GPS Controlled Aerial Photogrammetry*

Abstract

Increased efficiency in establishing geodetic control required for topographic mapping is promised by a merger of aerial photogrammetry and the NAVSTAR Global Positioning System (GPS). The purpose of this paper to discuss the concept of GPS-controlled aerial photogrammetry, its theoretical basis, and some results obtained to date. Horizontal accuracies better than 0.04 metres RMS without use of ground control have been demonstrated by GPS-controlled aerial photogrammetry. The paper concludes with a discussion of the problems, particularly for large scale mapping operations, that must be addressed to assure an orderly transition of this new technology into practice.

Introduction

As the NAVSTAR Global Positioning System (GPS) evolves and as technology to exploit its positioning potential is developed, GPS will be used to supplement or replace traditional control required by aerial photogrammetry. The purpose of this paper is to discuss the concept of GPS-controlled aerial photogrammetry, its theoretical basis, and some results obtained to date. The paper concludes with a discussion of the problems, particularly for large scale mapping operations, that must be addressed to assure an orderly transition of this new technology into practice.

Pioneering work has been done for large scale applications through the Texas Department of Highways and Public Transportation by Tommie Howell, Roger Merrell, and Frank Howard (Merrell, 1986). Their work, in cooperation with NOAA/NOS, provided an early demonstration of the potential for centimetre levels of accuracy from low altitude flight in a single engine Cessna 206 (Lucas, 1988).

Additional early work was done at the NOAA/NOS Coast and Geodetic Survey (C&GS) by Lewis Lapine, James Lucas, and Gerry Mader. They have demonstrated a fully GPS-controlled flight of a Cessna Citation aircraft at 6000 feet over the Transportation Research Center (TRC) range in Marysville, Ohio (Figure 1). With no ground control, the results, when compared to targeted known positions, indicated a root-mean-square (RMS) error of three centimetres (Lapine, 1990).

North Carolina, also working in cooperation with NOAA/NOS, has more recently accomplished an aerial calibration over the Ohio TRC with a Wild RC-20 camera in a Cessna 404 aircraft (Figure 2). This work, under the guidance of John Sherbert, Cecil Hinnant, Keith Johnston, and Carl Storch of the North Carolina Department of Transportation, also included a demonstration project flown in November of 1990 in the mountainous region of the Morganton/Lenoir area of North Carolina (Johnston and Storch, 1991). Results of this work clearly indicated that, without use of ground control, spatial accuracies could be obtained to produce maps at a scale of 1:600 (1 inch to 50 feet) and two-foot contour intervals.

Figure 1. The Transportation Research Center (TRC) near Marysville, Ohio.

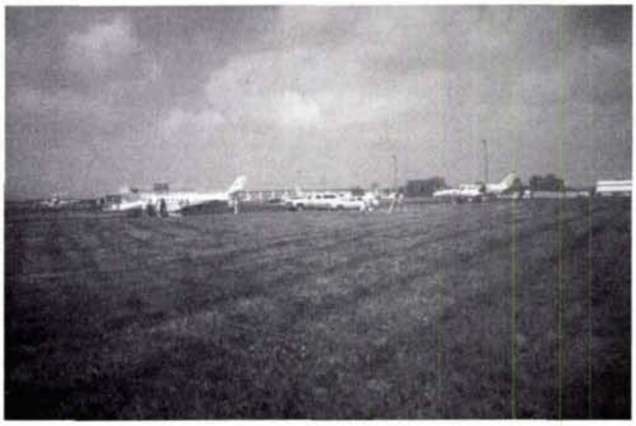

Figure 2. The NOAA and the NCDOT aircraft prior to a simultaneous calibration flight over the TRC in Ohio.

Other state departments of transportation that have or are currently experimenting with GPS-controlled aerial photogrammetry are Iowa, Ohio, and Washington.

Work conducted for Ontario Hydro is reported by Robert Tudhope (1991). This project consisted of 19 flight lines flown at 10,000 feet near Thunder Bay, Ontario to demon-

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strate GPS-controlled photogrammetry. The objective was to achieve adequate control for 1:20,000-scale mapping with 10-m contours and 1:10,000-scale mapping with 5-m contours. These objectives were met. The aircraft was a Douglas Dakota (DC-3) flying a Wild RC-10 camera and a Northstar 1000 GPS receiver.

