DIRECT POSITIONING AND ORIENTATION SYSTEMS
HOW DO THEY WORK?
WHAT IS THE ATTAINABLE ACCURACY?

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ABSTRACT

This paper describes how position and orientation measurement systems are used to directly georeference airborne imagery data, and presents the accuracies that are attainable for the final mapping products. The Applanix Position and Orientation System for Airborne Vehicles (POS/AV^{TM}) has been used successfully since 1994 to georeference airborne data collected from multispectral and hyperspectral scanners, LIDAR's, and film and digital cameras. The POS/ AV^{TM} uses integrated inertial/GPS technology to directly compute the position and orientation of the airborne sensor with respect to the local mapping frame. A description of the POS/AV^{TM} system is given, along with an overview of the sensors used and the theory behind the integrated inertial/GPS processing. An error analysis for the airborne direct georeferencing technique is then presented. Firstly, theoretical analysis is used to determine the attainable positioning accuracy of ground objects using only camera position, attitude, and image data, without ground control. Besides theoretical error analysis, a practical error analysis was done to present actual results using only the POS data plus digital imagery without ground control except for QA/QC. The results show that the use of POS/AV enables a variety of mapping products to be generated from airborne navigation and imagery data without the use of ground control.

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 such as the Optech ALTM, Interferrometric Synthetic Aperture Radar systems (InSAR) such as that produced by the Aero-sensing, multispectral and hyperspectral scanners such as the ITRES CASI, the new state-of-the-art digital line scanners systems such as the LH Systems ADS40, 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^{TM} use carrier phase differential GPS measurements integrated with an Inertial Measurement Unit (IMU). This paper gives an overview of how the systems work, and investigates what ground accuracy is attainable for typical applications such as mapping with a digital camera. This is supported through theoretical and practical results.

DESCRIPTION OF THE POS/AV^{TM} DIRECT GEOREFERENCING SYSTEM

The Applanix POS/AV^{TM} direct georeferencing system (see Figure 1) is comprised of four main components: an IMU, a dual frequency low-noise GPS receiver, a computer system (PCS) and 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 produced 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/AV^{TM} System

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 geographically 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 center) as possible. This ensures there is no flexure between the IMU and sensor, as shown in Figure 2. Typical high-quality IMU’s use force rebalance accelerometers and either Fiber 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 is size, bias drift, and noise. While the RLG technology produces the best performing gyro by far, their size precludes them 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/AV^{TM} systems use IMU’s containing both FOG and DTG technology.

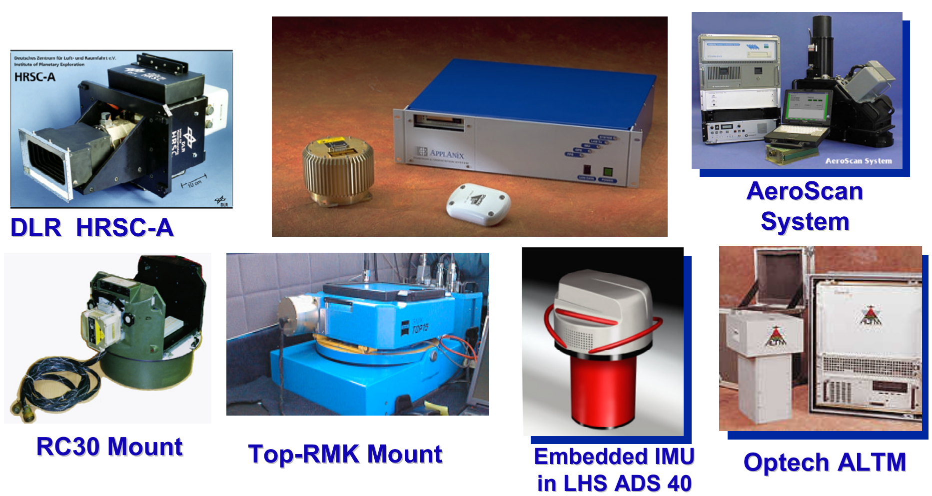

Figure 2. IMU Installation on Different Airborne Sensors

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 measurement. A 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 decimeter or better accuracy. POS/AV™ uses an embedded low noise dual frequency GPS receiver that provides phase and range data to the processing software.

