'Photogrammetric Week 01' D. Fritsch & R. Spiller, Eds. Wichmann Verlag, Heidelberg 2001.

GPS/IMU products – the Applanix approach

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ABSTRACT

In this paper the Applanix approach of integrating inertial data with GPS to produce products for Geomatics applications is presented. The core Applanix technology consists of sophisticated algorithms and advanced signal processing techniques for the integration of GPS and Inertial Measurement Unit data, for the purpose of real-time navigation and post-mission, high precision positioning and attitude determination. The Applanix products are briefly described. The airborne system is then discussed in some detail, followed by the theoretical and practical accuracy analysis of using such a system for photogrammetric mapping and LIDAR.

1. INTRODUCTION

A direct georeferencing (DG) system provides the ability to directly relate the data collected by a remote sensing system to the Earth, by accurately measuring the geographic position and orientation of the sensor without the use of traditional ground-based measurements. Examples of where DG systems are used in the airborne mapping industry include: scanning laser systems or LIDAR, Interferrometric Synthetic Aperture Radar systems (InSAR), multispectral and hyperspectral scanners, the new state-of-the-art digital line scanners systems, and more increasingly small format digital cameras and traditional film cameras such as the Leica RC30 and TOP RMK.

The current state-of–the-art direct georeferencing systems such as the Applanix POS/AV™ use carrier phase differential GPS measurements integrated with an Inertial Measurement Unit (IMU). This paper gives a detailed description on the Applanix approach to GPS/IMU integration followed by a brief overview of the various Applanix products and their applications. The achievable position and orientation accuracy of the POS/AV system is then presented. The use of POS/AV for LIDAR applications is briefly presented, then the photogrammetric application of POS/AV is discussed. On–the-ground accuracy is presented for different flight configurations, different imaging scales, and for different mapping products such as ortho-rectified images developed by a single photo plus a digital elevation model, or topographic mapping using stereo-photos. A practical error analysis is also presented using two real data sets collected in California and Ontario, respectively.

2. THE APPLANIX APPROACH

2.1. Components of a POS

As shown in Figure 1, an Applanix POS system is comprised of four main components:

1. An IMU
2. A GPS receiver
3. A computer system (PCS)
4. A post-processing software suite called POSPac^{TM}

The heart of the system however is the Integrated Inertial Navigation software that is implemented both in real-time on the PCS and in postmission using the POSPac^{TM} software. In this software the GPS measurements are used to aid the inertial navigation solution produced by integrating the IMU outputs to produce a blended position and orientation solution that retains the dynamic accuracy of the inertial navigation solution but has the absolute accuracy of the GPS.

Figure 1. The POS^{TM} System

2.1.1. Inertial Measurement Unit (IMU)

An IMU is comprised of triads of accelerometers and gyros, digitization circuitry and a CPU that performs signal conditioning and temperature compensation. The compensated accelerometer and gyro data are output as incremental velocities and angular rates via a serial interface to the PCS typically at rates of 200 to 1000Hz. The PCS then integrates the accelerations and angular rates in a so-called "strapdown" inertial navigator to produce position, velocity and orientation of the IMU referenced to the earth. Rigidly mounting the IMU to a remote sensor thus means the inertial navigator produces position, velocity and orientation of the sensor itself. To ensure maximum accuracy, the IMU's must be relatively small and lightweight so that they can be mounted as close to the sensor's reference point (perspective centre) as possible. This ensures there is no flexure between the IMU and sensor.

Typical high-quality IMU's use force rebalance accelerometers and either Fibre Optic Gyros (FOG), Ring Laser Gyros (RLG), Dry Tuned Gyros (DTG). New gyro technologies such as MicroElectroMechanical Systems (MEMS) are just now becoming available but it will take a few years until they reach the performance level required for direct georeferencing. The primary requirements on gyros for direct georeferencing are size, bias drift, scale factor, and noise characteristics.

While the RLG technology produces the best performing gyro. RLG size precludes it from being used in many airborne applications. At the moment the DTG has the smallest noise for its size, although recent signal processing advances are now being used to reduce the noise in FOG's to levels sufficient for some of the higher accuracy DG applications. The POS systems use IMU's containing RLG, FOG, and DTG technology.

2.1.2. GPS Receiver

The GPS system is comprised of a constellation of satellites and a remote receiver that uses range measurements to the satellites and triangulation techniques to compute the position of the receiver's antenna. Carrier phase differential GPS is an advanced technique that combines the phase data from two receivers so as to eliminate all significant errors except the integer ambiguities in the number of wavelengths between the receivers (both base and rover) and each satellite. Redundant phase observations from 5 or more satellites provide the information to resolve the ambiguities, thus translating each satellite's estimated phase cycles into precise range measurements. High precision satellite-to-receiver range measurements allow the computation of the baseline (interstation) vector between the receivers and hence the position of the remote receiver to decimetre or better accuracy. In most applications POS uses an embedded low noise dual frequency GPS receiver that provides phase and range data to the processing software.

2.1.3. POS Computer System (PCS)

The POS Computer System or PCS contains the GPS receiver, a mass storage system that writes data to a removable PC Card flash disk, and a computer that runs the real-time integrated navigation software. The real-time navigation solution is used as input to flight management systems and to point and control stabilized mounts. The PCS is also used to precisely time-tag external sensor data.

2.1.4. POSPac^{TM} Post-processing Software

The POSPac^{TM} post-processing software is used to compute an optimal integrated inertial navigation solution by processing the raw IMU and GPS data collected from the POS/AV^{TM} during the flight, along with GPS observables recorded form base station receiver(s). It computes a carrier phase GPS solution and then blends it with the inertial data using forward and reverse time processing. When using the POS/AV^{TM} in a photogrammetric application, as a final step a module called POSEO is used to compute the exterior orientation of each image at the moment of exposure.

2.2. Methodology

The key component of the POS system is the Integrated Inertial Navigation (IIN) software. This software runs in real-time on the PCS and in post-processing in the POSPac^{TM} software suite, and performs the integration of the inertial data from the IMU with the data from the GPS receiver. The functional architecture of the software is given in Figure 2. The software consists of the following components:

1. Strapdown inertial navigator
2. Kalman filter
3. Closed-loop error controller
4. Smoother (POSPac^{TM} only)
5. Feed forward error controller (POSPac^{TM} only)
6. In-flight Alignment

