Integrated GPS-aided Inertial Lidar and Optical Imaging Systems for Aerial Mapping

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ABSTRACT:

High-resolution airborne Lidar and optical imaging systems with onboard data collection based on the Global Positioning System (GPS) and inertial navigation syste ms (INS) technology may offer the means to gather accurate topographic map information. As a follow-up to earlier investigations, in May 2005 an airborne integrated GPS-aided inertial Lidar and optical imaging system was used to collect data over the southern San Andreas Fault. A major thrust of this paper is to compare the positional accuracy of Lidar and optical imaging system points obtained from these investigations. Presented herein are the collective results of those horizontal and vertical accuracy measurements and concluding remarks about their potential for aerial mapping in Antarctica. The marked change in relief of the Grand Canyon is similar to the Dry Valleys of Antarctica. These changes provide an excellent test for measuring the potential of the GPS-aided inertial Lidar and optical imaging systems for aerial mapping. The San Andreas Fault poses a major earthquake hazard to the greater metropolitan areas in southern California and Lidar and optical imaging systems could provide information vital to post-disaster response. All together, these findings of positional accuracy yield important information on a new approach for aerial mapping in Antarctica and other remote areas of the world.

Introduction

Many applications of geospatial data, especially in remote areas, are realized more efficiently by direct georeferencing using an airborne integrated system comprised of GPS receiver and inertial navigation system components. Direct georeferencing (DG) is the enabling technology for airborne Light Detection and Ranging (Lidar) and electro-optical imaging systems. Crucial issues to the direct georeferencing of Lidar and optical imaging is the positional accuracy and reliability achievable by the Lidar and digital camera integrated system.

Numerous documented GPS/INS-related field tests have been conducted over the years (Cramer, 1999; Cramer, Stallmann, and Haala, 2000). These tests, flown over mostly flat

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terrain, were evaluated by private and public institutions to meet National Mapping Accuracy Standards (NMAS) and American Society of Photogrammetry and Remote Sensing (ASPRS) accuracy standards for large -scale mapping. However, tests flown over steep terrain resulted in higher than normal vertical positional bias that did not meet positional accuracy standards for large-scale mapping (Cramer, 1999; Colomina, 1999; Greening and others, 2000; and, Sanchez and Hothem, 2002). Significant accuracy improvements have come about when operating in a multi -receiver configuration (Shi, 1994, Raquet, 1998, Bruton, Mostafa, and Scherzinger, 2001, Sanchez, 2004: Sanchez and Hudnut, 2005). The objective of this study, funded by the National Science Foundation and the U.S. Geological Survey, is to compare the positional accuracy of the Lidar and optical systems data obtained from previous investigations and examine the potential of airborne integrated GPS-aided inertial Lidar and optical imaging systems for aerial mapping in Antarctica.

Test Areas

Grand Canyon

The first test conducted in July of 2003 lies in the northernmost part of the Grand Canyon also referred to as Glen Canyon (Sanchez, 2004). The marked change in relief of the canyon are similar to the Dry Valleys of Antarctica and provide an excellent test for measuring the potential of the GPS -aided inertial Lidar and optical imaging systems aerial mapping (figure 1).

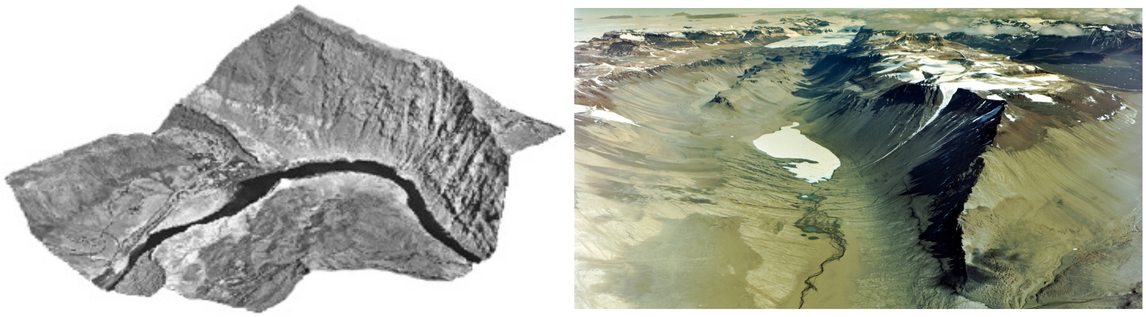

Figure1. Relief depiction of Glen Canyon (left) compared to the Dry Valley (right)

San Andreas Fault

The San Andreas Fault test areas were conducted in southern California in two phases. The first phase which was conducted in March 2004 traverses the foothills of the San Bernardino Mountains within a 1 km wide and 172 km long flight corridor (Sanchez and Hudnut, 2005). The second phase conducted in May 2005 covers approximately 1 km wide and 965 km in length from as far north as Parkfield and Bombay Beach and Salton Sea in the south (figure 2). This phase is also known as the B4 project. The surface topography is a rough succession of urban area, canyons, slopes, valleys and deserts carved out by arroyos and washes.