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.

POSPac™ Post-processing Software

The POSPac™ 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™ 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™ 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.

HOW THE POS/AV™ DIRECT GEOREFERENCING SYSTEM WORKS

The key component of the POS/AV™ system is the Integrated Inertial Navigation (IIN) software. This software runs in real-time on the PCS and in post-processing in the POSPac™ 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 3. The software consists of the following components:

- Strapdown inertial navigator
- Kalman filter
- Closed-loop error controller
- Smoother (POSPac™ only)
- Feed forward error controller (POSPac™ only)
- In-flight Alignment

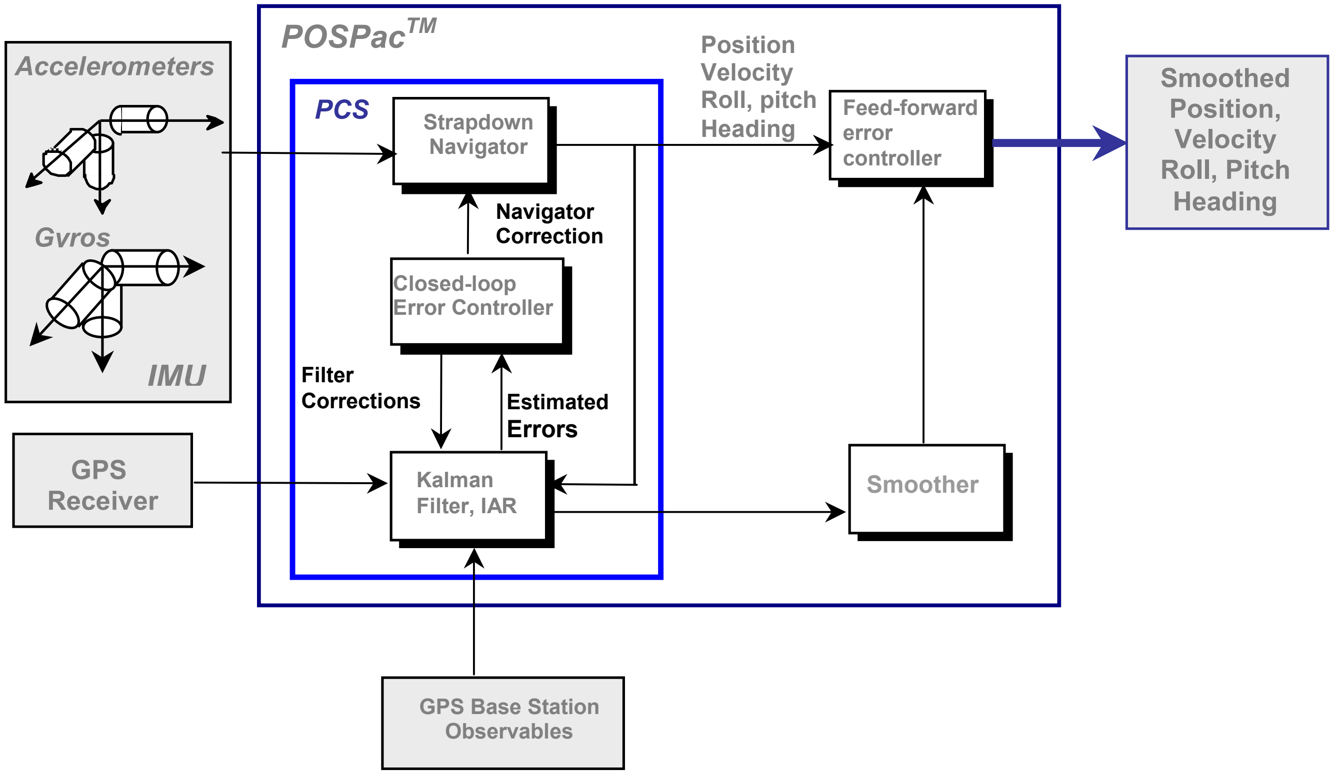

Figure 3. Closed-Loop GPS-Aided Inertial Navigation

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 *leveling,* 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 4.