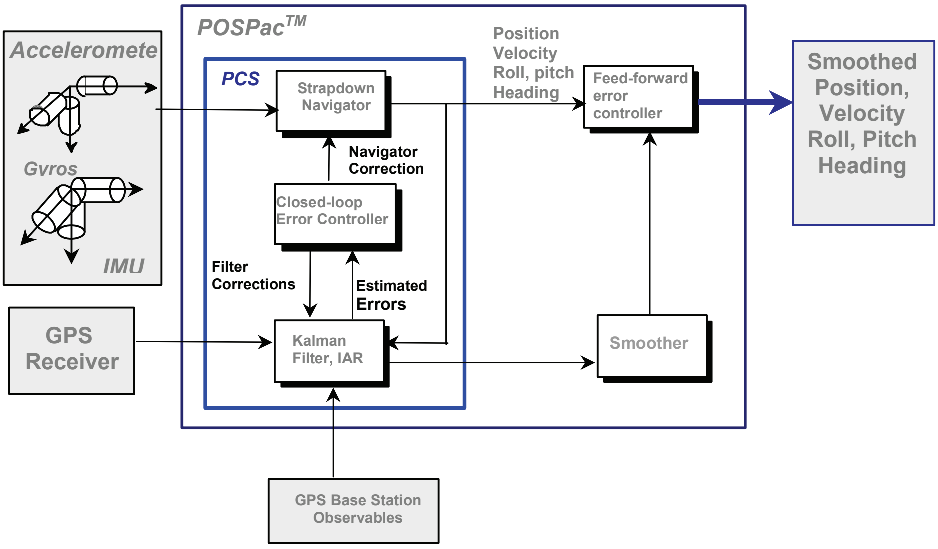

Figure 2. Closed-Loop GPS-Aided Inertial Navigation

2.3. Strapdown Navigator

The strapdown inertial navigator solves Newton's equations of motion on the rotating earth by integrating acceleration and angular rates sensed by the IMU. In order to do this, the inertial navigator must first be initialized with known position and velocity from the GPS, and aligned with respect to the true vertical and true North. Alignment with respect to the vertical is referred to as *levelling,* while alignment with respect to North is referred to as *heading alignment*. Once aligned the inertial navigator has established a local-level mathematical frame of reference called the navigation frame, whose heading is known with respect to North, and to which the orientation of the IMU is known, as shown in Figure 3.

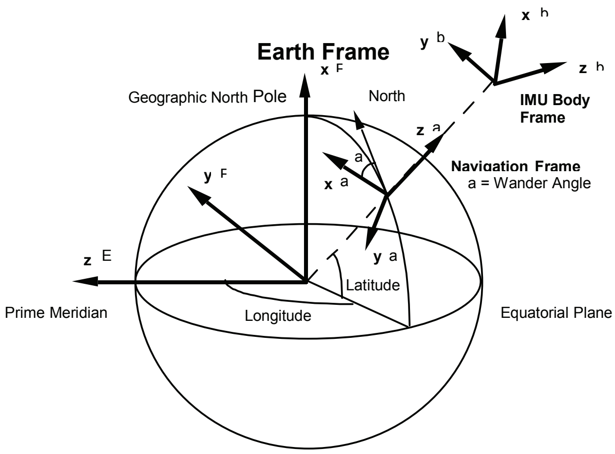

Figure 3. Frames of References Used in Inertial Navigation

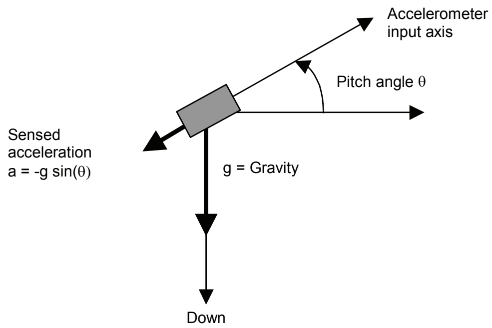

Figure 4. Coarse Leveling Using Accelerometers

After removing the rotation rate of the Earth (computed as a function of position), the navigator integrates the incremental angles from the IMU to continuously compute the change in orientation of the IMU with respect to the navigation frame. It then uses the orientations to resolve the incremental velocities from the accelerometers into the local-level navigation frame, which it then integrates to compute the position change of the navigation frame over the Earth. Note that this means any error in the orientation will directly contribute to a position error on the Earth. The solution it produces is dynamically very accurate; however, since the inertial navigator uses an integration process, any errors in the accelerometers and gyros will integrate into slowly growing position, velocity and orientation errors. GPS is an ideal aiding sensor for an inertial navigator since its positional errors are complementary to the inertial navigation errors in the sense that they are spectrally separate: the GPS position and velocity errors are bounded and noisy, while the inertial navigator errors grow unbounded but are essentially noise free. The GPS can thus be used to estimate and correct the errors in the inertial navigation solution.

2.4. Kalman Filter

In order to use the GPS to estimate the errors in the inertial navigator, a Kalman Filter is used. The Kalman Filter implements a linearized and discretized set of differential equations that model the inertial navigator errors and the IMU sensor errors that drive them. Differences between the position from the inertial navigator and the position from the GPS are processed in the Kalman filter (typically at 1 Hz), to estimate the slowly growing position error in the inertial navigator. Since this error is a function of both errors in the orientation and errors in the inertial sensors, (as modeled by the differential equations in the Kalman filter), observing the inertial position errors means the orientation errors and IMU sensor errors can also be estimated.

2.5. Closed-Loop Error Controller

The closed-loop error control algorithm is used to apply resets to the inertial navigator using the Kalman filter-estimated parameters. Estimates of the inertial sensor errors are also applied to the IMU-measured raw incremental angles and velocities before they are integrated, which has the same effect as calibrating the sensors. The resultant integrated inertial navigation solution has its position and velocity directly regulated to the absolute accuracy of the GPS position and velocity, and its orientation parameters controlled to corresponding levels of accuracy. This is the solution that is computed and output by the PCS in real-time.

2.6. Smoother

The Smoother is a module that computes the optimal estimates of the inertial navigator and IMU sensor errors, by processing the data backwards in time and then combining it with the estimates from the forward in time Kalman filter. The resultant error estimates are based upon all available information from the past and future, and hence are more accurate. The Smoother is implemented only in the POSPac™ software.

2.7. Feed-Forward Error Controller

The Feed-Forward Error Control module uses the optimal error estimates from the Smoother and applies them to the integrated inertial navigation solution at the IMU rate, thus generating what is referred to a the smoothed best estimate of trajectory (SBET). The Feed-Forward Error Controller is only used in the POSPac™ software after the Smoother is run.

2.8. In-Motion Alignment

An important feature of the POS system is its ability to align itself (establish initial navigation frame, see above) in the air. The alignment process is comprised of 3 stages: i) Coarse Levelling, ii) Coarse Heading Alignment, and iii) Fine Heading Alignment. Coarse Leveling uses a first-order low-pass filter on the accelerometer data to observe the mean gravity signal in each accelerometer, from which the approximate roll and pitch of the IMU are determined to within 1 to 2 degrees error (see Figure 4).

At this point, Coarse Heading Alignment is started which uses a Kalman filter error model to describe the initial 180 deg uncertainty in heading. The heading error of the navigation frame will cause the incorrect Earth rate to be removed from the gyro measurements during the integration process, causing an orientation error. This in turn will integrate into a velocity and position error. If the gyros errors are small enough, the position and velocity error due to the misresolved Earth rate can be detected in the differences with the GPS, and hence the heading error will be estimated by the Kalman filter (so-called gyrocompassing). However, since the gyros themselves can have biases anywhere from 0.5 to 20 deg/hr, usually the error due to the misresolved Earth rate is only sufficient to observe the heading error down to a few degrees at best.

Fortunately the heading error also causes the accelerations experienced by the IMU to be misresolved in the navigation frame, which then integrate into very large position and velocity errors that are observable against the GPS measurements. This allows the Kalman filter to estimate the heading error to small fractions of a degree, and as soon as Coarse Levelling is completed a single turn will complete the heading alignment. Once the Coarse Heading Alignment Kalman filter estimates the heading error to less than 10 degrees, the software changes to Fine Heading Alignment, which uses a small-angle error model Kalman filter to continuously estimate and refine the heading error.

3. POS PRODUCTS

3.1. POS FOR TRACK GEOMETERY (POS/TG™)

Major railroads and railroad regulating agencies systematically measure track geometry in order to monitor track deterioration and identify defects. Traditionally, track geometry was measured manually by a trained crew. However, this method is time consuming, costly, yet does not allow for geometry measurement under normal load conditions.

