PERFORMANCE ANALYSIS OF THE AIRBORNE INTEGRATED MAPPING SYSTEM (AIMS™)

Charles K. Toth and Dorota A. Grejner-Brzezinska

Center for Mapping

The Ohio State University

1216 Kinnear Road, Columbus, OH 43212-1154

E-mail: *toth@cfm.ohio-state.edu, dorota@cfm.ohio-state.edu*

USA

Commission II

KEY WORDS: Sensor Integration, Digital Imaging Sensors, GPS, INS, Airborne Mapping

ABSTRACT

The performance of an airborne tightly integrated GPS/INS system is investigated in this paper. The system has been developed by the Center for Mapping at The Ohio State University to support direct exterior orientation of the Airborne Integrated Mapping System (AIMS™) imaging component. A brief description of the essential features of the integrated system and its practical implementation is also presented. The performance of the AIMS™ system was primarily assessed based on the photogrammetric processing of 1:2,400 large-scale aerial imagery. In addition, the system has been tested against results provided by an independent multi-antenna GPS system. A comparison of GPS stand-alone and GPS/INS attitude solutions is presented together with accuracy analysis and discussion on the impact of direct orientation on the photogrammetric data extraction process.

1. INTRODUCTION

The use of GPS/INS integrated systems for direct georeferencing of aerial imagery has become of increasingly more interest to the airborne survey and remote sensing community over the past few years (Kerr III, 1994; Schwarz, 1995; Lithopoulos et al., 1996; Skaloud et al., 1996; Abdullah, 1997; Toth, 1997). The use of GPS to determine the camera perspective center position has been studied extensively, and is currently a commonly accepted procedure. The most pronounced advantage of GPS-supported aerotriangulation is the decrease of ground control, leading to a substantial cost reduction in aerial mapping. Moreover, an array of three or four GPS antennas mounted on the mobile platform can also provide attitude components. The stand-alone multi-antenna GPS, however, is currently not able to provide acceptable Exterior Orientation Parameters (EOP) for the most demanding applications. The accuracy of the GPS-derived attitude components is at best at the level of 30 arcsec, reaching 1-2 arcmin on average (Lachapelle et al., 1994).

The accuracy of the GPS-determined attitude depends on many factors. The major accuracy constraints are the accuracy of the phase observable, multipath level, antenna phase center variations, and antenna separation. The longer the baselines, the more accurate the orientation components derived from the GPS phases, but at the same time the ambiguity search volume is drastically increased (Van Graas and Braasch, 1992; Harvey and Cannon, 1997). Platform rigidity (or lack of rigidity) limits GPS antenna separation to some fixed length that is subsequently used in the ambiguity resolution procedure. If antenna separation exceeds the L1 (L2) wavelength, there are, potentially, multiple solutions to the attitude problem; therefore, integer ambiguities must be resolved reliably On-The-Fly (OTF) in order to obtain a unique solution for orientation angles. Adding an inertial sensor offers a number of advantages over a GPS-only attitude/position determination system, such as immunity to GPS outages, continuous attitude solution, and reduced ambiguity search volume/time. On the other hand, GPS contributes its high accuracy and stability over time, allowing continuous monitoring of inertial sensor errors. Implementation of closed-loop INS error calibration allows continuous, OTF error update that bounds INS errors, leading to increased estimation accuracy. Using a GPS-calibrated, high to medium accuracy inertial system for attitude determination can provide accuracy in the range of 10-30 arcsec (Schwarz, and Wei, 1994; Abdullah, 1997; Da, 1997; Grejner-Brzezinska, 1997, 1998). The Ohio State University Center for Mapping has developed an integrated GPS/INS system as a part of a fully digital Airborne Integrated Mapping System (AIMS™), designed for large-scale mapping and other precise mapping applications. The AIMS™ positioning module is based on a tightly integrated Global Positioning System and Inertial Navigation System, with an accuracy estimated at the level of 4-7 cm in position and better than 10 arcsec in orientation. Such accuracy is needed to support the extraction of geographically referenced information from the imaging component of AIMS™ without the need for ground control (Bossler and Schmidley, 1997). The elimination of aerotriangulation leads to substantial savings in data processing time in traditional production. Furthermore, it provides the basis for real-time applications.

