'Photogrammetric Week '97' D. Fritsch & D. Hobbie, Eds., Wichmann Verlag, Heidelberg, 1997.

GPS/INS Integration

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ABSTRACT

One of the major tasks in the evaluation process of remotely sensed data is the determination of the exterior orientation to relate the recorded data to a geodetic reference coordinate frame. This process is called georeferencing and is very close to the concept of inverse photogrammetry realized indirect via the use of ground control. With the availability of the Global Positioning System GPS and the decreasing costs of inertial navigation systems (INS) the direct measurement of the position and attitude parameters of the sensor stations during the time of exposure becomes feasible. Hence, the exterior orientation is independent of any ground control today. After a brief discussion of the mathematical model for georeferencing this paper will focus on the different approaches for direct georeferencing using integrated GPS/INS systems. Due to the complexity of this topic, only the basic facts without detailed description of the mathematical background are discussed. To motivate the integration approach, the major characteristics of the GPS and INS as stand-alone units are described and their complementary error behaviour is pointed out. Then the different levels of integration are given. Finally, the high potential of GPS/INS integrated systems is demonstrated reviewing the results of two airborne tests.

1. INTRODUCTION

In the process of georeferencing sensor or object data are related to a regional or global geodetic reference coordinate system. Therefore, this process is quite similar to the in airborne photogrammetry well known determination of the six parameters of exterior orientation of image data (Position X_0, Y_0, Z_0, Attitude ω, φ, κ). The mathematical formulation for the transformation of the sensor or image coordinate system p to the geodetic mapping frame m is given in Equation 1.

$$\begin{pmatrix} X_p \\ Y_p \\ Z_p \end{pmatrix}_m = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}_m + \alpha \, \boldsymbol{R_p^m} \begin{pmatrix} x_p \\ y_p \\ -f \end{pmatrix}_p \tag{1}$$

The point coordinates in the reference system (X_p, Y_p, Z_p) are functions of the six parameters of exterior orientation ($X_0, Y_0, Z_0, \omega, \varphi, \kappa$), the coordinates in the imaging sensor frame x_p, y_p, the focal length of the sensor f and a scale factor α. $\boldsymbol{R_p^m}$ as a function of the three attitudes ω, φ, κ is the three-dimensional transformation matrix which rotates the sensor frame into the geodetic mapping frame. Resolving this equation for the sensor coordinates, the collinearity equations are obtained.

Traditionally, in aerial photogrammetry the exterior orientation is determined using the indirect approach of inverse photogrammetry. Assuming a perspective projection the image coordinates of known control points are measured and related to the ground. Neighbouring images are connected via tie points. This process is highly accurate, but the evaluation of the images is time consuming and additionally the determination of ground control is costly and might be impossible in remote areas. In case of digital imagery (e.g. 3 line CCD images), parameters of exterior orientation are required for each scan line. Utilizing the indirect method to this problem is impossible due to the very large numbers of required ground control points.

Therefore, alternative approaches for georeferencing have been tested since many years to determine the exterior orientation or a subset of these six parameters directly, during the time of data recording. The success and the acceptance was limited due to the insufficient accuracy or high financial demands but with the advent of the global satellite positioning system GPS and the decreasing costs of inertial sensor technology this situation changes tremendously. Meanwhile, the accuracy of GPS positioning in photogrammetry is proved and accepted in practice (e. g. Ackermann & Schade, 1993). For the direct determination of the complete exterior orientation a combination of GPS and INS in an integrated system is normally used. The high potential of the direct approach using GPS/INS for georeferencing is shown several times (e.g. Škaloud et al., 1996).

$$\begin{pmatrix} X_p \\ Y_p \\ Z_p \end{pmatrix}_m = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}_m + \boldsymbol{R_b}^{\boldsymbol{m}} \begin{pmatrix} dx \\ dy \\ dz \end{pmatrix}_b + \alpha \; \boldsymbol{R_b}^{\boldsymbol{m}} \, d\boldsymbol{R_p}^{\boldsymbol{b}} \begin{pmatrix} x_p \\ y_p \\ -f \end{pmatrix}_p \qquad (2)$$

