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NEW TRENDS IN TECHNOLOGY, AND THEIR APPLICATIONS:
GEODESY

Mapping applications of the global positioning systems on airborne platforms

Paper submitted by the United States of America**

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INTRODUCTION

Numerous investigators have reported their experience using the GPS to support aerotriangulation through the determination of camera station positions at the time of exposure. The U.S. Geological Survey (USGS) began investigating this technnique to reduce the cost of acquiring ground-surveyed control for planimetric revision and digital orthophoto (DOQ) production. Images to support revision and DOQ production programs will largely be at 1:40,000-scale and acquired through the National Aerial Photography Program (NAPP). Current specifications require third-order, photoidentifiable, horizontal control points to be located at a spacing of 7.5 minutes around the perimeter of a project and at 15 minute spacing on the interior of a project to control aerotriangulation using NAPP images. The cost of establishing these points is estimated to be between $200 and $1,000 per point, depending on factors such as terrain type, number of points to be established in a given area, and spacing of existing, monumented control. For airborne GPS to provide a cost-effective alternative to conventional aerotriangulation, the acquisition and processing of GPS positions for the camera station must be less than the cost of acquisition of ground control over the imaged area. Thus, although the theory behind the use of airborne GPS seems well proven, the application of this technology to a large mapping program is dependent on cost and flexibility, as well as on technology.

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PREVIOUS INVESTIGATIONS

The theoretical potential for the use of GPS-derived camera positions to control block adjustments was presented by Lucas (1987). Through simulation studies, Lucas showed that if GPS observations were available with a standard error of 10 centimeters in each component (assuming an offset vector between the GPS antenna and camera known to 10 centimeters), then a block adjustment could be performed with results similar to an adjustment achieved using a conventional ground control configuration. Horizontal errors in the block containing GPS observations of the exposure station were only significantly larger than the ground-controlled adjustment at the corners of the block where ground point positions were tightly constrained. Vertical errors were consistently smaller for the GPS block, except in the corners of the block. Since Lucas' theoretical presentation of the potential for the use of GPS in photogrammetry to significantly reduce the amount of ground control necessary for aerotriangulation, many practical experiments have been performed to verify the concept.

The work of the National Ocean Service (NOS), National Oceanic and Atmospheric Administration (NOAA) has been prominent among projects reported in the literature. Lewis Lapine's work at Ohio State (1991) provided a thorough examination of a system calibration made possible by the incorporation of GPS observations of camera station positions to decorrelate interior and exterior orientation elements during in-flight calibration. Burgess and White (1992) reported the results of a joint project between the U.S. Army Topographic Engineering Center, NOS, the Seattle District, and Walker and Associates. The report of this project, conducted in 1990, provides a practical record of a large-scale GPS and photogrammetry mission. The problems encountered in this project, including those caused by frequent vendor software changes and numerous cycle slips, attest to the technical and logistical obstacles remaining to be overcome before the use of GPS-derived camera exposure station positions in photogrammetry may be considered routine.

Schuckman and others (1992) reported a good comparison between aerotriangulation results computed using code-phase vs. carrier-phase observations to determine camera exposure station positions for medium-scale (1:40,000) photography. The practical advantages of using code-phase observables in pseudorange solutions are clear in that initialization before takeoff and maintenance of continuous lock are not required. Ackermann and Schade (1993) also addressed the logistical problems associated with airborne GPS by introducing linear drift parameters in the block adjustment to account for unmodeled, systematic GPS errors present when only C/A code pseudoranges are used to estimate exposure station positions. The need for an initial integer ambiguity resolution is eliminated. However, either substantial sidelap (60 percent), cross-strips, or lines of vertical control along the ends of the flight lines are recommended to strengthen the block adjustment.