Figure2. Flight corridor of southern San Andreas Fault

System Configuration, Calibration, and Reference Stations

Grand Canyon

The commercial airborne integrated GPS/INS used in th e Grand Canyon is the Emerge Digital Sensor System (DSS) and POS AV (Position and Orientation Solutions for Airborne Vehicles) 410 from Applanix Corp., Richmond Hill, Ontario, Canada. (In October 2003, Trimble, Applanix's parent company, acquired Emerge and its product design). The DSS is a medium format (4092 x 4079 pixels) sensor, Appendix A lists specifications of the DSS used in this study. The Applanix POS AV 410 for Direct Georeferencing (DG) package comprises four main components: (1) a dual-frequency L1/L2 carrier phase embedded GPS receiver (NovAtel MiLLennium), (2) a POS Inertial Measurement Unit (Litton LR-86), (3) the POS computer system, and (4) the POSPac post-processing software (comprised of POSRT, POSGPS, POSPROC, and POSEO modules). The National Geodetic Survey's (NGS) Continuous Operation Reference Station (CORS) in Flagstaff, Arizona, served as the base station *(http://www.ngs.noaa.gov/CORS/Arizona_fst1.html1)*.

In addition, the author placed aerial panel points with documented horizontal and vertical coordinates along the flight corridor to test the accuracy of the position and height information. For the flight, the DSS and IMU are housed in an exoskeleton rigidly mounted to the port hole of a Cessna 172 aircraft and linked to the system computer. The GPS antenna is centered above the camera on top of the fuselage of the aircraft. Following the flight, the Applanix POSPac post-processing software computed the collected DSS raw data at the camera perspective center.

The spatial offsets between the different sensor components have to be identified to relate the position and orientation information provided by the GPS/IMU to the perspective center of the camera. "Boresight" components are the angular and linear misalignments between the POS IMU body frame and the imaging sensor. Before the actual fly-over of the Glen Canyon the boresight calibration occurred in a test flight over the Emerge test range in Florida. To resolve the boresight transformation, the Emerge staff compared the GPS/IMU positioning/orientation results with the aerial triangulation solution. The staff then used data from the POS/DG and aerial triangulation from the flight to resolve the fixed misalignment angles (omega, phi, kappa or between the IMU and the camera axes.

The Lidar data used in the positional accuracy test of this project were acquired over the Grand Canyon during three separate missions in the Spring and Fall of 2000. The Aeroscan ALMS sensor (operated by Earthdata, Maryland) was used to collect Lidar data in late March. ALMS is a bi-
wavelength. Data were collected at a flight altitude of 3,048 m, with a pulse rate of 15 kHz, and a scan rate of 13 Hz. This collection provided a swath width of 1,350 m, an average spot spacing of 3.75 m, and an average spot diameter of 1 m. The ALMS sensor data used dual-frequency GPS and IMU information to determine the position and elevation of each data point. All Lidar vertical data were delivered as orthometric heights (NVGD29, Geoid99).

San Andreas Fault

The commercial airborne integrated GPS/INS used in the first phase collection within the southern San Andreas Fault is the Applanix Digital Sensor System (DSS) and the Position and Orientation System for Aerial Vehicle (POS AV) 410 package from Applanix Corp., Ontario, Canada. The DSS camera is a medium format sensor with a 55.01 mm focal length and 4k x 4k pixel array. Each color image is digitally exposed every 2.5 seconds in three bands (red, green, and blue) with a base/height ratio of 0.5 – 1.0. For the test, the DSS was rigidly mounted in the Applanix's Cessna 182 aircraft. The GPS antenna was centered above the camera on top of the fuselage of the aircraft—the horizontal offset of the antenna phase center was very small and treated as zero. The DSS generated orthorectified images in this first phase collection are cross-referenced with Lidar and IfSAR in the test area collected by USGS and NOAA.

