Performance Analysis of Integrated Sensor Orientation

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Abstract

Integrated multi-sensor systems, with their major progress in terms of sensor resolution, data rate and operational flexibility, have become a very attractive mapping tool over the last decade. In aerial mapping application, for example, Exterior Orientation (EO) parameters for the imaging sensors are required. Using the integrated Differential Global Positioning System (DGPS) with Inertial Measurement Units (IMU), direct determination of the EO parameters can be obtained from the integrated system navigation solution. This process is referred to as Direct Georeferening (DG). DG provides substantial benefits over the indirect determination method of estimating the EO parameters from conventional Aerial Triangulation (AT) techniques using a block of images with a sufficient number of known control points. These benefits include the ability to map remote and inaccessible regions, and by replacing tie point measurements/matching and AT, significant cost-savings can be obtained for projects that do not require stereo models (such as projects with existing DEM or single image). The accuracy of DG, however, is limited by the accuracy attainable by the DGPS and any residual datum calibration errors. These can typically be as large as 10 cm RMSE, which is not sufficient for some large scale mapping applications. However, by combining the direct EO data a traditional block adjustment, AT techniques can be used to remove the residual errors in the solution. This technique is known as Integrated Sensor Orientation (ISO). It has several advantages over traditional AT, primarily because the stable geometry provided by direct EO can reduce the number of required GCP and tie-point to a minimum. At the same time, ISO provides an excellent tool for Quality Control/Quality Assurance (QC/QA) of the EO derived from a DG system. This paper examines the factors that determine the system performance for ISO. In addition, examples are given to illustrate the expected accuracy of an aerial mapping project using ISO under different qualities of DGPS/IMU data.

Introduction

During the recent revolution in aerial mapping, at least two major components have undergone rapid research and development. First, imaging sensors have rapidly changed from the traditional film camera, to large format digital frame and line scanners. As well, there are a plethora of new imaging sensors appearing including medium format digital cameras, multi- and hyper-spectral imagers, lidar and SAR; second, the determination of exterior orientation parameters (EO) from traditional aerial triangulation (AT) techniques to integrated multi-sensor systems using Differential Global Positioning System (DGPS) and Inertial Measurement Units (IMU). The first component focuses on the data acquisition format in which the digital mapping environment has played an important role. Instead of image positives, digital imaging sensors provide imageries in digital format, saving film development and scanning cost. The second component is a major change in aerial mapping workflow because EO parameters must be determined for orthophoto generation, regardless of the type of the imaging sensor being used. In some cases such as line scanners, lidar and SAR, EO cannot be obtained using the traditional AT technique.

This paper focuses on the second component, the determination of EO parameters. There are two basic approaches to estimate the EO of an imaging sensor, they are:

- directly by using on-board position and orientation sensors, and
- indirectly by extracting the EO parameters from a block of images with a sufficient number of known ground control points.

The first approach is known as Direct Georeferencing, most commonly achieved using an integrated DGPS/Inertial system. Such systems have been well studied and implemented commercially, such as Applanix's Position Orientation System for Airborne Vehicles (POS AV). The second approach uses AT, which relies on a network of tie points in a block of *frame* imagery with a sufficient number of known ground control points.

When the availability of ground control points is in question, such as in forests, snow, desert, or along a coastline, the ability of resolving the EO parameters *indirectly* is limited. Often these areas are very important when emergency response has to be taken place: forest fire, flooding, or hurricane. Such an application requires rapid orthophoto generation, and there is insufficient time and resources to extract EO parameters using traditional AT. In addition, some projects require only a single strip or single photo orientation. When stereo model is not necessary and an existing Digital Elevation Model (DEM) is available, the use of traditional AT to determine the EO parameters is unpractical because it requires excessive ground control points and additional overlapping photos. Hence, in many applications

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direct georeferencing is either the only practical solution, or the most cost effective solution.

In tradition, large area mapping projects however, there always exist a block of images with side and end-lap. Having such a block of images, it is possible to combine the advantages of both DG and AT by running an assisted AT or ISO. ISO has been discussed widely in the last few years, most extensively by the OEEPE test in 2001 (Heipke *et al.*, 2001). This paper discusses the use of ISO on blocks of images, and investigates what kind of EO accuracy from the DG system is required to optimize the workflow efficiency.

Direct Georeferencing

Benefits of Direct Georeferencing

Before investigating the benefits of ISO, an understanding of the benefits and capabilities of DG is required. The OEEPE test results showed that the high-end direct georeferencing systems can achieve an accuracy of 5 to 20 cm in horizontal, and 10 to 25 cm in vertical direction with traditional film cameras (at a scale of 1:5 000 and 1:10 000) by using directly acquired EO without performing bundle adjustment (Cramer, 2001a). This accuracy is good enough to perform mapping for reduced accuracy requirement applications such as orthophoto creation (Kruck *et al.*, 2001), and is ideal for projects such as corridor and single photo orientation where it is unpractical to collect numerous ground control points required for AT. An example of a high-performance direct georeferencing system is an Applanix POS AV 510.