The movement of airborne GPS away from research and toward an operational environment is clear from the trends in the literature. The USGS intends to take advantage of this trend by introducing airborne GPS into limited production in 1994. The lessons learned in research projects completed in 1991 and 1992 were invaluable in preparing the technical specifications requiring delivery of airborne GPS data with photographs acquired through the NAPP in 1993. The 1993 NAPP project should provide sufficient data to allow the USGS to resolve remaining technical problems, as well as to work toward a resolution of operational problems in the acquisition, processing, and use of airborne GPS data.

REQUIREMENTS

With the completion of the more than 54,000 7.5-minute, 1:24,000-scale USGS topographic quadrangles, the USGS is facing the task of maintaining these products of the National Mapping Program. Two of the programs that compose the maintenance phase are the planimetric revision of the 7.5-minute quadrangles and the production of 1:12,000-scale DOQ's. The DOQ program provides a current, image-based product, as well as a source of information for revising planimetric 1;24,000-scale data. Ground control requirements for these programs are as follows:

"Supplemental horizontal control spacing in support of aerotriangulation is required as follows:

> Control will be spaced at a 7.5-minute interval on the project/block perimeter, 15-minute interval on the project/block interior for projects that use National Aerial Photography Program (NAPP) photography..." (USGS, 1992)

Because vertical control requirements to support planimetric revision and DOQ production are much less stringent than the requirements to support 1:24,000-scale, 7.5-minute topographic quadrangle production, photoidentifiable vertical control used in the original topographic quadrangle production (along with map-derived vertical control) is often used in the aerotriangulation of new images.

The NAPP program

The objectives of the NAPP are to provide complete photographic coverage at 1:40,000 scale of the continental United States on a 5-year cycle. Six Federal agencies provide guidance and funding for the program, in cooperation with State agencies. Administration of contracts for the acquisition of photographs is performed by the USGS. An abbreviated list of the current specifications for NAPP photographs are shown in table 1.

Table 1. NAPP Specifications

Description	Specification
Flight Height Above Ground	20,000 ft
Flight-line Direction	North-south
Scale	1:40,000
Format	9X9" quarter quad-centered
Forward Overlap	60%
Sidelap	15-30%
No. of exposures to provide stereo cov. of 7.5′ quadrangle	10
Minimum sun angle	30 deg. (may be higher for mountainous regions)

Accuracy Requirements for 1:24,000-scale planimetric revision and 1:12,000-scale DOQ's

USGS products derived from NAPP images must meet national cartographic spatial accuracy requirements. DOQ's produced at 1:12,000-scale are currently required to meet National Map Accuracy Standards (NMAS). NMAS require that not more than 10 percent of points tested be in error by more than 1/30 inch (equal to 33.3 feet or 10 meters on the ground for 1:12,000-scale products) for maps published at scales larger than 1:20,000. Revised maps produced at 1:24,000-scale must adhere to the proposed U.S. National Cartographic Standards for Spatial Accuracy (NCSSA). The NCSSA was developed by the Subcommittee on Base Cartographic Data under the Federal Geographic Data Committee (FGDC). Although the FGDC has approved the new standard, it is proposed to replace the NMAS issued by the Office of Management and Budget (OMB). Therefore, the new standard must also be approved and issued by the OMB. The NCSSA is in the process of a final, public review prior to submission to the OMB.

For a map to be labelled Class 1, according to NCSSA specifications, "...the standard error...in both the x and y coordinates computed separately, shall not exceed ± 0.25 mm., measured at the publication scale." For a 1:24,000-scale map, this means the horizontal standard error must not exceed 20 feet on the ground in either the x or y coordinate. To support these accuracy requirements, the accuracy of positions established using aerotriangulation must be within approximately 2 meters horizontal and 4 meters vertical relative to positions established using ground surveys of a higher accuracy.

