Integrated Airborne Navigation Systems for Photogrammetry

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ABSTRACT

Integrated navigation systems are used in photogrammetry to provide the exterior orientation of the airborne imaging sensor, i.e. to determine position and attitude of the sensor at each exposure in a well defined coordinate system. By matching the accuracy of the external orientation parameters to the accuracy required on the ground, photo control isnot needed any more to estimate errors of exterior orientation. This greatly reduces the requirements for ground control which can now be configured in such a way that it optimizes camera calibration and transformation to a local coordinate system, where needed. The full potential of this approach for non-conventional airborne sensors, such as imaging scanners and digital frame cameras, is only now being explored, although some of the underlying ideas have been partially applied for several years in GPS-aided block triangulation. The paper briefly reviews the principle of airborne georeferencing and its implementation by using an inertial navigation system (INS) integrated with differential GPS. The accuracy requirements in different application areas are then stated and are compared to the accuracies achievable with current airborne imaging sensors. The position and attitude performance of INS and GPS are discussed and related to the user requirements. Finally, INS/GPS integration strategies are analyzed and results of two system implementations are presented. These results show that a low-cost INS/GPS integration is sufficient for many of the current and emerging mapping and resource applications.

1. INTRODUCTION

During the last three decades, airborne photogrammetry, when applied to mapping, has been performed in a single mode of operation: aerotriangulation with block adjustment of either bundles or stereo models. This mode was well justified by operational constraints. Because ground control was usually scarce, the geometrical strength of the bundle had to be used to the fullest. By creating homogeneity within the photogrammetric block, smooth residual errors could be expected which could be well approximated by simple interpolation procedures between a few data points.

With the advent of reliable methods of kinematic GPS positioning, the interpolation component of the process was considerably improved. By being able to position the projective center of each exposure with high absolute accuracy, the translational components of the block configuration were strengthened, and position biases, scale factors, and drifts in latitude and longitude could be estimated with high accuracy, independent of existing ground control. In addition, camera calibration became much easier provided a few ground control points were available either in the area or close to it. The orientation component was indirectly strengthened because coordinate constraints between exposure stations also constrained the relative orientation between adjacent bundles. The fact that this introduced a high correlation between translation and orientation components seemed not to be critical in practice because the geometrical strength of the individual bundle was comparable in accuracy to the derived orientation changes. Thus, GPS-aided aerotriangulation in block adjustment mode has emerged as the optimal procedure for those applications requiring high-precision optical cameras and area coverage, see for instance Ackermann (1994), Hothem et al. (1994), Lukas (1994), for details.

The paper, therefore, addresses applications where these conditions are not satisfied, i.e. either situations where sensors other than high-precision optical cameras are flown or strip or model coverage rather than block coverage is required. In these applications, external orientation becomes as important a parameter as external position has become in GPS-aided photogrammetry. The reason for this is that either the sensors used do not have the same geometrical strength as high-precision aerial cameras or that the photo coverage is such that the geometrical strength of the bundle for relative orientation is not sufficient. In the first case, digital frame cameras and line scanners come to mind. In the second case,

highway and powerline design, coastal mapping, and pipeline maintenance could be mentioned. These applications will be considered photogrammetric as long as the use of multiple images is an essential component of the process. The resulting methods will not rapidly replace high-precision mapping by GPS-aided conventional aerial photogrammetry, but they will be of increasing importance in resource mapping and in cases where high precision is required, but a block approach is not practical.
The emphasis of this paper will beon the georefencing of airborne sensors which is an underlying theme of all these applications. Integrated airborne navigation systems will therefore be understood as systems that provide both accurate position and orientation of the airborne sensor in a well defined coordinate frame. The ultimate goal of using such systems is the reduction of ground control, while at the same time increasing the accuracy and homogeneity of the results. Other components of integrated aircraft systems which could be very useful for photogrammetric applications, such as pointing or scanning lasers, will not be included in the discussion.

2. GEOREFERENCING AIRBORNE SENSORS

Georeferencing of airborne sensors is treated in some detail in Schwarz et al (1993). A brief review of the major concepts will be given here to provide a framework for the following discussion. Georeferencing describes a series of transformations necessary to obtain coordinates in a chosen mapping system (m) from the output of a remote sensing device in the body frame (b) of the aircraft. The important parameters for this transformation are depicted in Figure 1.

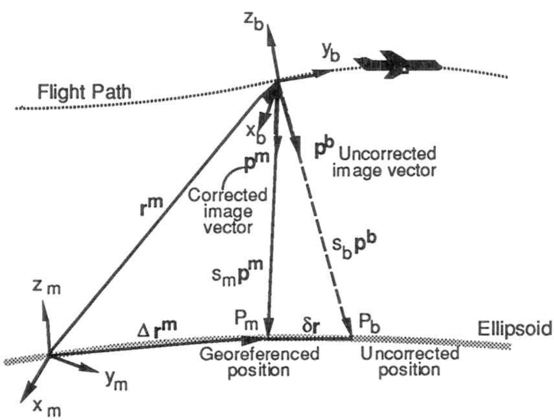


Figure 1: Georeferencing of Airborne Sensing Data.

