A PRACTICAL TEST OF A PHOTOGRAMMETRIC PROJECT CONTROLLED WITH AIRBORNE GPS

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ABSTRACT:

GPS derived camera exposure centers can greatly reduce or eliminate the need for ground control in aerotriangulation. Continuous kinematic processing of GPS carrier phase observations can produce camera positions accurate to 10 cm. Alternatively, code phase pseudo-range positions that have been post-processed can be accurate within 1 to 2 meters. During aerotriangulation, the GPS derived camera station coordinates, suitably weighted, control the bundle adjustment.

Although theoretically simple, there are many practical problems to solve before the use of airborne control becomes operationally efficient. These include selecting and mounting a GPS antenna on the aircraft, connecting the GPS receiver to the aerial camera, and determining the offset vector from the antenna to the camera nodal point.

In the project described, high-altitude photographs were taken while one GPS receiver in the plane and two on the ground recorded carrier phase as well as C/A and P code observations. The airborne receiver automatically recorded exposure times, so that camera coordinates could be interpolated from the GPS data. Constrained camera coordinates, combined with varying numbers of ground points, control the bundle adjustment. A traditional bundle adjustment, computed from a conventional ground control configuration, provides a basis for evaluating the accuracy of the results.

KEY WORDS: **GPS, Photogrammetry, Aerotriangulation**

1. INTRODUCTION

The main objective of this project was to evaluate the utility of GPS-controlled aerial photography for mapping purposes, in particular, for the efficient production of digital orthophotography for use as a GIS image layer. The ability to produce digital orthophotos with airborne GPS has the potential to save time and money through a reduction of ground control. In addition, airborne control eliminates the practical difficulty of obtaining access to private or protected land for targeting and control surveys.

This project was funded by the U.S. Forest Service. The USFS is planning to acquire 1:40,000 scale photography covering the state of California during 1993-1994. This paper assesses the potential of GPS-controlled photogrammetry for decreasing the costs and increasing the efficiency of such an effort. Researchers have already concluded that GPS supported aerial triangulation is ready for practical application (Freiss, 1991). However within the industry, questions remain concerning the operational implementation and dependability of GPS photogrammetry. This project provides a practical test of such methods in a production oriented environment.

The USFS provided ground control coordinates to check the results of the airborne GPS-controlled block. If the airborne control failed, this ground control alone would have been sufficient to complete the orthophoto project.

This discussion will compare the results of the traditional ground-controlled bundle adjustment to airborne GPS-controlled solutions with reduced or no ground control. The practicality of using pseudo-range processing versus continuous kinematic processing to derive camera positions for small-scale mapping will also be discussed.

The portion of this project involving the production of digital orthophotos will not be treated as it is not relevant to the evaluation of GPS airborne control for aerotriangulation.

2. PROJECT DESCRIPTION

The project area is located in the rugged mountains of northern California's Sierra National Forest, immediately south of Yosemite National Park. The area is defined by two U.S. Geological Survey 7.5 minute quadrangle maps, the Fish Camp quad and the White Chief Mountain quad. The site is typical for the USFS in California, one with much relief, significant geoid undulation, and sparse geodetic control.

A small airport in Mariposa, California was used as a base of operations for the photogrammetric mission. The airport is located about 25 kilometers west of the western edge of the project block. One GPS base receiver was set on a surveyed point at the airport, station WINDSOCK. A second base receiver was placed on a surveyed point on the western project boundary, station WATT ROAD.

3. GROUND CONTROL SURVEY

The ground control survey was performed with Trimble 4000 series receivers and software using static GPS techniques. The ground control points were not paneled prior to the photographic mission. Techniques of photo identification were to be used to tie image control points to ground survey points. However, scheduling required the survey to begin before the photography was available for image point identification.

Ground control points and azimuth marks were surveyed near planned image control point locations. The actual points were later specified from the photography and subsequently surveyed using a Geodimeter 410 total station. This approach is valid in a production environment intended to produce small-scale maps.