USGS AIRBORNE GPS RESEARCH

The work of Lucas and others provided the motivation for the USGS to conduct investigations into the use of NAPP-like images in conjunction with GPS positions of the exposure station to control aerotriangulation. The first of these tests was conducted in cooperation with the Texas Department of Transportation in October 1989. Although the results of this test were positive, photographs with only 10 percent sidelap were acquired, and it was necessary to add map vertical control to bring horizontal and vertical positions derived through aerotriangulation to within 2 and 4 meters, respectively, of positions established using GPS ground surveys. Substantial difficulties were encountered in the collection of the photographs and GPS data because of the lack of satellite availability at the time of the project. The use of airborne GPS within the NAPP was delayed pending further progress toward completion of the GPS satellite constellation. As satellite availability improved, two additional research projects were planned and executed. These tests, conducted near Phoenix, Arizona, over an approximately 1,500 square kilometer area, provided the USGS with a great deal of practical insight into the capabilities and limitations of airborne GPS. In addition, personnel were familiarized with critical operational aspects of this technology.

The Phoenix Projects

Figure 1 depicts the project area and control distribution for both the 1991 and 1992 missions. Thirty-four photoidentifiable positions were established using Trimble 4000ST GPS receivers in the static positioning mode. As shown in figure 1, control points were established near each 7.5-minute intersection. In addition, two test points were established within each quadrangle. Both horizontal and vertical coordinates were derived for each point using GPS observations collected at a 15-second rate. The data were processed using the program TRIMVEC+ with the broadcast ephemerides. Results were analyzed and adjusted with FILLNET, v. 2.0.

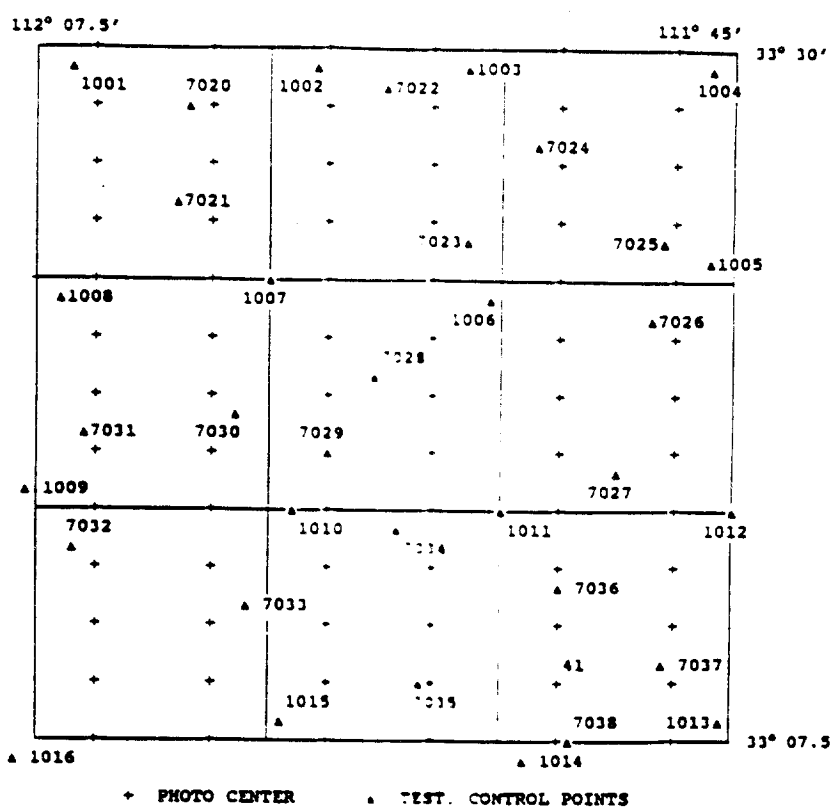

Figure 1. Phoenix project area and control diagram.

Three additional points were located relative to the network of control and test points. An "index point" (station SCOX) was established on the airport runway for the 1991 mission. Positions for two reference points to be used as sites for the location of continuously operating reference trackers were also established: one at the airport (station SCOT), located near the northern boundary of the project area, and one approximately 100 km west of the center of the project area (station TONA).