The mathematical model corresponding to this figure is

$$\Delta \mathbf{r}^m(t) = \mathbf{r}^m(t) + s\mathbf{R}^m{}_b(t)\,\mathbf{p}^b , \tag{1}$$

where

$\Delta \mathbf{r}^m$ is the position vector of an image object in the chosen mapping frame;
$\mathbf{r}^m$ is the coordinate vector from the origin of the mapping frame to the centre of the position sensor on the airplane, given in the m-frame;
$\mathbf{R}^m{}_b$ is the three-dimensional transformation matrix which rotates the aircraft body frame (b-frame) into the mapping frame;
s is a scale factor derived from the height of the sensor above ground;
$\mathbf{p}^b$ is the vector of image coordinates given in the b-frame.

Equation (1) is only a first approximation of the actual situation. Since the three sensors for positioning, attitude determination, and imaging are at different locations in the aircraft, another set of transformations is necessary to relate all sensors to the origin and the axes of the chosen body frame in the aircraft. The parameters of these transformations can be considered fixed for one mission and are obtained through a pre-flight calibration, for details see Schwarz et al (1994).

The resulting modelling equations are

$$\Delta \mathbf{r}^m (t) = \mathbf{r}^m (t) + \mathbf{R}^m{}_b (t) \{ s \, d\mathbf{R}^b{}_c (\mathbf{p}^c + d\mathbf{r}^c) + d\mathbf{r}^b \} \quad (2)$$

The additional vectors and matrices in equation (2) are as follows:

$d\mathbf{R}^b{}_c$ is the transformation matrix which rotates the camera frame (c-frame) into the body frame;
$\mathbf{p}^c$ is the imaging vector in the c-frame
$d\mathbf{r}^b$ is the translation vector between the centre of the attitude sensor and the perspective centre of the camera, and
$d\mathbf{r}^c$ is the translation vector between the centre of the positioning sensor and the perspective centre of the camera.

The camera frame is defined as having its origin in the perspective centre of the camera, its z-axis along the vector between the perspective centre and the principal point of the photograph, and its (x,y)-axes in the plane of the photograph with origin at the principal point. The corresponding image vector is therefore of the form

$$\mathbf{p}^c = \begin{pmatrix} x - x_p \\ y - y_p \\ -f \end{pmatrix} \quad (3)$$

In case of pushbroom scanners and CCD frame imagers, the second vector component is replaced by

$$y^c = (y - y_p) / ky$$

where ky accounts for the non-squareness of the CCD pixels.
It should be noted that the origins of the position and attitude sensors are not identical. Furthermore, the vectors $\mathbf{r}^m$ and $\Delta\mathbf{r}^m$, as well as the rotation matrix $\mathbf{R}^m{}_b$ are time dependent quantities while the vectors $\mathbf{p}^c$ and $d\mathbf{r}^b$ as well as the matrix $d\mathbf{R}^b{}_c$ are not. This implies that the aircraft is considered as a rigid body whose rotational and translational dynamics is adequately described by changes in $\Delta\mathbf{r}^m$ and $\mathbf{R}^m{}_b$. This means that the translational and rotational dynamics at the three sensor locations is uniform, in other words, differential rotations and translations between the three locations have not been modelled. It also means that the origin and orientation of the three sensor systems can be considered fixed for the duration of the flight. These are valid assumptions in most cases but may not always be true.
The quantities $\Delta\mathbf{r}^m$, $\mathbf{R}^m{}_b$ and $\mathbf{p}^c$ in equation (2) are determined by measurement, the first two in real time, the third in post mission. The quantities $d\mathbf{R}^b{}_c$ and $d\mathbf{r}^b$ are determined by calibration, either before or during the mission, see Schwarz et al (1993) for details. For the georeferencing process, the parameters $\Delta\mathbf{r}^m$ and $\mathbf{R}^m{}_b$ are obviously of prime importance. They are usually determined by combining the output of an inertial measuring unit (IMU) with that of one or several receivers of the Global Positioning System (GPS). Although other observables can be used, they are less suited for the task at hand and will not be treated here. To obtain position and orientation as functions of time, they are modelled as functions of the time-dependent IMU and GPS observables. The resulting model is a system

of first-order differential equations in which $\Delta\mathbf{r}^m$ and $\mathbf{R}^m{}_b$ are variables. In engineering applications, such a system is often called a state vector model. It is the model underlying Kalman filtering and is therefore well-suited for both system integration and optimal real-time estimation, see for instance (). The advantage of using a state vector model lies in the possibility of imposing smoothness conditions on the solution by the definition of covariances for the state vector elements and of the spectral densities.