Assuming an integrated system to determine the position and attitude of an imaging sensor (e.g. aerial camera) directly, Equation 1 has to be modified in the following way (Equation 2): Since normally the positioning sensor (GPS antenna) and the attitude device (INS) are physically shifted from the imaging sensor a constant displacement vector $d\boldsymbol{r} = (dx, dy, dz)_b^T$ given in the body system has to be added to the GPS/INS position X_0, Y_0, Z_0 to obtain the position of the camera perspective centre in the mapping reference frame. The body system b is defined by the sensor axes of the INS. Similarly, a constant misorientation matrix $d\boldsymbol{R_p}^{\boldsymbol{b}} = f\,(\delta\omega, \delta\varphi, \delta\kappa)$ exists between the body frame and the imaging sensor. This offset has to be taken into account to obtain correct orientation parameters of the camera perspective centre because the determined attitudes ω, φ, κ in the $\boldsymbol{R_b}^m = f\,(\omega, \varphi, \kappa)$ matrix from GPS/INS describe the transformation from the body frame system to the mapping frame and not from the imaging sensor frame to the mapping frame. Finally, the measurements of the integrated system are interpolated on the exposure times of the imaging sensor to overcome the time offset between the different sensors. With known displacement dx, dy, dz - measured with standard surveying techniques - and misorientation $\delta\omega$, $\delta\varphi$, $\delta\kappa$ - obtained for example from in-flight alignment (Škaloud et al., 1994) - and utilizing the direct determined exterior orientation from the integrated positioning and attitude sensors (GPS/INS) the image coordinate frame is related to the mapping frame without any additional ground control. The reliability aspect of georeferencing without ground control is discussed in Ackermann (1997).

2. THE GLOBAL POSITIONING SYSTEM

In the beginning of 1994 the GPS system was declared operational and now it provides data of high absolute and consistent accuracy. The system is based on range measurements of radio signals transmitted by the GPS satellites revolving the earth and received by the GPS receivers of the individual users. Utilizing these signals three dimensional positioning, velocity and - using a special multi-antenna GPS receiver or a combination of several GPS receivers - attitude informations can be obtained all over the world at any time of the day. The basic observables are the pseudoranges p and the carrier phases Φ. Their observation equations are well known and given in Equations 3 and 4 (e.g. Wells et al., 1986).

$$p = \rho + c\,(dt - dT) + d_\rho + d_{ion} + d_{trop} + \epsilon_p \qquad (3)$$

$$\Phi = \rho + c\,(dt - dT) + \lambda N + d_\rho - d_{ion} + d_{trop} + \epsilon_\Phi \qquad (4)$$

The pseudorange is the time difference between the transmission time of the signal at the satellite and the receiving time at the GPS receiver. Multiplying the measured time with the speed of light the range between satellite and user in [m] can be obtained. Due to the non-synchronization between satellite and receiver clocks this distance is called pseudorange. The three unknown receiver position parameters and the clock offset are solved by measuring at least four pseudoranges to different satellites

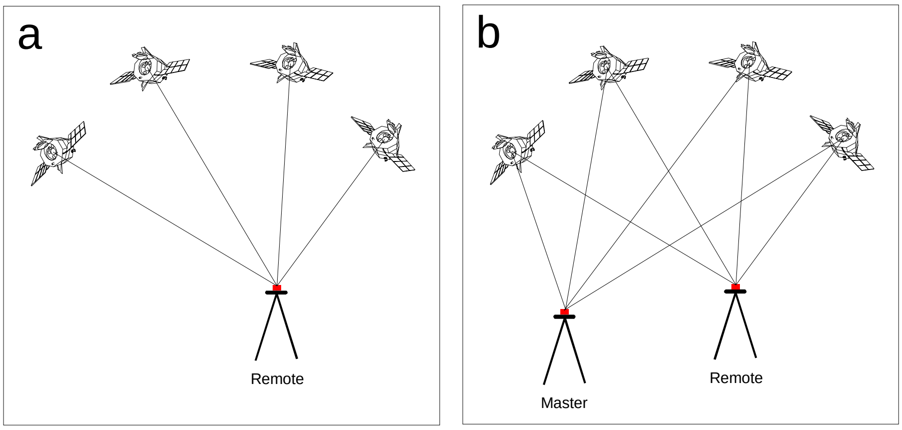

Figure 1: Principle of GPS positioning (a) absolut, (b) differential.