Direct georeferencing also allows the generation of the so-called "fast orthomosaic" by allowing automatic DEM extraction and subsequent orthomosaic generation without AT and little operator intervention. An example of this has been performed on the Applanix's Digital Sensor System (DSS), which consists of a medium format digital camera (4,092 $\times$ 4,077 pixels) and a POS AV 410 system. Comparing the "fast orthomosaic" with DGPS surveyed checkpoints, the Root Mean Square (RMS) horizontal accuracy is about +/−0.5 meter, which meets the 1:600 USGS mapping standard. (Ip *et al.*, 2004a).

Direct Georeferencing on Large Scale Projects

The accuracy on the ground when using a DG system is dependent upon the GPS accuracy for position, and the IMU accuracy for orientation. The orientation error produces a position error on the ground as a function of flying height (or scale). At best, GPS provides about 5 to 10 cm RMS under dual frequency differential processing. For a high-performance DG system using ring-laser, fiber optic or dry-tuned gyros, the orientation accuracy is typically about 0.005 degrees RMS for roll and pitch, and about 0.008 degrees RMS heading. For large scale mapping projects that are flown at relatively low altitude above the ground, the ground accuracy becomes dominated by the DGPS position error (Mostafa, 2001). Therefore, for large scale mapping (>1:1 000) projects requiring sub-centimeter accuracy, direct EO usage from a DG system is insufficient. To overcome this problem, further research to improve DGPS accuracy is currently being done. However, using AT to improve the GPS accuracy has long been considered by researchers as an acceptable solution, and has been introduced in the OEEPE tests as ISO.

Integrated Sensor Orientation

Benefits of Integrated Sensor Orientation

Assisted AT or ISO combines the benefits from both DG and traditional AT, *when the imagery is flown in a block configuration with sufficient overlap*. By using EO parameters from DG systems as observation and initial approximate for aerial triangulation, only a limited number of tie points in the overlapping area are needed, and ground control points are only required to check for datum shifts and to correct systematic residual errors in the DGPS solution. Furthermore, the direct EO in the tie-point matching process reduces the computational time and numbers of blunders, making the entire process seamless and fully automatic.

Using ISO as a Quality Assurance/Quality Control Tool for Direct Georeferencing

One of the key assumptions in the use of DG is that the calibrated system parameters are constant over the flight mission. These parameters include GPS/IMU lever arm offset, boresight mis-alignment and a description of the camera's internal geometry. The GPS/IMU lever arm offset can be estimated during DGPS/IMU post-processing, and therefore it is not an issue except for real-time application. Boresight misalignment refers to the physical misalignment angles between the IMU and the camera axes. These angles are small in magnitude (through installation), but are required to be measured highly accurately in order to achieve the required ground accuracy. Since it cannot be estimated in DGPS/IMU post-processing, terrestrial or flight calibration must be used to determine its value. As for the camera's internal geometry, large format aerial film or digital cameras usually have very stable residual errors, as they are designed for aerial usage. Only the focal length of the film cameras might slightly change over time as a function of temperature and pressure. In contrast, some small and medium format digital cameras need to be monitored at a regular basis to ensure that the camera parameters are stable within certain accuracy. Like the IMU boresight, the camera interior geometry is usually calibrated terrestrially and/or through a flight calibration.

Although one could run a terrestrial and flight calibration before every mission to check against the boresight values and camera parameters, this is not practical due to the processing time and cost. Instead ISO can be used to run a cost efficient Quality Assurance (QA)/Quality Control (QC) procedure using actual photos from part of the image block, or from a small QA/QC block flown before or after the mission. The QA/QC procedure should at least have three strips with eight photos per strip (Ip *et al.*, 2004b), and tie points collected automatically is preferred. By running ISO, boresight values can be refined and self-calibration can be performed for the camera. In addition, if one or two ground control points are available in the projects area, datum shifts in the mapping frame can also be determined. Notice that the QA/QC procedure does *not* refine the EO parameters; it is only used to refine the calibration parameters. The final EO parameters are calculated from the DGPS/INS solution.

Reducing System Cost

Except for large scale engineering projects which are limited by the accuracy of DGPS, a high-performance DG system is sufficiently accurate to perform all types of projects: corridor mapping, single photo orientation, and mapping in remote areas. This total solution provides the flexibility of being able to do nearly any project without the need to fly in a block configuration. However, it is useful to understand if a lower accuracy direct georeferencing system, and hence lower cost, can achieve similar accuracy to a high end system when ISO is used. If this is the case, then a user who only flies projects that contain a block of images can be benefited.

One may argue that the collection of tie points in a block of images is a time consuming process, and hence this limits any benefits that ISO with a lower cost/lower accuracy

DG system might achieve. However, the EO parameters from the less accurate DGPS/INS system provide an important piece of information for the automatic tie point collection module. The search area for potential tie point location can be minimized, and therefore both performance and accuracy are significantly improved. In addition, if the number of tie point required to perform ISO can be optimized, processing time can also be minimized.