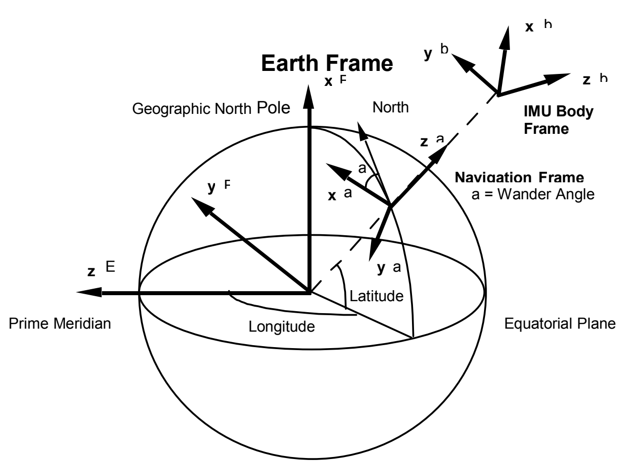

Figure 4. Frames of References Used in Inertial Navigation

After removing the rotation rate of the Earth that (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.

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 implicitly estimated.

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 accuracy indirectly improved by the calibration of the inertial sensor errors. This is the solution that is computed and output by the PCS in real-time.

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.

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.

In-Flight Alignment

An important feature of the POS/AV™ 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 Leveling, 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 5).

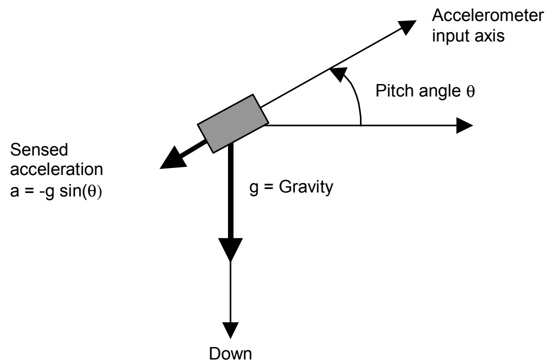

Figure 5. Coarse Leveling Using Accelerometers

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 of 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 fractions of a degree, and as soon as Coarse Leveling 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.

ACCURACY OBTAINABLE FROM POS/AV^{TM}

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^{TM} smoothed navigation position from POSPac^{TM} will also typically be 5 to 30 cm RMS.

Orientation Accuracy

The orientation accuracy of the POS/AV^{TM} 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.

Roll and Pitch Accuracy

The absolute roll and pitch accuracy of the POS/AV^{TM} 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.

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 6). The smoother will then extrapolate the reset backwards in time to reduce the overall error (see Figure 7). Hence in order to maintain heading accuracy to the maximum level, it is important that a maneuver 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).

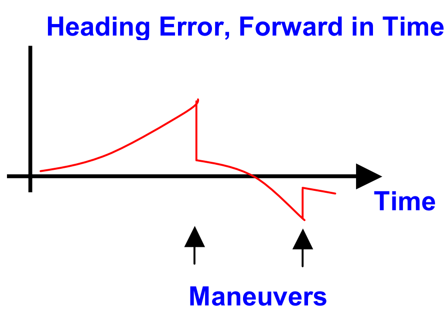

Figure 6. Heading Error Improvement after maneuvers (Forward Solution)

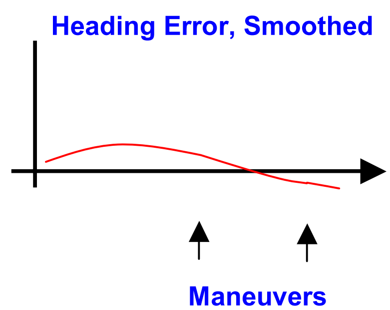

Figure 7. Heading Error Improvement after maneuvers (Smoothed)

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

DIRECT GEOREFERENCING OF DIGITAL IMAGES USING POS/AV™

Direct digital image georeferencing using POS implies the direct measurement of position and orientation of each single image frame or scan line at the moment of data acquisition. In principal, this allows immediate map production using the photogrammetric unit (either a stereopair of images, or a single image+DEM). Ultimately, this approach totally bypasses the aerotriangulation step with no ground control point requirement, except for Q/A and Q/C. Figure 8 shows the georeferencing concept.

