An Integrated INS/GPS Approach to the Georeferencing of Remotely Sensed Data

Abstract

A general model for the georeferencing of remotely sensed data by an onboard positioning and orientation system is presented as a problem of rigid body motion. The determination of the six independent parameters of motion by discrete measurements from inertial and satellite systems is directly related to the problem of exterior orientation. The contribution of each measuring system to the determination of the three translational and three rotational parameters is treated in detail, with emphasis on the contribution of inertial navigation systems (INS) and single- and multi-antenna receivers of the Global Positioning System (GPS). The advantages of an integrated INS/GPS approach are briefly discussed. Positioning and orientation accuracies obtainable from available systems are then highlighted using selected results to emphasize significant points. The implementation of the general georeferencing concept is demonstrated by brief descriptions of a number of projects in which The University of Calgary group is currently involved. They include aerial photography applications, airborne tests with pushbroom imagers, motion compensation for SLAR systems, and the development of a mobile survey system for a road inventory GIS using digital frame cameras. The paper concludes with a brief discussion of some application areas which offer a high potential for future development.

Introduction

Aerial remote sensing has evolved from the exclusive use of film-based optical sensors to fully digital electro-optical and active electronic sensors with multispectral capabilities in many cases. These sensors can be roughly categorized as frame-based, as in the case of aerial cameras, or as line scanners (or pushbroom imagers), as represented by the MEIS system (Gibson *et al.*, 1983) or **casi** system (Babey and Anger, 1989).

Traditionally, frame imagery has relied on the process of visually or digitally correlating ground control points with their corresponding images for achieving georeferencing. This process, which involves the estimation of the position and attitude information for each exposure, has become commonly known as aerotriangulation. It is efficiently accomplished due to the stable geometric nature of frame-based imagery along with the use of ground control points (GCPs) of sufficient number, distribution, and accuracy. Unfortunately, the costs associated with the establishment of these GCPs has represented a significant portion of the aerotriangulation budget. In some cases, these costs can be prohibitive, especially when imagery is to be acquired and georeferenced in remote areas such as are found in many developing countries.

In the case of pushbroom imagery, the georeferencing problem is further complicated due to the need for the instantaneous position and attitude information at each line of imagery. Ground control alone is not sufficient to resolve all of the three position and three orientation (attitude) parameters associated with each exposure station, of which there may be thousands in a single mission. In order to overcome these problems, systems have been proposed whereby multiple look angles are simultaneously recorded with slight variations in alignment (Hofmann *et al.*, 1988).

Another approach has been through the use of auxiliary position and navigation sensors which have been simultaneously flown during imaging missions. Output of these sensors is used to determine the six parameters of exterior orientation, either completely or partially, and thus eliminate the need for dense ground control. This approach will be called onboard exterior orientation in the following. Such sensors have included statoscopes, laser profilers, stellar cameras, inertial navigation systems (INS), and Global Positioning System (GPS) receivers. Each of these systems has the potential to resolve all or a subset of the six parameters required for individual exposure stations. Only recently have two of these systems, namely INS and GPS, been fully integrated such that all six orientation parameters are determinable with sufficient accuracy at any instant of time.

Further problems are encountered when using multi-look side-looking radar (SLAR), for which aircraft velocity information is required in order to compensate for the finite time interval over which the image is generated. In this case, real-time motion compensation is needed which, from an operational point of view, puts a number of constraints on the model implementation. Velocity information is directly available from an integrated INS/GPS system which is proposed to be simultaneously flown onboard the remote sensing aircraft.

This paper discusses the underlying principles of onboard exterior orientation through the use of a fully integrated INS/GPS positioning and orientation system, highlights some of the results achieved, and outlines some future plans. The proposed method has demonstrated initial success and is being tested in an ongoing manner with various imaging sensor arrangements, including frame cameras, pushbroom scanners, and SLAR.

Remote Sensing with Onboard Exterior Orientation

Conceptually, the problem of exterior orientation can be reduced to defining the transformation between the sensor gen-

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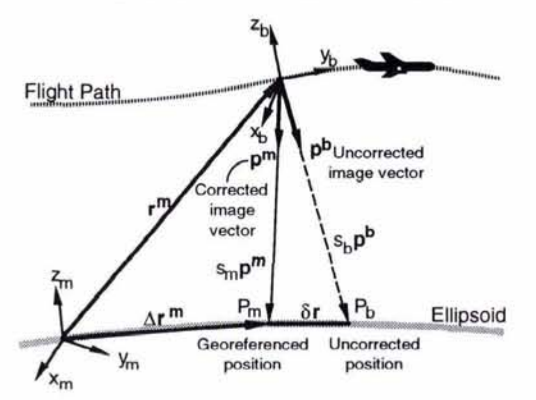

Figure 1. The relation between the mapping frame and the body frame.

erated images or records and the coordinate system in which the results are required. For convenience, the latter will be called the mapping frame and will be denoted by m. It can be a system of curvilinear geodetic coordinates (latitude, longitude, height), a system of UTM or 3TM coordinates, or any other conveniently chosen Earth-fixed reference system. In order to transform the sensor output to the mapping frame, three essential steps are necessary. First, the motion of the sensor frame with respect to the Earth-fixed mapping frame has to be determined. Second, the image coordinates have to be corrected for both the rotational and translational part of this motion. Third, the corrected image coordinates have to be transformed into the mapping frame. The total procedure is usually called georeferencing.