The models for determining georeferencing parameters from either IMU or GPS observables will not be presented in detail. A brief discussion is given in Schwarz et al (1993), while Wei and Schwarz (1990) should be consulted for details on the IMU model and Schwarz et al (1989) for details on the GPS model. What follows is brief descriptive account of the salient features of each system and the reasons for integrating them.

A strapdown IMU outputs three components of the specific force vector and three components of the angular velocity vector in the body frame system. To use these observables to derive position, velocity, and attitude in an earth-fixed coordinate system, the attitude between the measurement frame and the earth-fixed frame must be determined as a function of time. This is accomplished by determining the initial attitude in the so-called alignment procedure, by correcting the measured angular velocities for earth rotation and by then integrating them in the earth-fixed frame. Since attitude is now known as a function of time, the specific force measurements can be transformed into the earth-fixed frame. By subtracting gravity from the transformed measurements, vehicle acceleration is obtained. By integrating acceleration once with respect to time velocity is obtained, by integrating twice position is obtained. The earth-fixed frame is in principle arbitrary but is usually chosen either as a local geodetic frame or a geocentric Cartesian frame. Because of the integrations involved in the process, initial errors, caused for instance by sensor biases, grow quickly with time. Thus, a free inertial system will show systematic errors in position, velocity, and attitude which oscillate with a period of 84 minutes, the so-called Schuler period. The presence of these errors is the major reason why integration with GPS is advantageous and why it results in a far superior determination of the georeferencing parameters.

GPS observables are either of the pseudorange type or of the carrier phase type. Models to transform the resulting range equations into positions and velocities are well-known, see, for instance, Wells et al (1986). In the process, orbital models as well as atmospheric models are needed and the Earth rotation rate is again assumed to be known. By locating one receiver at a known master station and referencing the moving receiver to it, major errors in the GPS measurement can be eliminated. These differential procedures can be applied to pseudorange measurements as well as to carrier phase measurements and will be assumed as the modus operandi in the following. In the typical case of one ground receiver and one moving receiver, only the translational vector $\mathbf{r}^m(t)$ can be determined because one antenna does not fix a vector within the rigid body and thus the determination of rotational parameters is not possible. Three body-mounted antennas, preferably orthogonal to one another, are the minimum requirement for the determination of $\mathbf{R}^m{}_b(t)$. The attitude matrix in the body frame is obtained by using double differenced carrier phase measurements, see El-Mowafy (1994) for details. The distance between antennas must be considered as constant and accurately known and a proper initialization of the $\mathbf{R}^m{}_b$-matrix is required while the system is stationary.

Thus, the georeferencing parameters, position and attitude, can be obtained from either an IMU or a multiple receiver GPS system. However, each of the individual solutions has drawbacks which can be largely eliminated by a system integration. GPS positioning using differential carrier phase is superior in accuracy as long as no cycle slips occur. GPS relative positions are, therefore, ideally suited as INS updates and resolve the problem of systematic error growth in the IMU trajectory. On the other hand, the IMU-derived attitude is usually superior to that obtained from a GPS multi-antenna system. In addition, IMU-derived position differences are very accurate in the short term and can thus be used to detect and eliminate cycle slips and to bridge loss of lock. Because of the high data rate, they provide a much smoother interpolation than GPS. Integration of the two data streams via a Kalman filter thus provides results which are superior in accuracy, reliability, and homogeneity.

To determine $d\mathbf{R}^b{}_c$ by calibration, a minimum of three well determined ground control points is required, while dr^b can be obtained by direct measurement on the ground. The scale factor s changes with flying altitude of the aircraft above ground. It can, therefore, either be approximated by assuming a constant flying altitude, calibrated by introducing a digital terrain model, or determined by measurement, using either stereo techniques or an auxiliary device such as a laser scanner. For precise georeferencing, the latter technique is the most interesting to be investigated because it would provide all necessary measurements from the same airborne platform and thus avoid datum problems.

3. USER ACCURACY REQUIREMENTS AND CURRENT HARDWARE PERFORMANCE

A discussion of user accuracy requirements and current sensor performance has been given in Schwarz et al (1994). It will be briefly summarized here, without any detail on the underlying assumptions. Table 1 shows user requirements in different application areas. The numbers indicate that two distinct accuracy classes have to be considered. Accuracies in the sub-decimeter range are required in cadastral and engineering projects, while accuracies at the meter level are needed for the bulk of the work in cartographic mapping and resource applications. There are some applications which fall in between these two classes, but they are not as important as those in the two major areas.

Application Area	RMS Accuracy for	
	Position	Attitude
Engineering, Cadastral	0.05 - 0.1 m	(15" - 30")
Cartographic Mapping 1:10 000	1-5 m	10' - 20'
Forestry (General)	2 - 5 m	20' - 30'
Forestry (Detailed)	0.2 - 1.0 m	1' - 3'

Table 1: Accuracy Requirements.