The POS/TG™ system, developed by Applanix Corporation with the assistance of Plasser American Corporation, uses a specialized track geometry car, which can be self-propelled or attached to a regularly scheduled train. When travelling along the track, the measurement system onboard such a car computes the geometry parameters of the track, namely, superelevation, twist, longitudinal profiles (left and right), curvature and its rate of change, alignment (left and right) and grade. For details see Oberlechner, et al (2000).

In real-time, POS/TG™ in conjunction with Plasser Analyzer system allow the operator to graphically view the track geometry parameters and, therefore, be aware of geometry exceptions through real-time warnings. All data is stored for archiving, post-mission display, or further analysis. POS/TG™ is capable of continuously computing track geometry measurements at a user selectable interval (typically every 0.25m), within a speed range of near zero to well above 300km/h.

POS/TG™ consists of an IMU, embedded GPS receiver, POS computer system (PCS), a distance-measuring instrument (DMI), and an optical gauge measurement system (OGMS). Besides the GPS/IMU functions, the DMI outputs pulses representing fractional revolutions of the wheel, which when summed, provide a measure of the distance traveled. OGMS is a laser range measuring system that measures the displacement of each rail from the IMU centre. When combined with positional data, the OGMS pinpoints the location of each rail and allows for the computation of accurate alignment and horizontal space curve parameters. Figure 5 shows the hardware installation on a track geometry car.

Figure 5 POS/TG hardware installation: OGMS installation (left), DMI Installation (middle), IMU Installation (right)

3.2. POS FOR MARINE VEHICLE (POS/MV™)

POS/MV™ uses the same Applanix approach of GPS/IMU integration customized for marine applications. In addition, it uses a GPS azimuth measurement subsystem (GAMS™) for heading aiding. The major marine applications where POS/MV is used are:

1. Surveying around and under bridges and oilrigs, where extensive GPS outages are very common to be experienced.
2. Surveying of ports and harbours, which are difficult to survey due to traffic, obstructions and, therefore, GPS outages.
3. Surveying of inland and coastal waterways.
4. Pipelines and cable route surveys.
5. Geophysical surveys.

In addition, modern multi-beam sonar systems can be limited in their performance by the use of conventional motion sensors. The limiting factor is that the accuracy of conventional sensors degrades with increasing dynamics. This results in shorter operational windows and reduced survey accuracy. POS/MV has been developed to meet the accuracy requirements of today's multibeam sonar systems. POS/MV provides high accuracy attitude data regardless of platform dynamics, or latitude; for details, see Woolven and Scherzinger (1997) and Scherzinger et al (1997). Figure 6 shows a sea floor map in Nova Scotia, Canada.

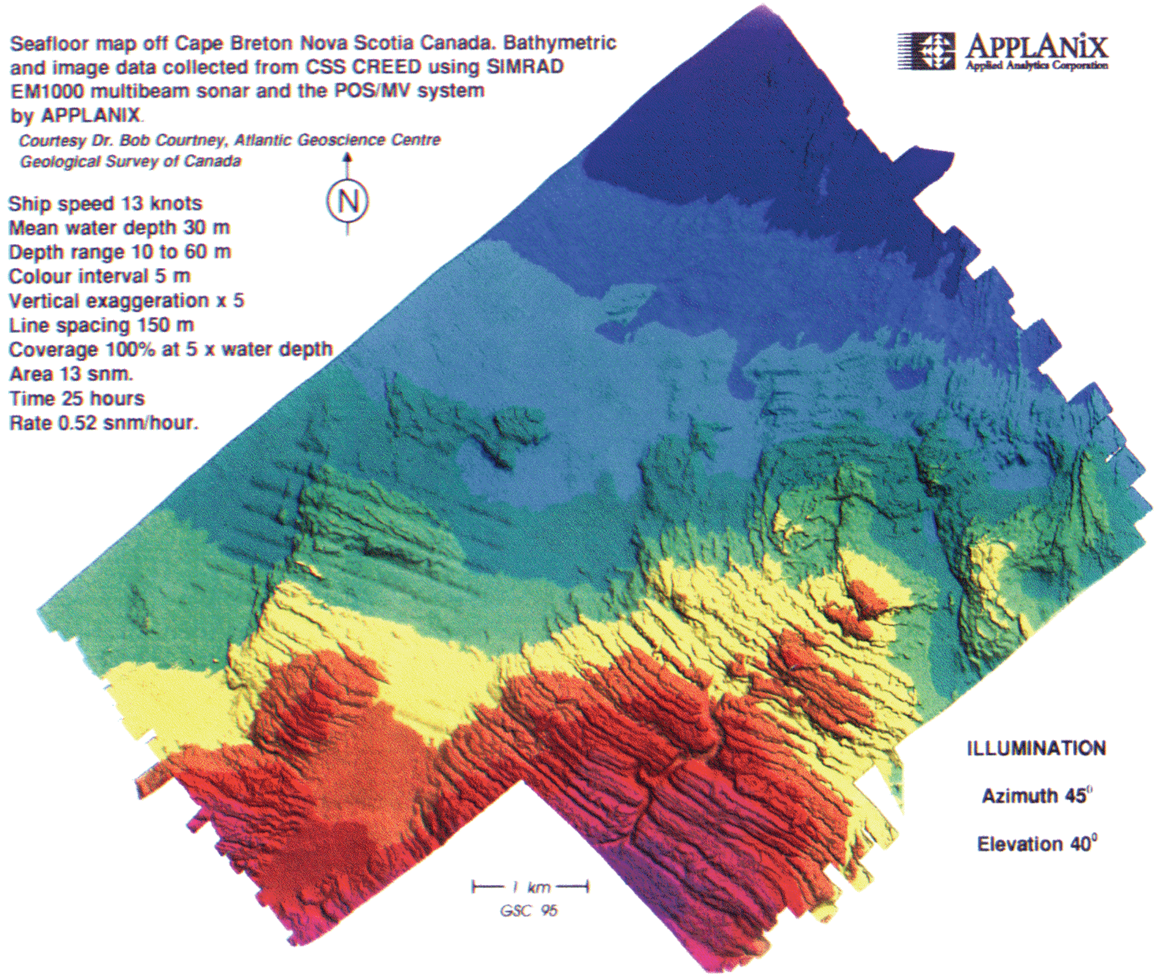

Figure 6 A Sea Floor Map Developed using SIMRAD Multibeam Sonar and Applanix POS/MV

3.3. POS FOR LAND VEHICLE (POS/LV^{TM})

POS/LV^{TM} uses the same Applanix approach of GPS/IMU integration customized for land mobile applications. It measures land vehicle position, velocity, and attitude. Current applications for POS/LV are:

- Road surface mapping (when integrated with a primary sensor package such as a rut bar)
- Corridor surveys (when integrated with a video or still digital cameras, as shown in Figures 7 and 8)
- Vehicle dynamics testing and safety

POS/LV^{TM} integrates GAMS (GPS Azimuth Measurement Sub-System), IMU, and a Distance Measuring Instrument (DMI). Combining GPS, GAMS, DMI data, allows for on-line calibration of inertial sensors and, therefore, it maintains the dynamic fidelity of the inertial solution. This also allows for the removal of the long-term drifts from the inertial-derived position and orientation information. Further, such data combination allows for improving the computed position and velocity while navigating through an extended GPS outage or periods of bad GPS reception caused by multipath or obstacles. The DMI technology provides added benefit be keeping the position and error growth rates linear for extended time periods – unlike the error growth rates that would be quadratic in nature without the DMI influence