The concept of georeferencing is shown in Figure 1. The airborne sensor has a coordinate system assigned to it which changes position and orientation with respect to the mapping frame (m) as a function of time. The sensor frame is usually called body frame (b) and corresponds to the photo coordin ate frame in photogrammetry. If the sensor is rigidly mounted in the aircraft, the changes of the b-frame with respect to the m-frame will correspond to those of the aircraft. In general, small differential movements between aircraft frame and sensor frame can occur, however, and these have to be measured.

For simplicity, it will be assumed that the b-frame is defined such that forward motion defines the y_b-axis, sideward motion to the right of the forward motion, the x_b-axis, and upward motion, completing the three-dimensional Cartesian frame, the z_b-axis. Assuming that the mapping frame is a curvilinear geodetic coordinate system (latitude, longitude, height), then a local coordinate frame can be defined with x_m pointing east, y_m pointing north, and z_m pointing upward along the ellipsoidal normal. This frame is called the local-level or the local geodetic frame. In this frame pitch, roll, and yaw are defined as the three right-handed rotations which transform the m-axes into the corresponding b-axes. Using unit vectors $\mathbf{e}$, the transformation from the b-frame to the m-frame is of the form

$$\mathbf{e}^m = \mathbf{R}_b^m \, \mathbf{e}^b = \mathbf{R}_3(\kappa)\, \mathbf{R}_1(\omega)\, \mathbf{R}_2(\varphi)\, \mathbf{e}^b \tag{1}$$

where $\mathbf{R}_1$, $\mathbf{R}_2$, $\mathbf{R}_3$ are elementary rotations about the primary, secondary, and tertiary axes, respectively, and ω, φ, and κ stand for pitch, roll, and heading. The notational conventions used are the ones defined in Britting (1971). Vectors are denoted by lower case letters, matrices by upper case letters. Vector superscripts define the coordinate frame in which the vector elements are expressed. Matrix superscripts and subscripts indicate the direction of the rotation which is from subscript to superscript. Thus, $\mathbf{R}_m^b$ defines the rotation from the m-frame to the b-frame. The inverse rotation is simply given by an interchange of subscript and superscript. Thus, $\mathbf{R}_b^m$ is the inverse of $\mathbf{R}_m^b$. The analytical form of the rotation matrix $\mathbf{R}_b^m$ is

$$\mathbf{R}_b^m = \begin{pmatrix} \cos\kappa\cos\varphi - \sin\kappa\sin\omega\sin\varphi & -\sin\kappa\cos\omega & \cos\omega\sin\varphi + \sin\kappa\sin\omega\cos\varphi \\ \sin\kappa\cos\omega + \cos\kappa\sin\omega\sin\varphi & \cos\kappa\cos\omega & \sin\kappa\sin\varphi - \cos\kappa\sin\omega\cos\varphi \\ -\cos\kappa\sin\varphi & \sin\omega & \cos\omega\cos\varphi \end{pmatrix} \tag{2}$$

Note that these rotations correspond to the ones often used in photogrammetry if the frame conventions for b and m are the same. They express rotations from the system of ground coordinates to the system of photo coordinates at a point where the z-axis of the ground coordinate system coincides with the ellipsoidal normal. The main difference between the control coordinate system and the local geodetic system is that one is a planar, and the other an ellipsoidal approximation of the Earth's surface.

Georeferencing is possible if at any instant of time (t) the position of the perspective center of the camera or the scanner is given in coordinates of the m-frame, i.e., $\mathbf{r}_m$, and the rotation matrix $\mathbf{R}_b^m$ has been determined (see Figure 1). The georeferencing equation can then be written as

$$\Delta\mathbf{r}^m(t) = \mathbf{r}^m(t) + s_m \mathbf{R}_b^m(t)\, \mathbf{p}^b(t)\,, \tag{3}$$

where $\Delta\mathbf{r}^m$ is the position vector in the chosen mapping system, $\mathbf{r}^m$ is the position of the center of the remote sensing device, s_m is a scale factor derived from the height of the sensor above ground, and $\mathbf{p}^b$ is the vector between the projective center and an arbitrary point (x,y) in the image plane given in the b-frame. The vector $\mathbf{p}^b$ may be rotated into the m-frame as $\mathbf{p}^m$ and is then given by

$$\mathbf{p}^m = \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \mathbf{R}_b^m \begin{pmatrix} x \\ y \\ -f \end{pmatrix} = \mathbf{R}_b^m \mathbf{p}^b \tag{4}$$

where (x,y) are the image coordinates in the b-frame and f is the sensor focal length, while (x',y',z') are coordinates of the image vector transformed to the mapping frame. For a line scanner, y would be the pixel displacement along the scan line and x would be zero. A more detailed discussion of line scanning georeferencing is given in Cosandier et al. (1992).