Type of Sensor	Georeferencing Accuracy Achievable		
	Position	Attitude	Velocity
Aerial Camera (low flying)	0.05-0.1 m	(15"-30")	not requ.
Digital Scanning Systems (CCD)	0.25-1.0 m	1'-3'	1-2 cm/s
SAR Systems	2 - 4 m	(10"-40")	0.02-0.05 cm/s

Table 2: Imaging Sensor Accuracies.

Table 2 shows the georeferencing accuracy required to fully utilize the resolution of current airborne imaging sensors. It is interesting to note that most of the mapping and resource applications are already within the range of available digital scanning systems and frame cameras. By providing airborne georeferencing, the full potential of the imaging sensors can be used. High-precision optical cameras are currently the only ones that can meet accuracy requirements in cadastral and engineering applications. Table 3 shows the positioning and attitude determination capability of GPS for different observables and processing methods. In general, these results are achievable in post-mission mode. The table shows that all required positioning accuracies can be met but that operational constraints may be necessary to satisfy the requirements of high accuracy applications. For details under which circumstances these results are achievable, see Cannon and Lachapelle (1992), Lachapelle et al (1994), Shi and Cannon (1994). In general, the relative accuracy over short time spans, say one minute, are better than the numbers quoted.

Model	Separation	Accuracy	Mode
Pseudorange point positioning (single rev) using precise orbits and clock corrections		100 m horizontal 150 m in height 1 - 2 m horizontal 2 - 4 m in height	real time post mission
Smoothed pseudorange Pseudorange differential positioning	10 km 500 km	0.5 - 3 m horizontal 0.8 - 4 m in height 3 - 7 m horizontal 4 - 8 m in height	post mission (or real time)
Carrier phase differential positioning	10 km 50 km 200 km (with precise orbits)	3 - 20 cm horizontal 5 - 30 cm in height 15 - 30 cm horizontal 20 - 40 cm in height 15 - 30 cm horizontal 20 - 40 cm in height	post mission
Attitude determination	1 m 5 m 10 m	18-30 arcminutes 4 - 6 arcminutes 2-3 arcminutes	post mission (or real time)

Table 3: GPS Positioning and Attitude Accuracies.

Table 4 shows position, velocity, and attitude performance of inertial navigation systems (INS) for two different accuracy classes. Because INS errors are a function of time, they are quoted for different time intervals. Most of the time-dependent errors follow a systematic pattern and can therefore be greatly reduced by appropriate update measurements. The residual noise level for a navigation grade INS after GPS-updating will usually be close to the value given for the one second interval. For a low performance system the noise level will be above the one second value.

Error in	System Accuracy Class			
	nav. grade		Accuracy	
Attitude	pitch & roll;	azimuth	pitch & roll;	azimuth
1 h	10" - 30"	60" - 180"	0°5 - 1°0	1° - 3°
1 min	5" - 10"	15" - 20"	0°1 - 0°3	0.2° - 0.5°
1 s	3" - 5"	3" - 20"	0°01 - 0°02	0.02° - 0.05°
Velocity				
1 h	0.5 - 1.0 m/s		200 - 300 m/s	
1 min	0.03 - 0.10 m/s		1 - 2 m/s	
1 s	0.001 - 0.003 m/s		0.002 - 0.005 m/s	
Position				
1 h	500 - 1000 m		200 - 300 km	
1 min	0.3 - 1.0 m		30 - 50 m	
1 s	0.02 - 0.05 m		0.3 - 0.5 m	

Table 4: Current INS Performance.

Table 5 shows potential system options, their range of applications, and a rough estimate of the hardware costs. Total system costs will be higher and depend on the sophistication of the integration and the software. The overview shows that a number of options are available and that their price varies with accuracy and operational flexibility. A detailed discussion of each option goes beyond the scope of this paper but some important principles will be discussed in the next section.

Accuracy Required	System Configuration	Airborne Sensor	Cost (US$) (K$=$1000)	Characteristics
0.05 - 0.1 m 15" - 30" 0.0002 - 0.0005 m/s	Navigation-grade INS plus DGPS (carrier phase)	All airborne sensors	K$250	Suitable for all applications
1 - 5 m ≥ 10' 0.01 - 0.02 m/s	DGPS (pseudo-range) plus GPS multi-antenna system	Pushbroom scanner, CCD frame imagers	K$40	Low data rate. Attitude transfer to imaging sensor is problematic (stability)
1 - 5 m ≥ 1' 0.0002 - 0.0005 m/s	DGPS (pseudo-range) plus low accuracy INS	Pushbroom scanners, CCD frame imagers, some SAR applications	K$25	Long-term velocity may be marginal

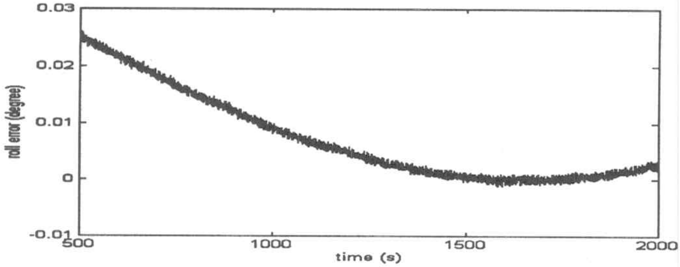
Table 5: Options for Integrated Georeferencing systems.