During the 1991 mission, an Ashtech model LD-XII GPS receiver was operated on board a Cessna 340 aircraft. The antenna was positioned on the aircraft's fuselage, directly above the camera. The offset between the phase center of the antenna and the camera's focal plane was measured using a Wild T-2 theodolite and steel tape. The distance between the focal plane and the front nodal point of the camera was obtained from the camera manufacturer. Ashtech LD- and P-XII receivers, along with an antenna positioned on the vertical stabilizer of the aircraft, were used in the 1992 mission. The antenna was positioned on the vertical stabilizer in an attempt to reduce the effects of multipath. Antenna to camera offsets were again measured with a Wild T-2 and steel tape. For both the 1991 and 1992 missions, the cameras were operated in a "locked-down" position, thus keeping the offset between the antenna and camera constant.

The cameras used in 1991 were the Zeiss RMK Top 15 and LMK 2000. An RMK Top 15 was used for the 1992 mission. In both the 1991 and 1992 projects, camera exposures were recorded as "events" by the GPS receivers so that the precise time for each exposure was known. The time offset between the camera exposure and the record of the event in the GPS data was assumed to be less than 50 milliseconds, based on manufacturers' testing. GPS observables recorded for the 1991 and 1992 missions are shown in table 2. The sampling rate for both missions was 1 second and the mask angles set for 2° on the aircraft and 5° at the ground reference stations. Flights were planned so that a minimum of five satellites would be in view at the time of the mission.

GPS data were postprocessed (processed after the conclusion of the mission) using the OMNI software, developed at NOAA, for double difference carrier phase processing, and the PPDIFF software, developed by Ashtech, for differential GPS processing by corrections to pseudoranges smoothed with the aid of the carrier phase. The results of both the OMNI and PPDIFF processing were positions at the antenna on the aircraft for each 1-second epoch, established relative to one of the reference stations on the ground. Processing was completed for several missions relative to more than one ground reference station so that results could be compared. The positions

Table 2. GPS Observables

1991	1992
L1 C/A code phase L1 carrier phase L2 carrier, codeless (half-wave)	L1 C/A code phase L1 carrier phase L1 P-code phase L2 carrier phase, P-code (full-wave) L2 carrier phase, codeless (half-wave) L2 P-code phase

established using the OMNI software were estimated to be accurate within approximately 10-20 centimeters (1 sigma) and the positions established using the PPDIFF software were estimated to be accurate within 1-2 meters (1 sigma).

The program GAPCET, also developed at NOAA, was used to interpolate positions of the antenna at the time of exposure of the camera. These interpolated positions were then provided as input to the General Integrated Analytical Triangulation Program (GIANT), version 3.1. This version of GIANT allows input of antenna to camera offset measurements and standard input, including image measurements, camera calibration information, and ground coordinates for points to be used as control in the adjustment.

Numerous adjustments were performed for the study area to compare the results obtained while varying (1) the amount and type of ground control used to constrain the adjustment, (2) the accuracy of GPS positions of the antenna on the aircraft (OMNI vs PPDIFF processing results), and (3) the reference station used in GPS data postprocessing. One adjustment was performed in the conventional manner, without the use of GPS-derived positions of the cameras and using ground coordinates for control points. In all cases, test point positions established in the GPS ground survey were withheld from the block adjustment.

Figures 2, 3, and 4 are plots of differences in test point coordinates established by block adjustments versus coordinates for the same points established in the GPS ground survey. All figures are derived from data collected in a single mission, using the ground reference station (SCOT) at the airport. Figure 2 shows the results of the conventional aerotriangulation using no GPS-derived camera positions and ground control at 7.5-minute intersections. Figure 3 shows the results of the aerotriangulation using camera positions established through PPDIFF processing (positions estimated to be accurate within 1-2 m) and vertical control at 7.5-minute intersections and along the northern and southern boundary of the block. Vertical