Equation 3 is the simplest form of the georeferencing equation. It relates points in the image plane to points on the ground, using the defined mapping frame. It implies that the coordinates of the projective center of the imaging sensor can be directly determined. This is usually not the case because the positioning equipment—GPS antenna or INS system—is physically displaced from the imaging sensor. If the vector between any two centers (e.g., GPS and imaging sensor) is given in the body frame as $\mathbf{a}^b$, Equation 3 can be augmented in the following way:

$$\Delta\mathbf{r}^m(\mathrm{t}) = \mathbf{r}^m(\mathrm{t}) + \mathbf{R}_b^m(t)\,(s_m \cdot \mathbf{p}^b - \mathbf{a}^b) \tag{5}$$

The vector $\mathbf{a}^b$ can be determined by measurement before the start of the mission.

Similarly, the orientation sensor (e.g., INS) may not be completely aligned with the aircraft-fixed imaging sensor. This will introduce a constant misorientation $d\mathbf{R}$ into the rotation matrix and will result in an error in the georeferenced position. Equation 5 then takes the form

$$\Delta \mathbf{r}^m(t) = \mathbf{r}^m(t) + (\mathbf{R}_b^m(t) \cdot d\mathbf{R})\,(s_m \cdot \mathbf{p}^b - \mathbf{a}^b) \qquad (6)$$

A convenient way to eliminate this error is by flying the system over a test field with precisely coordinated points for purposes of calibration. If the flight area contains ground control of sufficient accuracy, this calibration can also be done during the mission. Due to the inaccuracies in the alignment of both the INS and GPS multi-antenna systems, a misorientation can always be expected and precautions must be taken to eliminate it.

Time-variable rotations between the imaging sensor and the orientation sensor can be caused by differential vibration behavior at the two sensor locations, as for instance by wing flutter in case of a wing-tip mounted GPS multi-antenna system. In some cases, they can be measured by additional sensors. In other cases, they may be avoidable by taking vibration behavior into account during sensor installation.

The scale factor s^m in Equations 3, 5, and 6 can be derived from the flying altitude of the aircraft above ground. Variations in topography further complicate the estimation of scale factors. They can be eliminated by incorporating a terrain model or by applying photogrammetric stereo techniques.

Comparing onboard georeferencing to the standard approach of georeferencing by ground control, some obvious differences become apparent. While onboard georeferencing allows a clear separation and, thus, determination of the different influences, this is not the case when using georeferencing by ground control. The only information available in the latter case are the coordinate differences **dr** between ground control points and sensor-derived coordinates (see Figure 1). These differences are the result of aircraft motion, sensor offsets, and misorientation. Usually, an approximate interpolation method is used to model the effects of aircraft motion on the derived coordinates from the se differences. From a modeling point of view, the method has the major drawback in that it tries to solve a spatial problem from what is essentially two-dimensional information.

Modeling Rigid Body Motion by Measurement

Georeferencing requires the determination of $\mathbf{r}^m$ and $\mathbf{R}_b^m$ as time dependent functions from discrete measurements. If the sensor can be considered as a rigid body, the problem of onboard exterior orientation is equivalent to finding the six parameters of rigid body motion, i.e. three translations and three rotations. Because this has to be done utilizing discrete measurements, modeling, estimation, and interpolation have to be combined to accomplish the task. Modeling relates the observables to the required parameters. Estimation uses actual observations to determine these parameters, i.e., it adds an error process to the model, and solves the resulting estimation problem in some optimal sense. Interpolation connects the discrete points resulting from the estimation process and generates a trajectory by formulating some appropriate smoothness conditions.

The two types of measuring systems that will be considered for this task are strapdown inertial measuring units (IMU) and differential GPS positioning and orientation systems. A strapdown IMU outputs three components of the specific force vector and three components of the angular velocity vector in the body frame system. They will be denoted by $\mathbf{f}^b$ and $\boldsymbol{\omega}_{ib}^b$, respectively, in the following. The subscripts of the angular velocity vector indicate the direction of the rotation, the superscript the frame in which the vector is expressed. In this case, the *b*-frame is rotating with respect to the *i*-frame, and the vector is coordinated in the *b*-frame. The *i*-frame is a properly defined inertial reference frame in the Newtonian sense, and thus can be considered as being non-accelerating and non-rotating. Specific force and angular velocities can be used to determine all parameters required for georeferencing by solving the following system of differential equations (see Schwarz and Wei (1990)):

$$\begin{pmatrix} \dot{\mathbf{r}}^m \\ \dot{\mathbf{v}}^m \\ \dot{\mathbf{R}}_b^m \end{pmatrix} = \begin{pmatrix} \mathbf{D}^{-1}\mathbf{v}^m \\ \mathbf{R}_b^m\mathbf{f}^b - (2\boldsymbol{\Omega}_{ie}^m + \boldsymbol{\Omega}_{em}^m)\mathbf{v}^m + \mathbf{g}^m \\ \mathbf{R}_b^m(\boldsymbol{\Omega}_{ib}^b - \boldsymbol{\Omega}_{im}^b) \end{pmatrix} \qquad (7)$$

The vector on the left hand side has nine components, three for position $\mathbf{r}^m$, three for velocity $\mathbf{v}^m$, and three for orientation $\mathbf{R}_b^m$. It describes the changes of these components with time. By solving this system of equations, most information necessary for the solution of the georeferencing problem can be obtained.

