Practical Considerations for the Use of Airborne GPS for Photogrammetry

Abstract

The term "GPS photogrammetry" is applied to the use of an airborne global positioning system (GPS) receiver in conjunction with the collection of aerial photography. There are two important reasons to use airborne GPS: to perform accurate flight-line navigation, and to reduce the amount of ground control required for the aerotriangulation adjustment. Research has shown that the use of GPS-derived camera exposure centers in aerotriangulation can greatly reduce or even eliminate the need for ground control. A number of successful tests have been conducted in research environments where great care has been taken to control systematic errors, and bundle adjustment programs have been specially modified to incorporate GPS-derived exposure stations.

The photogrammetric mapping community has recognized the potential savings in time, effort, and expense offered by the use of GPS photogrammetry. The success of the photographic mission, however, depends on a good understanding of the operational requirements, and their effect on flight planning and data processing. There are many practical issues that must be addressed before undertaking a GPS photogrammetry project. These issues 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 phase center of the GPS antenna to the camera nodal point. Knowledge of the basics of the global positioning system, GPS data processing, and photogrammetric block adjustments is also required.

Introduction

Placing a global positioning system (GPS) receiver in an aircraft performing a photographic mission serves two main purposes: flight-line navigation and control for aerotriangulation.

A GPS receiver linked to the camera can be used to derive the position of the camera exposure station at the time of each photo exposure. The exposure stations can be determined to within 10 cm using the GPS kinematic mode, or to within 50 to 100 cm using the GPS pseudorange, or code-phase, mode. Such accuracies at the exposure stations are sufficient to control a bundle adjustment for many mapping applications, thereby greatly reducing or even eliminating the need for ground control in the photogrammetric block.

Used in the real-time mode, GPS-derived positions assist with precise flight-line navigation, reducing gaps and excessive overlaps in the photo coverage. A connection between the receiver and the aerial camera can trigger exposures at planned locations. Integrated flight management systems are becoming available to provide automated preflight planning, in-flight navigation and automatic exposure functions, and postflight analysis of photographic coverage.

A number of researchers have made important contributions to this field over the last decade (Ackermann, 1992; Friess, 1991; Lapine, 1990; Lucas, 1987; Merchant, 1991). As GPS receiver technology has advanced, and as new software processing techniques have been developed, applications to photogrammetry have become more widespread. However, there are a number of practical aspects of the use of GPS photogrammetry that, if understood, will greatly enhance the likelihood of a successful mission. This paper will review some of these practical considerations, and offer suggestions that can reduce the number of problems associated with the adoption of this new technology.

GPS Overview

The Global Positioning System consists of a series of orbiting satellites that transmit data on two carrier frequencies that can be received by stationary and moving receivers on and above the Earth's surface. There are currently 21 active satellites, orbiting at an altitude of 20,200 kilometres. A minimum of four satellites must be visible at the receiver location in order to compute a three-dimensional position. Most regions of the world now have close to 24 hours per day of three-dimensional coverage. However, it is often advantageous to have at least five satellites in view for aerial mapping applications.

The satellites transmit data on two carrier frequencies, normally referred to as L1 and L2. The L1 frequency is modulated with two codes, called C/A-code and P-code. The L2 frequency is modulated with P-code only. Depending on receiver design, one or more of the codes and one or both of the carrier frequencies are used to compute positions.

Many light-weight, low-cost GPS receivers use only the C/A-code for position computation and navigation purposes. A single C/A-code receiver operating in autonomous mode can compute positions to within 30 to 100 metres, depending on the level of selective availability, or S/A, that is present. S/A is used by the U.S. Department of Defense to deliberately reduce the positional accuracy obtainable by a single receiver. By using a base receiver located over a known point to correct the positions at the remote receiver, accuracies of 2 to 5 metres can be achieved with C/A-code. This differential correction can be done in real time, with a radio link between the base receiver and the remote, or by postprocessing the data files collected by both receivers. Normally, the base should be within 300 kilometres of the second receiver. S/A