Figure 7 POS/LV installed on a van for mobile mapping

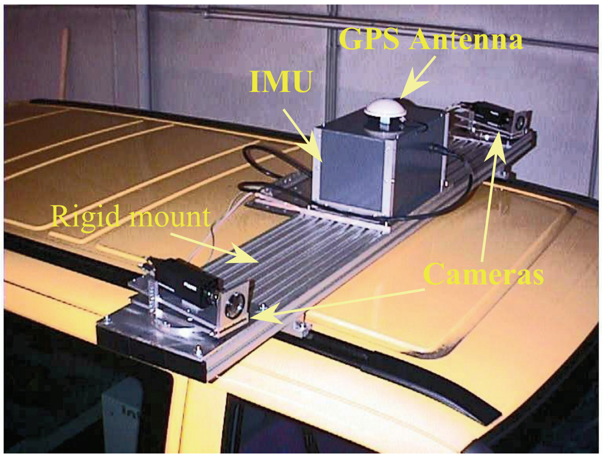

Figure 8 Hardware Configuration

3.4. POS FOR LAND SURVEY (POS/LS^{TM})

Traditionally, positioning in geophysical projects has been performed using conventional survey instruments and methods. Theodolites and/or total stations are used to perform a stakeout survey. In post-processing, the coordinates, elevation profiles and maps of every seismic source and receiver point are computed. Line-of-sight is a must for all survey lines and, thus, tree cutting is required in forested areas with added expenses to the survey operation. DGPS techniques (using post-mission or RTK) have released seismic surveys from the inter-station line-of-site problem, yet added satellite-to-receiver line-of-site problem. Consequently, in tree-covered areas or in the presence of obstacles such as mountains, deep valleys or buildings in constructed areas, GPS reception is often problematic. In these cases, seismic positioning is still done using the traditional technique (c.f., Gillet et al, 2000).

The POS/LS system is an implementation of Applanix approach of GPS/IMU integration customized for the land survey field of applications. It is designed to target the following applications:

1. Oil and Gas Survey
2. Precision Forestry
3. Utility Survey
4. Environmental Services
5. Mining

POS/LS is a portable backpack system comprising an Inertial Navigation System seamlessly integrated with RTK GPS to provide reliable positioning in situations that are problematic using either conventional optical instruments or GPS. During use, POS/LS continually monitors position quality to request Zero Velocity Updates (ZUPTs) in order to limit error propagation. Simultaneously, POS/LS automatically incorporates available GPS for real time Position Updates. When GPS is unavailable, POS/LS allows the operator to command manual position updates from survey control points to provide a positioning device for all conditions.

3.5. POS FOR AIRBORNE VEHICLE (POS/AV™)

Applanix Corporation developed the first practical DG system for aerial photogrammetry in 1996 that was usable on existing cameras such as the Leica RC30 or Zeiss LMK (Hutton et al, 1997). The methodology proposed by Applanix to aerial photogrammetry companies was to aid or replace aerial triangulation with direct measurement of the camera exterior orientation (EO) parameters and thereby realize significant cost savings per project. Early adopters of this methodology pioneered its successful field usage and demonstrated its practicality to the industry during 1996-99. Since then, direct georeferencing has become an accepted alternative to the traditional AT methodology in the small-scale photography projects. Figure 9 shows the IMU mount on different cameras.

TOP RMK IMU Mount | Embedded IMU in Z/I DMC | RC30 Mount | Embedded IMU in LHS ADS 40

Figure 9. IMU mount on different aerial cameras

4. ACCURACY OBTAINABLE FROM POS/AV™

4.1. Positional Accuracy

With proper mission planning, careful flight operations to minimize satellite loss of lock, and multiple base station deployment to ensure the maximum baseline separation between the remote and base receivers are within 10 - 50 km, position accuracies in the range of 5 to 30 cm RMS are achievable using post-processed carrier phase Differential GPS. Most of the position error is due to residual propagation delays caused by the ionosphere, which are low frequency in nature and cannot be removed by blending with the inertial data. This means the absolute accuracy of the POS/AV™ smoothed navigation position from POSPac™ will also typically be 5 to 30 cm RMS.

4.2. Orientation Accuracy

The orientation accuracy of the POS/AV™ smoothed navigation solution is described best in terms of *absolute accuracy* and *relative accuracy*. The *absolute accuracy* is the total RMS error including mean, while the *relative accuracy* describes the high frequency sample-to-sample error. It is convenient to do this since in most cases the orientation error is comprised of a slow varying signal with almost no noise, and in some applications it is the accuracy of the change in orientation that is most important (such as that in a digital line scanner). The relative accuracy of the roll, pitch and heading is a function of the gyro noise and residual gyro bias after smoothing.

4.2.1. Roll and Pitch Accuracy

The absolute roll and pitch accuracy of the POS/AV™ smoothed navigation solution is a function of the residual error in estimating the accelerometer biases after smoothing. Errors in the roll and pitch will cause gravity to be misresolved, causing apparent horizontal accelerations that integrate into ramping velocity and quadratic position errors when compared to GPS. However an accelerometer bias will also produce the same error signature, so the Kalman filter will only be able to estimate the roll and pitch error down to the level where the misresolved gravity cancels out the accelerometer biases.

4.2.2. Heading Accuracy

As described above in the In-Air Alignment section, the heading error is observed primarily through accelerations. During straight-and-level flight with little or no accelerations, the heading error will grow at a rate defined by the gyro noise and residual gyro bias. As soon as a significant acceleration is experienced, the heading error will be observed and the error reset (see Figure 10). The smoother will then extrapolate the reset backwards in time to reduce the overall error (see Figure 11). Hence in order to maintain heading accuracy to the maximum level, it is important that a manoeuvre be performed periodically (usually every 10 to 30 minutes, depending upon the quality of the IMU, which is typically not a problem for aerial survey missions).

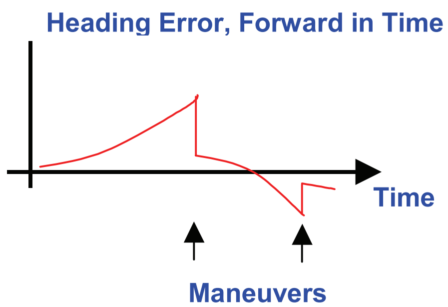

Figure 10. Heading Error Improvement after manoeuvres (Forward Solution)

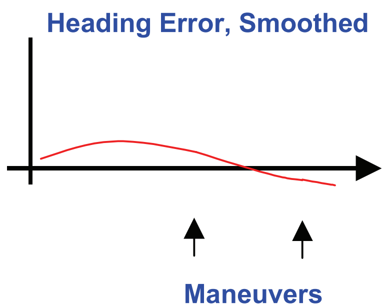

Figure 11. Heading Error Improvement after manoeuvres (Smoothed)

The post-processed *absolute* accuracy for each POS/AV™ model is given in Table 1, for a typical survey mission profile including turns every 10 minutes or so. The post-processed relative orientation accuracy for each POS/AV™ model is given in Table 2.