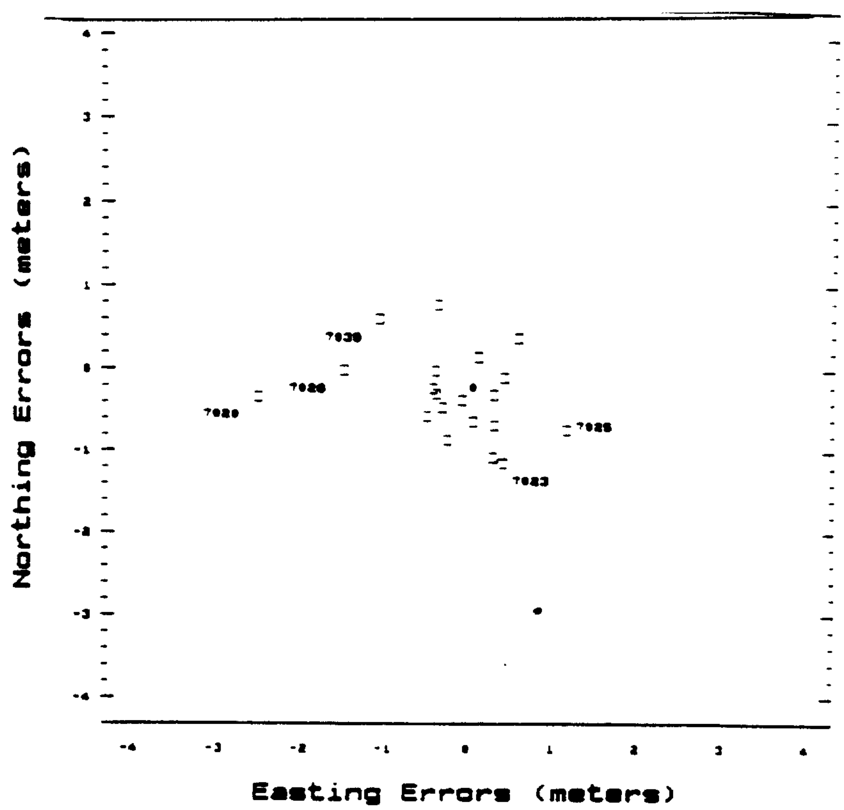

Figure 2. Differences in coordinates from GPS ground survey and those from GIANT adjustment completed without GPS-derived positions of exposure stations and with a conventional control configuration.