Achieving Maximum Accuracy

While DG systems allow direct determination of EO parameters in high accuracy and reliability, there exist projects that require sub-centimeter accuracy. Such projects require refinement on the direct EO parameters, since the accuracy is limited by the DGPS solution. In this case, ISO can be used to perform assisted AT using the direct EO data as initial approximates, providing maximum accuracy towards these DGPS/INS systems.

The following sections investigate these benefits of ISO using actual flight test data from a high accuracy DG system, plus simulated data from a lower accuracy system. The analysis focuses on the effects due to differing direct EO accuracy only, and does not look at the contributions of system calibration errors

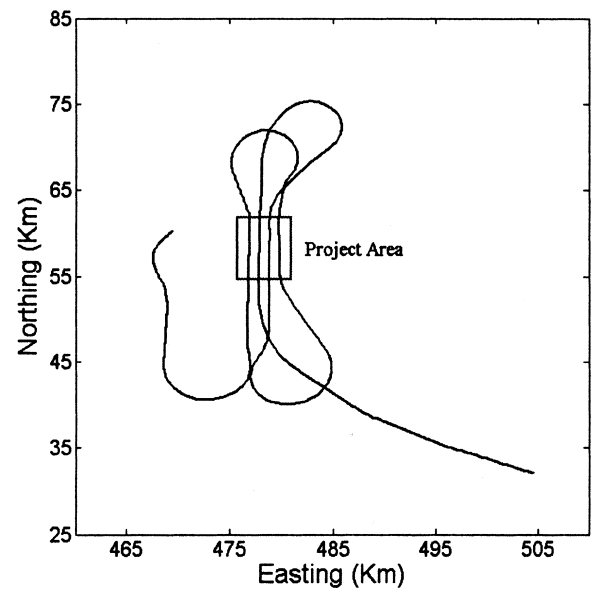

Figure 1. Flight trajectory.

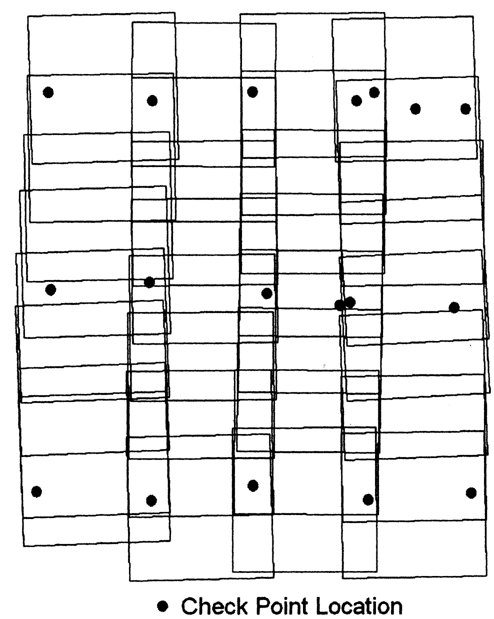

Figure 2. Block configuration.

Test Data Preparation

The ISO investigation was performed using real-flight test data from a high-performance Applanix POS AV 510, and a simulated data on the same flight based on a less accurate POS AV 310. The reason of using a simulated data is to allow direct comparison towards identical operating conditions: ground coverage, number of photos, and flight trajectory. To simulate the performance of the a accurate system, the IMU data from the POS AV 510 was degraded using statistical error models based upon Applanix proprietary simulation tools.

Referencing System Description

A RMK TOP film camera equipped with an Applanix POS AV 510 system was selected for the test. The project parameters are listed in Table 1, with the flight trajectory and the block configuration shown in Figure 1 and Figure 2, respectively. The published accuracy specifications for the POS AV 510 system are presented in Table 2.

In order to create as close to a perfect system calibration as possible residual boresight errors were minimized using the Quality Control/Quality Assurance procedure documented by Applanix Corporation with its IMU/Camera Calibration Software: POSCal™ (Madani and Mostafa, 2001). Camera self-calibration was performed during the QA/QC procedure and confirmed that both focal length and principle point offsets written in the USGS calibration report are within micron accuracy. Therefore, camera self-calibration is not applied throughout the test results presented in this paper.

TABLE 1. DATASET INFORMATION

Location	University of Kentucky, United States
# of Strips	4
# Photo/Strip	8
Flying Height (m)	900 AGL
Scale	1: 6000
Photo Scan Resolution (μm)	15
Forward Overlap	60%
Side Overlap	20%
Mapping Projection	State Plane Zone 1601
Datum	WGS84
Height	Orthometric
No. of Check Points	18
DGPS/INS System	Applanix POS AV 510

Less Accurate Direct Georeferencing Data Simulation

A POS AV 310 system was chosen to be a less-accurate GPS/INS system as a base for the data simulation because it is approximately 3 times poorer in orientation performance than the POS AV 510 (Mostafa *et al.*, 2001). Table 3 presents the published specifications of the POS AV 310.