To solve the system, the observables $\mathbf{f}^b$ and $\boldsymbol{\omega}_{ib}^b$ are needed as well as the scaling matrix **D**, the gravity vector $\mathbf{g}^m$, the Earth rotation rate $\boldsymbol{\omega}_{ie}^m$, and the dimensions of the implied reference ellipsoid. The observables can be identified on the right-hand side of the equation, where the angular velocity vector is contained in $\boldsymbol{\Omega}_{ib}^b$ which is a skew-symmetric matrix of the vector elements. It is also used to determine $\mathbf{R}_b^m$ by integration. The gravity vector can be approximated by the so-called normal gravity model, while the Earth rotation is known with sufficient accuracy. The scaling matrix **D** and the additional angular velocities are obtained in the integration process using the dimensions of the implied reference ellipsoid. It is possible to use other mapping frames besides the local geodetic frame (for details, see Wei and Schwarz (1990)). As can be seen from the second set of equations, rotational and translational parameters are needed to integrate the velocity equations. Because position is obtained by a direct integration of velocity, the position and rotation parameters are interrelated.

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. To facilitate comparison with the INS model, the GPS-trajectory equations will not be expressed in terms of the original observables but in terms of position and velocity which can be considered as GPS pseudo-observables. The trajectory model is then of the form

$$\begin{pmatrix} \dot{\mathbf{r}}^m \\ \dot{\mathbf{v}}^m \end{pmatrix} = \begin{pmatrix} \mathbf{v}^m \\ 0 \end{pmatrix} \qquad (8)$$

which can be used for pseudorange measurements with a single receiver or for differential pseudorange or carrier phase measurements for a pair of receivers. The use of differential carrier phase data will be assumed in the following discussions.

In principle, the first set of equations in Equation 8 would be sufficient to model the translation vector $\mathbf{r}^m$ using carrier phase observables if constant velocity between updates can be assumed. However, experiments have shown that the observation of phase rates improves the estimation process and that, therefore, the model (Equation 8) is more appropriate. It assumes constant acceleration between measurement epochs. This assumption is certainly justified for

TABLE 1. AIRCRAFT KINEMATIC RESULTS (AFTER CANNON ET AL., 1992)

Monitors	Coord	Position			Velocity		
		Mean (cm)	RMS (cm)	Std dev (cm)	Direct	Mean (cm/s)	RMS (cm/s)
Metcalfe-	φ	9.1	11.3	6.7	north	0.0	0.8
Mallorytown	λ	10.5	11.5	4.7	east	0.0	0.6
(100 km)	h	0.4	17.6	17.6	height	0.0	1.8
Metcalfe-	φ	−49.8	60.8	34.9	north	0.0	0.8
Telescope	λ	5.3	10.9	9.5	east	0.0	0.5
(218 km)	h	22.2	46.0	40.3	height	0.0	1.7
Mallorytown-	φ	−58.9	70.0	37.8	north	0.0	0.8
Telescope	λ	−5.3	11.9	10.7	east	0.0	0.5
(239 km)	h	21.8	53.4	48.7	height	0.0	1.7

the high internal data rates of GPS receivers. In cases where the output data rate is used for trajectory interpolation, other models may be more appropriate (see, for instance, Schwarz *et al.* (1989)).

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. Two antennas on the aircraft will give such a vector but will not allow the resolution of rotational motion about all three axes, i.e., the determination of $\mathbf{R}_b^m(t)$ will not be possible. Three body-mounted antennas, preferably orthogonal to one another, are the minimum requirement for the determination of $\mathbf{R}_b^m(t)$. The resulting state equations are then of the form

$$\begin{pmatrix} \dot{\mathbf{r}}^m \\ \dot{\mathbf{v}}^m \\ \dot{\mathbf{R}}_b^m \end{pmatrix} = \begin{pmatrix} \mathbf{v}^m \\ 0 \\ \mathbf{R}_b^m \mathbf{\Omega}_{mb}^b \end{pmatrix} \quad (9)$$

where the angular velocities in the body frame are obtained by differencing between antennas, satellites, and epochs. The distance between antennas must be considered as constant and accurately known, and a proper initialization of the $\mathbf{R}_b^m$ matrix is required while the system is stationary. In some cases, it may be appropriate to add another set of equations to this system, similar to the second set of equations. This would constrain the angular velocities to be constant between measurement epochs. Note that both trajectory models resolve the translational parameters by differencing between the ground station receiver and the moving receiver, while the rotational parameters in Equation 9 are resolved by differencing between the moving antennas only. Thus, the determination of the two parameter sets is independent.