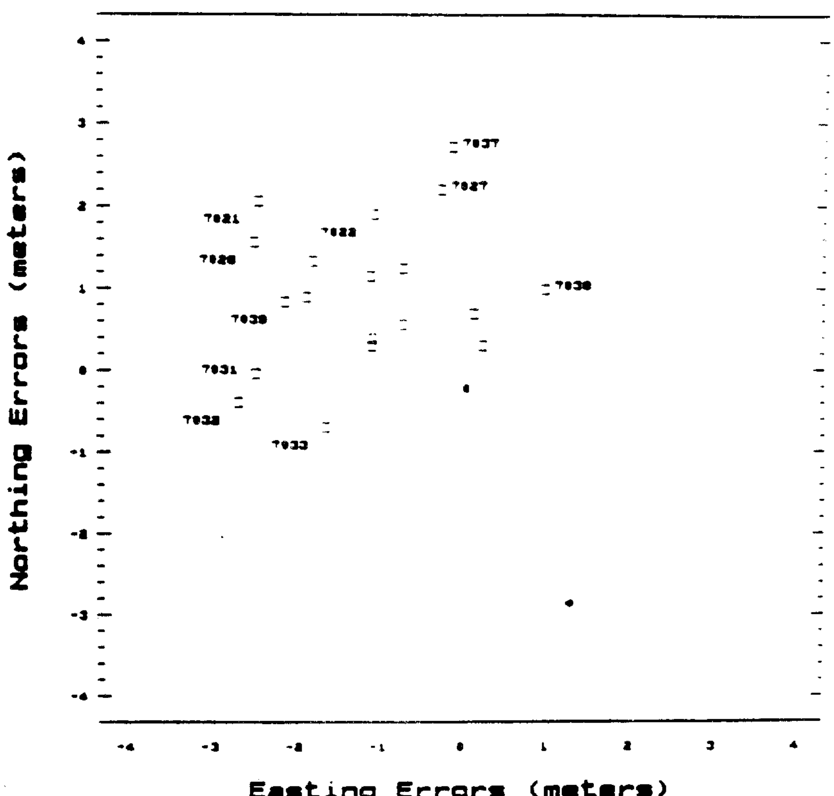

Figure 3. Differences in coordinates from GPS ground survey and those from GIANT adjustment completed using positions of exposure stations derived from PPDIFF and using vertical control.

coordinates were derived from both the GPS ground survey and USGS 7.5-minute topographic quadrangles and were weighted in the block adjustment to appropriately reflect the method used to derive them. Figure 4 shows the results of the aerotriangulation constrained only by the positions of the camera exposure stations derived from the OMNI postprocessing results. Results displayed in figures 2-4 are summarized in table 3. In all cases the results are within the required accuracy for DOQ production and 1:24,000-scale planimetric revision. It should be noted, however, that additional vertical control was necessary to bring the PPDIFF results within specifications. Without the added vertical control a bias of approximately 6 meters in the vertical component of test point positions was observed.

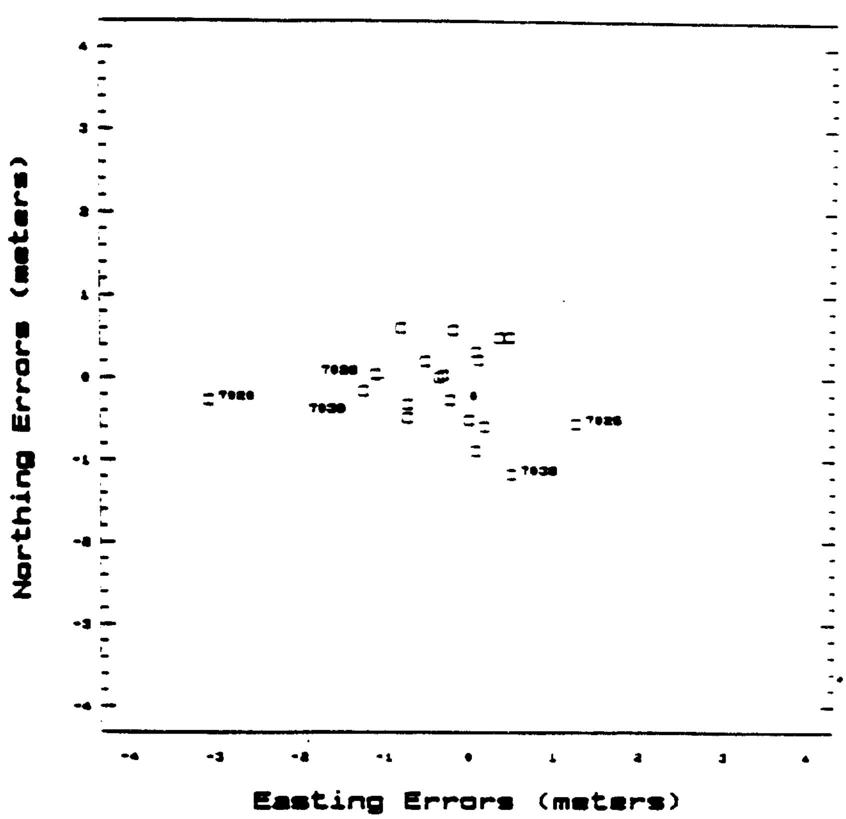

Figure 4. Differences in coordinates from GPS ground survey and those from GIANT adjustment completed using positions of exposure stations derived from OMNI (double difference carrier phase processing) and no ground control.