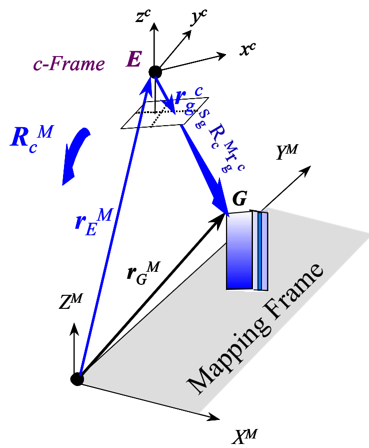

Figure 8. Image Georeferencing

In this context, a brief description on the subject is presented and the obtainable accuracy is introduced using theoretical and practical analysis. Certain Calibration aspects have to be dealt with to ensure successful map production with no aerotriangulation or ground control. Therefore, calibration will be briefly highlighted.

Digital Orthophoto Production Data Flow

As shown in Figure 9, 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 camera), boresight calibration, and lever arm calibration. The Earth-Fixed Earth-Centered (ECEF) position and orientation angles derived by POS/AV™, as shown in Figure 3, 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, POSEO™ solves for them 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.

Ground Accuracy From Theoretical Analysis

The necessary error models have been developed for two different cases of orthophoto production, namely, using either a single digital image or an image stereopair. Some assumptions have been made to account for different practical aspects. As an example of these theoretical studies, a specific case was studied which involved a digital camera of a 3k x 2K CCD chip and a 28 mm lens. This example is presented due to the availability of a real airborne data set to back up the theoretical analysis. Figure 10 depicts the horizontal DRMS theoretical accuracy (in left panel) and the height accuracy (in right panel) when using a stereo model of digital images for different Ground Sample Distance (GSD) when using POS/AV™ 210, 310, 410, and 510, respectively. Figure 11depicts the horizontal DRMS theoretical accuracy using a single digital image and 1 foot accuracy DEM (in left panel) and the horizontal DRMS theoretical accuracy using a 10 feet DEM (in right panel). Note that Figures 10 and 11 show the accuracy at image/model edge to represent worst case scenario. In practice, however, image points will not all be at image or model edge.