The primary difference in system performance between a POS AV 310 and a POS AV 510 system is the orientation accuracy, which is directly a function of the IMU. Therefore,

Table 2. Specification of the POS AV 510 System

Post-Processed Accuracy	Absolute Value
Position (m)	0.05 – 0.3
Velocity (m/s)	0.005
Roll & Pitch (deg)	0.005
True Heading (deg)	0.008
Noise (deg/sqrt(hr))	0.02
IMU Drift (deg/hr)	0.1

Table 3. Specification of the POS AV 310 System

Post-Processed Accuracy	Absolute Value
Position (m)	0.05 – 0.3
Velocity (m/s)	0.0075
Roll & Pitch (deg)	0.013
True Heading (deg)	0.035
Noise (deg/sqrt(hr))	0.15
IMU Drift (deg/hr)	0.5

the raw POS AV 510 IMU data was brought into Applanix's simulation tool (Scherzinger, 1997) and purposefully degraded into a POS AV 310 performance. The simulation tool superimposes additional random bias, scale factor, and misalignment errors on both the accelerometer and gyro data. After running through the simulation tool, the degraded IMU data was then post-processed with the original untouched GPS data using Applanix's Post-Processing Package: POSPac™. The simulated POS AV 310 solution was then differenced with the original POS AV 510 solution to compute the Root Mean Square (RMS) differences in both position and attitude. To statistically evaluate the simulation, a Monte Carlo analysis was performed using 10 sets of random number seeds (1 to 10) in the simulation tool. The 10 sets of position and attitude RMS differences were then used to compute an ensemble RMS. Finally, the RMS error of the simulated POS AV 310 data was estimated as the Root Sum Square (RSS) of the ensemble and the RMS performance of the POS AV 510 system. Table 4 presents the theoretical RMS value for the differences between a POS AV 510 and POS AV 310 based upon their specifications. After the Monte Carlo analysis the ensemble RMS differences are very close to the theoretical values (Table 4).

Figure 3 presents one of the orientation RMS differences (Trial No. 9) from the Monte Carlo Analysis throughout the mission. Further evaluating the simulation, each Monte Carlo trial was analyzed using the EO Analysis tool from the Z/I ImageStation® Automatic Triangulation software (ISAT) (Madani and Mostafa, 2001).

Direct Georeferencing EO Analysis Test

This test was performed to evaluate the simulated data in mapping environment. As mentioned before, the POS AV 510 data had been quality controlled and therefore a reference boresight misalignment was determined. Using this reference boresight values, EO parameters of both the POS AV 510 data and the simulated POS AV 310 data were computed using Applanix's Exterior Orientation software: POSEO. Again Monte Carlo analysis is was used on the simulated data. The sets of EO were imported into ISAT and perform EO Analysis. The EO Analysis evaluates the quality of exterior orientation parameters by comparing the given coordinates of surveyed check points (accuracy of approximately 20 cm in both horizontal and vertical direction) with the intersection of the rays of these points (collected at approximately 0.5 to 1 pixel accuracy) as projected on overlapping photo pairs by the EO data. Table 5 presents the EO analysis result for both the POS AV 510 (after QC) and the simulated POS AV 310 data. Notice that the EO Analysis results present the statistics of checkpoint residuals for all checkpoints used in the EO Analysis.

Table 4. RMS Difference of the Simulated POS AV 310 Data

Navigation Parameters	RMS difference: Theoretical	Monte Carlo Analysis
Northing (cm)	0	2.85
Easting (cm)	0	2.40
Vertical (cm)	0	1.57
Roll (arc minute)	0.72	0.74
Pitch (arc minute)	0.72	0.71
Heading (arc minute)	2.04	2.08

From Table 5, it is seen that the ground accuracy of a POS AV 510 system is very accurate where the 3D position is <15 cm in each coordinate direction and the parallax is less than one pixel. In contrast, the simulated POS AV 310 data shows higher check point RMS, and the magnitude of parallax is significant; but this is expected for a lower accuracy system. To evaluate these results, they are compared with the error budget analysis performed by Applanix (Mostafa *et al.*, 2001). In such report, the horizontal ground position accuracy of a POS AV 310 is about 2 times poorer than that of a POS AV 510 system, while the vertical accuracy is about 1.5 times poorer (both for the mapping scale of 1:6 000). The actual differences in ratio are slightly higher because the error budget analysis is optimized under an error free system. In the simulated POS AV 310 data, additional errors such as boresight residual, checkpoint accuracy, and image measurement noise were contributed to the determination of the check point RMS. Based on the evaluations using Monte Carlo analysis, the simulated data can represent the performance of a POS AV 310 system under airborne environment.

Integration Sensor Orientation Test

After evaluating the simulated data (Table 5), it is certain that less accurate GPS/INS system is not recommended to be used for mapping and ISO should be processed to improve the EO accuracy. On the other hand, the quality controlled high accuracy GPS/INS data has shown impressive performance without the use of aerial triangulation. Can ISO further improve the EO parameters for some special applications? Also, for both ISO cases, is the use of ground control point necessary? The follow results provide some answers to these questions.