Table 1. Post-processed POS/AV™ Absolute Accuracy

Parameter Accuracy (RMS)	POS/AV™ 210	POS/AV™ 310	POS/AV™ 410	POS/AV™ 510
Position (m)	0.05 –0.30	0.05 –0.30	0.05 –0.30	0.05 –0.30
Velocity (m/s)	0.010	0.010	0.005	0.005
Roll & Pitch (deg)	0.040	0.013	0.008	0.005
Heading (deg)	0.080	0.035	0.015	0.008

Table 2. Post-processed POS/AV *™* Relative Orientation Accuracy

Parameter Accuracy	POS/AV™ 210	POS/AV™ 310	POS/AV™ 410	POS/AV™ 510
Random Noise (deg/sqrt(hr))	0.20	0.15	0.07	< 0.01
Residual Bias (deg/hr), 1 sigma	0.75	0.5	0.5	0.1

5. LIDAR APPLICATION OF POS/AV™

In an airborne LIDAR installation, a POS/AV system is used to measure the position of the laser reference point and the orientation of the laser range at the exact time of measurement. In a scanning LIDAR system, laser reference point is the mirror; in a fiber optic system it is the fiber optic bundle. The orientation is given in as Euler angles with respect to the North, East and Down directions. The POS/AV IMU is mounted to the LIDAR housing so that it is rigid with respect to the laser reference point. During a mission, the POS/AV system records the IMU and GPS data and the time of each laser scan, all in a common time base such as GPS time. The POSPAC post-processing software computes the time tagged position and orientation of the laser reference point at a high data rate, typically 200 Hz. The LIDAR post-processing software then interpolates the position and orientation data to the exact time of scan. With this data and the range measured by the laser, it computes the 3-dimensional ground spot coordinates of each laser range. Typically the software first computes the earth-centered-earth-fixed (ECEF, also called Cartesian) coordinates and then converts these to the desired mapping frame. The resulting three-dimensional elevation map contains the data required for a DEM. Figures 11 and 12 show a LIDAR-derived DEM using POS/AV systems in Grand Canyon and Toronto, respectively

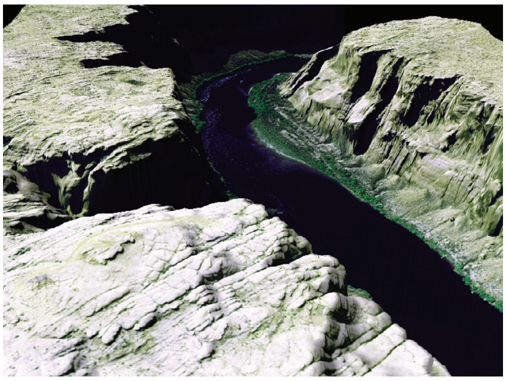

Figure 11 DEM of Grand Canyon (Courtesy of Earth Data Technologies)

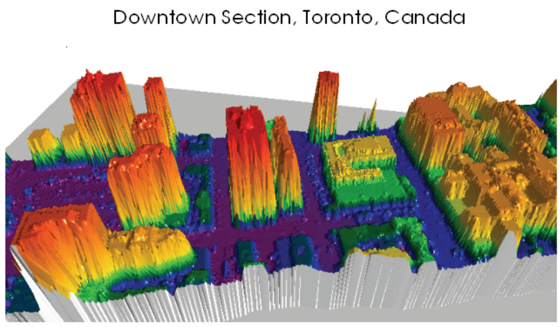

Figure 12 DEM of Toronto Down Town (courtesy of Optech Inc)

6. PHOTOGRAMMETRIC APPLICATION OF POS/AV™

6.1. Seamless Digital Data Flow

As shown in Figure 13, a digital data flow of a typical Orthophoto production project includes calibration, navigation data processing and image data processing. The calibration consists of imaging sensor calibration (e.g., a digital or an optical camera), boresight calibration, and lever arm calibration. The Earth-Fixed Earth-Cantered (ECEF) position and orientation angles derived by POS/AV™ are compensated for the boresight and lever arm calibration parameters. The trajectory parameters are then interpolated at the recorded camera events and transformed into the required local mapping frame (M-frame) using POSEO™. If the calibration parameters are not available, camera and boresight calibration parameters are computed using POSCal™ module in POSEO™ using the navigation and image data. This yields the exterior orientation (EO) parameters of each single image frame or scan line coordinatized in the local mapping frame (X, Y, Z, ω, ϕ, and κ). In a Softcopy, image data and exterior orientation data are processed either in single image mode or in stereo mode to produce ortho mosaics using either available DEMs or produced DEMs from stereo imagery, respectively.

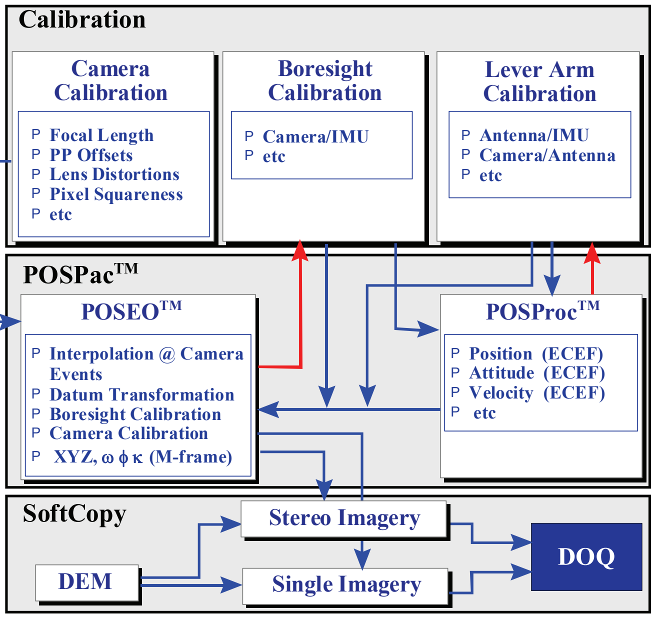

Figure 13. Digital Orthophoto Production Data Flow

6.2. Accuracy Analysis

6.2.1. Theoretical Analysis

The standard error propagation technique is used to derive the ground object 3D positioning accuracy as a function of the exterior orientation parameter accuracy. Two cases are presented here. In the first instance - referred to as The Single Photo Case – the result is a single directly georeferenced photo, that is used along with an available Digital Elevation Model (DEM). This produces an orthorectified image. The second illustration - referred to as The Model Case - illustrates the typical photogrammetric photo stereo model that is used to do the mapping. For details, see Mostafa et al (2001).

The determination of ground object position using a single photo is currently done for two reasons. First, this approach makes use of the currently available quality DEMs - especially, those derived by LIDAR. Second, this approach provides a shorter turn-around-time to produce digital orthophotos - making use of the available POS/AV™ derived exterior orientation elements for each

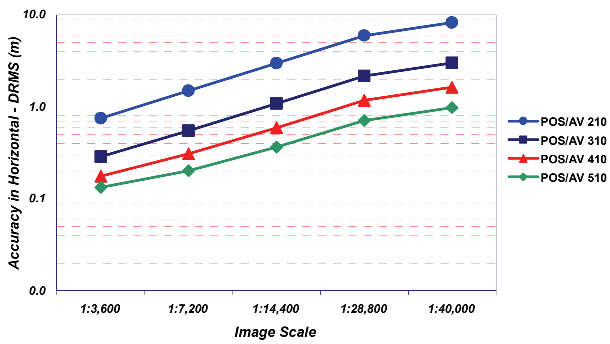

Figure 14. Ground Horizontal Precision (DRMS) The Single Photo Case - 0.3 m DEM Accuracy, 6” Lens Cone

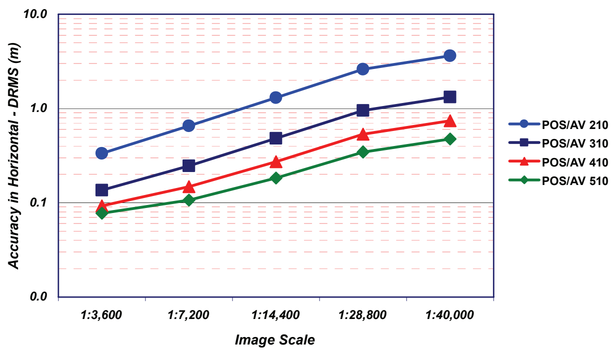

Figure 15. Ground Horizontal Accuracy (DRMS) The Model Case - 6” Lens Cone

single photo. A 9” x 9” format camera equipped by a 6” lens is used in this simulation. Image precision is taken as 5 µm; for details on the theoretical analysis, see Mostafa et al (2001). Figure 14 shows the horizontal accuracy (DRMS) of ground positioning for the family of POS/AV^{TM} systems using different image scales. Note that the vertical axis of Figure 14 is logarithmic. Figure 15 shows the same for the typical model case used for topographic mapping.