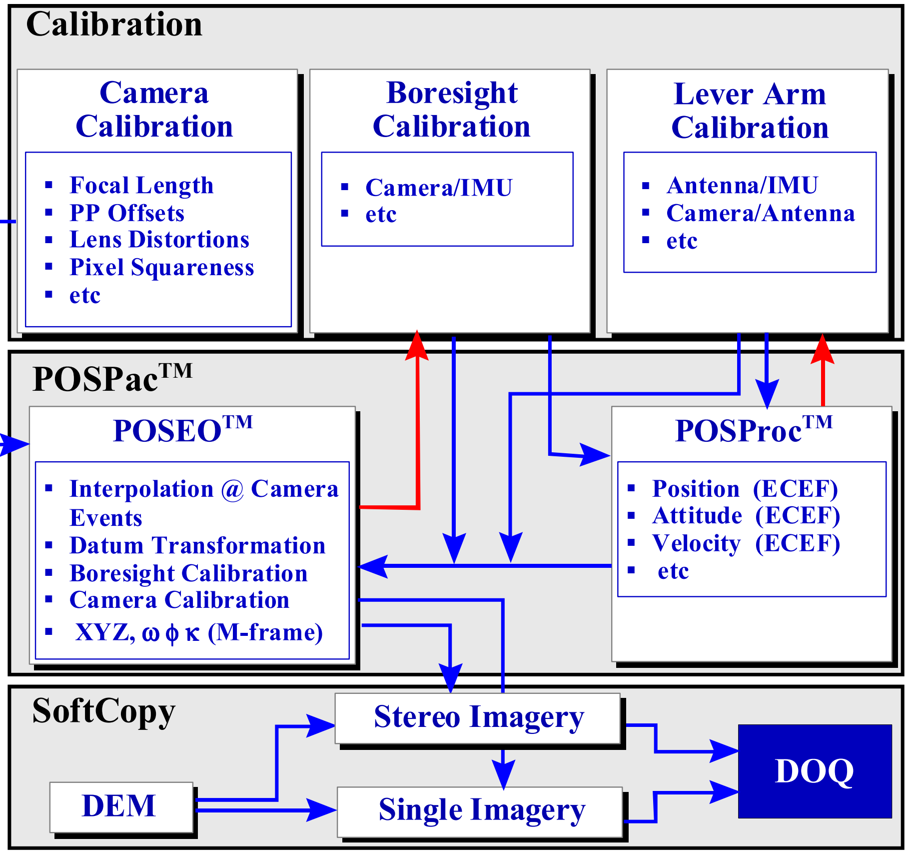

Figure 9. Digital Orthophoto Production Data Flow

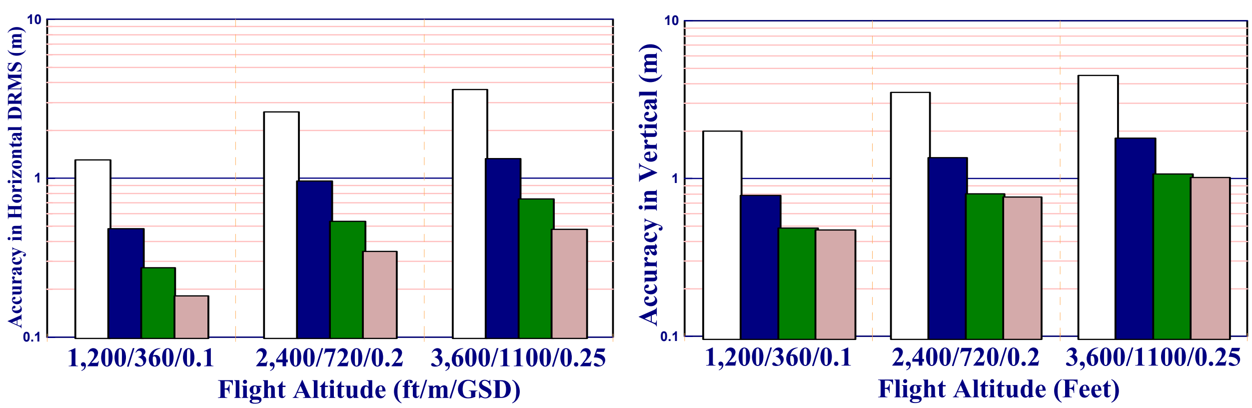

Figure 10. Ground Horizontal Accuracy (Left) and Height Accuracy (Right) Using a Stereo Model
For a 3k x 2k Digital Camera Equipped with a 28 mm Lens

Ground Accuracy From Practical Analysis

A flight test data 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™ 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™.