In addition to the direct comparison between the two types of GPS/INS data, the relationship between ISO performance and the number of tie points being used in the solution is analyzed. Such results are very useful to optimize the ISO workflow. Achieving this requires the use of the Point Per Von Gruber (PPVG) value in ISAT. This option divides a photo into nine PPVG. By changing the PPVG value the module can limit the number of tie points collected in each region after blunder detection and point thinning process.

Quality Controlled DG versus ISO

One of the benefits in using the DG technology is that the use of ground control points is not mandatory. But targeting for the maximum accuracy, most mapping projects consist of image blocks have some GCPs available. Therefore, the comparison between quality controlled DG and ISO is divided into two categories: control-free and the use of one ground control point around the center of the test block. As

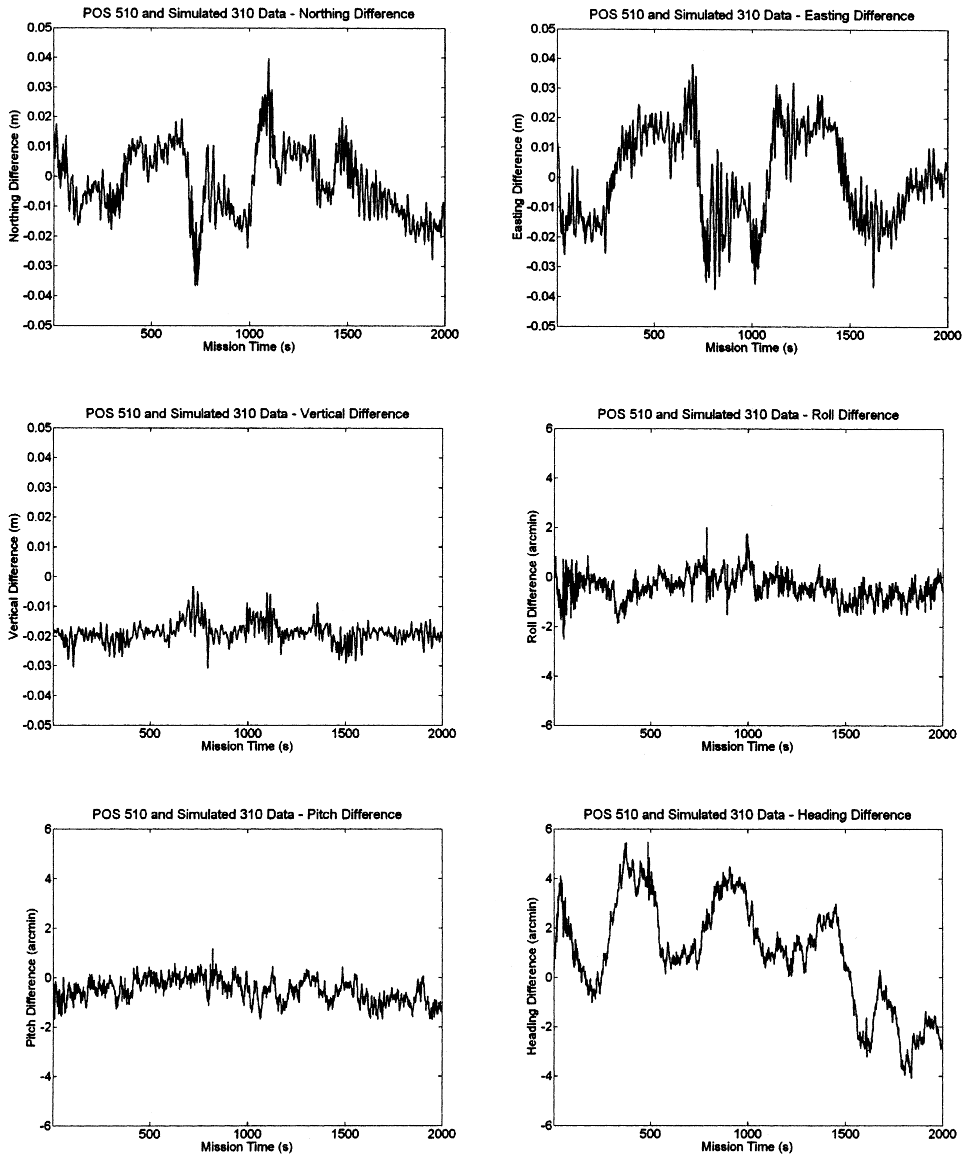

Figure 3. RMS difference between POS AV 510 and simulated POS AV 310 data (Trial No. 9).