AIMS™ has been tested over baselines ranging from 20 to 200 km, in order to assess the accuracy of the positioning component. Extended discussion about the system architecture, integrated Kalman filter design, and GPS/INS error sources and modeling, as well as test results was presented in (Da, 1997; Grejner-Brzezinska, 1997; Toth, 1997; Grejner-Brzezinska, 1998). This paper presents the results of the recent airborne tests performed during early 1998, when the AIMS™ prototype was completed (Table 1). In mid-1997 a test flight, with high-resolution aerial camera, was conducted over Oakland, CA. Results from this mission are presented here as a comparison between AIMS™ and aerotriangulation solutions.

	DATE	LOCATION	CAMERA	SUPPORT
1	1/12	New Mexico	DDP BigShot™	Image America
2	1/13	Yuma, AZ	DDP BigShot™	Image America
3	1/14	Phoenix, AZ	DDP BigShot™	Image America
4	4/23	St. Louis, MO	DDP	Image America
5	4/24	St. Louis, MO	DDP	Image America

Table 1. AIMS™ test flights, 1998.

2. AIMS™: AN OVERVIEW

The AIMS™ positioning component currently comprises two dual-frequency Trimble 4000SSI GPS receivers, and a medium-accuracy and high reliability strapdown Litton LN-100 inertial navigation system, based on Zero-lock™ Laser Gyro (ZLG™) and A-4 accelerometer triad (0.8 nmi/h CEP, gyro bias – 0.003°/h, accelerometer bias – 25μg). The LN100 firmware, modified for the AIMS™ project, allows for access to the raw IMU data, updated at 256Hz (Litton Systems, 1994). Estimation of errors in position, velocity, and attitude, as well as errors in inertial and GPS measurements is accomplished by a centralized Kalman filter that processes GPS L1/L2 phase observables in double-differenced mode together with the INS strapdown navigation solution (Da, 1997; Grejner-Brzezinska, 1997).

The AIMS™ imaging component in the current configuration consists of a digital camera based on a 4,096 by 4,096 CCD with a 60 by 60 mm imaging area (15-micron pixel size), manufactured by Lockheed Martin Fairchild Semiconductors. The imaging sensor is integrated into a camera-back (BigShot™) of a regular Hasselblad 553 ELX camera body together with a supporting data acquisition interface (Figure 1). The camera installed on a rigid mount together with the INS is shown in Figure 2. The current 6-sec image acquisition cycling rate is limited mainly by the CCD read-out rate; however, it is already feasible for real-time applications. Since the BigShot™ camera-back interface has no support for time-tagging the actual lens opening, an external signal conditioning circuit was designed and built, tapping into the lens shutter signal and providing a TTL-compatible output for the timing system, such as the GPS external event marker or timer board input.

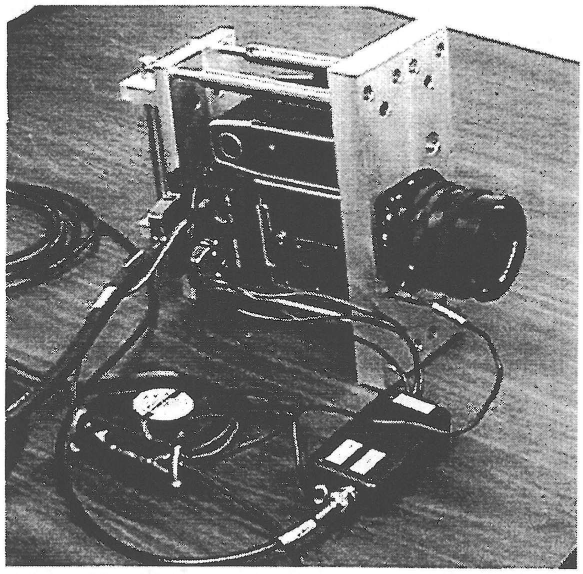

Figure 1. BigShot™ Hasselblad camera.