4. DESIGN CONSIDERATIONS AND TESTING OF GEOREFERENCING SYSTEMS

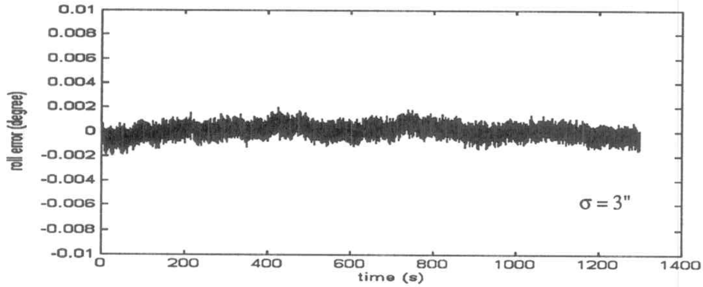
In this section, some design considerations for georeferencing systems will be discussed and results of two system implementations will be presented. Since they are at different ends of the accuracy spectrum, they should provide a good understanding for the range of available options.

Figure 2a shows the attitude output of a navigation-grade INS in static mode over a period of about 25 minutes. The systematic error is smooth and reaches a minimum after about 21 minutes. It is clearly part of the Schuler-type oscillation. The noise about this trend is very small and shows white noise characteristics. After eliminating the trend, the noise pattern in Figure 2b results. It shows the system attitude noise which is at the level of 3 arcseconds (RMS) and presents the attitude accuracy achievable under ideal conditions. Figure 2c shows the noise of the same system mounted in an aircraft with the engines switched on. As before, the trend has been eliminated. In this case, the low noise level of the lab test cannot be maintained. The noise is now between 15 and 20 arcseconds and is mainly due to aircraft vibrations. If the vibrational effects above the aircraft dynamics of 10 Hz are eliminated, the noise drops again to 5-6 arcseconds in pitch and roll. Adding error components due to the interaction of synchronization errors and aircraft dynamics, the pitch and roll noise to be expected under dynamic conditions will be about 10 arcseconds. Figure 2d shows the system attitude noise for a low-accuracy system. Again, the trend has been subtracted, so that Figure 2d is directly comparable to Figure 2b, showing the difference between a high performance and a low performance IMU. The comparison shows that the noise is at a level of about 100 arcseconds and that it does not have white noise characteristics but clearly displays the effects of short-term drift.

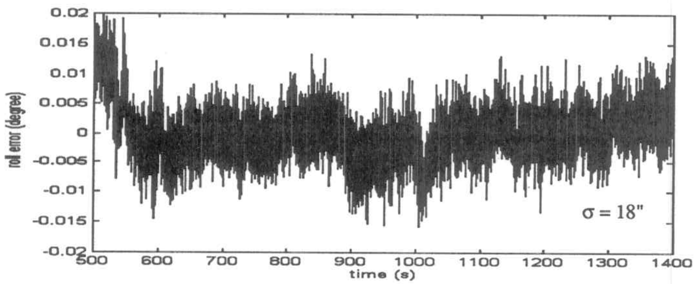
The analysis of Figures 2a to 2d and Tables 4 and 5 reveals some important principles for the design of an integrated INS/GPS for georeferencing. First of all, the required position accuracy can be achieved by GPS for all applications, although high-precision applications would require master stations in the immediate area and carefully defined operational procedures. The orientation requirements can also be met if attitude noise is the only type of error that has to be considered.



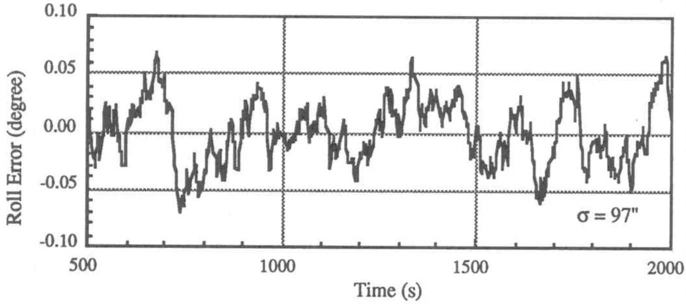
2a Nav-grade IMU, total roll error, static case, lab conditions



2b Nav-grade IMU, roll noise, static case, lab conditions



2c Nav-grade IMU, roll error, static case, aircraft engine switched on



2d Low-cost IMU, roll noise, static case, lab conditions

Figure 2: IMU Attitude Noise.