Note that for the single photo case the effect of the DEM elevation accuracy is very important. Figure 16, 17, and 18 show the ground point accuracy in horizontal (DRMS) for different POS/AV^{TM} systems, for different image scales using a 0.3 m, 1 m, and 3 m DEM accuracy, respectively.

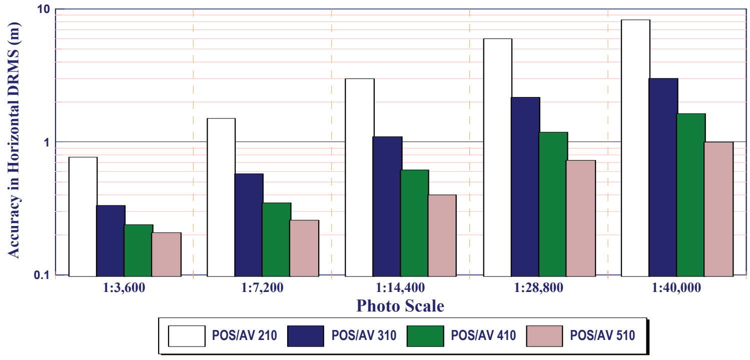

Figure 16.Ground Horizontal Accuracy (DRMS) - Using Single Photo (0.3 m DEM Accuracy)

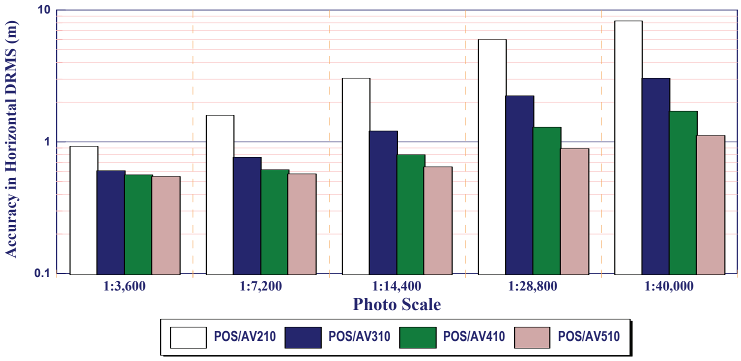

Figure 17.Ground Horizontal Accuracy (DRMS) - Using Single Photo (1 m DEM Accuracy)

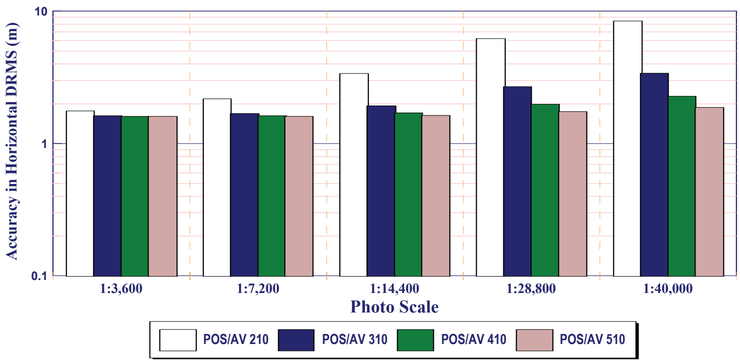

Figure 18.Ground Horizontal Accuracy (DRMS) - Using Single Photo (3 m DEM Accuracy)

6.2.2. Practical Analysis

6.2.2.1. Optech Calibration Flights

A test flight data (shown in Figure 19) was collected using POS/AV 410 and a digital frame camera of 3k x 2k and 28 mm lens. The digital camera was calibrated to compute the focal length, the principal point offsets, and the lens distortion parameters. Boresight calibration took place to determine the misalignment angles between the IMU body frame and the image coordinate frame. The lever arms were calibrated using POSEO^{TM} utilizing the measured lever arms between the GPS antenna, the IMU center, and the camera lens perspective center. The airborne navigation data was processed in POSPac^{TM}.

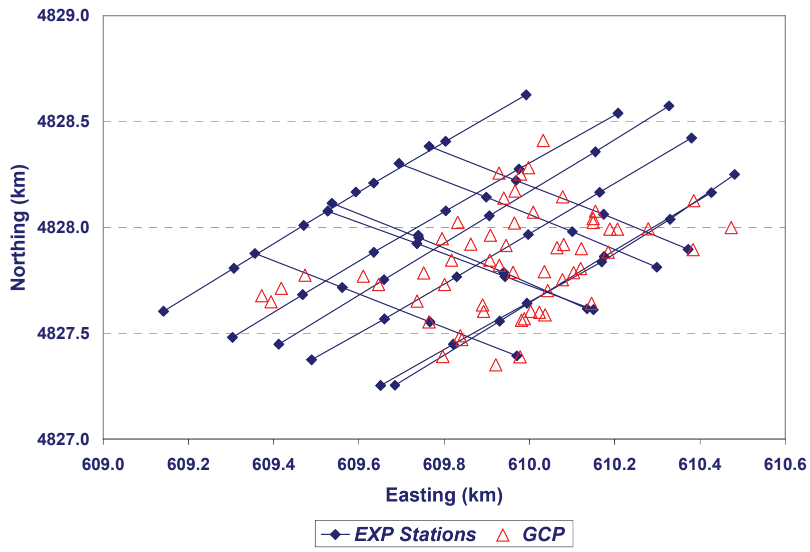

Figure 19 Optech's System Calibration Flight Showing Flight Lines, Camera Exposure Stations, and GCP

The camera/IMU boresight and the digital camera were calibrated by flying the system over Square One Mall in Mississauga, Ontario, on two different days using two different flying altitudes. About 60 ground features were surveyed. In addition, a high accuracy Digital Elevation Model (DEM) was developed using the ALTM and provided by Optech.

Using Applanix POSEO^{TM} package and POSCal^{TM} module, the digital camera and the boresight were calibrated. Almost 50% of the available ground control points were used in the calibration process while the other half was used as independent checkpoints.

To check the boresight and camera calibration parameters in the actual map production environment, all airborne data (imagery, INS/GPS position and attitude, and calibration parameters) were used in the direct georeferencing mode with no GCP, in order to position points on the ground using photo stereopairs. Then, the resulting coordinates of these points were compared to their independently land-surveyed coordinates. An example of checkpoint residuals is shown in Table 3 for the first day of flight.

To check the stability of the calibrated parameters, a second flight was done using the same integrated system. Applying the calibration parameters derived from Day 1 flight, the calibrated parameters proved to be very stable. Table 4 shows the statistics of Checkpoint residuals; for details, see Mostafa (2001).