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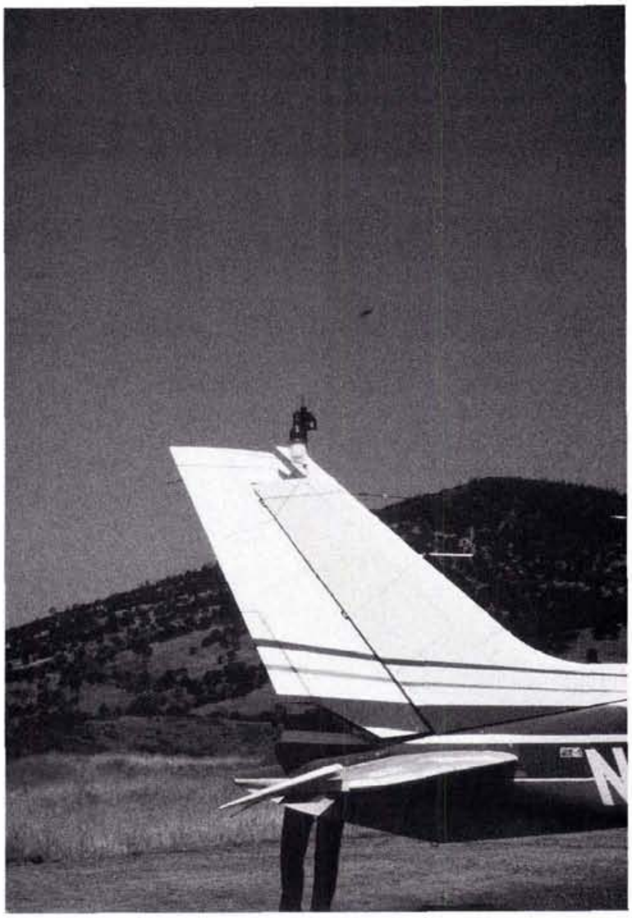

Figure 1. GPS Antenna mounted on tail of aircraft.

has little effect on the accuracy of differentially corrected C/A-code positions.

The use of differentially corrected P-code allows somewhat more accurate position determination. Recent experiments have shown that accuracies of better than one metre can be achieved, even in the highly dynamic situation of a small aircraft. At some time in the future, the P-code will be encrypted, and replaced with the Y-code. This process is called anti-spoofing, or AS. Civilian GPS users will not have access to the Y-code. Several recent advances in receiver design, using various techniques such as cross-correlation of the L1 and L2 signals, allow users to achieve comparable results to those obtainable with P-code, even during encryption. Also, newer receiver designs have improved C/A-code performance such that differentially corrected positional accuracies on the order of one metre are possible.

Traditionally, static GPS baselines have been determined by collecting an hour or more of data at two stations. The receivers measure the fractional part of the arriving carrier wave, but extensive processing is required to compute the integer number of full wavelengths between the receiver and the satellites. Newer, "fast-static" techniques have reduced the required occupation times to 5 to 10 minutes. Such carrier-phase processing is usually not affected by S/A.

Receivers designed for surveying track and measure the L1 carrier (single frequency receivers) and sometimes also the L2 carrier (dual frequency receivers) as well as the C/A and P-codes. Baseline accuracy specifications are normally from 5 to 10 millimetres, plus 0.5 to 1 part per million (ppm) of the baseline length, depending on the duration of the baseline occupation and ambient conditions. Because computed baselines are vectors between two receivers, one receiver must be located on a station with known coordinates to derive the position of the second receiver.

In order to track a moving platform with surveying accuracy, kinematic GPS techniques are required. Initialization between the two receivers in a static mode is required to determine all of the integer wavelength counts. Once initialization is complete, one receiver is free to move, as long as continuous tracking of at least four satellites is maintained. If tracking is interrupted (called a cycle slip), the number of integer wavelengths cannot be recovered, and baselines can no longer be determined.

When using L1 and L2 carrier tracking for GPS photogrammetry, traditional postprocessing techniques require continuous tracking of four or more satellites from takeoff until the end of the photography. There are several new processing techniques that will remove this restriction on kinematic carrier-phase GPS, but they are not yet in common use. These new techniques are discussed in later sections of this paper.

Kinematic data consist of only a single set of observations at each point. Accuracies are not as high as with static surveying, and are normally on the order of 1 centimetre plus 2 ppm of the baseline distance. In the airborne case, the baseline will be the distance from the base receiver to the aircraft. Base stations should therefore be located such that kinematic accuracies will meet the project requirements.