This, in turn, would require that the Schuler-type oscillations in the attitude can be eliminated by 1 Hz GPS velocity and position updates. Whether or not this is possible will be analyzed in the following. It also appears feasible to use a GPS multi-antenna system for attitude requirements at the 10 arcminutes level. However, in this case, the data rate may be insufficient for trajectory approximation and the variance of the white noise may cause large gradients over time intervals of one second.
It appears from Figures 2b and 2d that the Schuler oscillations can be largely eliminated by GPS updates and that the remaining noise is only dependent on the combined INS/GPS noise. This is true for pitch and roll but not for heading. To show this, consider the relationship between INS acceleration errors δv, misalignment errors ε, accelerometer biases b, and specific force components f. They are of the form

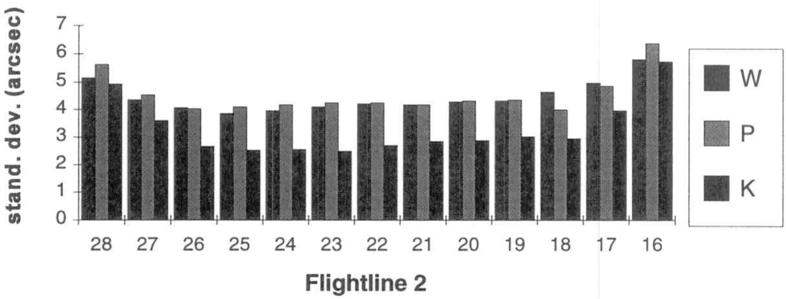
$$\begin{aligned} \delta\dot{v}_e &= f_u\varepsilon_n - f_n\varepsilon_u + b_e \\ \delta\dot{v}_n &= -f_u\varepsilon_e + f_e\varepsilon_u + b_n \\ \delta\dot{v}_u &= f_n\varepsilon_e - f_e\varepsilon_u + b_u \end{aligned} \tag{4}$$

where the subscripts n,e,u denote north, east, and upward. The upward component of specific force contains the effect of gravity and is thus always considerably larger than the north and east component. In a photogrammetric flight, constant velocity along a straight line is the prefered operational environment. Thus, f_n and f_e are rarely larger than 0.1 m/s^2, while f_u is always about 10 m/s^2.
Rewriting the second equation with respect to ε_u and ε_n results in

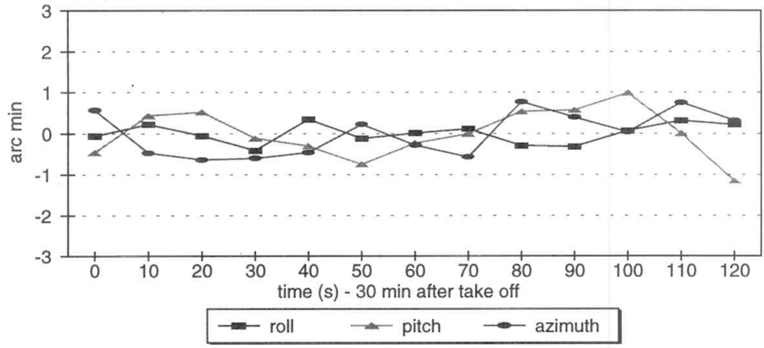
$$\begin{aligned} \varepsilon_u &= \frac{f_u\varepsilon_n - \delta\dot{v}_e + b_e}{f_n} \\ \varepsilon_n &= \frac{f_n\varepsilon_u + \delta\dot{v}_e + b_e}{f_u} \end{aligned} \tag{5}$$

Assuming a flight to the north, these equations show the heading and roll errors as functions of specific force, misalignment, acceleration error, and accelerometer bias. Assuming the same magnitude of errors in both cases and introducing typical error sizes, the following conclusions can be drawn. Due to the size of the specific force component in the denominator, the determination of roll (and pitch) will usually be at least a hundred times more accurate than the determination of heading. Actually, the better the constant velocity condition is maintained, the better pitch and roll will be determined and the poorer the estimation of heading will be. Only when the aircraft manoeuvres in such a way that major horizontal accelerations are introduced, will the heading accuracy be improved. It can therefore be concluded that GPS updates are sufficient to eliminate pitch and roll oscillations to the level of INS attitude noise, but that similar results cannot be achieved in heading without a regular pattern of large horizontal aircraft accelerations. For a more detailed discussion of these interrelationships, see Schwarz and Wei (1994) and Zhang (1995).
In the following, tests with two different georeferencing systems will be used to illustrate the theoretical results. The first system has been used by the U of C for some time and consists of an LTN 90/100, a navigation-grade INS, which has been integrated with two Ashtech Z12 receivers, one on the airplane and one at the master station. A Zeiss LMK aerial camera was used to obtain a block of photographs of a well controlled test field. Targetted points in the photographs were then used to determine the attitude of the camera from the known ground control points by a bundle adjustment. The estimated attitude was compared to the attitude obtained from the integrated INS/GPS. For details of this test, see Skaloud (1995). Figure 3 shows the accuracy of the attitude angles determined from the ground control. They are typically at the level of 4-5 arcseconds in each component, about twice as accurate as expected from the INS under the best circumstances. The comparison with the INS-derived attitude is shown