According to Gerald Kinn of the Applanix Corporation, the individual sensor calibration of the DSS was done in the Applanix Lab and the overall systems calibration of the antenna, camera, and inertial measurement unit (IMU) lever arms, and the IMU/camera boresight, were carried out by Applanix at their Florida test range. To resolve any boresight transformation, Applanix compares the GPS/IMU positioning/orientation results with the aerial triangulation solution, then used the data from the POSEO and aerial triangulation from the flight to resolve any fixed misalignment angles between the IMU and the camera. "Event markers are recorded during the aerial survey to precisely identify shutter release times for frame cameras. These event markers are extracted during post-processing." (Applanix website at ω, Φ, κ)
http://www.applanix.com).

Five of the continuous Southern California Integrated GPS Network (SCIGN) operating reference sites (http://www.scign.org/) provided the multiple base stations used in combination with carrier phase DGPS post-processing to achieve optimum accuracy. The SCIGN reference station data were processed in conjunction with the airborne GPS raw observables to determine the aircraft position which was then used to aid the inertial data processing in a closed loop manner to end up with a full resolution of the trajectory parameters, namely position, velocity, and attitude which were then used to generate exterior orientation data to support aerial mapping. directional,

The NSF supported Center for Airborne Laser Mapping (NCALM) airborne integrated GPS/INS used in this second phase combined the Redlake MS4100 optical image system and the Airborne Laser Terrain Mapper (ALTM) 1233 with the Applanix POS AV 410 package. In addition, an ALTM 3100 with the Applanix POS AV 510 package was made

available by Optech Incorporated, Ontario, Canada. The Redlake camera is a small format sensor with a 25.97 mm focal length and 2k x 1k pixel array. Each color image is digitally exposed every 2.0 seconds in three bands (red, green, and blue) with a base/height ratio of 0.5 – 1.0. For this phase test, the Redlake and ALTM 1233 were rigidly mounted in the NCALM's Cessna 337 aircraft and the ALTM 3100 in a Twin Cessna Flyer 310. The camera did not always function properly during Lidar acquisition. Consequently, only the ALTM 3100 collected data is used in the positional accuracy test of this study. The ALTM 3100 sensor (operated by Optech)
Data were collected at a flight altitude of 600 m, with a pulse rate frequency (PRF) of 70 kHz, and a scan rate of 45 Hz. This collection called for an individual swath width of 285 m, and a point density at 70 kHz PRF of 4-5 point/m² (on average the point density proved to be around 2 points/m²). All the Lidar vertical data were delivered as ellipsoid heights. The GPS antenna for each system was centered above the camera on top of the fuselage of each aircraft—the horizontal offset of the antenna phase center was very small and treated as zero .

The Redlake camera calibration was conducted at the USGS-Sioux Falls facility prior to the phase two mission. Other sensor calibration was done in the NCALM and Optech labs and the overall systems calibration of the antenna, sensor, and inertial measurement unit (IMU) lever arms, and the IMU /sensor boresight, were carried out by NCALM at their Florida test range. To resolve any boresight transformation, Applanix compares the GPS/IMU positioning/orientation results with the aerial triangulation solution, then used the data from the POS EO and aerial triangulation from the flight to resolve any fixed misalignment angles between the IMU and the sensor.

The continuous Southern California Integrated GPS Network (SCIGN) operating reference sites (http://www.scign.org/) provided the multiple base stations used in combination with carrier phase DGPS post-processing to achieve optimum accuracy. The SCIGN reference station data were processed in conjunction with the airborne GPS raw observables to determine the aircraft position which was then used to aid the inertial data processing in a closed loop manner to end up with a full resolution of the trajectory parameters, namely position, velocity, and attitude which were then used to generate exterior orientation data to support aerial mapping .

Aerial panels were setup over existing benchmarks throughout the project corridor by project team members. These panels provided valuable ground control points for the photogrammetric test measurement of position and height.

Positional Accuracy Analysis

Grand Canyon

To obtain the positional accuracy we examined absolute orientation using the horizontal and vertical coordinates of the visible panel point in the stereo models and the values of their corresponding surveyed reference positions. Then we measured the difference between the logged surveyed reference positions and corresponding panel points displayed in the stereoimage on the digital photogrammetric workstation. We determined the difference by subtracting the values of the panel point from the surveyed reference position. For example, the measured panel point values in the stereoimage were roughly parallel to the ground level at an average DSS vertical positional bias of +4.05 m. Table 1 show the results of the comparison of the panel point coordinates in the stereoimages against the values of the logged DSS survey referenced positions.