Table 3. Statistics of Checkpoint Residuals for Individual Models of Day 1 Flight

Coordinate Component	dX (m)	dY (m)	dZ (m)
Statistics for Model # 6-7			
Minimum	-0.209	-0.108	-0.290
Maximum	0.029	0.110	0.260
Mean	-0.010	0.020	0.091
RMS (m)	**0.133**	**0.044**	**0.121**
Statistics for Model # 7-8			
Minimum	-0.111	-0.189	-0.199
Maximum	0.129	0.195	0.204
Mean	-0.020	0.041	0.081
RMS (m)	**0.072**	**0.120**	**0.104**
Statistics for Model # 8-9			
Minimum	-0.150	-0.198	-0.419
Maximum	0.129	0.185	0.390
Mean	0.016	0.014	0.098
RMS (m)	**0.064**	**0.075**	**0.195**

Table 4. Statistics of Checkpoint Residuals for Individual Models of Day 2 Flight

Coordinate Component	dX (m)	dY (m)	dZ (m)
Statistics for Model # 6-7			
Minimum	-0.198	-0.158	-0.3629
Maximum	0.190	0.141	0.310
Mean	0.030	0.028	0.081
RMS	**0.093**	**0.064**	**0.151**
Statistics for Model # 7-8			
Minimum	-0.110	-0.149	-0.169
Maximum	0.137	0.197	0.204
Mean	-0.032	0.041	0.098
RMS	**0.087**	**0.113**	**0.114**
Statistics for Model # 8-9			
Minimum	-0.201	-0.161	-0.419
Maximum	0.196	0.178	0.390
Average	0.031	-0.014	0.098
RMS	**0.106**	**0.097**	**0.211**

6.2.2.2. HJW Flight

In order to verify the theoretical error analysis, an airborne data set provided by HJW of Oakland, California is presented here. It includes image data, precisely surveyed GCPs, POS/AV^{TM}510 GPS/IMU raw observables and a post-processed GPS-assisted aerotriangulation reference.

For this flight, the POS/AV^{TM} 510 system was used, coupled with a Zeiss RMK Top camera. A 1:6000 scale, four-strip flight was flown with minimum banking angles (to avoid GPS cycle slips) and resulting in a block of 4 strips of 11 images each (a 44-image block) as shown in Figure 20. The flight lines were flown in opposite directions in order to achieve good boresight calibration. A total of 27 well-distributed GCPs were included in the block. Using the POSPac^{TM} post-processing package, a smoothed best estimate trajectory was produced. Then, using the POSEO^{TM} package the interpolated camera exposure station position and image orientation angles, at the moment of each camera exposure, were extracted for each photo from the trajectory, coordinated in the US state-plane mapping frame. The constant boresight angles between the camera and the IMU were removed using POSCal^{TM} module of POSEO so that the practical error analysis could be compared with the theoretical one. This was done by processing the POS/AV^{TM} derived position and orientation angles along with the image measurements in the POSCal^{TM} software package. After removing the boresight angles, the camera station positions and image orientation produced independently by aerotriangulation were differenced with the exterior orientation generated by the POS/AV^{TM}510. The image orientation angle differences are shown in Figure 21. Their statistics are shown in Table 5. The results are consistent with the POS/AV^{TM} 510 system specifications listed in Table 1. Note that the difference between aerotriangulation angles and POS angles has both Aerotriangulation and POS errors.

Table 5. The Difference between Aerotriangulation and POS/AV^{TM}510

Stats.	dX (m)	dY (m)	dZ (m)	dOmega (ArcSec)	DPhi (ArcSec)	dKappa (ArcSec)
Min	-0.064	-0.029	-0.034	-39.2	-22.7	-68.0
Max	0.040	0.031	0.070	33.1	25.2	61
Mean	-0.004	0.000	0.000	-1.4	-0.3	0.4
Std Dev	0.026	0.017	0.023	19.1	11.9	32.1
RMS	0.030	0.020	0.020	19.2	11.9	32.1

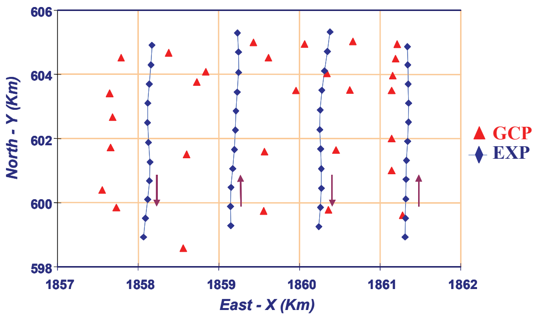

Figure 20 HJW flight in California, USA

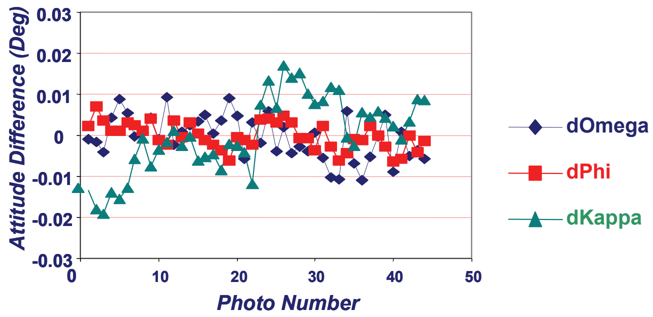

Figure 21 Difference Between POS Angles and Air Trig Angles in HJW Flight

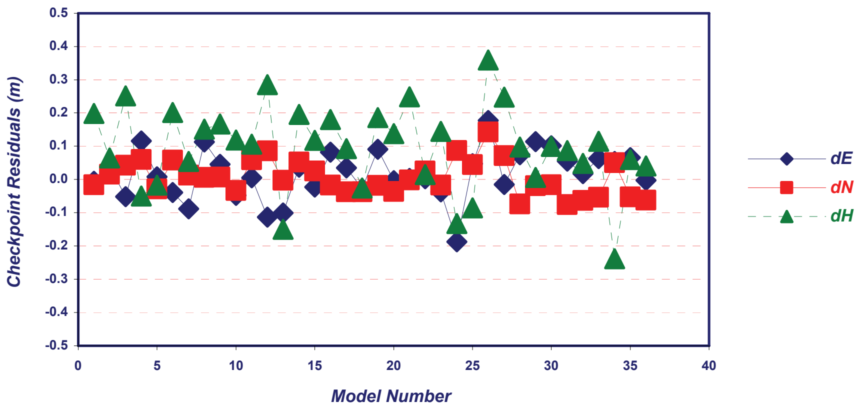

Figure 22 Checkpoint Residuals for Individual Models

To determine the absolute ground accuracy of the direct georeferencing approach using POS/AV™ exterior orientation without GCPs, 36 models were processed individually using only one image point (with known ground coordinates) per model. In each model, the exterior orientation data derived by POS/AV™ were used, along with the image point coordinates on both model photos, to determine the conjugate ground point position using the space intersection concept. The determined ground coordinates were then compared to the reference land-surveyed values. The checkpoint residuals are shown in Figure 22, while their statistics are depicted in Table 6. It is obvious from the checkpoint residuals that the accuracy of direct georeferencing using POS/AV™ 510 is consistent with the theoretical accuracy, thus validating the analysis; for details see Mostafa (2001).