Table 5. EO Analysis Results for the POS AV 510 (after QC) and Simulated POS AV 310 Data

POS AV System	Check Point RMS (m) Easting	Northing	Vertical	Py RMS (m)
510	0.10	0.13	0.15	14.8
Simulated 310	0.24	0.40	0.28	63.5

described in OEEPE test (Cramer, 2001b), the use of accurate standard deviation is very important in a bundle block adjustment. Therefore, the RMS navigation errors estimated by the Kalman Filter after DGPS/INS processing in POSPac™ are used as the standard deviation for the EO parameters instead of the general specification of the system as shown in Table 2 and Table 3.

While a large quantity of data has been processed, especially in the simulated data, results for each Monte Carlo trial are not presented. Instead, the ensemble values can statistically represent the performance of the simulated data. Results from different number of strip combinations are presented, which is very useful to analyze the optimal operation condition of ISO. Table 6 presents the results of the quality controlled POS AV 510 data and the ISO result of the simulated POS AV 310 data. For the simulated POS AV 310 data, Figure 4 presents the results graphically to analyze the correlation with different PPVG values.

Table 6 has similar representation as Table 5 and both check point residuals and parallax for different strip combinations are presented. After running ISO on the simulated POS AV 310 data, the checkpoint RMS is improved in all cases. However, the instability over the single strip gives insignificant improvement (an overall of approximately 10 percent improvement in all directions) and makes it cost ineffective; unlikely other combinations

TABLE 6. ISO RESULTS, POS AV 510 (AFTER QC) VERSUS SIMULATED POS AV 310 DATA, CONTROL FREE

	Control Free							
	POS AV 510 (after QC)				Simulated POS AV 310 (after ISO)			
	Check Point RMS (m)				Check Point RMS (m)			
# of Strip	Easting	Northing	Vertical	Py RMS (μm)	Easting	Northing	Vertical	Py RMS (μm)
1	0.11	0.06	0.16	7.0	0.14	0.15	0.21	4.7
2	0.09	0.10	0.14	16.1	0.08	0.12	0.15	4.0
3	0.09	0.12	0.15	15.4	0.09	0.13	0.17	4.3
4	0.10	0.13	0.15	14.8	0.08	0.14	0.15	4.0

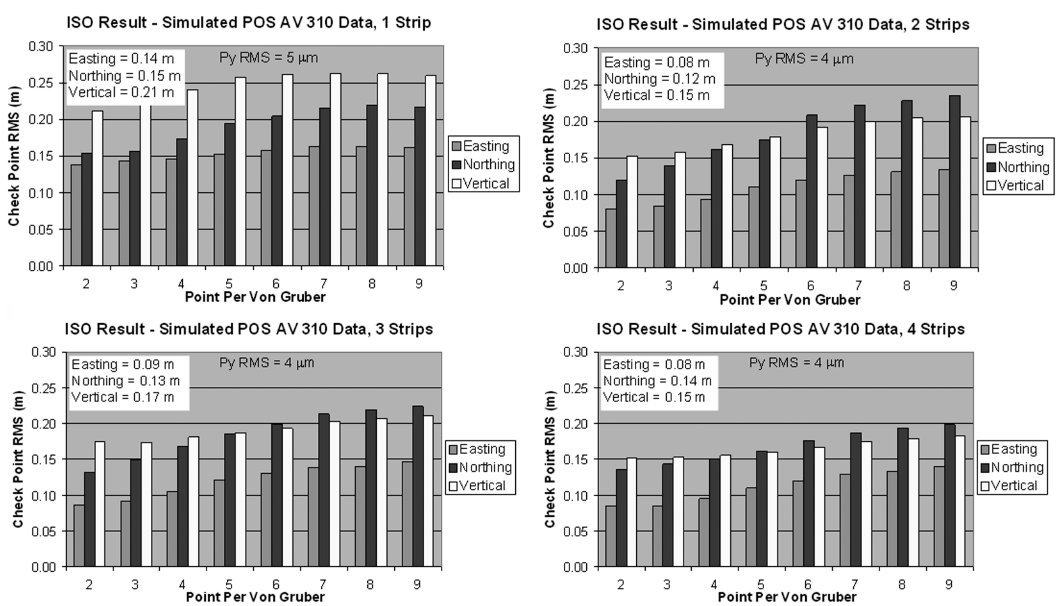

Figure 4. ISO results of simulated POS AV 310 data.

approximately 50 percent improvement in the horizontal directions and approximately 30 percent improvement in the vertical direction. Further analysis the results, the parallax of models is minimized to approximately 4 μm in all cases. This is a significant improvement (from approximately 60 μm) which allows the less accurate GPS/IMU data to be used for almost any stereo mapping application. Overall, the ISO results over the simulated POS AV 310 data shows similar accuracy as the quality controlled POS AV 510 data, except for the strip/corridor case. This is due to the lacking of side overlapping area, the instability in the omega angle slightly degrades the check point residuals, especially in the easting (North-South flight lines) and vertical direction (check points being used are located near the two edges of the strip). Following the second category, a center GCP is used at the QC block for the POS AV 510 data to minimize any possible local datum shift in the project, then EO analysis is performed for each strip combination. On the other hand, a center GCP is used in each ISO solution of the simulated POS AV 310 data. Corresponding resulting results are presented in Table 7.