The control survey extended from the airport to the southeast corner of the White Chief Mountain Quadrangle, a distance of about 70 kilometers. The survey tied in one first-order triangulation station, "Shultz 1931" about 14 kilometers west of the airport. Control was extended to the airport taxiway to provide an initialization point for the aircraft antenna.

Four second-order benchmarks were found in the project area to use as vertical control. The benchmarks were set in the 1930's by the USGS. In the control net, each benchmark was tied directly to one control point in the center of the project area at the top of Miami Mountain. Discrepancies of up to two meters in the vertical were found but could not be resolved with the available information.

The final network adjustment was performed by the USFS and was forced to fit the existing vertical control. An adjustment was carried out on WGS84 using GEOID90 (Milbert, 1991) to determine the ellipsoid heights of the benchmarks. The ground coordinates in WGS84 were then used as ground truth for the remainder of this study.

4. FLIGHT PLAN

The area to be mapped is rectangular, having dimensions of approximately 22 kilometers east to west, and 14 kilometers north to south, with elevations ranging from 2100 feet to 8800 feet above sea level. The photo scale was specified as 1:40,000. All flight lines were oriented in the north-south direction. Four flight lines of five exposures each would have provided stereo coverage with approximately 60 percent endlap and 40 percent sidelap.

Computer simulations tested the behavior of this flight plan using airborne GPS as the only control for aerotriangulation. The simulations showed some geometric weakness due to a hinge effect between adjacent strips. Doubling the number of flight lines increased sidelap to 70 percent. Simulations based on this revised plan showed a significant increase in geometric strength.

A gyro-stabilized camera mount, with digital readout of the camera orientation angles (Lorch, 1991), was not available for this project. Therefore, it was necessary to lock the camera down in its mount so that the vector from the GPS antenna to the camera nodal point would remain constant and could be directly measured. To insure that locking down the camera would not result in stereo gaps, endlap was increased to 80 percent.

Steep climbs, banks and descents can cause the GPS satellite signals to be obstructed by some part of the aircraft. Because of this, a single flying height was planned for all flight lines to minimize altitude changes. To allow very wide turns and shallow banks, the flight lines were flown out of sequence.

The photo mission was flown with a twin engine Cessna 310 aircraft. The plane carried a Zeiss RMK TOP 15 aerial mapping camera with a six-inch focal-length lens. This camera features an interface for GPS receivers. At the midpoint of each exposure, the camera sends an electronic pulse to the GPS receiver, which logs the time of the event to the nearest microsecond. These event markers allow interpolation of the camera station coordinates during data processing.

5. EQUIPMENT SETUP AND CALIBRATION

A Trimble 4000 SST GPS receiver was connected to the Zeiss RMK TOP camera during the flight. A Tecom FAA certified dual frequency GPS antenna was mounted on the vertical stabilizer of the aircraft. This location was chosen to minimize interference from the wings during turns, and to minimize multipath, or signal reflection, which can occur when the antenna is located just above large reflective surfaces. Multipath can be one of the most significant error sources during GPS data collection.

When GPS-derived camera positions are used as photgrammetric control, the spatial relationship of the GPS antenna to the focal point of the camera must always be known. For this project, that meant the camera had to be locked down in its mount. The camera operator was allowed to level and crab the camera for the first flight line but could not adjust the camera again for the remainder of the mission. On the following morning, a survey was done to determine the position of the GPS antenna in the camera coordinate system.

Two theodolite stations were established about six feet apart on the pavement about ten feet away from the aircraft. With the cargo door open and the film magazine removed, the focal plane of the camera could be seen from each of the stations. Using a Topcon GTS-1, horizontal and vertical angles were observed to each fiducial mark and to the GPS antenna on the tail. Distances were also measured with a tape to four of the eight fiducials and to the antenna.

A least-squares adjustment of this small survey network was computed using the STAR*NET (Curry, 1989) software to obtain XYZ coordinates of the fiducials and the GPS antenna in an arbitrary local coordinate system. The calibrated distances between fiducial marks were included in this adjustment for added geometric strength.