REF. NO	PANEL ID	d_Easting	d_Northing	d_Vertical
1	211	+4.04	+1.34	+3.92
2	212	+3.17	+1.44	+4.67
3	214	+3.08	+1.38	+3.56
Average		+3.43 m	+1.39 m	+4.05 m

Table1. The statistical difference or delta (e.g., d_Easting) between the DSS ground-surveyed reference points and corresponding panel points measured on the digital photogrammetric workstation.

Figure 3 below shows the vertical position comparison between the DSS, ALMS, and panel point. The statistical difference of the vertical heights between the ground-surveyed reference points of the optical imaging, Lidar, and panel point #212 are +4.67 m and +0.22 m, respectively.

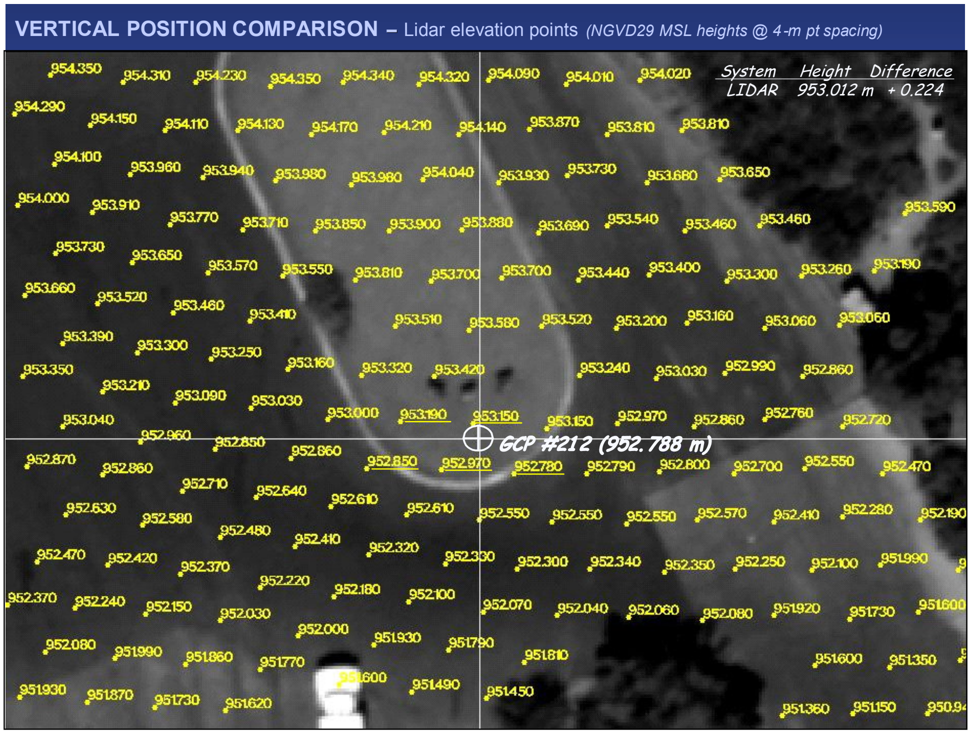

Figure3. Optical image vertical comparison with ALMS Lidar points

San Andreas Fault

As in the Grand Canyon study, absolute orientation was examined using the horizontal and vertical coordinates of the visible panel points in the stereo models and the values of their corresponding surveyed positions on the ground. The difference between the logged surveyed coordinates and corresponding panel points displayed in the stereoimage were measured on the SOCET Set photogrammetric workstation. The difference was determined by subtracting the values of the panel point from the coordinates derived by the San Bernardino County and the USGS static method of survey. The measured panel point values in the stereoimage were roughly parallel to the ground level at an average positional offset of -1.46 m (delta x), -0.27 (delta y), and -0.74 m (delta vertical).

A statistical comparison of the difference between the San Bernardino County surveyed coordinates and their corresponding panel positions displayed on the digital photogrammetric workstation, in meters, is shown in table 2.

A comparison of the average positional accuracy of the San Bernardino County kinematic-surveyed panel coordinates and their corresponding panel positions in the stereoimages with that of the USGS static-survey panel coordinates for the same panel positions is shown in table 3.