The formulation of a state vector model has the advantage that standard methods are available to estimate $\mathbf{r}^m$ and $\mathbf{R}_b^m$ directly as functions of time. While this is a natural way of solving the problem with INS observables, their use with GPS observables is not so obvious. In the latter case, the system outputs position and velocity directly. Thus, the trajectory could be determined by estimating a sequence of positions and associated velocity vectors from the GPS observations and by fitting a curve through them. If the measurement statistics are properly taken into account, this will result in an acceptable solution. The advantage of using a state vector model lies in the possibility to impose smoothness conditions on the solution by the definition of covariances for the state vector elements and spectral densities. From a conceptual point of view, the state vector model offers a convenient way to discuss and implement GPS/INS integration (see Wei and Schwarz (1989) and (1990)).

GPS and INS are in many ways complementary systems for accurate positioning and attitude determination. 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 they resolve the problem of systematic error growth in the INS trajectory. On the other hand, INS measurements are very accurate in the short term and can thus be used to detect and eliminate cycle slips. Because of the high data rate, they provide a much smoother interpolation than GPS. They also give the rotation matrix $\mathbf{R}_b^m$ with high accuracy. Integration utilizing a Kalman filter seems thus to be appropriate, using INS for the basic integration and GPS for the updating. For a more detailed discussion, see Schwarz (1992).

Accuracies Achievable with Current Inertial and Satellite Hardware

The determination of position, attitude, and velocity is possible with either GPS or INS, or with an integrated system making use of the complementary features of the two devices. In this section, a brief discussion of the accuracies achievable with current hardware will be given. In some cases, it will not be possible to compare GPS or INS results to control data of superior accuracy because these data are simply not available. In other words, the accuracy of the two systems is such that kinematic control values of equal or superior accuracy cannot be obtained without extremely high costs. In those cases, results of repeatability and consistency checks will be employed. Results will be given separately for position $\mathbf{r}^m$, attitude $\mathbf{R}_b^m$, and velocity $\mathbf{v}^m$.

For precise position determination, differential GPS is clearly the primary method. The accuracy of the results using single frequency GPS hardware in airborne applications are a function of the separation between the ground monitor GPS receiver and the aircraft. One of the difficulties in assessing the accuracy of GPS positions is the ability to provide an independent check. In general, two methods can be used: first, an internal consistency check in which the aircraft's trajectory can be compared through the use of more than one ground monitor station, and second, through the use of large-scale photogrammetry with ground control which provides accurate coordinates of the perspective center at times of exposure. Although the second method is preferred because it is independent, it is also significantly more expensive.

A GPS internal consistency test described in Cannon *et al.* (1992) utilized three ground monitor stations separated by distances between 100 and 200 km. In this case, the aircraft trajectory was determined from each of these monitor stations using differential carrier phase processing techniques. Table 1 shows the results for the three separate combinations. As can be seen, the agreement (characterized by standard deviation) of the trajectories generated from the Metcalfe and Mallorytown stations is within 20 cm, while the agreement for the other two cases is within 50 cm. Noting that the separation between the Telescope station and the other two stations was over 200 km, a degradation in agreement can be expected when using this monitor station.

Figure 2 shows a plot of the differences between the heights determined from the Metcalfe and Mallorytown monitor stations. The agreement clearly changes with time which, in general, is a function of the monitor-aircraft separation.

The development of new GPS technology which provides dual frequency carrier phase data (e.g., P codeless receivers)

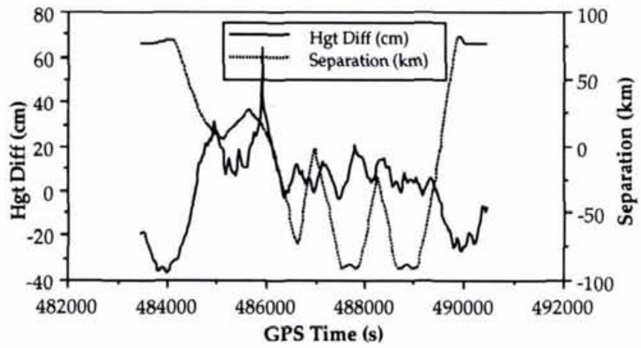

Figure 2. Height differences between aircraft solutions from Metcalfe and Mallorytown.

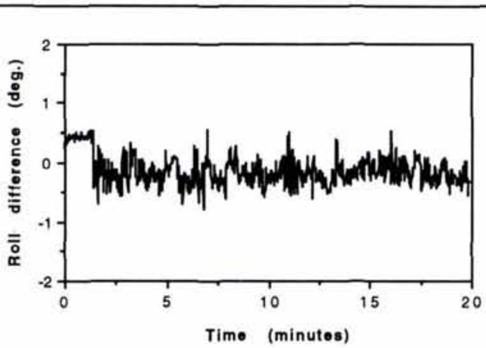

Figure 3. Error in roll for multi-antenna system.

will increase the performance of GPS for airborne surveys. This performance will be improved by the ability to correct for effects from the ionosphere and to use widelaning (e.g., Abidin, 1991). These two factors will improve the reliability of the results and will extend the range at which high accuracy positions can be achieved.

