method. The internal and external reliability formulas are given as (Deren and Jie, 1989):

$$\nabla_0 L_i = \sigma_{L_i} \cdot \frac{\delta_0}{\sqrt{r_i}} = \sigma_{L_i} \cdot \delta_{0,i} \tag{5}$$

$$\overline{\delta}_{0,i} = \sqrt{1 - r_i} \cdot \delta_{0,i} \tag{6}$$

where

σ_{L_i}	is RMSE of the ith observation L_i,
δ_0	is the non-centrality parameter,
$\delta_{0,i}$	is the internal reliability factor of observation L_i,
$\nabla_0 L_i$	is the minimum blunder that can be detected statistically,
$\overline{\delta}_{0,i}$	is the external reliability factor of observation L_i,

with the significant level, $\alpha = 0.1\%$, and the power of the test, $\beta = 93\%$, the non-centrality parameter, δ_0, is then equal to 4.0.

4. 2. Results With Simulated Data

Many experiments were conducted to evaluate the performance of the new model. We considered one single strip of 50 photographs. The interior and exterior orientation parameters were predefined. The image coordinates of all object points (pass points and tower points) were computed using the known exterior orientation of each photograph. Table 1 lists the information concerning this simulated strip.

Table 1. Simulated Strip

Strip Information	
Number of Photos	50
Photo Scale	1:5000
Focal Length	152 mm
Terrain Elevation Difference	150 m
Average Flying Height	900 m
Forward Overlap	60%
Photograph Format	23 cm x 23 cm
Accuracy of Image Coordinates	5 μ m
Accuracy of Ground Control Points	0.1 m
Accuracy of GPS	0.25-1.0 m
Tower Height	15 m
Number of Towers	50
Number of Pass points per Photo	15

The behavior of the new model was studied under different conditions, such as varying GPS accuracies at the perspective centres. The performance of the technique was evaluated using the standard deviations of the coordinates of pass points obtained from their variance-covariance matrix and comparing the adjusted coordinates with simulated coordinates. The following methods of the strip adjustment were carried out:

1- GPS-Photogrammetric strip adjustment with 2 ground control points and without tower points
2 - GPS-Photogrammetric strip adjustment with no ground control points and with tower points
3 - Full control strip adjustment (no GPS data)

Figure 1 shows the root mean square error (RMSE) of X, Y, and Z coordinates of all pass points without using tower points and Figure 2 shows the RMS of X, Y, and Z coordinates of all pass points including tower points. The RMS of X, Y, and Z coordinates of pass points for the full ground control adjustment are 45, 57, and 197 mm, respectively.

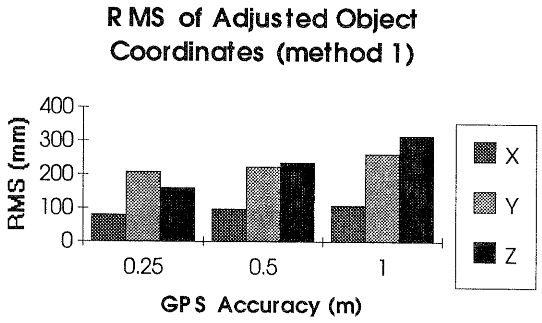

Figure 1. RMS of X, Y, and Z Coordinates of All Object Points (method 1)

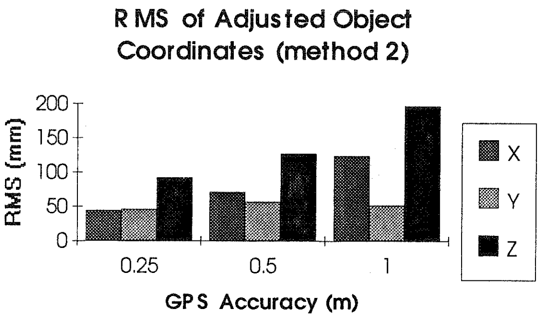

Figure 2. RMS of X, Y, and Z Coordinates of All Object Points (method 2)

Comparing Figures 1 and 2 show that if GPS can provide accuracy at the level of 0.25 to 0.5 m for camera exposure stations coordinates, the RMS values for all object coordinates are better or equal to those obtained from the full ground control version. These results confirm that constraint information from the tower points can replace the ground control points and eliminates the need for the second strip of photography which has been adopted conventionally to improve the geometry of the strip. To see how this technique recovers the roll angle of the aircraft, Figures 3, 4, and 5 show the adjusted roll angle of each photo obtained from the 3 methods (σ_{GPS}=0.25 m)

As seen in these Figures, the adjusted roll angle recovered from method 2 (tower points included) is almost the same as what has been obtained from method 3 (full ground control version).