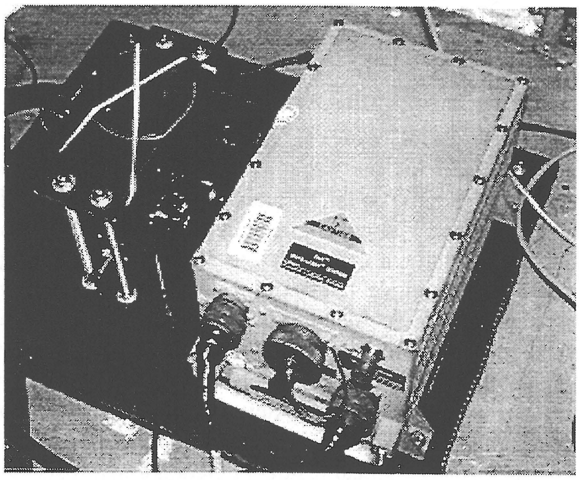

Figure 2. AIMS™ hardware configuration – INS and digital camera mount.

3. IMAGE GEOREFEENCING

Image georeferencing, or sensor orientation, is defined by finding a transformation between the image coordinates specified in the camera frame and the geodetic (mapping) reference frame. It requires knowledge of the camera interior and exterior orientation parameters. The interior orientation, i.e., principal point coordinates, focal length, and lens geometric distortion characteristics are provided by the camera calibration procedure. In traditional aerial photogrammetry, the six exterior orientation parameters (spatial coordinates of the perspective center, and three rotation angles known as ω, φ, and κ) are determined based on the collinearity equations, defining correlation between ground control points and their corresponding image representations. In the case of frame imagery, only one set of exterior parameters per image must be determined. However, for other sensors, such as push broom line systems or panoramic scanners, perspective geometry is valid only at a specific projection time, and varies with the swing angle (panoramic scanners), and each scan line (push broom systems). It is not (practically) possible to determine exterior orientation for all of the scan lines. For example, using the Direct-Digital Panoramic system (DDP), with an image size of 6,114×32,768 with each line having its own EOP, one would normally end up with 196,608 unknowns. Not only are these parameters too numerous, they are also highly correlated. When EOP can be determined directly from onboard sensors, such as GPS/INS, the number of control points can be reduced dramatically, and might eventually lead to the elimination of aerotriangulation in the traditional sense. Eventually, the GPS base station would be the only ground control point applied in the aerial mapping process, translating into tremendous economical savings. In the case of line scanners, where the number of EOP is very large, the advantages of using direct orientation are most pronounced. More importantly, emerging sensors such as laser scanner or radar depend exclusively on direct orientation.

Special attention, however, must be paid to accuracy and reliability of the mapping products generated by direct orientation aerial systems. The requirements of position and attitude accuracy are application dependent, defined mainly by the scale of the resulting maps. For example, cadastral or precise engineering projects require sub-decimeter and at least 3-arcminute accuracy in position and orientation, respectively (Skaloud et al., 1996). For less demanding applications and scale 1:10,000 and smaller, one-meter accuracy in position and a few tenths of a degree in attitude would be satisfactory. Typical results of standard aerial survey projects with high-accuracy requirements, completed at The Ohio State University for different photo scales, are presented in Table 2. The measurement error for the examples listed in Table 2 was 7 μ.

In order to estimate accuracy requirements for the AIMS™ direct orientation components, simulations based on von Gruber point locations were run for several point sets, with camera EOP perturbed, as shown in Table 3. The 4K × 4K sensor with 10 μ pixel size, focal length of 50 mm, and flying height of 500 m were assumed. Clearly, in order to obtain the highest positioning quality, the direct orientation has to be accurate to 5 cm and 5 arcsec, respectively.

PHOTO SCALE	FLYING HEIGHT	RMS	UNITS
2500	300	3	cm
2800	440	1	cm
3800	576	5	cm
13000	2200	0.15	meter
15000	2500	0.14	meter

Table 2. Accuracy estimates for aerial mapping projects completed at The Ohio State University.