The use of INS for positioning in these applications will usually be restricted to interpolation and cycle slip detection. Inertial systems combine very high short-term accuracy and high data rates (50 Hz and higher), and, thus, are ideally suited for this task. They can provide measured position information for each individual scan line. Because their long-term error behavior is characterized by large position errors, regular updating by GPS is needed to maintain long-term accuracy. Thus, an integrated INS/GPS is the best solution to satisfy all requirements. It also offers an independent check on cycle slips, which have to be eliminated in order to achieve the positioning accuracy quoted above.

For attitude determination, INS is the primary system. In terms of long-term performance, the basic limitation of a high precision inertial system is the drift rate which is the one error source that grows unbounded. Typical values for the drift rate are 0.01 degree per hour, although systems with considerably smaller drift rates are available. Short-term accuracy is much better and is mainly affected by gyro noise and, in some cases, by vibrational effects from the aircraft. Bench tests indicate that integrated gyro noise affects orientation accuracy at the level of 10 to 30 arcseconds. It has not been possible, however, to confirm such accuracies under flight conditions (see Cannon (1991) for some of the problems encountered).

During the last few years, GPS multi-antenna systems have been studied as an alternative for attitude dete rmination. In this case, changes in the orientation matrix $\mathbf{R}_b^m$ are directly determined from changes in the GPS data between a fixed cluster of GPS antennas connected to a common receiver (for details, see Cohen and Parkinson (1991)). The accuracy of orientation determination is largely dependent on the distance between antennas and on the magnitude of multipath in the measurements. Figure 3 shows the results of a kinematic test for roll in which a high accuracy inertial system was used to provide the independent control data. The RMS error is about 0.3 degrees for a baseline of about 1.7 m in length. Results for the other two axes are similar. A detailed analysis of the results indicated that the GPS noise may actually be smaller and that part of the error may be due to differential vibrations (for details, see Schwarz *et al.* (1992)). Comparable accuracies have been reported by Lu *et al.* (1993). In most cases, remote sensing applications would require a higher short-term orientation accuracy than currently provided by GPS multi-antenna systems. They may be useful, however, on very long missions to bound gyro drift in inertial systems. Remaining concerns are differential rotations between the imaging sensor and the GPS orientation system because the latter will usually have to be mounted on the fuselage and the wings of the aircraft.

Precise velocity is primarily needed for motion compensation in side-looking radar. In this case, short-term stability is of utmost importance while long-term stability has a somewhat lower priority. The geometrical distortions resulting from long-term velocity biases are usually corrected by using position information in post-mission mode. In general, velocity information from INS is used in the real-time correction process because of its smooth short-term behavior and the slow changing long-term biases which are dominated by the Schuler period of 84 minutes. Typical results are shown in Figure 4. It represents two minutes of data several hours into the flight. Note the small variations of the velocity data in northing (vn) and easting (ve) around the slope generated by Schuler-type errors. For motion compensation, the smoothness of the curve is essential while the slope can be eliminated in post mission.

The accuracy of velocity derived from GPS is a function of the mode in which the data is processed, i.e., single point versus differential. For the case that Selective Availability (SA) is off, accuracies of a few cm/s can be achieved for periods of up to an hour. Figure 5 shows typical vertical velocity

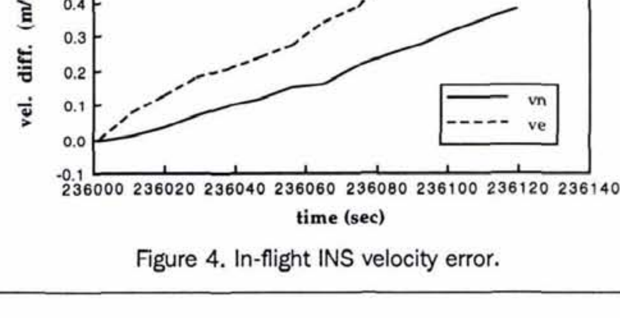

Figure 4. In-flight INS velocity error.

errors from single point positioning with SA off. Although the high frequency noise is higher than for the INS, there is virtually no bias in the data. Such data would, therefore, be excellent to eliminate geometrical corrections in real time. With adequate smoothing, they could also be used for sensor pointing, especially when combined with the INS data.

When SA is on, the achievable velocity accuracy is significantly degraded due to the satellite clock dither. In this case, the velocity error displays a sinusoidal error with amplitudes that may reach upwards of 50 cm/s, as shown in Figure 6. Because SA can be expected to be turned on indefinitely, differential techniques must be used to regain the level of accuracy that was achieved prior to SA. Referring to the airborne results given in Table 1, velocities derived from differential processing using various monitor stations agreed within a few cm/s. This is the typical accuracy that can be expected with good satellite geometry.

Updating INS velocity by SA-affected single receiver velocity may be an option in very long missions to reduce the bias in the INS velocity results. Care has to be taken, however, that the short-term accuracy is not affected by the update process. Another problem might be a more rapidly changing pattern of geometrical corrections. The use of differential methods would eliminate this problem. Because a real-time data link is needed in this case, the total system will be more complex and may thus be less acceptable from an operational point of view.