simultaneously. Hence, the receiver position and the clock error are estimated from the four observations. This absolute GPS positioning is shown in Figure 1a. To obtain correct results, the remaining error terms describing the satellite position error d_{ρ}, the ionospheric and tropospheric refraction error d_{ion}, d_{trop} and the satellite and receiver clock error dt, dT in Equation 1 have to be modelled. Alternatively, the errors can be eliminated or at least reduced significantly using a differential approach for processing.

The carrier phase is obtained by measuring the delay between the Doppler shifted incoming satellite signal and a reference signal generated by the receiver. Only the fractional part of one cycle can be measured accurately. Hence, an additional unknown appears in Equation 4, the carrier phase ambiguity N. The ambiguity is the number of complete integer cycles between the satellite and the receiver. It remains constant for every satellite as far as no cycle slips during measurements occur.

Differentiation of Equation 4 results in the observation equation for the phase rates. These observations are used for the velocity determination of the GPS receiver. Again, to obtain high accuracy the unknown parameters have to be modelled or eliminated via differencing and especially the unknown ambiguity has to be resolved correctly.

As mentioned before, the unknown parameters in Equations 3 and 4 can be more or less completely eliminated using a differential approach for the processing. The principle of this approach is shown in Figure 1b. Using an additional second GPS receiver installed on a known position (master station) simultaneously, corrections for the obtained GPS observations can be determined. Utilizing these corrections for the remote receiver the accuracy of the GPS results is increased significantely. This is the so-called GPS processing using differential techniques. The single difference is the difference between the observations at the master and the remote station for the same satellite. It cancels out the atmospheric errors and the errors in the satellite position and the satellite clock. Forming the difference between two single differences of two satellites, the receiver clocks are eliminated additionally. This second difference is called double difference. Modifying the observation Equations 3 and 4 for the double difference observation results in the Equations 5.

$$\begin{aligned} \nabla\Delta p &= \nabla\Delta\rho + \nabla\Delta d_{ion} + \nabla\Delta d_{trop} + \nabla\Delta d_{\rho} + \epsilon_{\nabla\Delta p} \\ \nabla\Delta\Phi &= \nabla\Delta\rho + \lambda\nabla\Delta N - \nabla\Delta d_{ion} + \nabla\Delta d_{trop} + \nabla\Delta d_{\rho} + \epsilon_{\nabla\Delta\Phi} \end{aligned} \tag{5}$$

The remaining orbital and atmospheric errors are due to the spatial separation between the rover and the master station. The correct differential approach is only satisfied if the error influences caused by troposphere, ionosphere and satellite orbits are exactly the same for both receivers. Normally, since the receivers are spatial separated some residuals still remain in the double differenced observations.

Additionally, the unknown double differenced ambiguities can be found in the $\lambda\nabla\Delta N$ term and have to be determined to guarantee correct results.

To summarize, the accuracy of the GPS data processing is mainly dependent on the chosen observables and the processing approach. Additional errors are caused due to the actual test configuration and geometry. Multipath, variation of the antenna phase centres and receiver noise are possible error sources. Furthermore, in highly kinematic environments like in the airborne case the GPS phase observations are quite susceptible to carrier phase cycle slips, and due to the steep banking angles during the flight turns outages caused by shading are possible. Therefore, the given GPS positioning and attitude accuracies for the different observables and processing techniques in Table 1 (from Schwarz et. al., 1994) are application dependent and might be slightly different for every test environment. Nevertheless, the GPS offers high absolut accuracy measurements and is not deteriorated by any systematic time dependent errors.