$\sigma_{X_oY_oZ_o}$, $\sigma_{\omega_o\varphi_o\kappa_o}$	MEAN	RMS	MEDIAN [M]
5 cm, 5"	0.130	0.077	0.113
10 cm, 10"	0.260	0.153	0.226
20 cm, 20"	0.505	0.290	0.429
30 cm, 30"	0.768	0.481	0.651

Table 3. Positioning accuracy with direct orientation.

3. TEST FLIGHTS WITH DIRECT-DIGITAL PANORAMIC SYSTEM

In 1997 and early 1998 a total of 6 missions comprising 14 test flights were conducted to evaluate the performance of the integrated positioning/orientation component. The majority of the missions were performed without the AIMS™ digital camera on board, since the imaging component of the AIMS™ prototype became available in the fourth quarter of 1997, and is still in the calibration stage. In this section only the recent flights, conducted with St. Louis-based Image America, as listed in Table 1, will be discussed. Earlier results were presented in (Da, 1997; Grejner-Brzezinska, 1997, 1998; Toth, 1997).

Image America (formerly OMNI Solutions International Ltd.) is an AIMS™ associate partner, and has provided airplane support for the system testing since the early stages of the project. Since the company plans to acquire the AIMS™ positioning module, the major objective of the test flights performed in early 1998 with Image America was to test the AIMS™ GPS/INS component for direct orientation of the Direct-Digital Panoramic (DDP) system, and provide the company with hands-on experience. DDP is based on a retrofit Fairchild KA-55 panoramic camera, with Dalsa linear CCD assembly of 6,114 pixels installed on the rotating arm of the camera, collecting 32K image lines over a full swing, resulting in a peak data rate of 150 Megapixel/sec. The panoramic cameras scan the scene from side to side, in the direction normal to the flight direction. As compared to the frame cameras, they are known for good area coverage and for delivering very large amounts of data. They also tend to produce images with greater details. However, panoramic images lack the geometric strength of frame cameras, and might produce variable atmospheric effects in different portions of the image, as a result of varying altitude.

The imagery acquired by DDP system is currently georeferenced by means of traditional aerotriangulation. Additional hardware component includes Ashtech GPS 3DF-ADU multi-antenna system, capable of providing 2Hz position/attitude information, with accuracy estimated at 0.2° RMS for heading, and 0.4° RMS for pitch and roll, based on 1-meter square antenna array (3DF-ADU Manual). Attitude accuracy, limited by multipath effect, increases with the antenna separation. Period and amplitude of multipath oscillations varies significantly depending on vehicle dynamics and environment. Generally, in a mobile environment the multipath effect will be less severe, as compared to stationary case, due to the fact that multipath, as a correlated error becomes more noise-like under vehicle dynamics, and therefore, tends to be canceled out.

The accuracy of GPS-derived attitude components is highly competitive, compared to their counterparts determined from the stand-alone inertial navigation system. Unlike gyros, the heading derived from GPS is not affected by Schuler oscillations, does not drift over time, and does not need compensation for speed or course-induced errors. Obviously, accuracy is much higher, at a very comparable cost.

There are, however, some disadvantages of GPS-based attitude determination systems, such as much lower update rate than inertial systems, possible discontinuous solution due to losses of lock, and strong dependence on OTF ambiguity recovery. Consequently, the closest approch to the optimal solution – the integrated systems that utilize GPS accuracy and reliability, with high INS update rate and continuous operation, are currently being introduced in aerial mapping applications.

Two airborne missions, consisting of five test flights, were conducted with the Beechcraft Starship aircraft from Image America (Figure 3). The aircraft is currently equipped with the Direct-Digital Panoramic camera and the four-antenna 3DF GPS attitude determination system. The INS was tightly attached to the camera, whereas the GPS antennas were mounted on the fuselage, tail end, and the aircraft wings, providing bases of about 10 m in length, leading to the approximated angular accuracy of 1-3 arcmin. The attitude components were acquired by both systems, 3DF and GPS/INS, and compared for several portions of the flights, where the GPS solution was continuous. The average estimated RMS of the heading, pitch, and roll obtained from AIMS™ GPS/INS module is at the level of 4-7 arcsec, respectively (Grejner-Brzezinska, 1998), offering much higher accuracy, as compared to the multi-antenna stand-alone GPS.