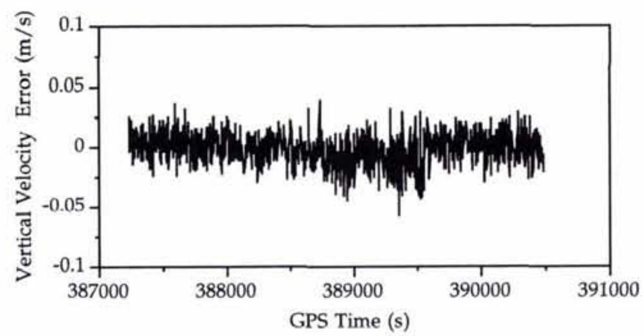

Figure 5. Single point velocity errors using land data with Selective Availability off.

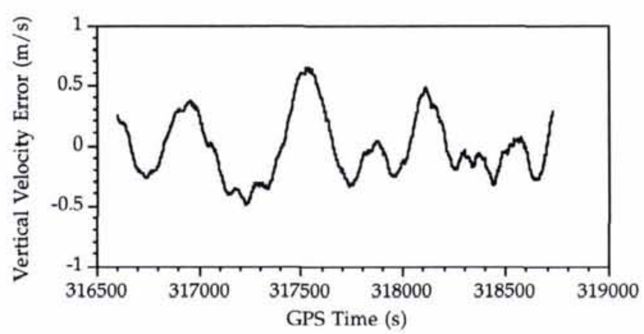

Figure 6. Single point velocity errors using land data with Selective Availability on.

Projects in Progress

The general concept of onboard exterior orientation using INS/GPS has been tested by The University of Calgary group in a number of different applications. Some of the ongoing projects will be briefly described in the following. First test flights were done as early as 1988. Others are in the planning stage right now and will be flown in the spring and summer of 1993. These test flights have been possible due to the established working relationships with local private companies, federal government agencies, and foreign universities. While preliminary results have been promising, it is expected that more meaningful data will be generated during the upcoming missions.

Large Scale Photogrammetric Tests for Assessment of Navigation Components

Cooperative research has been done between the UofC and the University of the Federal Armed Forces in Munich, Germany in which large scale photogrammetric tests were conducted over an open-pit mine near Cologne in the summer of 1988. This particular area has extensive accurate ground control which was used to generate accurate exterior orientation information of the camera at times of exposure. Positioning information generated from DGPS/INS was then compared to these "kinematic check points" and an agreement of 10 to 15 cm was obtained. The attitude component could not be fully analyzed in this case due to an offset between the INS and camera which caused relative motion between the two systems. Further results from this test are reported in Baustert *et al.* (1989) and Cannon (1991).

A recent test jointly conducted by the UofC and the Institute for Photogrammetry at Stuttgart University was designed to assess the capability of multi-antenna GPS technology for precise attitude determination. The UofC's Ashtech 3DF system was installed on the aircraft with two antennas mounted on the fuselage and two antennas on the wings. Accurate attitude information derived from the aerotriangulation will be used to compare with the GPS-determined attitude. This test was conducted in the fall of 1992 and results will be available in summer, 1993.

Calgary Flights with casi

Over the past several years, cooperative research has been pursued by Itres Research Ltd., Calgary and the Department of Geomatics Engineering at The University of Calgary (UofC). In the fall of 1992, this led to a test flight over the City of Calgary during which several positioning and navigation sensors were employed in conjunction with the **casi** system (see Cosandier *et al.* (1993)). The positioning and navigation systems consisted of a dual axis vertical gyroscope (Sperry VG-14A) which was supplied by Itres Research Ltd. and an integrated GPS (Ashtech) and strapdown inertial system (LTN-90) which was furnished by the UofC. The vertical gyroscope has a reported long term accuracy of 0.25° and short term accuracies (scan line to scan line) of 0.07°. The strapdown inertial system has verified drift rates on the order of 0.02° per hour. Due to a hardware problem, only a short span of usable data was acquired during the fall test flight. A second flight using the above mentioned sensor configuration was flown at the writing of this paper. Initial indications suggest that the data are quite reliable, and the results will be reported in the summer of 1993.

Test Flights with MEIS/CCRS

Since the inception of the Department, a strong research relationship has existed with the Data Acquisition Division of the Canada Centre for Remote Sensing (CCRS) in Ottawa. The original cooperative test flights were flown over Kananaskis, Alberta in the summer of 1983. The onboard sensors included an INS (LTN-52), an airborne laser profiler, a film-based aerial camera (Wild RC-10), and the MEIS system (Thyer *et al.*, 1989a; 1989b). While these initial tests produced reasonable ground coordinate results, the absence of airborne GPS data prohibited the evaluation of the accuracy of the absolute position of the exposure stations. Many other flights have been flown by CCRS using the aforementioned system configuration, and recently these have been enhanced with the inclusion of GPS receivers (Gibson and Chapman, 1987).