The coordinate system of the camera has its origin at the perspective center of the lens and is referenced by the focal plane and the fiducial marks. The focal plane was not level, since it remained in the position in which it had been used the day before. To compute camera coordinates for the antenna, the arbitrary local XYZ survey coordinates (which were on a level datum) were subjected to a three-dimensional least-squares coordinate transformation, matching the surveyed fiducial coordinates to the calibrated values.

The resulting camera-to-antenna vector was -13.74 feet in X, -1.92 feet in Y, and +7.04 feet in Z. It is estimated that the vector was determined with a standard error of approximately 0.010 feet in each component.

6. GPS DATA COLLECTION

Differential GPS data can be collected and processed in two different modes: carrier-phase and code-phase. During this mission, all receivers collected dual-frequency carrier-phase observations, as well as C/A- and P-code data. Data was collected at a 2.0 second rate.

Kinematic processing of carrier-phase measurements can provide centimeter-level accuracy, however continuous lock on at least 4 satellites is required. The airborne receiver was run in kinematic mode during the entire flight. Data collection in kinematic mode requires that the system be initialized before takeoff. The known baseline method of initialization, rather than the antenna swap, is suitable for use with an aircraft-mounted antenna.

A nail had been placed in the airport taxiway as part of the ground control survey previously described. Using a theodolite, a point was marked on the underside of the plane directly beneath the center of the antenna. Before takeoff, the airplane was positioned so that the marked point was plumb over the nail. Antenna height was then measured, and the receiver turned on. After several epochs of GPS data were collected, the aircraft taxied for takeoff. The entire initialization procedure took only a few minutes.

Recent advances in GPS data processing (such as rapid static) will now allow initialization of the system simply by sitting still anywhere on the runway and collecting data for five to ten minutes.

For kinematic purposes, a known base station must be near the airport to guarantee accurate initialization. Depending on satellite configurations and atmospheric conditions, this distance could be up to twenty kilometers. However, if the project area is a long way from the airport, kinematic solutions for the camera positions may be less accurate. The requirement of locating a known base station close to both the airport and the project area is one of the current limitations of this technique. In the future, it may be possible to use multiple base stations to remove this limitation.

Code-phase processing can achieve absolute accuracy of one to two meters in three-dimensional position, when both C/A- and P-code pseudoranges are collected. In the pseudoranging mode, a minimum of four satellites must be visible, but continuous lock on the satellites is not required. Signal interruptions due to banking the plane do not affect the GPS-derived camera positions as long as lock is regained a minute or two before the exposure of photography. Continuous lock should be maintained along any single flight line to ensure consistency of the results.

The collection of pseudo-range data does not require any initialization, nor does it require a base station near the airport. The base station can be located at any known point in or near the project area. Both the base and airborne receivers can begin collecting data when the aircraft enters the project area. This saves a considerable amount of receiver storage, an important practical consideration when data is being collected at the very rapid intervals required for photogrammetry.

The flying time required for this project was approximately two and one-half hours from take-off to landing. The photography was acquired over a one and one-half hour period. Five satellites were available for the initialization and takeoff. The photography took place during periods of four and five satellites. Several constellation changes occurred, causing momentary instabilities in PDOP, but continuous lock was maintained throughout the flight.

The aircraft antenna was plumbed over the initialization point after landing, and kinematic processing later verified closure of 1.4 meters in X, 1.9 meters in Y, and 1.1 meters in Z. Factors contributing to this misclosure may include inaccurate positioning of the airplane over the mark, undetected cycle slips, or drift in the GPS solution due to incorrect initialization of the kinematic solution. The maximum distance between the base station and aircraft was about 70 kilometers.

7. GPS DATA PROCESSING

The carrier-phase observations were first processed in continuous kinematic mode with Trimble's 4000 series software. The USFS had the NGS program OMNI (Mader, 1991) to use as an independent check on the kinematic solution, but these particular data sets were not collected in an OMNI-compatible format. The scale of this photography probably does not require the centimeter accuracy of kinematic processing to achieve satisfactory results from the aerotriangulation (Ackermann, 1992). This project provided an opportunity to compare kinematic and pseudo-range accuracies. Accuracy requirements can then be weighed against the practical constraints of data collection.