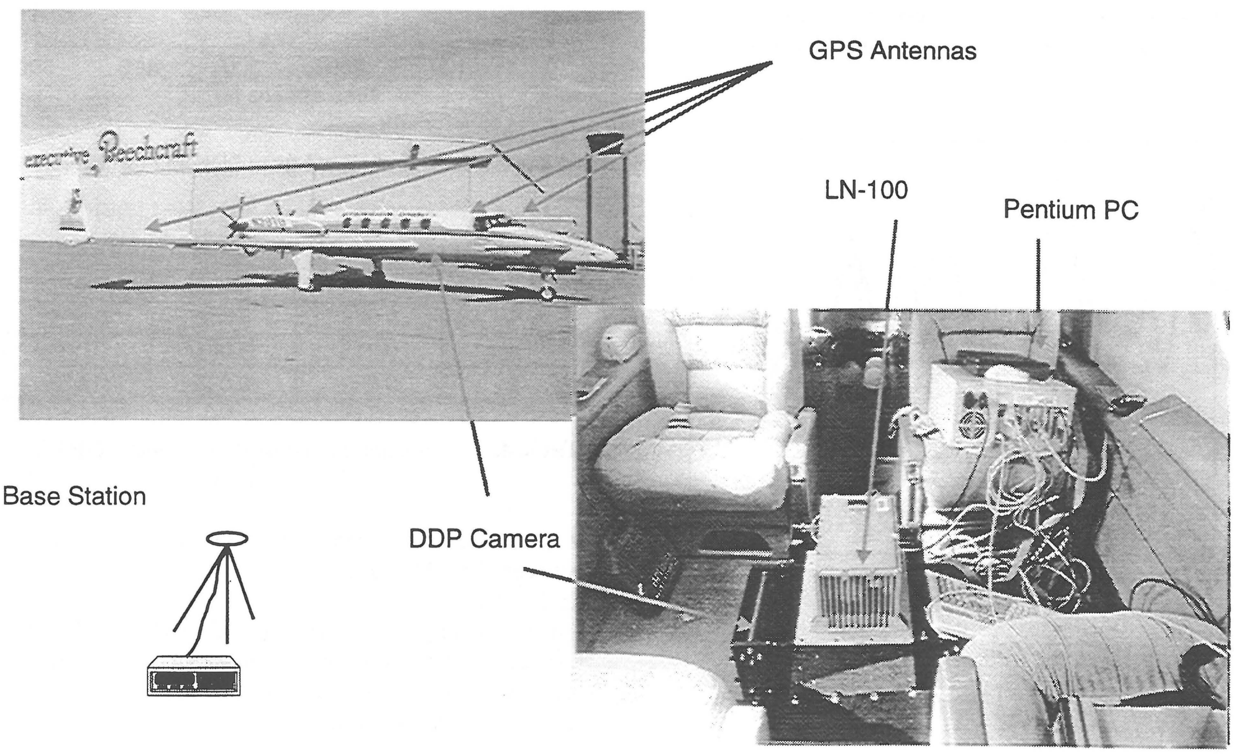

Figure 3. Flight configuration.

Attitude comparison was performed under the assumption that the unknown boresight components between the multi-antenna system and the IMU body frame would be estimated approximately as a byproduct of the data correspondence. The goal was to evaluate the difference between both solutions, knowing that there should be a constant "angular offset" between respective attitude counterparts, as long as the system is permanently mounted in the aircraft. Typical results are presented in Figures 4-6, and Table 4.

As can be observed in Figures 4-6, both solutions follow each other closely, and they are separated, as expected, by a nearly constant angular rotation that expresses the boresight components between the IMU body and the antenna system. Average angular separation for all three components is presented in Table 3 for four different flight segments listed in Table 1. Angular separation is clearly very similar for the flight pairs: 2 and 3, and 4 and 5, respectively, as presented in Table 4. The INS system was removed from the airplane between the respective pairs of test flights, therefore, the boresight components differ in both cases. Moreover, the pitch component, which in 3DF is defined by the rotation about the axis along the aircraft wings, is less stable as compared to heading and roll, due to the random variation and flex of the aircraft wings. Figure 7 presents the angular differences between both solutions with the constant (1st order) effect removed, according to Table 4, for the flight segments referred to in Figures 4-6. The differences presented in Figure 7 contain only the random component, and their amount practically matches the 3DF accuracy for the 10-meter baseline separation.