Table 3. Differences between test point positions established through aerotriangulation and positions established using GPS ground survey (in meters)

	Conventional	PPDIFF	OMNI
Easting	0.8	1.8	0.9
Northing	0.6	1.4	0.5
Vertical	0.9	0.8	1.4

Although the results summarized in table 3 were derived from data collected in a single 1991 mission, they are representative of results obtained for other missions flown in 1991 and 1992. Results of block adjustments performed using camera positions established relative to the TONA ground reference station, located approximately 100 km to the west of the center of the project area, were not significantly different from results obtained using reference station SCOT.

The main conclusion derived from the Phoenix projects was that acceptable results could be obtained from aerotriangulation of NAPP images controlled by GPS-derived positions of camera exposure stations. Although in some cases additional ground control was necessary to bring aerotriangulated positions to within acceptable accuracy limits, highly accurate GPS-derived camera positions seemed to reduce the need for additional ground control. Based on these conclusions, a limited project was undertaken within the NAPP to contract for delivery of GPS positions for camera exposure stations in addition to the NAPP images for the project area.

The NAPP Utah Project

The project area for which GPS-derived camera positions were included as deliverables along with NAPP images covers approximately one-third of the State of Utah, between 110° 45′ and 112° 15′west longitude. This area was chosen because of a favorable satellite configuration prediction during the flying season, as well as the mountainous terrain that covers much of the project area. Specified deliverables for the contract include (1) GPS observations in equipment-dependent raw format, (2) GPS observations in the RINEX format, (3) a flight mission log for GPS observations, (4) GPS processing solution and adjustment output files, (5) GPS-determined coordinates and associated data for each camera exposure station in the GIANT aerotriangulation software input format, and (6) a postmission summary of the analysis for each flight mission. GPS-determined coordinates for camera exposure station positions were required to be within ± 30 centimeters (1 sigma) horizontal and ± 60 centimeters vertical. These coordinates were also to be determined by processing relative to at least three reference stations on the ground. The intent of this requirement was to provide redundancy and a means by which to check positions without having to perform a conventional aerotriangulation to establish whether camera station positions met accuracy requirements.

At the time of writing this article, the initial collection of images and GPS data over the project area had been completed by Horizons, Inc., and processing of GPS data were underway. A test project similar in size to the Phoenix projects is planned for an area near Salt Lake City. This project will provide additional information about the accuracy of GPS-derived camera station positions and will allow standardized production procedures to be developed.

FUTURE PLANS AND CONSIDERATIONS

Future plans to incorporate airborne GPS-derived camera positions into cartographic production procedures include completion of processing and testing of the Utah data and contracting for collection of GPS data along with NAPP images in 1995. Because the major motivation for using this technology is to reduce the cost of acquiring ground control to support aerotriangulation, cost comparisons derived from several projects will be necessary to make valid judgements concerning cost-effectiveness. As operating procedures become more standardized, it is expected the cost associated with the collection and processing of GPS data to derive camera positions will become a small percentage of the total cost of image acquisition. This is particularly true in light of the increased use of the GPS as a navigational tool. Additionally, as a national network of continuously operating ground reference stations becomes available, it will not be necessary for the government or the NAPP contractor to establish and operate independent stations.

In summary, some technical questions concerning the use of GPS-derived exposure station positions in a production environment for large areas remain to be resolved. The optimum accuracy of exposure station positions necessary to keep ground control to a minimum must be determined, given current NAPP flight mission parameters. Additionally, the required rate at which GPS observations must be recorded to achieve the necessary accuracy must be determined so that the volume of data collected is not unnecessarily large. Determination of these critical technical specifications will play a role in determining the cost of acquisition and processing of GPS data under the NAPP. When technical

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questions are resolved, standardized specifications for acquiring GPS-derived coordinates for NAPP images can be developed and operating procedures put in place.

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