in Figure 4. It indicates that the differences are at the level of about 20 arcseconds, which was expected in this case because no vibration filtering had been applied. Thus, the differences represent largely the INS noise under operational conditions. Schuler oscillations in attitude have been eliminated down to the noise level. It should be noted, however, that the time interval shown is only two minutes. For longer mission times, a degradation of the azimuth accuracy due to drift effects can be expected. For photogrammetric applications, the accuracy in pitch and roll will be sufficient for all accuracies required. Since the azimuth is not needed with the same accuracy, navigation-grade inertial systems will usually be sufficient for all airborne imaging applications.



Figures 3: Accuracy of Camera Attitude Angles as Computed from Available Ground Control.

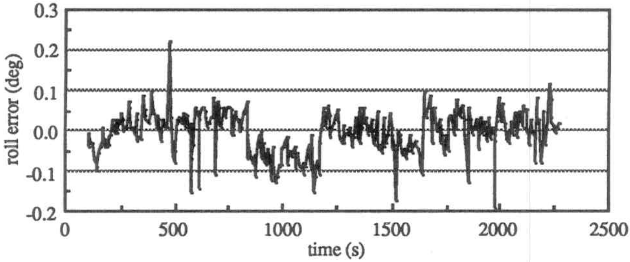


Figures 4: Differences in Attitude Angles as Computed from INS/GPS and from Ground Control.

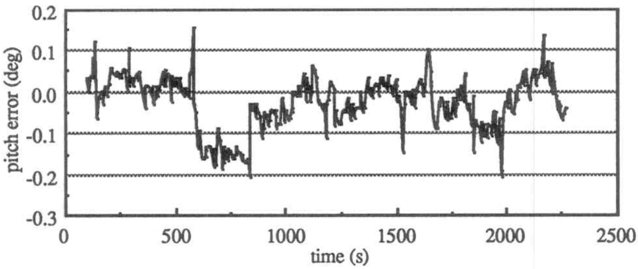
The second system was designed to explore the potential of a low-cost georeferencing system with hardware costs of about $ 25 000 for mapping and resource applications, see Schwarz and Zhang (1994). The IMU chosen was the MotionPak manufactured by Systron Donner. It consists of three gyros and three accelerometers, sealed with micro-electronics in a compact, rugged package. The angular rates are sensed using subminiature oscillating quartz elements, while linear accelerations are sensed using a served quartz flexure pendulum. The MotionPak is small enough to fit easily on an airborne digital sensor. It is directly powered by a DC battery and provides three analog DC rate signal outputs, three analog DC acceleration signal outputs and one analog DC temperature output. An AT-MIO-16X data acquisition board manufactured by National Instruments has been used to convert the MotionPak analogue outputs into digital data. Since the quality of the MotionPak inertial sensors is very low, the compensation of the inertial sensor error is key to the low-cost integrated INS/GPS system. The accuracy of the compensation is the main criterion for the system accuracy achievable. The inertial sensor error compensation implemented in the software of the low-cost integrated INS/GPS system includes low-pass filtering, temperature effect compensation, scale factor error and misalignment compensation.

Two different integration modes have been used to analyse the results. In integration mode 1, only double differenced pseudorange and Doppler observations are used for INS updating. As discussed above, heading results will be poor in this case because the lack of accelerations in the horizontal channels coupled with relatively large short-term drifts, will make attitude determination very weak. Position, pitch and roll results are continually updated by GPS and will result in errors that corresponds to the GPS noise level. In integration mode 2, heading from a GPS dual-antenna system is added as an update measurement to the previous ones, in order to eliminate the weakness in integration mode 1. The long-term accuracy of the GPS-derived heading will essentially depend on the distance between the two antennas on the aircraft. To achieve an accuracy of 0.1 degree reliably, the distance should be at least 1.5 m. In both cases, results of the integrated navigation-grade INS were used for comparison, for details see Zhang (1995).

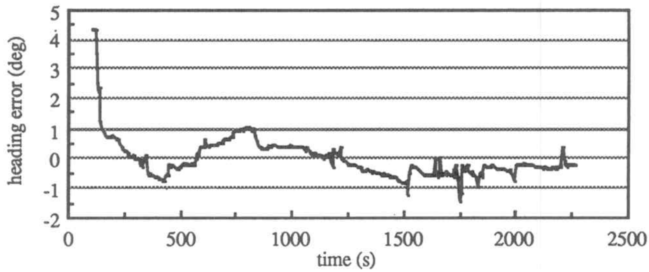
Attitude results for integration mode 1 are shown in Figure 5 and statistics are tabulated in Table 6. Note that the residual errors are clearly not white noise and that RMS-values should therefore be regarded with caution. The errors show that this solution is marginal for the intended applications. Heading accuracy meets specifications only after about 10-15 minutes of convergence time. The errors follow a rather erratic pattern and the poor heading resolution seems to affect the positioning accuracy in f and l. This is confirmed by results from integration mode 2, where the heading update of the GPS dual-antenna system has been used. The attitude errors are shown in Figure 6 and the summary statistics are given in Table 7. The reduction of the heading error goes hand in hand with a considerable improvement in all three coordinates. Results clearly show that the accuracy requirements of airborne resource mapping applications can be met by such a system.



a. Roll errors (deg.)



b. Pitch errors (deg.)



c. Heading errors (deg.)