Some research has been done using code phase positioning to determine exposure stations for aerotriangulation (Schuckman *et al.*, 1992). The major advantage of using pseudorange data is that continuous tracking is not required. If the aircraft banks steeply in a sharp turn, and is tracking fewer than four satellites, position information is lost only until at least four satellites are reacquired. The exposure stations will be determined less precisely with pseudoranges than with kinematic data. However, this may be sufficient for many high-altitude projects.

More information on the GPS system and the various data collection and postprocessing techniques is available from Wells (1987) and Leick (1990).

GPS Antenna

The GPS antenna should be mounted on the aircraft in a place where it is free to receive the GPS signals with a minimum of obstruction. Recommended locations include on the fuselage directly over the camera, or on the tip of the vertical stabilizer (Figure 1). The fuselage location has the advantage that the phase center of the antenna can be located along the optical axis of the camera, which greatly simplifies the measurement and modeling of the antenna offset vector, discussed later in detail. However, the fuselage location may be more subject to multipath (the reception of reflected signals in addition to the direct signal) off other parts of the airplane. Multipath degrades the accuracy of the calculated position. Depending on aircraft wing placement, the fuselage location may also be more subject to shadowing of the antenna (blocking of GPS signals) during turns, causing cycle slips.

The vertical stabilizer location is usually less susceptible to multipath and shadowing. Also, the actual mounting of the antenna may be simplified, as some aircraft already have a strobe light mount in that location that can be adapted for use with an antenna. The disadvantage is that measurement of the antenna offset vector is more involved. However, once the antenna and camera are permanently mounted in the plane, the offset vector need be determined only once; the measurement can be reused for a number of missions.

As a practical matter, the best location for the GPS antenna is the one that is most likely to best receive the GPS signals. This location is dependent on the design of the aircraft. The antenna offset vector can be accurately modeled in the bundle adjustment, regardless of its length or number of components. There is no way to recover from GPS observations degraded by multipath. It is difficult to recover from cycle slips.

Airframe modifications for mounting an antenna must be supervised by a certified aircraft mechanic. Several manufacturers make aviation type antennas, in varying physical configurations, available for single and dual frequency receivers. The GPS receiver manufacturer can recommend a variety of antennas that will work with a particular receiver. A preamplifier compatible with the GPS receiver is required on the antenna cable close to the antenna.

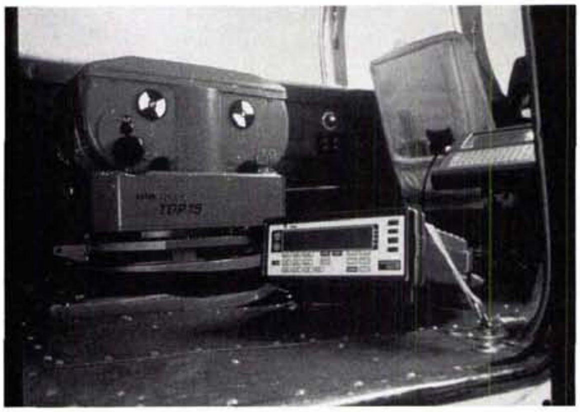

Figure 2. GPS Receiver and Photogrammetric Camera in aircraft.

Receiver-Camera Connection

The GPS receiver and the aerial camera (Figure 2) must be connected so that events of interest, such as camera exposures, can be recorded and correlated with the GPS positions. Modern aerial cameras have a so-called "center of exposure" pulse available for output to the receiver. These pulses are usually repeatable to some tens of nanoseconds. Older cameras can usually be modified to output an exposure pulse, but the repeatability may not be as good. Also, there may be some pulse lag that will require calibration. Several firms have developed camera retrofit kits to provide the exposure pulse.

The GPS receiver records data at regular intervals, called epochs, which can be set by the user; a typical interval for photogrammetric applications may be every half-second. However, camera exposures can come at any time, and the camera position at the time of exposure is usually interpolated from the GPS positions. Theoretically, the camera can record exposure times to high accuracy, and the interpolation can be performed from those times. However, because GPS receivers have an extremely accurate time base, and because most receivers allow a simple cable connection from the camera, it is preferable to record event times in the receiver. Every time an exposure occurs, the camera pulse is sent to the receiver, and the event time and identifier are recorded in the receiver data file. GPS receivers can also produce an accurate pulse-per-second signal that can be used to trigger the camera at the GPS epoch closest to the desired exposure time.