The pseudo-range observations were reduced using PostNav II, a Trimble software package designed for post-processing of differential code-phase datasets. PostNav II uses an 8-state Kalman filter and backward smoother allowing optimum position and velocity estimates to be calculated at every epoch. Using a combination of C/A- and P-code measurements, suitably weighted, a three-dimensional solution is obtained from four or more satellites. A minimum of four satellites should have nearly-contiguous measurements with a signal-to-noise ratio (SNR) of greater than eight. PostNav II outputs SNR and a measurement residual for every epoch, giving the user a measure of the integrity of the estimates.

Another important feature of PostNav II is its ability to use knowledge of the vehicle dynamics of the mobile receiver during processing. The program is able to accommodate changes in position consistent with the environment in which the data were recorded. The user selects one of five filtering modes that control the noise gain used in data smoothing. Vehicle dynamics may be declared as static (no velocity), steady state (constant velocity), or low, medium or high acceleration environments. The high dynamic mode was used to process the data for this project.

Table 1 summarizes the pseudo-range solution using station WINDSOCK as a base. Residuals are grouped by photographic strips (when the plane is flying straight and level), and the averages and RMS values shown in units of meters. These results show that for three of the four strips, pseudo-range positions should be accurate to approximately one meter. Strip 6 is the exception, with a RMS slightly greater than one meter, probably due to a satellite constellation change that occurred during this period.

	Strip 2	Strip 4	Strip 6	Strip 8
mean	-0.03	0.26	-0.03	-0.04
rms	0.86	0.95	1.16	0.34

Table 1. Residuals from PostNav II pseudo-range processing, in meters.

Mean residuals close to zero indicate that the error in position is randomly distributed. Accuracy of the position estimates can be inferred from the RMS values. These results support the claim that combined C/A- and P-code observations can be used to achieve meter, or even sub-meter, accuracies. It is reasonable, therefore, to adopt an a priori standard error of one meter for the GPS antenna positions in the aerotriangulation phase.

8. AEROTRIANGULATION

When the photography had been processed and reviewed, it was decided that only the four original flight lines would be used. Flight lines

2,4,6 and 8 had sufficient sidelap to permit a strong aerotriangulation. The 80 percent endlap along flight lines also proved to be unnecessary. Every other photo was used, providing 60 percent endlap with no stereo gaps, even though the camera had been held fixed. The final aerotriangulation block then consisted of four flight lines of five exposures each.

The block was designed with a configuration of at least four pass and tie points distributed across the center of each photo, perpendicular to the direction of flight. Sidelap was sufficient to permit two points on each side to be tied to the photos of the adjacent strip. This network of double overlapping tie points created a very strong internal block geometry.

The photographs were printed on DuPont Aerial Flexiglass Diapositive Film for aerotriangulation. The pass points and tie points were marked in stereo on each photograph with a Wild PUG-4 point transfer instrument. The photo measurements were made with a Kern MK-2 monocomparator.

All the ground control points were photo identified natural images. To avoid destroying the image detail with PUG marks, the ground control points were measured using stereocomparator techniques on a Zeiss C-120 analytical stereo plotting instrument. These measurements were then combined with the monocomparator data.

The initial aerotriangulations were computed with the bundle adjustment program BINGO (Kruck, 1985). The first solution used only the 12 ground control points and was a routine exercise that needs no special discussion. It served as the "benchmark" against which the airborne control solution could be evaluated.

The airborne-controlled aerotriangulation was computed using an interesting feature of BINGO, which was actually designed for use in close range photogrammetry. It allows for eccentricity when a camera is set up over a known control station. The following observation equation is then included in the bundle adjustment:

$$\mathbf{x}_S = \mathbf{x}_C + \mathbf{Re} - \mathbf{i}$$

Where $\mathbf{x}_S$ is the position vector of the control station, $\mathbf{x}_C$ is the position vector of the lens perspective center, $\mathbf{R}$ is the camera rotation matrix (photo to ground), $\mathbf{e}$ is the eccentricity vector.