Including one GCP into the QC process, the checkpoint residual is improved by approximately 2 to 3 cm in vertical direction. This states such an amount of local datum shift may exist in the project. Notice that the accuracy of local datum shift correction is GCP accuracy dependent and therefore such magnitude of local shift may not be observed when another GCP is used. In the POS AV 310 ISO results, using a single GCP has strengthened the strip/corridor combination and checkpoint residuals are improved. But in other case the improvement is minimal because the control free solution is very stable. In both cases there show GCP is not mandatory for QA/QC and ISO procedures. But, it is very useful to include 1 or 2 check points within the image block to resolve any possible local datum shift in the projects, especially when the project is required to deal with multiple mapping datum transformation.

ISO Testing on Quality Controlled POS AV 510 Data

As a final test the quality controlled POS AV 510 data is processed to observed the performance gain by applying ISO over high quality GPS/INS data, with and without the use of GCP. Corresponding results are shown in Table 8 and Figure 5.

When running ISO over high quality GPS/INS data, models of parallax are minimized from approximately 1 pixel to approximately one-third pixel. This is expected from a triangulated solution, but it does not improve the absolute accuracy of the EO as presented by the checkpoint

Table 7. ISO Results, POS AV 510 (after QC) versus Simulated POS AV 310 Data, One Center GCP Used

	One Center GCP Used							
	POS AV 510 (after QC)				Simulated POS AV 310 (after ISO)			
	Check Point RMS (m)				Check Point RMS (m)			
# of Strip	Easting	Northing	Vertical	Py RMS (μm)	Easting	Northing	Vertical	Py RMS (μm)
1	0.07	0.08	0.12	7.9	0.12	0.13	0.18	4.6
2	0.08	0.09	0.11	13.9	0.08	0.12	0.15	4.0
3	0.07	0.12	0.12	13.9	0.09	0.13	0.18	4.3
4	0.08	0.12	0.11	12.9	0.09	0.13	0.15	4.0

Table 8. ISO Results of POS AV 510 (after QC) Data, Control Free versus One Center GCP Used

	Control Free				One Center GCP used			
	Check Point RMS (m)				Check Point RMS (m)			
# of Strip	Easting	Northing	Vertical	Py RMS (μm)	Easting	Northing	Vertical	Py RMS (μm)
1	0.12	0.10	0.15	4.3	0.15	0.17	0.16	4.5
2	0.08	0.11	0.12	3.2	0.08	0.10	0.12	4.2
3	0.08	0.12	0.16	3.5	0.08	0.12	0.16	4.7
4	0.08	0.13	0.13	4.4	0.08	0.14	0.13	4.4

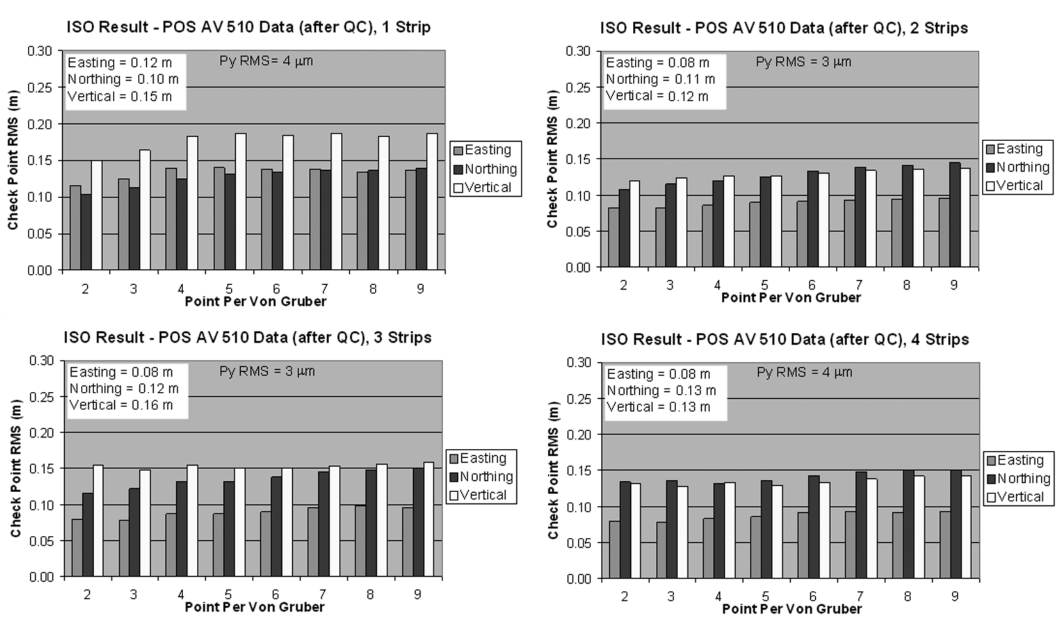

Figure 5. ISO results of POS AV 510 (after QC) data.

residuals. Similar results are observed when a center GCP is used. This states again that the use of GCP is not mandatory, under the condition that local datum shift is minimal or has been resolved through the QC process. Based on the results (Table 8) and the project configuration, project scale of 1:6 000 and 15 μm scanning resolution, such model of parallax gives a relative accuracy up to 3 cm. In most mapping application such accuracy is not required but this might be very useful for GIS and geological applications, which requires distance, size, and area measurement in centimeter level of accuracy.