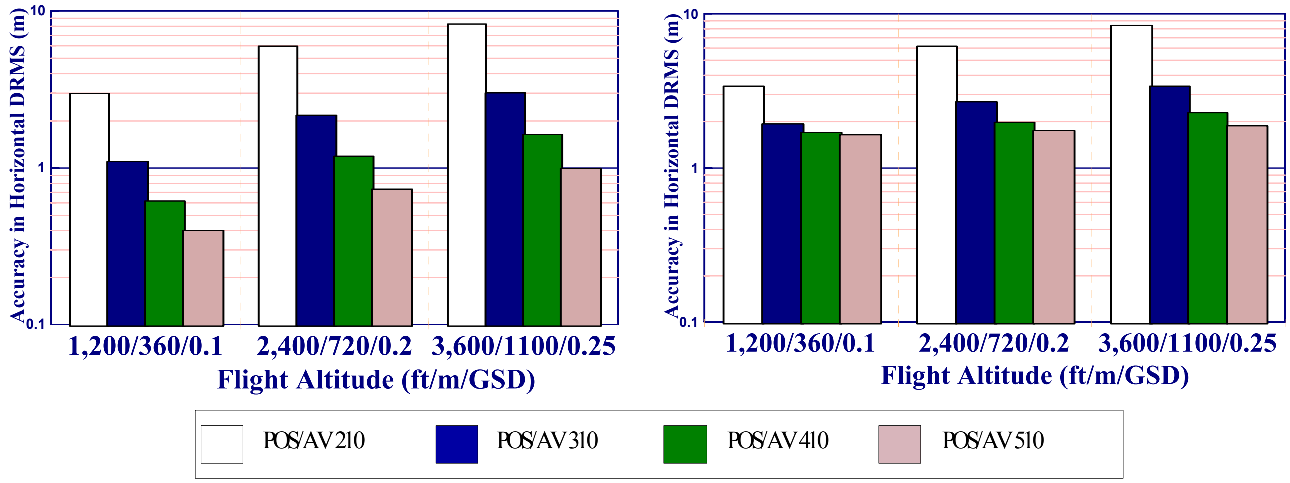

Figure 11. Ground Horizontal Accuracy Using a Single Digital Image + DEM For a 3k x 2k Digital Camera Equipped with a 28 mm Lens for a 1 ft DEM Accuracy (left) and for a 10 feet DEM Accuracy (right)

The image data together with POS data were used to compute the coordinates of the ground control points that appeared in different stereo models. A total of 20 models have been analyzed to account for different point location in the model. The POS-derived ground coordinates were then compared to the land-surveyed ones. The results are shown in Table 3.

SUMMARY AND OUTLOOK

In this paper, a brief description of direct georeferencing systems has been introduced through Applanix's POS systems. The basic concepts of inertial GPS integration have been described, along with the accuracy that can be achieved using such techniques.. Then the ground accuracy using POS integrated with a digital frame camera was analyzed. The results show that direct georeferencing can be used to obtain digital orthophotos to an accuracy that can meet many mapping or remote sensing requirements.

Ongoing research and analysis at Applanix include defining a standard procedure for quality control for fault detection and repair including but not limited to: boresight calibration residual errors, residual y-parallax, camera calibration errors.

Table 3. Ground Point Accuracy Derived by POS Compared to GCP Surveyed Reference

Model ID	*Easting (m)*	*Northing (m)*	*Horizontal (m)*	*Height (m)*
1	-0.08	0.10	0.13	-0.59
2	0.07	-0.10	0.12	-0.11
3	0.13	0.09	0.16	0.88
4	0.38	-0.18	0.42	-0.02
5	-0.24	0.01	0.24	0.71
6	-0.18	-0.32	0.37	-0.40
7	0.19	-0.08	0.20	0.00
8	-0.07	0.07	0.10	-0.45
9	-0.25	-0.05	0.25	0.34
10	0.06	0.20	0.21	-0.15
11	0.28	-0.10	0.30	0.28
12	0.13	-0.37	0.39	0.39
13	0.35	-0.20	0.40	-0.05
14	0.09	0.17	0.19	0.52
15	0.34	-0.02	0.34	1.34
16	-0.06	0.06	0.09	0.30
17	-0.21	0.15	0.25	-0.01
18	-0.04	-0.34	0.34	0.53
19	0.21	-0.10	0.24	0.03
20	-0.20	-0.11	0.23	-0.64
		Statistical Summary		
Min	-0.25	-0.37	0.09	-0.64
Max	0.38	0.20	0.42	1.34
Mean	0.04	-0.06	0.25	0.15
Std	0.21	0.17	0.10	0.50
RMS	0.21	0.18	0.27	0.52

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