Use of the exposure pulse to mark the occurrence of an event raises the question of what exactly defines the instant of a photographic exposure. In forward motion compensation cameras, the exposure pulse is usually triggered when the fiducials are exposed onto the film. However, in older cameras, the situation is not as clear. One school of thought states that an image is created as soon as enough photons hit the silver halide crystals to cause the ground control targets to begin to be exposed. The errors caused by these timing differences are usually small, but for high accuracy at large photo scales the errors may become significant. Some bundle adjustment programs, GAPP (Lucas, 1989) for example, allow the user to correct for systematic exposure-timing errors.

After the flight is completed, and the film processed, it is necessary to correlate the individual frames with the GPS event markers. Some cameras have the ability to accept data from the receiver, making it possible to imprint the time and approximate coordinates onto the margin of the film. Lacking such a sophisticated system, one can set the camera clock to GPS time, so that GPS time is recorded on every frame, thus making the match to GPS event markers easier.

Antenna-Camera Offset

During the flight, the GPS receiver stores position information for the GPS antenna at the instant of the photograph exposure. However, the coordinates of the camera exposure station are required for the bundle adjustment. The offset vector between these two points must therefore be determined. If the antenna has been located directly along the camera optical axis, the offset vector consists of a single vertical component. If not, a more complex measurement is required. The antenna offset can be measured directly by a close-range survey, with angular and distance measurements between the fiducial marks of the camera and the estimated location of the phase center of the antenna (Curry *et al.*, 1991). The antenna manufacturer should be able to provide the phase center location.

In order to extrapolate from the GPS antenna location to the exposure station location, the antenna offset vector must be transferred to a georeferenced coordinate system. A three-dimensional coordinate transformation can be applied if the three angular rotations are known. During flight, the orientation of the aircraft (and therefore the camera coordinate system) is constantly changing with respect to the ground coordinate system. The three angular components of aircraft attitude, often called roll, pitch, and yaw, can be used to correctly transfer the GPS antenna position to the exposure center.

A bundle adjustment determines the components of aircraft attitude in the form of the camera orientation parameters. For use with airborne GPS, the bundle adjustment program must be modified to resolve the offset vector into the ground coordinate system at every iteration, based on the updated values of the orientation parameters. Coordinates for the exposure station can then be calculated. A formulation for this modification is given by Erio (1992). Note that the antenna position is actually held fixed in the adjustment, while the exposure station moves about in space with respect to the antenna.

The previous discussion assumes that the camera is locked down in its mount. Traditionally, aerial cameras are allowed to tilt in their mounts so that the optical axis stays approximately perpendicular to the ground, a factor that contributes to the high quality of the photographic imagery. Depending on the variation in attitude of the aircraft during flight, locking down the camera in its mount may result in slightly nonvertical photography. Additional leeway should therefore be provided in planning of overlap and sidelap to ensure complete stereo coverage.

If the camera is not locked down, its orientation changes with respect to the aircraft during flight, and therefore the components of the antenna offset vector in the camera coordinate system also change. If the antenna is mounted directly above the camera, along the optical axis, this change in orientation angles (especially crab) can often be ignored, and the offset can be treated as a constant. Accuracy requirements of the project determine whether or not the error introduced by this assumption is significant.

If the antenna is mounted on the tail and the camera is not locked down, it is necessary to record the orientation angles in flight for each frame and supply them to the bundle adjustment. As gyro-stabilized camera mounts become available with digital output, it will be possible to record the orientation angles for each photograph in a camera data file, and use these data in the bundle adjustment as observed parameters.

Mission Planning and Flight Concerns

Careful mission planning is the key to the successful use of GPS photogrammetry. All GPS receiver manufacturers supply planning software that helps to determine the satellite constellation at a particular date, time, and location. Although a minimum of four satellites in view is required for three-dimensional positioning, flights should be planned for periods when at least five or six are in view. That way, if one or two are obscured during a turn, carrier-phase processing can continue. Even if only C/A-code data are being collected and processed, additional satellites will improve the results through increased redundancy and improved satellite geometry.

The location of the base receiver (Figure 3) should be carefully planned to minimize obstructions and multipath. To reduce noise due to atmospheric effects, data are normally collected from satellites only when the satellites are 15 degrees or more above the horizon. An elevation mask can be set in the planning software and can also be programmed in the receiver. It is recommended that mission planning be done with an elevation mask of 15 degrees; however, it is often useful to set a lower mask on the receivers during data acquisition. Tracking low satellites can help to salvage a data set where cycle slips occur during turns. The low-elevation data can be filtered out by the post-processing software if it is not needed.