In the above tests, Figure 4 and Figure 5 are presented to analyze the relationship between ISO performance and the number of tie points being used. In aerial triangulation without GPS/INS, the bundle adjustment is based on the collected tie points and GCP measurement only. In this case, measurement redundancy can be maximized by measuring tie points in overlapping areas only, while each tie point is

Figure 6. Distribution of automatic collected tie points.

visible from at least 3 to 4 photos. This corresponds to the recommended 60 percent forward and 20 percent side overlap block configuration for most mapping projects. While automatic tie point collection is based on the search of potential tie point over the each photo, the PPVG value provides the operator a control on the number of tie points to be collected, and therefore minimize the processing time. Although less tie points are collected, the redundancy is still maximized by keeping the tie points in the overlapping area with multiple rays and within the user-specified accuracy threshold. This can only be achieved by integrating the EO parameters (from GPS/INS system or estimated by network of GCP) into the module and therefore filtering process can be applied throughout the tie point collection. In Figure 6, a distribution of automatic collected tie points over one of the photo in the test data is shown (PPVG = 7). Notice that the tie points are collected over the overlap areas only. In the case when a higher PPVG value is used, the additional points collected in other areas may not provide similar accuracy (>1 pixel) and geometry (2-fold only) as previously collected tie points, especially in remote areas, where availability of ground features are limited. Therefore, when running ISO with a high PPVG value, the result will not always be improved, even though the measurement redundancy is increased. Although one can argue to recheck all collected tie points manually before running ISO, this is unpractical in the GPS/INS workflow and the use of an automatic tie point module. Instead, a smaller PPVG value is recommended only to provide enough tie points to be used in the bundle adjustment, with the filtering to be handled by the module automatically. It can be easily recognized in a project located in a remote area. While insufficient ground features are available for tie point collection, forcing a higher PPVG to collect tie points in suspicious area is meaningless. In this case the benefits of using a high quality GPS/INS system are easily observed.

Conclusion

This paper reviews several uses of Integrated Sensor Orientation. First, it can be used as a QA/QC tool to refine the system calibration parameters. If GCPs are available, local datum shift can be resolved. Second, it can be used on a high-performance direct georeferencing system to achieve maximum accuracy in large scale mapping projects, where the DGPS position error is not always sufficient to meet the desired ground accuracy. Finally, when flown in a block configuration with a minimum of two strips and eight photos per strip, ISO can be used in conjunction with a lower accuracy system. This can lower the cost of direct georeferencing system, while maintaining similar performance of a high-performance system, all without the use of any ground control points.

From the Monte Carlo EO analysis presented above, it is easy to understand why a less accurate DGPS/INS system is not suitable for high accuracy direct georeferencing applications: the ground error of a POS AV 310 is 2 times larger than the POS AV 510, and the parallax can be as large as four pixels RMS versus one pixel for the POS AV 510. However, if a block of photos with at least two strips is *always* available in the project, the advantages of ISO can be exploited with the lower accuracy system. Using an advanced automatic tie point collection module such as ISAT by Z/I Imaging, highly accurate tie points can be collected instantly using the EO parameters from the DG system. Then, without the help of any ground control points, ISO can be performed with the collected tie points to refine the EO parameters. Given the cost difference between the lower accuracy POS AV 310 and high-performance POS AV510 (about a factor of 1.5 to 2), ISO seems to make sense; however this is only true if the additional processing time required to do the tie-point matching and ISO can be minimized. When inefficient software and workflow are used in the ISO process, the cost savings in the system is not realized. The results presented above show that the processing time can be optimized with proper use of the EO parameters in the tie point matching software (as is done in ISAT), and in the tie point collection strategy (PPVG value). Results from both POS AV 510 and simulated POS AV 310 Monte Carlo data shows that there is no need to include numerous tie points, since additionally collected tie points may not maintain a similar level of accuracy as those initially collected. This can be easily observed in remote areas where ground feature availability is limited. Through the seamless workflow of today's mapping using GPS/INS data, it is unpractical to revisit every single tie point collected. This is an important conclusion: only *a minimum* of tie points is recommended to be used to perform ISO, which in turn also helps reduce the processing.

The simulation presented here focuses on the direct comparison of the performance between two types of GPS/INS systems under the same flight conditions, trajectory, and block configuration. Although the results presented provide a good insight into the use of Integrated Sensor Orientation, further work is required before any firm conclusions can be made. This includes conducting tests using an actual POS AV 310 system on a film camera.

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