Discussion

Concept

The concept of GPS-controlled aerial photogrammetry is logical. GPS signals are transmitted from four or more satellites, collected by an airborne receiver, and processed to produce refined phase data (Figure 3) at selected time intervals. A second GPS receiver, on a point of known location, simultaneously collects data for use in a "differencing" mode of data reduction. This is sufficient to estimate the spatial coordinates of the phase center of the receiver's antenna at each specified instant of time. As a minimum, three non-linear exposure stations are sufficient to determine the orientation of the photo block to the survey system of coordinates. For the highest accuracies, a second receiver, occupying a known ground point, simultaneously collects data. Subsequent differencing of the signals received at the aircraft and on the known ground station eliminates relatively large bias errors and makes it possible to determine aircraft phase centers to centimetre accuracies. In concept, it remains only to relate the phase center of the antenna to the *entrance node* of the camera in both space and time.

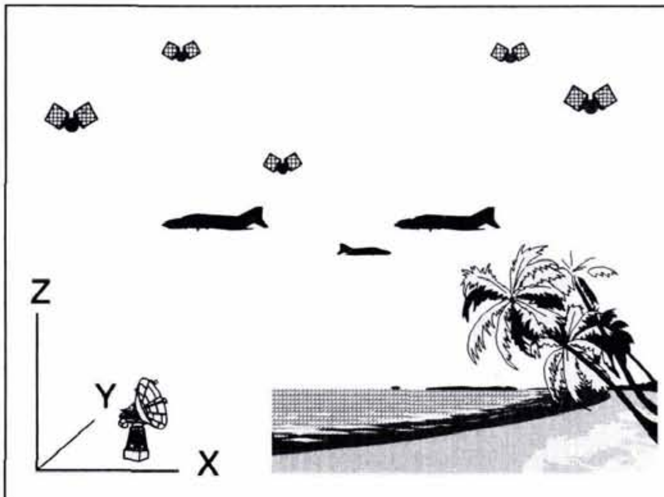

Figure 3. GPS aided photogrammetry.

Theoretical Basis

Spatial aspects of the relationships between camera, aircraft and survey coordinate systems are shown in Figure 4. Assume that the photo coordinate system (*x, y, z*) is co-aligned with the aircraft system (*U, V, W*). The aircraft coordinate system is fixed with respect to the framework of the aircraft. The survey coordinates provided by GPS (*X, Y, Z*) are in the WGS84 system. The problem, therefore, reduces to that of projecting the predetermined offsets (*DU, DV, DW*) between the phase center and the camera node into their equivalent components in the survey system. These survey components are then added to survey coordinates of the phase center to produce survey coordinates of the camera node or exposure station.

The change in camera mount settings necessary to assure the camera flies straight down the flight track must be treated in practice. These small angular changes can be observed and used to premultiply the offset vector before computing the transformation to the survey system (Merchant, 1989).

Just as it is not practically possible to collocate the phase center with the entrance node in space, it is not practically possible to cause the exposure and the GPS fix to occur simultaneously. Most modern aerial cameras will delay exposure from the time of request by variable amounts up to several seconds under the worst cases.

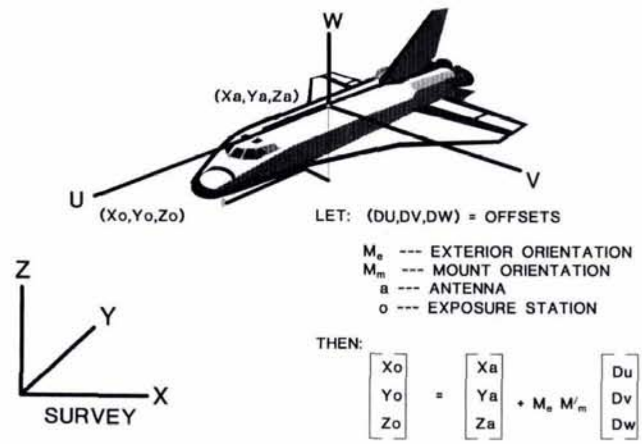

Figure 4. Transformation—phase center to exposure station.

Results

Some early results by Duane Brown (1969) lend confidence that an aerial, film-based, photographic system can sustain the high resolution and stability necessary to project (extrapolate) from the exposure-based control provided by GPS to the ground detail. In Brown's work with the USAF USQ-28 system, which uses a reseau-based camera in an RC-135 aircraft flown at 12,000 feet over a controlled range, he was able to demonstrate internal spatial accuracies approaching one part in three hundred thousand (see Figure 5). For the USQ-28 work, three terrestrial-based stellar cameras were used to position the aircraft. Today, GPS can replace the cameras for the positioning task.

Results by Clyde Goad (1989) indicate the potential for GPS positioning of the moving phase center to millimetre accuracies. In this work, conducted at White Sands Proving Grounds for the U.S. Army Corps of Engineers, a GPS receiver was mounted on a sled that moved along a controlled track at about 10 mph. A second receiver occupied nearby control. The GPS position was compared to the known sled position at about six second intervals. After removing a 3 mm bias, the discrepancies in terms of distance along the track were about 4 millimetres RMS. These results certainly lend encouragement for the aerial applications of GPS.