All GPS receivers calculate an indicator of the accuracy of position computations. Positional dilution of precision (PDOP) is determined by satellite geometry, and is available from the planning software. PDOP should be in the 3 to 5 range for good results, and flights should not be planned when PDOP is greater than 7 or 8 during any portion of the mission. There are frequently brief spikes (high values) in PDOP as satellites rise and set. If necessary, it may be possible to continue calculating positions through a PDOP spike and achieve good results on either side.

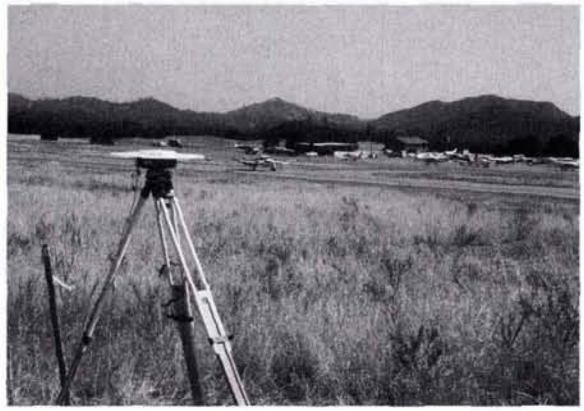

Figure 3. Aircraft taking off, with GPS reference station in the foreground.

GPS data should be recorded in the receiver at a rate commensurate with the required accuracy of the photogrammetric project. Normally, a one-second or half-second rate is sufficient. Many survey receivers have sufficient memory to record the observations from five or six satellites at a half-second data rate for three or four hours in dual frequency mode. For longer flights, data can often be recorded in an external device such as a PC. It may also be possible to upgrade the receiver by adding additional memory.

The base receiver and the aircraft receiver should start logging at approximately the same time, because only those data collected simultaneously at both receivers can be differentially corrected. If only code-phase data are being collected, no initialization process is required; both receivers can be turned on at any convenient time during the flight. If conventional kinematic carrier-phase mode is being used, the aircraft receiver must be initialized. This can be done by sitting on the runway for 5 to 10 minutes and performing a fast-static survey to determine a baseline between the receivers, or by physically lining up the aircraft antenna over a known point on the runway, measuring the antenna height, and collecting a few seconds of GPS data. To postprocess in kinematic mode, continuous lock must be maintained on at least four satellites for the duration of the photographic mission.

Whenever possible, data should be collected such that both carrier and code postprocessing methods can be used. In particular, when a firm first begins to use GPS photogrammetry, it should fly a test block with a normal ground control configuration, while collecting both carrier and code data. Then it can experiment with various post-processing techniques to see exactly what levels of accuracy are possible under varying conditions.

Before the aircraft takes off, it is advisable to shoot a few test exposures with the camera connected to the GPS receiver, to make sure that the exposure events are being properly logged. Most receivers display an event counter that indicates that an event has been recorded. This test should be made before every flight; otherwise, one may obtain good GPS data and good photography, but no event markers to tie them together.

During the flight itself there are few additional tasks that the flight crew must perform. The receiver itself requires no attention, although it should be monitored for sufficient battery power and for satellite tracking. If continuous carrier data are being collected, to avoid cycle slips, the bank angles should be restricted to 20 or 25 degrees during turns, depending on the satellite elevations. For mission planning, it is important to note that wide, flat turns will extend the duration of the flight.

It is useful to repeat the kinematic initialization procedures after landing the plane, so that GPS data can be processed backwards to the last loss of lock during the flight. Note, however, that if lock were lost more than once during the flight, there will be a segment in the middle that cannot be solved.

Data should be immediately downloaded to a computer and scanned for loss of lock, to determine whether the day's mission was successful. The postprocessing software should contain a utility that quickly scans the GPS data for cycle slips. The use of a GPS-based flight management system enables the field crew to evaluate photo coverage immediately after the flight.