Figure 5: Attitude Errors in Integration Mode 1.

Error	Mean Error	Maximum Error	RMS
latitude (m)	0.8	10.2	4.5
longitude (m)	-2.1	-8.0	3.5
height (m)	-2.5	-11.5	5.1
pitch (deg)	0.18	0.21	0.19
roll (deg)	0.07	0.32	0.09
heading (deg)	0.11	-2.3	0.66
(after convergence)	0.30	-1.4	0.40

Table 6: Attitude Errors in Integration Mode 1.

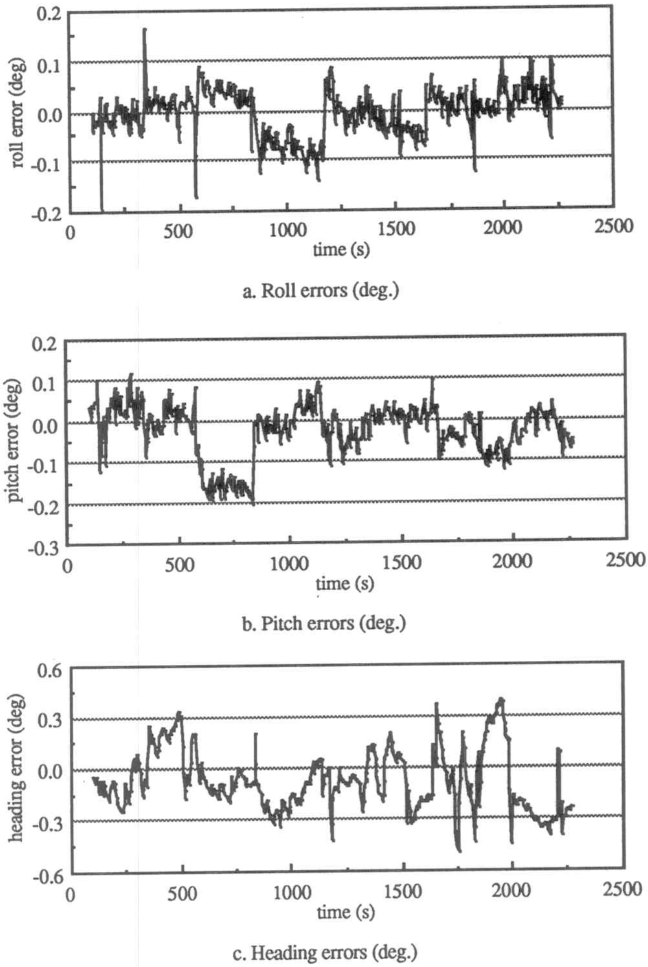


Figure 6: Attitude Errors in Integration Mode 2.

Error	Mean Error	Maximum Error	RMS
latitude (m)	0.08	1.8	0.85
longitude (m)	0.01	-1.1	0.46
height (m)	0.81	4.3	1.46
pitch (deg)	-0.03	0.11	0.07
roll (deg)	-0.01	-0.20	0.05
heading (deg)	0.08	-0.48	0.19

Table 7: Attitude Errors in Integration Mode 2.

5. CONCLUSIONS

Georeferencing of airborne imaging sensors will considerably extend current photogrammetric applications and will greatly simplify the use of digital imaging sensors. It will also add flexibility to the use of current high-precision aerial cameras and considerably reduce the need for accurate ground control.

The integration of inertial and GPS satellite techniques currently offers the best potential for implementing georeferencing systems at different levels of accuracy and for combining them with existing and future airborne imaging sensors. Major advantages are the high data rates of the inertial measuring unit, compactness which allows direct mounting on the sensor head, and uniform high accuracy due to continuous GPS updating.

Theoretical studies and tests results, analyzed in this paper, indicate that all accuracy requirements in position and attitude can be met by commercially available hardware components. Furthermore, costs can be considerably reduced by using low-cost inertial measuring units and customizing them to specific application areas. Test results show that the system accuracy achievable with a low-cost integrated INS/GPS is 0.1-0.2 degrees in attitude and 1-2 meters in position. It is therefore suitable for georeferencing airborne imaging sensors for mapping and resource applications with an accuracy that is compatible with current sensor accuracies.

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