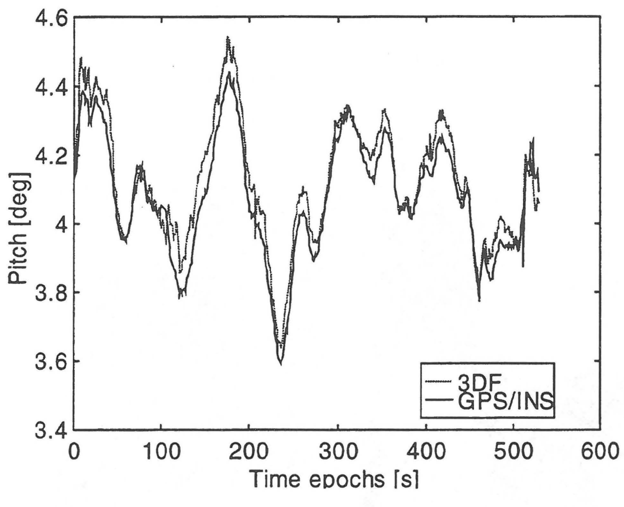

Figure 4. Heading obtained from 3DF and GPS/INS.

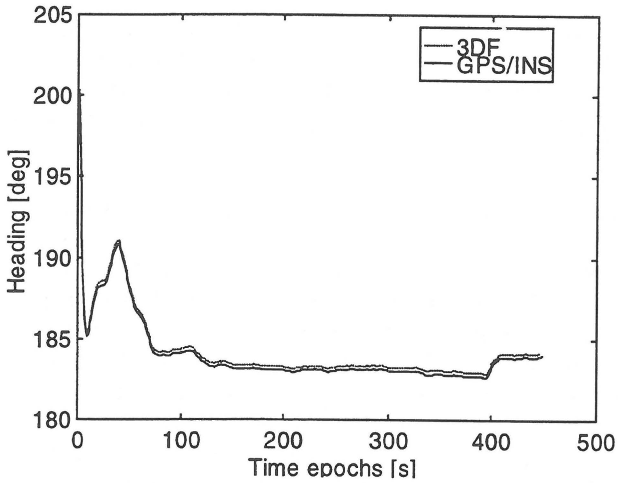

Figure 5. Pitch obtained from 3DF and GPS/INS.

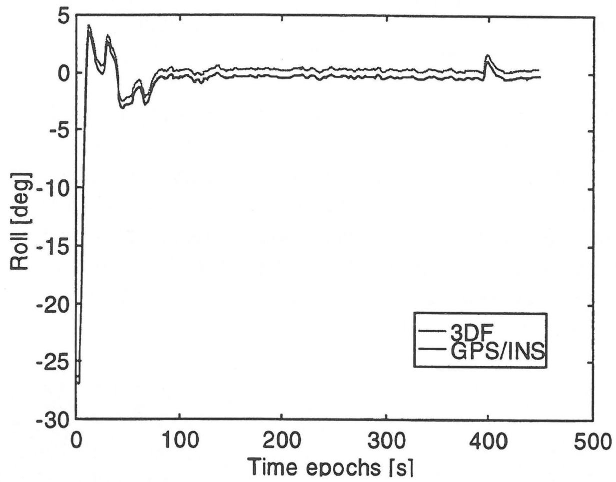

Figure 6. Roll obtained from 3DF and GPS/INS.

FLIGHT NO.	HEADING	PITCH	ROLL
2	0.354	0.120	0.652
3	0.369	0.096	0.655
4	0.215	0.041	0.600
5	0.220	0.020	0.629

Table 4. Average angular separation between GPS/INS and 3DF solutions.