Model	Antenna separation	Accuracy
Pseudorange point positioning		100 m horizontal 150 m vertical
Smoothed pseudorange (differential)	10 km	0.5 - 3 m horizontal 0.8 - 4 m height
Pseudorange (differential)	500 km	3 - 7 m horizontal 4 - 8 m height
Carrier phase (differential)	10 km	3 - 20 cm horizontal 5 - 30 cm vertical
	50 km	15 - 30 cm horizontal 20 - 40 cm vertical
Attitude determination	1 m	0.2 - 0.5 deg

Table 1: Achievable GPS accuracies.

3. INERTIAL NAVIGATION SYSTEMS

An inertial navigation system is a self-contained positioning and attitude device that continuously measures three orthogonal linear accelerations and three angular rates. The theory of inertial navigation is based on Newton's second law describing the fact that the measured specific force $f_b(t)$ of a moving vehicle with respect to an inertial coordinate frame can be obtained as linear combination of the linear accelerations $a(t)$ of the system and the gravitational acceleration $g(t)$. With known gravitational accelerations the linear accelerations can be calculated from the sensed specific force. These measurements are integrated to obtain the velocities from the linear accelerations. The second integration of the obtained velocities results in the desired positioning information. Additionally, the rate measurements are integrated with respect to time to compute the attitude information.

In general two different types of inertial navigation systems are in use: The platform or gimballed systems and the strap-down systems. In a gimballed system the accelerometer triad is rigidly mounted on the inner gimbal of three gyros. The inner gimbal is isolated from the vehicle rotations and its attitude remains constant in a desired orientation in space during the motion of the system. These

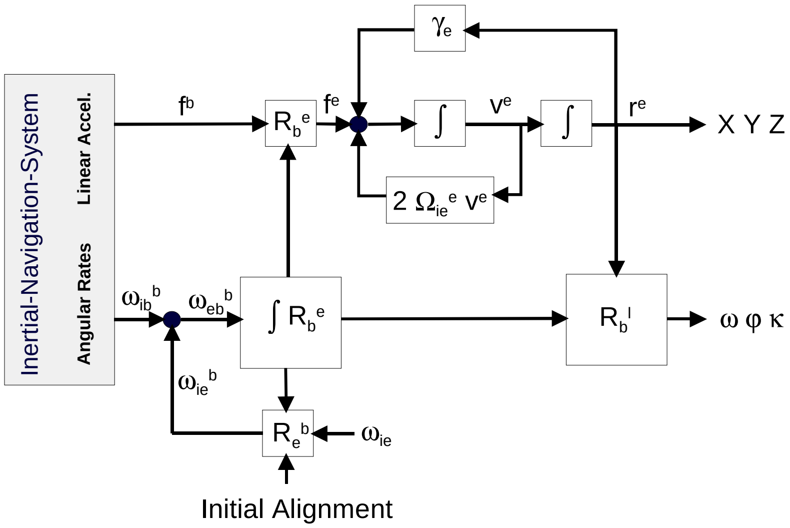

Figure 2: INS data mechanization algorithm.

systems are very accurate, because the sensors can be designed for very precise measurements in a small measurement range. On the other hand, the systems are very complex from the mechanical point of view and due to this fact high priced. In contrary, a strap-down inertial navigation system uses orthogonal accelerometers and gyro triads rigidly fixed to the axes of the moving vehicle. The angular motion of the system is continuously measured using the rate sensors. The accelerometers do not remain stable in space, but follow the motion of the vehicle. Due to this fact the mechanical part of a strap-down INS is much simpler and therefore, these systems are cheaper compared to the platform systems. Additionally, the manufacturing costs of the electronic components are decreasing. Although the platform systems provide highest accuracy, the strap-down systems are more and more in use due to the financial constraints. Therefore, the paper is focused on these systems in the following.