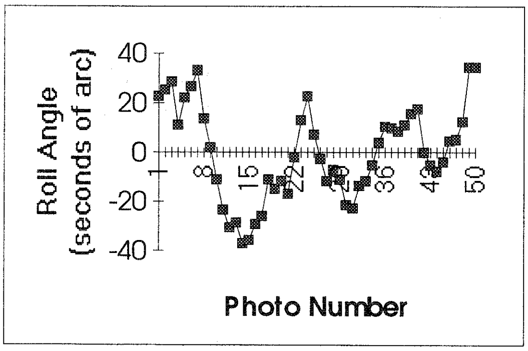

Figure 3. Adjusted Roll Angle from Method 1

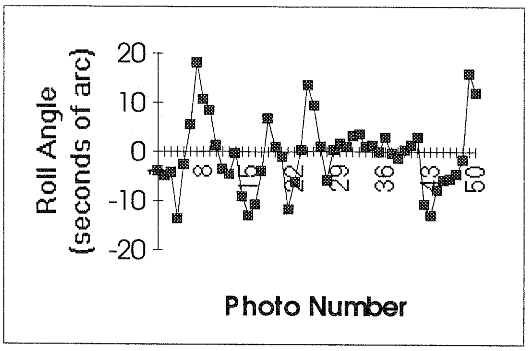

Figure 4. Adjusted Roll Angle from Method 2

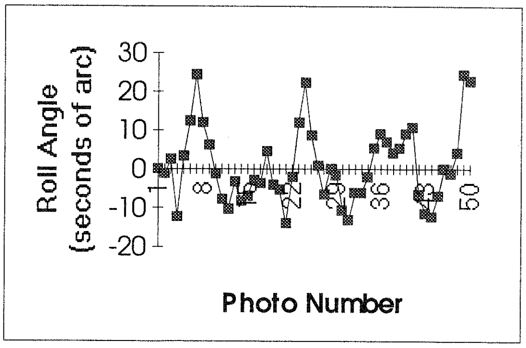

Figure 5. Adjusted Roll Angle from Method 3

In the reliability analysis, redundancy numbers, internal reliability factors, and external reliability factors were computed for various observations (image coordinates, GPS coordinates of exposure stations). Table 2 and 3 show the reliability measures for image coordinates and GPS coordinates of exposure stations for the various methods.

Table 2. Reliability Measures for Image Coordinates

Method Reliability Measure	1		2		3	
	x	y	x	y	x	y
r_i	0.28	0.11	0.34	0.54	0.23	0.39
$\delta_{0,i}$	8.34	12.52	8.41	5.73	9.96	6.61
$\bar{\delta}_{0,i}$	7.21	11.85	7.11	3.93	8.98	5.21

Table 3. Reliability Measures for GPS Coordinates of Exposure Stations

Method Reliability Measure	1			2		
	X	Y	Z	X	Y	Z
r_i	0.74	0.80	0.84	0.74	0.85	0.82
$\delta_{0,i}$	4.65	4.47	4.36	4.66	4.34	4.42
$\bar{\delta}_{0,i}$	2.36	1.98	1.72	2.37	1.67	1.85

These values are rated as good ($0.5 < r_i$, $\bar{\delta}_{0,i} < 4.0$), acceptable ($0.1 \le r_i < 0.5$, $4.0 \le \bar{\delta}_{0,i} < 10.0$), bad ($0.04 \le r_i < 0.1$, $10.0 \le \bar{\delta}_{0,i} < 20.0$), and not acceptable ($r_i < 0.04$, $20.0 \le \bar{\delta}_{0,i}$)(Förstner,1985). The best values for the reliability measures have been obtained from method 2 which imply that including tower points in the GPS controlled strip triangulation improves the reliability of both image coordinates especially the y coordinates of image points and GPS observations.

4. 3. Results With Real Data

Encouraging results from the simulated data have convinced us to apply this new technique on real data. The results from the real data was not available at the time of writing this paper. These results will be presented during the conference.

5. CONCLUSIONS

GPS controlled strip triangulation was carried using geometric constraints of man-made structures (power towers) to replace the ground control points needed to recover the roll angle of the camera. The results obtained from the simulated data show that if kinematic GPS can provide decimeter accuracy for the camera exposure stations, then the strip adjustment can be done without any ground control points as long as the datum transformation is known. Normally, two or three strips of photography are taken to recover the roll angle of the aircraft and to increase the geometry of a single strip. This new technique for single strip adjustment eliminates the need for multiple strips of photography and reduces both the time and the cost of the mapping project.

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