It should also be mentioned that direct comparison between GPS/INS and aerotriangulation results based on DDP imagery cannot, for the time being, provide reliable quality assessment for GPS/INS, since the accuracy of the aerotriangulation results is presently at the level of 1-2 meters and a few arc minutes, respectively (Image America).

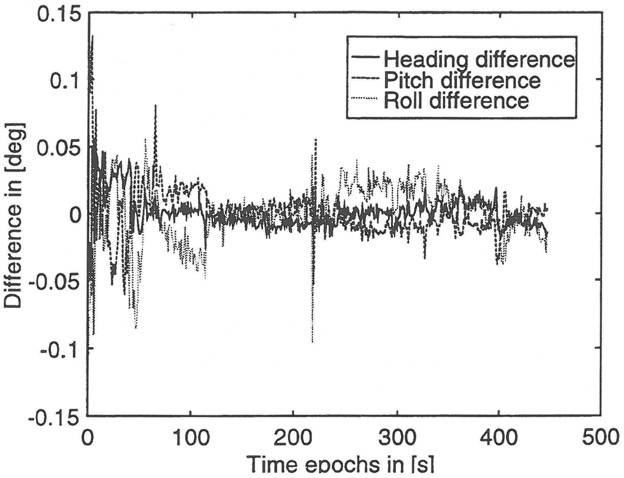

Figure 7. Random difference between GPS/INS and 3DF solutions.

4. GPS/INS PERFORMANCE EVALUATION

In mid-1997 the test flight over Albany, CA, involving GPS/INS data collection and Zeiss RMK Top aerial camera was conducted in cooperation with Hammon, Jensen, Wallen & Associates, Inc. The purpose of this test was to perform independent validation test of the AIMS™ positioning component. Four flight lines were flown with 60% overlap and 30% side lap, collecting a total of fifteen photos at the scale of 1:2,400. Project area included forty existing ground control points, with accuracy at the range of 10 cm per coordinate (1 sigma). The aerial photographs were processed on an analytical plotter, and photo coordinates were observed with an estimated a priori accuracy of 7μ. The camera exterior orientation components were obtained from bundle block adjustment based on ground control. The results are listed in Table 5. Unfortunately, the quality of the ground control was not satisfactory for the high-accuracy project requirements; therefore, the results show RMS of position and orientation of the camera projection center at the level of 20-40 cm, and 1.4-3.5 arcmin, respectively. Due to the rather modest quality, these results cannot serve as a reliable reference for GPS/INS evaluation. AIMS™ estimated errors are significantly smaller, being at the level of 2-4 cm RMS in position and 4-7 arcsec in attitude (Grejner-Brzezinska, 1998).

The projection center coordinates obtained from both methods were compared, nevertheless, and examples are presented in Table 6 below. These results show that the RMS of fit is around 14-15 cm in both horizontal and vertical directions, which is consistent with the order of magnitude of the initial quality of the project area plus estimated errors of GPS/INS and photogrammetric processing.

COOR-DINATE	IMAGE POINT MEASUREMENT RMS	PERSPECTIVE CENTER RMS	CONTROL POINT RMS
X	5μ	0.4 m	0.059 m
Y	6μ	0.4 m	0.062 m
Z	N/A	0.2 m	0.058 m
ω	N/A	3.5 arcmin	N/A
ϕ	N/A	3.2 arcmin	N/A
κ	N/A	1.4 arcmin	N/A

Table 5. Photogrammetric adjustment results.

PHOTO ID	EAST COORDINATE DIFFERENCE [M]	HEIGHT DIFFERENCE [M]
1011	-0.09	0.22
1012	-0.03	-0.06
1213	0.28	-0.05
1014	-0.11	0.18
4041	0.09	-0.04
4042	-0.31	-0.10
4043	-0.12	0.22
2021	0.06	-0.11
2022	0.05	-0.10
2023	0.15	-0.20
2024	-0.04	-0.01
RMS	0.15	0.14

Table 6. GPS/INS positions vs. aerotriangulation.