GPS Postprocessing

Various methods of processing can be used to calculate the antenna positions, depending on the type of GPS data collected. If C/A-code is collected with a real-time radio link from the base station to the aircraft, then positions accurate to about one metre are already available and no postprocessing is needed. If there is no radio link, some form of differential correction must be performed. Some postprocessing software for pseudorange data provides the option of applying filtering and smoothing to the raw positions.

If continuous kinematic carrier-phase data are collected for centimetre-level accuracy, a more complex postprocessing pass is required. As before, the data files from the base and the remote receivers are processed together in a software package supplied by the receiver manufacturer. However, because of the requirement for continuous tracking on at least four satellites, the processing is more complicated and time-consuming. Also, if there are a lot of cycle slips in the data, some manual intervention in the processing may be needed.

Recent advances in GPS postprocessing have made possible the initialization of a carrier-phase kinematic survey while the receiver is in motion. This technique, often called integers-on-the-fly, is still relatively new, and it works best with dual-frequency receivers and good satellite geometry. The base receiver can be placed in the project area, and the airborne receiver turned on when the aircraft approaches the project area. It is not yet known how much uninterrupted data will be required to compute the integers reliably. However, once this procedure is readily available, it will simplify the use of carrier-phase positioning, and restrictions on aircraft banking angles may be eliminated entirely, increasing the efficiency of the mission. As described in the next section, a variant of integers-on-the-fly is available now for photogrammetry through a specialized bundle adjustment method.

Aerotriangulation

Each photograph in a bundle adjustment has six parameters controlling its location and orientation in space. The exposure station coordinates, derived from GPS observations of antenna positions and the offset from antenna to camera center, are treated as direct observations in the least-squares adjustment. The three orientation parameters (κ,ϕ,ω) are computed during the adjustment. It is a common misconception that camera orientation angles must also be supplied to the bundle adjustment when using GPS exposure station coordinates. This is only true in a single frame or single strip of photography, where no ground control is present. In a block or in a single strip with ground control, no orientation angle input is required.

Several GPS manufacturers have developed specialized systems that use a single receiver to determine the orientation of a rigid frame, mounted on the aircraft, holding an array of antennas. The antenna separation is on the order of one metre, and the three orientation angles can be determined to approximately 1 milliradian. Such systems may have applications for single strip photography and with other types of airborne sensors.

The GPS data allow the computation of the antenna phase center at regular intervals, such as every half second. However, the exposure pulses from the camera can come at any time. Therefore, the coordinates of the antenna at the exact moment of exposure must be interpolated. Some bundle adjustment programs (Lucas, 1989) allow the user to input the antenna phase center coordinates at each GPS epoch directly from the postprocessing step. The software then interpolates the phase center coordinates for each exposure event, and computes the camera center coordinates using the offset vector. Other software packages require the user to preprocess the data independently in order to interpolate the coordinates at the moment of exposure. A discussion of various interpolation algorithms can be found in Lapine (1990).

Bundle adjustment software for use with GPS-derived exposure centers should allow for the independent weighting of camera center coordinates, particularly if C/A-code or P-code positions are being used; however, only a few of the well-known bundle adjustment packages have this capability. Because code positions are determined independently and may vary significantly in accuracy, the most accurate adjustment is achieved by independent weighting. Kinematic positions from continuous carrier-phase tracking are not independent, because they are derived from the same initialization solution. Therefore, the adjustment software should also allow global weights to be assigned. Some indication of appropriate *a priori* standard errors can be obtained from the GPS processing software, but experience is required in using these weights in the bundle adjustment.*

An interesting bundle adjustment approach is described by Friess (1991). This method provides centimetre-level kinematic accuracy without the need for initialization and is a variant of initialization-on-the-fly. Carrier-phase data are collected in the air and at the base, and data from each strip are processed as continuous kinematic data. Initialization is performed using a differential C/A-code position at the beginning of the strip. Because that position may be in error by several metres, the kinematic solution "drifts" over time, and computed coordinates contain systematic errors. Additional pa-

*GPS positions are calculated by a least-squares adjustment of observables from a constellation of GPS Satellites. As long as a group of positions is determined from the same constellation, the positions are statistically correlated regardless of the mode of observation (code- or carrier-phase). It is not strictly correct to use a simple *a priori* standard error for the GPS-derived camera exposure stations instead of a fully populated variance-covariance matrix. If rigorous analysis of error propagation is expected from a bundle adjustment that uses airborne GPS for camera station control, significant modification of the bundle adjustment software is required. This is probably unnecessary for most mapping applications, but would be important in more advanced photogrammetric applications, such as photogrammetric control densification.

rameters are added to the bundle adjustment to model these errors on a strip by strip basis. In order to strengthen the block in the presence of the added parameters, cross strips are flown at each end of the block, and a minimal ground control pattern is used.