The most encouraging results are those obtained by Lewis Lapine (Lapine, 1990) in his work with a NOAA Citation aircraft operating at about 6000 feet over the TRC range in Marysville, Ohio. The camera was a Wild RC-10 modified to include a reseau. For this work, both the spatial and time offsets were carefully measured. The system was calibrated in the air because GPS observations provided the necessary decoupling of interior from exterior parameters. Results of the offset measurements and the aerial calibration were used to control a conventional aerial block over the TRC. Table 1, taken from the work of Lapine (1990), indicates that, without ground control, an RMS error of planimetric point positioning of about 3 centimetres in X and Y was achieved from 6000 feet altitude above the ground.

A second RC-10 camera without a reseau was subjected to the same calibration procedures; however, the planimetric errors were about twice those obtained with the reseau cone. The elevation errors were both rather large values of about 10 centimetres, but with clearly large bias errors present.

Results of work conducted by other state departments of transportation indicate a strong potential for GPS to provide control from the air sufficient to conduct large scale photogrammetric mapping. Of early significance is the work at the Texas Department of Highways and Public Transportation reported in papers by Roger Merrell (1986) and Jim Lucas (1988).

North Carolina Department of Transportation (NCDOT) results, as reported by Johnston and Storch (1991), confirm the ability of airborne GPS-controlled photogrammetry, without benefit of ground control, to produce a high level of spatial accuracy, provided a full aerial calibration procedure is used. Results of spatial accuracy testing for their work are summarized in Table 2.

Both Tables 1 and 2 indicate results when data is used from a systems (aerial) approach and from a laboratory (conventional) approach to calibration.

Table 1. Spatial Differences (metres) between GPS-Controlled Aerial Photogrammetric Positions Obtained without Use of Ground Control Compared to Known, Targeted Ground Positions from an Altitude of 6000 Feet (Lapine, 1990)

	Aerial Calibration			Conventional Calibration		
	X	Y	Z	X	Y	Z
Mean (bias)	−0.001	0.005	−0.065	0.081	0.090	0.704
Std. Dev.	0.033	0.028	0.085	0.371	0.429	0.180
RMS	0.032	0.028	0.106			

Table 2. Spatial Differences (metres) between GPS-Controlled Aerial Photogrammetric Positions Obtained without Use of Ground Control Compared to Known, Targeted Ground Positions from an Altitude of 6000 Feet (Johnston and Storch, 1991)

	Aerial Calibration			Conventional Calibration		
	X	Y	Z	X	Y	Z
Mean (bias)	0.041	−0.014	−0.036	−0.037	0.031	−0.63
Std. Dev.	0.034	0.040	0.073	0.179	0.194	0.073
RMS	0.052	0.042	0.080	0.179	0.179	0.640

Problems to Be Addressed

Hardware Development

In the last few years the GPS receiver has undergone significant improvements aimed at efficiency in field applications. Advances in reliability and capability coupled with the trend toward reduced price have made this method of spatial positioning even more attractive. These trends will undoubtedly continue.

The accuracy of the navigation task is degraded by "selective availability" and "anti spoofing" for those without access to the classified code. Under these circumstances, real-time positioning is reduced to several hundred metres, a result which is only marginal for most large scale photogrammetric applications. Recent work by NOAA has shown that, by transmitting corrections to the pseudorange position determined from data collected at a known station, the real-time position of the aircraft can be determined to an accuracy of several metres. As a result, developments of this accurate navigation information have advanced to the point where the camera is controlled directly from the on-board computer. An indication of photo coverage in real time is provided to the photo-navigator in a graphical manner to confirm that the required photo coverage has been obtained. Such real-time techniques of field procedure enhance the already strong potential of airborne GPS aerial photogrammetry to provide cost-effective means for meeting demands for more accurate and timely spatial data.

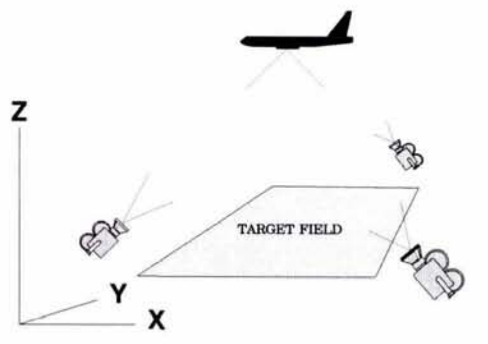

Figure 5. Brown's USQ-28 experiment at McClure, Ohio (1969):
* RMS error of fit of 36 reseau = 2 micrometres;
* proportional accuracy to flight height;
  - horizontal, 1 part in 300,000
  - vertical, 1 part in 100,000