5. CONCLUSIONS

The hardware/software prototype of the GPS/INS integrated positioning system developed for airborne mapping is capable of providing direct orientation for any type of sensor, offering the possibility of eliminating the need for ground control and aerotriangulation. It provides more accuracy and reliability than the stand-alone GPS system, with its continuous solution and much higher sampling rate, critical in high-dynamic situations, where high accuracy is required. The attitude components derived from GPS/INS compare with the GPS-only-derived counterparts with an accuracy equal to the estimated accuracy of the 3DF system, which is at least 10 times worse than the estimated accuracy of the GPS/INS solution. Moreover, the direct orientation system offers a great cost reduction in photogrammetric processing, and shorter turnaround time, as compared to traditional photogrammetry. However, further investigation is recommended to assess the full reliability of the system.

ACKNOWLEDGEMENTS

The AIMS™ project is supported by the NASA Stennis Space Center, MS, Commercial Remote Sensing Program grant #NAG13-42, and a grant from Litton Systems, Inc. Special thanks go to Image America for providing test flight support and the 3DF solution.

REFERENCES

Abdullah, Q., (1997): Evaluation of GPS-Inertial Navigation System for Airborne Photogrammetry, presented at 1997 ACSM/ASPRS Annual Convention and Exposition, April 7-10, Seattle, WA.

Bossler, J. D., and Schmidley, R. W. (1997): Airborne Integrated Mapping System Promises Large-Scale Mapping Advancements, *GIS World*, Vol. 10, No. 6, pp. 46-48.

Da, R. (1997): Investigation of Low-Cost and High-Accuracy GPS/IMU System, Proc. ION National Technical Meeting, Santa Monica, pp. 955-963.

Da, R. (1997): Analysis and Test Results of AIMS GPS/INS System, Proc. ION GPS, pp. 771-780.

Grejner-Brzezinska, D. A. (1997): Airborne Integrated Mapping System: Positioning Component, Proc. 53rd ION Annual Meeting, Albuquerque, NM, pp. 225-235.

Grejner-Brzezinska, D. A. (1998): Positioning Accuracy of the Airborne Integrated Mapping System, Proc. ION Technical Meeting, Long Beach, CA, pp. 713-721.

Harvey, R., Cannon, M. E. (1997): Operational Results of a Closely Coupled Integrated Vehicle Heading System, Proc. ION GPS, Kansas City, Missouri, pp. 279-288.

Kerr III, T. (1994): Use of GPS/INS in the Design of Airborne Multisensor Data Collection Mission (for Tuning NN-based ATR Algorithms), Proc. ION GPS, Salt Lake City, Utah, pp. 1173-1188.

Lachapelle, G., Lu, G., and Loncarevic, B., (1994): Precise Shipborne Attitude Determination Using Wide Antenna Spacing, Proc. KIS94.

Lithopoulos, E., Reid, B., Scherzinger, B., 1996. The Position and Orientation System (POS) for Survey Applications, International Archives of Photogrammetry and Remote Sensing, ISPRS Comm. III, Vol. XXXI, part B3, pp. 467-471.

Litton Systems, Inc. (1994), *LN-100G EGI Description*, Litton Systems, Inc., September 1994.

Scaloud, J., Cramer, M., Schwarz, K.P., (1996): Exterior Orientation by Direct Measurement of Camera Position and Attitude, International Archives of Photogrammetry and Remote Sensing, Vol. XXXI, Part B3, pp. 125-130.

Schwarz, K. P. (1995): INS/GPS as a Georeferencing Tool for Multi-Sensor Systems, presented at the Mobile Mapping Symposium, May 24-26, Columbus, OH.

Schwarz, K. P., Wei, M. (1994): Aided Versus Embeded A Comparison of Two Approaches to GPS/INS Integration, Proc. IEEE Position Location and Navigation Symposium, April 11-15, Las Vegas, NE, pp. 314-321.

Van Graas, F., Braasch, M. (1992): GPS Interferometric Attitude and Heading Determination: Initial Flight Test Results, *Navigation*, Vol. 38, No. 4, pp. 359-388.

Toth, C. (1997): Direct Sensor Platform Orientation: Airborne Integrated Mapping System (AIMS), ISPRS Comm. III, Vol. XXXII, part 3-2W3, pp. 148-155.