This method has produced excellent results, and has several significant advantages over traditional continuous kinematic processing in aerial applications. Initialization by observation of a static baseline on the ground is not required. The aircraft can make steep, banking turns between flight lines. The possible resultant loss of lock does not inhibit data processing. One disadvantage to this approach is that specially designed software is required for GPS data processing and for the bundle adjustment. Another disadvantage is that some ground control is always required.

Datums and Coordinate Systems

GPS coordinates are always directly referenced to Earth-centered, Earth-fixed (ECEF) Cartesian *X*, *Y*, and *Z* axes, and are converted to latitude, longitude, and ellipsoid height. Photogrammetric block adjustments have traditionally been carried out with reference to map projections, such as State plane coordinate or UTM zones. Vertical control has always been referenced to a vertical datum representative of the geoid, which deviates substantially from the mathematical neatness of an ellipsoid. The magnitude of separation between the ellipsoid and geoid may be in the tens of metres, negative or positive, and may be variable within the areal extent of a photogrammetric block.

It is common practice to use only the horizontal coordinates of GPS ground control in many photogrammetric adjustments, due to the difficulty of converting ellipsoid heights to the appropriate vertical datum. It is possible, however, to obtain very accurate vertical positions from GPS when referenced to the ellipsoid. This is good news for those in photogrammetry who would like to completely eliminate the need for ground control, but it requires a change in traditional thinking.

Airborne GPS can provide three-dimensional control at every exposure station. Based on our basic understanding of GPS, we conclude that these exposure stations are very precisely located with respect to each other, and with respect to the ellipsoid. In addition, the redundant observations of pass and tie points in the imagery solve the relative orientation of all of the photos. The block is now a very strong geometric figure. Converting the airborne control coordinates to a map projection or vertical datum based on the geoid degrades the block adjustment and is not recommended.

Most photogrammetrists are not accustomed to performing adjustments in latitude-longitude-height coordinates or in ECEF *X-Y-Z*. For the purposes of debugging and fine-tuning the block, most would prefer the results in a coordinate system based on northing-easting-up. A simple three-dimensional transformation can be made from ECEF to a local space rectangular (LSR) system without distorting the geometry of the bundle. Many bundle adjustment programs have the capability to perform this transformation as a part of the adjustment process.

A correction for the effect of Earth curvature is usually made when a photogrammetric block is adjusted to fit a map projection. In many aerotriangulation systems, the Earth curvature correction is applied during image coordinate refinement, along with corrections for lens distortion and atmospheric refraction. Following the approach described above, adjusting the block to fit an LSR coordinate system, the Earth curvature correction no longer applies. The image coordinate refinement software used as a part of a GPS photogrammetry system should therefore permit the user to exclude the Earth curvature correction.

After the adjustment process is complete, the output can be transformed to State plane, UTM, or whatever local projection is required for mapping. The heights can be transformed to geoid elevations using a local geoid model. Of course, the accuracy of the converted elevations depends on the accuracy of the geoid model in the local area. Within North America and Europe, government agencies and universities have cooperatively made great strides in defining the shape of the geoid, and accurate information should not be difficult to obtain in these areas.

Summary

Practical considerations for installing GPS antennas and receivers in an aircraft have been discussed in general. Specific installation requirements are determined by the design of the aircraft, the type of camera and receivers available, and the accuracy requirements of the mapping projects. Any modifications to aircraft must be supervised by a certified aircraft mechanic. In some cases, FAA approval may be required.

The offset from the camera focal point to the antenna phase center must be measured as a vector in the camera coordinate system. Both Lapine (1990) and Curry *et al.* (1991) explain this procedure in detail. Antenna location and the type of camera mount determine whether the camera must be locked down during the mission. The aerial camera must be tested with respect to the consistency and repeatability of the exposure pulse. The exposure pulse is recorded as an event in the GPS data, and the event time is used to interpolate the camera position at the moment of exposure.