Table 6. Statistics of Checkpoint Residuals

Stats.	East (m)	North (m)	Height (m)
Min	-0.19	-0.08	-0.24
Max	0.18	0.14	0.36
Mean	***0.02***	***0.01***	***0.09***
Std. Dev.	0.07	0.05	0.13
RMS	0.08	0.05	0.16

6.3. Quality Assurance and Quality Control (QA/QC)

6.3.1. Mission Planning

The absolute accuracy of the blended position of a GPS/inertial system is limited to the absolute positional accuracy of the GPS. Hence it is important that proper mission planning be conducted to ensure that the best possible GPS accuracy is achieved.

The best GPS positioning accuracy (5 to 15 cm) is achieved using carrier phase DGPS techniques. To obtain this accuracy, a mission must be planned to provide conditions for reliable ambiguity resolution throughout the mission. Error sources that can prevent maintenance or re-fixing of integer ambiguities include ionospheric delays, multipath, and poor satellite geometry. Even if the correct ambiguities are found and maintained for the entire mission, these error sources that can, if not properly managed, still degrade the accuracy of the solution. Airborne mission planning should therefore include the following components.

Static Data Collection

A mission should begin and end with a static data acquisition each lasting a minimum of 5 minutes. The static data allows the GPS post-processing software uses the constant position information to obtain the correct initial and final ambiguities with high probability of success.

Minimizing Multipath

Multipath reflections can be a major source of position error and cause for integer ambiguity resolution failures. All base receivers should use antenna choke rings or ground planes to attenuate low elevation signals, and should be mounted at least 100 m away or above all reflecting surfaces.

Limiting Baseline Separation

If the mission requires the 2-10 centimetre position accuracy that a kinematic ambiguity resolution solution can provide, then the maximum baseline separation must be limited to 10 to 50 km depending on the diurnal and seasonal solar activity. This allows the GPS processing software to recover fixed integer ambiguities following cycle slips or loss of phase lock at any time during the mission. For missions with flight lines greater than 100 kilometres, multiple base receivers must be used to ensure the maximum separation between the aircraft and any base receiver is less than 50 kilometres. Currently, POSGPS™ processing software package processes data from multiple base receivers to produce an optimal combined solution with highest possible precision (c.f., Mostafa and Hutton, 2001a).

Planning for PDOP

The mission should be planned during times of good satellite coverage so that PDOP is 3 or less throughout the mission. At the time of writing, the GPS constellation comprises 29 satellites, which provides for a poor PDOP relatively infrequently. A simple satellite prediction software tool provides the information needed to plan for best PDOP.

Inertial Navigator Alignment

POS/AV can align itself while stationary or in motion. In fact, the in-air alignment is accelerated and the quality of the alignment improved if the aircraft performs an accelerating manoeuvre such as take-off or a turn. An in-air alignment requires about 3 minutes of nominally straight and level flight to allow POS/AV to compute an initial roll and pitch, followed by a series of turns to align the heading. Thereafter POS/AV improves its alignment with every manoeuvre. A typical zigzag survey pattern provides the manoeuvres required by POS/AV to maintain a high quality alignment. Figure 23 shows a frequently changed velocity of an aircraft due to manoeuvres and Figure 24 shows the total acceleration due to such manoeuvres.

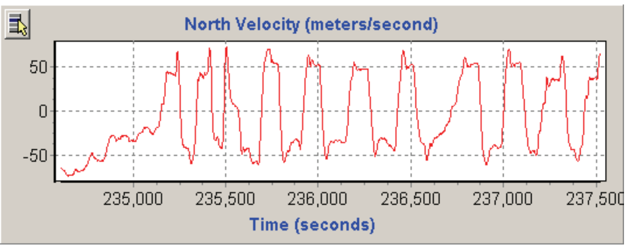

Figure 23 North Velocity Frequent Changes During Manoeuvres

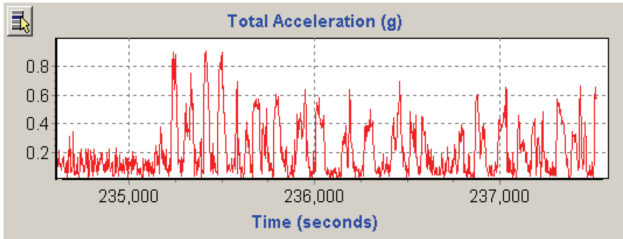

Figure 24 Total Acceleration Frequent Changes During Manoeuvres

6.3.2. Quality control

The quality of the data generated by a POS/AV system does not become directly apparent until it is combined with the imaging system data. Consequently quality control for a POS/AV system becomes a process of managing each step in the data acquisition and post-mission processing phases to achieve a consistent and reliable quality assessment.

Proper mission planning goes a long way towards obtaining repeatable results. Once the mission begins, the POS/AV system must be monitored frequently for GPS dropouts or other data acquisition failures. A severe failure such as loss of GPS data for an extended time period may be grounds for aborting the mission. Once the aircraft has landed, the recorded data should be checked at the hanger for outages and other immediate indications of bad or missing data. This allows the mission to be re-flown possibly the same day.

If the recorded data are seemed to be acceptable, then the data are handed over to post-mission processing. POSPAC^{TM} has several quality assessment indicators. The most basic of these are the inertial-GPS residuals. These are the corrected differences between the inertial and GPS position solutions at each GPS epoch, and indicate the consistency between the solutions. The residuals will appear to be random in a successful inertial-GPS integration, indicating that the integration process has removed all sources of bias errors in the data. The processing software will typically perform a statistical analysis on the residuals and report a simple quality indicator to the user.

Once all the data have been processed and the georeferenced data assembled, the final quality is given by the separation between computed and true positions of ground control points in the georeferenced data. This is the first direct measurement of quality, and comes at the end of the mapping process. If the previous steps have been managed properly, then the final quality measurement will be consistent, reliable and reproducible.
Currently, an ongoing research is targeted towards quality control procedure to check the last step mentioned in the preceding paragraph using all available navigation and image information to check

the calibration data, the GPS data, the IMU data, and the boresight calibration values. In the following sub-sections, a brief description of quality control steps currently being implemented.

6.3.2.1. Automated Boresight Calibration Using POSCAL™

As previously shown in Figure 13, the POSEO™ package has been augmented by POSCAL™ module. The POSCAL™ module has a basic least squares filter, where the corresponding matrices have been augmented to accommodate the three unknown boresight angles. GPS/IMU post-processed data, image coordinate measurements, camera calibration information, and checkpoint coordinates are used simultaneously to determine the boresight angles either airborne or in close-range (c.f., Mostafa et al, 2001 and Mostafa, 2001).

6.3.2.2. In-Flight Camera Calibration Using POSCAL™

Valid camera calibration parameters are essential for the success of direct georeferencing concept. Therefore, the POSCAL™ module allows for camera calibration parameters to be refined using flight mission data, or in close-range. Camera lab-calibrated focal length, principal point offsets, and lens distortion parameters can, therefore, be refined using aeril flight data, where GPS/IMU post-processed data helps to recover such parameters using a small block of images of the actual flight mission image and navigation data.

6.3.2.3. POSEO Interface with Digital Photogrammetric Workstations

Direct exterior orientation parameters computed in POSEO are interfaced directly with the major digital photogrammetric workstations such as Z/I Imaging ISAT, LH-Systems ORIMA, and PCI OrthoEngine. This allows the quality control process to be done directly in the digital photogrammetry workstation environment using image and GPS/IMU data.

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- HJW, Oakland, California, USA, provided aerial image data, ground control point information, and aerial triangulation reference

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