The photogrammetric camera and supporting equipment, however, require some development. The ability to cause the exposure on demand, or nearly so, presents a particularly difficult problem for large scale photo collection missions due to relatively turbulent air and consequences of interpolating from the GPS fix to the point of effective exposure. Some of the most recent cameras are capable of signaling shutter mid-point pulse time to an accuracy of at least 0.1 millisecond and have the ability to cause an exposure within 50 milliseconds from the time of request. Other cameras can indicate the mid-point of shutter by a TTL pulse or can be instrumented and calibrated to do so. Although not an absolute requirement, but necessary for higher accuracies, equipment can be developed to cause the exposure to occur within at least a few tenths of a second of the instant of exposure request. Most GPS receivers make provision for storing the time of an external event such as a TTL pulse generated by the camera at mid-point of exposure.

The angular setting of the mount should be recorded for use in modifying the transformation computations of phase center to entrance node as described earlier. This could be manually recorded, but the air crew is already overburdened, particularly at low altitudes where things happen fast and where the air tends to be turbulent. The flight missions at low altitude bear a great similarity to crop dusting missions. Therefore, an automatic recording of mount angles should be developed for the majority of mounts that currently do not make provisions for recording.

The GPS antenna must be mounted on the aircraft after consideration of the line of sight to the satellites, multi-path problems, and the need to maintain small spatial offsets between the antenna and the camera. This requires some development of an antenna mount and appropriate approval from the FAA or its equivalent elsewhere.

Hardware System Calibration

For the aerial photogrammetric methods, control is traditionally provided on the ground. This allows systematic errors remaining in the photogrammetric system to be compensated by a fitting of the imagery within regions bracketed by control—essentially an interpolative process. Errors caused by incomplete camera calibration, non-linear film deformation, or platen unflatness can be accommodated by a false exposure station. With GPS, the exposure station position is forced on the solution and the "projective compensation" mechanism is no longer free to work. This suggests that what was only an ideal before, i.e., a full calibration of the total system under operational conditions, may now become a necessity.

An example of the magnitude of the influence of residual systematic errors on exposure station coordinates was demonstrated by the Method of Mixed Ranges (MMR). The differences in exposure station coordinates computed by resection based on laboratory camera calibration information and on information obtained by the MMR, essentially an operational calibration, was 6.6 metres in elevation, 0.9 metres in the along-flight direction, and 4.1 metres in the cross-flight direction (Merchant, 1974). The altitude for this test, performed above the Casa Grande, Arizona test range, was about 16,000 feet.

The work of Lapine (1990) further confirmed the need for aerial system calibration. The systematic and the RMS planimetric discrepancies compared to ground control all increased by about one order of magnitude when a non-system calibration was used. This conclusion was also supported by the tests performed by the NCDOT (Johnston and Storch, 1991).

Technology Transfer to Users

After the GPS-controlled aerial photogrammetric hardware and system calibration problems have been satisfied, training the users in collection and data reduction steps necessary to fully use the new photogrammetric procedure remain. Operational specifications, including check lists, should be developed for such purposes.

Periodic checking of the accuracy performance of the system as a quality control measure is also essential. For this, the concept of "Measurement System Calibration," as suggested by Eisenhart (1963), is of fundamental importance. His concept requires that, for a measurement system to be calibrated, it must first be fully defined in terms of hardware, materials, and procedures termed "specifications." The system must then be exercised within the limits of the specifications and its results compared to a standard of higher accuracy, in this case a targeted control field. When sufficient data are obtained to reliably predict the measurement system's accuracy performance, the system is said to be in a "state of statistical control" and will provide predicted accuracies.

Installation of GPS and supporting equipment in the aircraft, offset measurements, and calibration of the entire aerial photogrammetric system are typically one-time efforts and would likely be accomplished by a specialized outside organization for any specific user.

Conclusion

Recent work of federal and state agencies demonstrated the potential of GPS-controlled aerial photogrammetry to provide the survey control necessary to produce large scale maps. Planimetric accuracies of 3 centimetres RMS have been achieved without ground control from an altitude of 6000 feet. To achieve this demonstrated potential in practical production applications, sufficient experience with a specific aerial collection system, including the aircraft, camera, and GPS receivers, must be obtained by comparison of the spatial results to control provided by a test field. This concept of "measurement system calibration," proposed by Eisenhart (1963), clearly delineates the path to take to achieve a reliable GPS-controlled aerial photogrammetric system.

For those interested in maintaining close contact with developments in GPS-controlled photogrammetry, it is recommended that they join the ASPRS Committee, "GPS Applications to Photogrammetry."

With some moderate equipment development, coupled with the use of aerial measurement system calibration under operational circumstances, control accuracies necessary to produce topographic maps at scales of 1 inch to 50 feet (1:600) can be achieved by GPS-controlled aerial photogrammetry.

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