The block adjustment must be controlled in a reference system that does not distort the bundle geometry. Earth curvature effects can be eliminated through the use of a local space rectangular coordinate system. Transformations to map projections and vertical datums must be made after the adjustment has been completed. Information concerning the geoid in the project area must be available in order to convert elevations.

Conclusions

The use of GPS-controlled aerial photography for photogrammetry has great potential for reducing the amount of ground control required for photogrammetric blocks. Various researchers and commercial users have demonstrated its capabilities under different conditions. Fortunately, as more satellites are launched, the number of useful satellite windows is increasing. It can still be a challenge, however, to find a period of good satellite geometry, correct sun angle, and the good weather required for photogrammetry.

This paper has attempted to present the practical considerations to a GPS photogrammetry system designed for mapping. A thorough understanding of the GPS topics presented in this paper is a prerequisite to planning and executing a successful GPS photogrammetry mission. GPS is a rapidly advancing technology, and it is easy to be enticed by results from leading-edge research. With careful planning, worthwhile results and economic savings can be achieved by applying widely practiced GPS surveying methods. Potential users of GPS photogrammetry should review the available literature in the field and should perform independent tests with their cameras and GPS receivers before undertaking large projects.

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References
Ackermann, F., 1992. Operational Rules and Accuracy Models for GPS Aerotriangulation, Commission III Invited Paper, *ISPRS Proceedings*, Washington, D.C.

Curry, S., G. Salsig, and K. Whitaker, 1991. A Practical Test of a Photogrammetric Project Controlled With Airborne GPS, *Proceedings of the 1991 ASPRS/ACSM Convention*, Baltimore, Maryland.

Erio, G., 1992. Practical Considerations for Block Adjustment Programs Using Airborne GPS, Presented at the ASPRS/ACSM/RT 92 Convention, Washington, D.C.

Friess, P., 1991. Aerotriangulation with GPS – Methods, Experience, Expectations, *Proceedings of the 43rd Photogrammetric Week*, Stuttgart, Germany, pp. 43-50.

Lapine, L., 1990. *Analytical Calibration of the Airborne Photogrammetric System Using A Priori Knowledge of the Exposure Station Obtained from Kinematic GPS Techniques*, Ph.D. Dissertation, The Ohio State University, Columbus, Ohio.

Leick, A., 1990. *GPS Satellite Surveying*, John Wiley & Sons, New York.

Lucas, James R., 1987. Aerotriangulation without Ground Control, *Photogrammetric Engineering & Remote Sensing*, 53(3):311–314.

———, 1989. *GPS-Assisted Phototriangulation Package (GAPP) User's Guide, Version 1.02*, Rockville, Maryland.

Merchant, D., 1991. GPS-Controlled Aerial Photogrammetry, Summer Workshop Meeting of the Transportation Research Board.

Schuckman, K., S. Curry, M. Zhao, and G. Salsig, 1992. A Practical Test of a Photogrammetric Project Controlled with Airborne GPS, *Proceedings of the 1992 ISPRS Convention*, Washington, D.C.

Wells, D., 1987. *Guide to GPS Positioning*, Canadian GPS Associates, Ottawa, Canada.

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Karen Schuckman is a cartographer in the Research, Technologies, and Applications Branch of the U.S. Geological Survey in Menlo Park, California. She is currently completing an M.S. in Civil Engineering (Surveying and Photogrammetry) from the California State University, Fresno.

Awards

Do you know an individual or group whose outstanding contributions to the Society or to the mapping sciences professions are deserving of recognition by their peers? Why not nominate these people for one of the ASPRS awards listed below?

- V. Talbert Abrams Award
- Autometric Award
- John I Davidson President's Award for Practical Papers
- ERDAS Award - Best Scientific Paper in Remote Sensing
- ESRI Award - Best Scientific Paper in GIS
- Intergraph Award - Best Scientific Paper in Spatial Data Standards
- Photogrammetric Award - Fairchild
- Alan Gordon Memorial Award
- ASPRS Fellow Award
- ASPRS Honorary Member Award
- Region of the Year Award
- Region Newsletter of the Year Award
- Outstanding Service Award
- Merit Award
- Certificate of Appreciation for Meritorious Service
- Honor Award

All awards are open to deserving candidates, regardless of whether they are employed in the public or private sector. Call ASPRS headquarters for a nomination form.

Deadline for Nominations is 1 December 1993.