Ref.	Panel	d_easting	d_northing	d_vertical
1	5	-1.40	-0.16	-0.51
2	6	-1.40	-0.32	-0.99
3	8	-1.63	0.00	0.41
4	12	-1.17	-0.32	-0.27
5	15	-1.40	-0.16	-1.80
6	16	-1.63	-0.32	-1.60
7	17	-1.63	-0.64	-0.38
Average		-1.46	-0.27	-0.74

Table 2. Difference between the San Bernardino County surveyed panel coordinates and their corresponding panel positions in the stereoimage, in meters

Crew (*survey*)	d_easting	d_northing	d_vertical
SB Cty (kinematic)	-1.46	-0.27	-0.74
USGS (static)	-0.28	+0.25	-0.55

Table 3. The average positional accuracy results using the San Bernardino County kinematic survey values in comparison with those of the USGS static survey, in meters.

The statistical difference of the vertical height between this ground-surveyed reference point #16 and the DSS and ALTM 3100 are +1.60 m and +0.13 m, respectively.

Phase I (DSS)	D_easting	D_northing	D_vertical
Preliminary solution	-1.46	-0.27	-0.74
Final solution	-0.28	+0.25	-0.55
Phase II (ALTM 3100)			
Preliminary solution	-0.36	+0.04	-0.23
*Final solution**			

Table 5. Comparison of the positional accuracy offset averages of Phase I using the Applanix DSS and Phase II using the Optech 3100 Lidar sensor. (*Final solution is in process).

Phase II (ALTM 3100)	Horizontal Accuracy	Vertical Accuracy
B4 Project	15 – 20 cm	3 – 4 cm
OSU Reference	5 – 10 cm	2 – 3 cm

Table 6. Comparison of the positional accuracy offset averages of Phase I using the Applanix DSS and Phase II using the Optech 3100 Lidar sensor. (Final solution is in process).

According to Charles Toth, Ohio State University (OSU), based on 20 percent completion as of June 30, 2006, higher positional accuracy measurements have been obtained by the OSU field crew using experimental Lidar specific circular ground targets. These positional accuracies are shown in Table 6 are based on processed points and past reference data. The center coordinates accuracies were determined from the Lidar point cloud and from the GPS survey.

Conclusions

The overall positional accuracy of the optical imagery and Lidar data collected for this study improved considerably in comparison with past tests conducted by the USGS. Achieving the demanding horizontal position and height accuracy (15 cm or 6 inches) calls for a higher precision of the exterior orientation than was achieved in this project. The multiple reference base station approach using the SCIGN sites did show improvement in the positional accuracy when compared to the single station approach. The average positional offset of the SCIGN multiple reference station approach in the first phase of SAF test were 0.28 m (delta x), 0.25 m (delta y), and -0.55 m (delta vertical), and -0.36 m (delta x), 0.04 m (delta y), and -0.23 m (delta vertical) in the second phase.

The Applanix airborne integrated digital camera and Lidar GPS-aided inertial navigation system, together with the GPS base station network provided by the SCIGN at 10 km spacing, allowed us to perform extraordinarily achieve reasonably accurate aerial mapping. The high informational content and interpretability of the DSS color images enabled us to immediately view scarps, steep slopes and cliffs at the edge of plateaus or ridges formed by erosion, and other features.

This unprecedented positional accuracy and spatial resolution and permits the aerial mapping of intricacies and complexities of slip-strike to help test the dynamic and static strength of faults, leading to a vastly improved physical understanding of geomorphological processes vital to researchers. When combined with Lidar for vertical accuracy the digital aerial camera can be reliably used for large scale topographic mapping in Antarctica.

Recommendations

Although, the position and height results found in this study appear not meet the large-scale positional accuracy of less than 15 cm, with proper mission planning, GPS-aided inertial technology has the potential to meet large scale aerial mapping requirements. Based on the findings of this study and previous studies, the single most important step to achieving the overall positional accuracy required is careful mission planning. Therefore, where the highest GPS position and height accuracy is needed the following recommendations are proposed:

1) Simultaneous collection of data using a combined GPS-aided inertial navigation digital imaging and Lidar system.
2) Conduct boresight tests near the project area before and after the flight mission, and retain results and other calibration information.
3) Design the project to minimize multipath by using closely spaced multiple base stations or a base-line separation of less than 30 km.
4) Operate when six or more satellites are available and PDOP is minimized.
5) Minimize rotation in heavy cross-winds by using a heavier aircraft or changing the flight profile.
6) Minimize cycle slips from occurring by minimizing aircraft bank angles by flying relatively flat turns.

7) After each flight mission check the logged data for gaps, inertial sensor errors, and assure raw GPS observables have no major cycle slips.
8) Retain raw observation data for later evaluation and validation.

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