The NGS program, GAPP, (Lucas, 1987), which was designed for use with GPS airborne photgrammetric control, was used as an independent check against the BINGO solution. GAPP contains an observation equation which accounts for the camera to GPS antenna vector that takes the form:

$$\mathbf{x}_A = \mathbf{x}_C + \mathbf{Re'}$$

where $\mathbf{x}_A$ is the position vector of the antenna, $\mathbf{x}_C$ is the position vector of the camera perspective center, $\mathbf{R}$ is the camera rotation matrix (photo to ground), and $\mathbf{e'}$ is the vector from the camera perspective center to the antenna, expressed in the camera coordinate system.

Antenna positions corresponding to precise event marker times must be interpolated to provide camera positions. A linear interpolation scheme was used with BINGO. GAPP performs the interpolation based on a cubic polynomial fit to the epoch-by-epoch positions.

9. RESULTS AND CONCLUSIONS

Four airborne-controlled bundle adjustments were computed using GAPP, two with kinematic camera stations, and two with pseudo-range camera stations. In each case, aerotriangulation was first performed without any ground control. The adjustments were repeated, adding the four ground control points closest to the corners of the block. Coordinates of 79 triangulated pass points were compared to the conventional ground-controlled adjustment as a check. The average differences and RMS errors for all four comparisons in presented in Table 2. All heights were referenced to the WGS84 ellipsoid.

	Number of Ground Control	dX	dY	dZ
KINEMATIC	0			
mean		-0.4	-0.4	-0.8
rms		1.8	1.8	1.5
KINEMATIC	4			
mean		-0.1	-0.2	-0.3
rms		1.1	1.2	1.2
PSEUDO-RANGE	0			
mean		-1.5	-0.1	-0.4
rms		1.4	1.4	1.4
PSEUDO-RANGE	4			
mean		-0.9	0.1	0.2
rms		0.5	0.6	1.1

Table 2. Average Differences between Ground-Controlled Solution and Airborne-Controlled Solutions for 79 Pass Points, in meters.

Kinematic GPS-derived camera centers were equally weighted with an a priori standard error of 0.5 meters. Difficulties in processing the kinematic data, due to poor satellite geometry and abrupt changes in PDOP, reduced confidence in the kinematic solution. For this reason, a large a priori error, by kinematic standards, was used.

The pseudo-range positions were equally weighted with a standard error of 1.0 meters based on the statistics of the PostNav II solution. The ground control provided by USFS was also considered accurate within one meter. The standard error of unit weight, σ_o, for each bundle adjustment is shown in Table 3. The fact that in all cases, σ_o is near 1.0 indicates that the a priori standard errors assumed for the GPS positions were appropriate.

	Number of Ground Control	σ_x	σ_y	σ_z	σ_o
KINEMATIC	0	0.50	0.50	0.50	1.03
KINEMATIC	4	0.50	0.50	0.50	1.06
PSEUDO-RANGE	0	1.00	1.00	1.00	0.96
PSEUDO-RANGE	4	1.00	1.00	1.00	0.99

Table 3. A priori Standard Errors and Standard Error of Unit Weight for Airborne-Controlled Bundle Adjustments, in meters.

In conclusion, we were able to collect both airborne kinematic and pseudo-range data on a two and one-half hour flight with no significant loss of satellite signal strength. The acquisition of photography and the aerotriangulation proceeded routinely, and the expected results were obtained. The accuracy limitations inherent to small-scale photography and methods of photo ID control made it difficult to find significant differences between the kinematic and pseudo-range results.

This project has demonstrated the utility of using code-phase measurements to control high-altitude photography. No initialization is required, the quantity of data required to produce a solution is much less than for continuous kinematic, and the post-processing itself is easier. In addition, segments of the data can be processed separately, making it possible to reduce the effects of short periods of poor satellite geometry on the solution.

The USFS accepted the GPS airborne control for the processing of the digital orthophoto job which followed the aerotriangulation. This project demonstrated that it is possible to effectively collect airborne GPS data in an operational environment. No precautions were made to control systematic errors that would be considered unusual for a small-scale, production mapping mission. For this reason, it is a project which should be of immediate interest to the commercial industry.

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