Another set of test flights is planned by CCRS for the spring of 1993 during which the UofCs integrated GPS and strapdown inertial system will be included. These proposed test flights will take place over the National Research Council's test range near Sudbury, Ontario. Several hundred precisely located GCPs are located in this test range, making it ideally suited for evaluating the performance of the airborne positioning and attitude systems. The positioning and attitude data will be processed along with the MEIS data using a specially developed photogrammetric bundle adjustment (see Cosandier and Chapman (1993) and Chapman and Tam (1989)).

Motion Compensation for Intera's STAR-1 System.

A recent involvement is the development of real-time software for precise velocity estimation to be used in the motion compensation algorithms for the STAR-1 system (see Mercer *et al.* (1986) for a description of the system concept). The work is done under contract to Intera Information Technologies Corporation. The overall objective is to extract low-noise velocity information for motion compensation and at the same time minimize the long-term geometrical distortions. Initial airborne tests have shown that the short-term accuracy can be achieved by INS alone. Current investigations therefore concentrate on the use of GPS to eliminate the long-term distortions generated by Schuler-type oscillations of the INS errors. From an operational point of view, the use of a single onboard receiver is preferable. In such a case, the GPS-derived velocity is severely degraded when Selective Availability (SA) is on. Although it is still useful in removing INS velocity biases on long missions, the geometrical distortions would in that case change more rapidly because the SA-induced clock dither typically has periods of 15 to 20 minutes compared to the Schuler period of 84 minutes. Special filtering techniques are currently under investigation to dampen the Schuler amplitudes without destroying the smoothness of the error curves. Alternatively, differential carrier phase methods could be used. They would provide superior accuracy (see Figure 5) and would eliminate geometrical distortions almost completely. The price to be paid is a more complex system and additional delay problems due to the real-time data link. Both ideas will be implemented and tested in the summer of 1993.

Development of a Mobile Survey System for a Road Inventory GIS.

This application differs from the previous ones because it does not use an airborne carrier for the integrated system. It shows, however, the flexibility of the georeferencing approach discussed in this paper and will, therefore, be briefly presented. Work on this project started in 1988/1989 under contract to Alberta Transportation. The objective was to provide their mobile video-logging system with a precise positioning and orientation component. This objective was achieved, resulting in positioning accuracies of the integrated INS/GPS of about 10 to 15 cm (see Schwarz *et al.* (1990) for details). However, the video information of this system was not fully integrated with the positioning and attitude information. In 1992, the concept was expanded to a fully integrated INS/GPS/CCD Camera System, to be used as a mobile survey system, capable of locating every detail in a road corridor of 50 m with an accuracy of better than 30 cm. The high accuracy distinguishes this system from others that are currently on the market. The development of the system , which will carry the trade name VISAT, is funded by a contract from Geofit Inc. A prototype system will be tested in the fall of 1993 and the operational system will be delivered a year later. Recently, a similar system for such an application has been reported by Bossler and Novak (1993).

Future Applications Considerations

The initial driving force behind the development of airborne positioning and orientation systems was the desire to minimize the often prohibitive costs associated with the establishment of ground control points. In particular, the ground breaking work was directed towards the support of traditional topographic mapping operations where aerial film-based cameras have been employed. By addressing this particular problem, the most stringent accuracy requirements were confronted head-on because the resolution of aerial photography is still unrivaled by even the most sophisticated of digital imaging systems which are commercially available. However, it is evident that the resolution gap between these two technologies is rapidly closing.

As a result of the multidisciplinary approach to this research initiative, it became readily apparent that image resolutions and, therefore, position and orientation requirements were quite varied. The required accuracies ranged from a few centimetres to the metre level in position and a few arcseconds to several arcminutes in orientation. With these aspects in mind, it became progressively apparent that a variety of applications would conveniently lend themselves to these innovations. A few of these possibilities currently under investigation and foreseen in the near future are presented in the sequel.

In the case of forest inventory assessment, parameters such as tree diameter, height, volume, and species composition require the use of a multispectral imager which gives the necessary spatial and spectral resolutions. Such sensors will progressively require higher accuracy requirements in terms of airborne positioning and orientation sensors. Airborne sensors such as SLAR for lineament detection have lower positional and orientation demands but require velocity data for the correction of multi-look data. Multispectral sensors will also find increased application as a result of the current emphasis put on environmental monitoring and impact assessment. These applications will require the use of multiple sensors in order to acquire sufficient data. The georeferencing problem associated with integrating these disparate image types will impose relatively stringent accuracy requirements. This will eventually lead to real-time mapping needs for change detection such as currently required in right-of-way monitoring (Chapman, 1989).

The promising results of these investigations will undoubtedly lead to the transfer of the technology to other application areas. In particular, some of the road vehicle inventory systems under development will incorporate integrated INS/GPS systems in support of imaging sensors (e.g., CCD cameras). A parallel development is also occurring in the commercial and personal automobile industry where vehicle navigation has already recognized the merit of GPS and

INS technologies. These and other possibilities will become more attractive as the associated hardware costs are reduced.

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Errata

The name of William R. Straw was omitted from the list of Active Certified Photogrammetrists published in the September issue of *PE&RS*.

ASPRS regrets the error.