As mentioned before, the positioning and attitude informations are integrated from the original acceleration and rate measurements. This integration or the so-called mechanization of the raw measurements to obtain position and attitude can be done in different coordinate systems. Common are the mechanization in a local level and in a geocentric earth fixed cartesian coordinate frame. Both algorithms have their own advantages and disadvantages: The local level mechanization is used very often for navigation purposes because of the direct output of geographic coordinates and the navigation angles. The earth fixed cartesian mechanization is advantagous in case of integration of INS with GPS because the INS positions after mechanization are obtained in the GPS coordinate system. Therefore, no additional coordinate transformations are necessary for the GPS/INS integration. The flowchart of this mechanization algorithm is given in Figure 2.

Starting with an initial alignment the initial transformation matrix R_e^b between the body system b defined by the sensor axes of the INS and the earth fixed frame e as the chosen coordinate frame for integration is determined. Using the measured INS angular rates - reduced by gyro drift and earth rotation ω_{ie} - this matrix is updated at every measurement epoch. In a second step, the matrix R_e^b is transposed and used to rotate the sensed linear accelerations, reduced by the accelerometer offsets, to the e frame. After correction of the normal gravity field and coriolis acceleration the integration is done to obtain the geocentric position X, Y, Z. Using this position and the R_e^b matrix a transformation R_b^l from the INS body frame b to the local level coordinate frame l can be found. Last but least, the three attitude angles (ω, φ, κ) defined as rotation angles from the body to the local level system can be calculated from the elements of R_b^l using trigonometric functions. More details about this algorithm and the mechanization in a local level coordinate frame on the other hand can be found for example in Wei & Schwarz (1990a) and Wong (1988), respectively.

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The INS provides very high relative accuracy but the absolut accuracy deteriorates with time if the system is running in stand-alone mode and no external update measurements are available. As the INS uses integration techniques to obtain the actual position and attitude, the positioning and attitude errors grow with time. Due to the time dependent error behaviour INS can be grouped in different accuracy classes. In Table 2 one possible classification in three accuracy classes is given (after Schwarz et al., 1994). Additionally, the approximate costs of the different systems corresponding to their accuracy are given. The attitude numbers given for the attitude accuracies are for the roll and pitch angle, those for the heading are three to five times larger. Utilizing appropriate external position or velocity update measurements (e.g. provided by GPS observations) the systematic error effects can be mostly eliminated and improved accuracies within the one second interval are theoretically possible. This topic is discussed in the next section of the paper.

Timeinterval	High (> $750 000)	Medium (~ $100 000)	Low (~ $10 000)
Position			
1 h	0.3 - 0.5 km	1 - 3 km	200 - 300 km
1 min	0.3 - 0.5 m	0.5 - 3 m	30 - 50 m
1 s	0.01 - 0.02 m	0.03 - 0.1 m	0.3 - 0.5 m
Attitude			
1 h	3 - 8 mdeg	0.01 - 0.05 deg	1 - 3 deg
1 min	0.3 - 0.5 mdeg	4 - 5 mdeg	0.2 - 0.3 deg
1 s	< 0.3 mdeg	0.3 - 0.5 mdeg	0.01 - 0.03 deg

Table 2: INS accuracy classification.

4. PRINCIPLES OF GPS/INS INTEGRATION

In the previous two sections the typical error characteristics of the GPS and INS have been described and their contrary error behaviour was pointed out. Integrating both systems will now improve the overall accuracy and reliability of the integrated GPS/INS significantly compared to the stand alone units. Hence, this integration is proposed since the last years. Its benefits are quite obvious: The high short term stability of the INS is used to smooth the observation noise of the GPS. The predicted INS position and velocity helps the GPS receiver for detecting carrier phase cycle slips and bridging satellite outages. The bridging capability is dependent on the performance of the utilized INS. On the other hand, the GPS exhibits the high long term stability and therefore its observations are appropriate to compensate the systematic and time dependent INS error effects.

Basically, the integration is possible on different levels: the hardware and the software level. The integration on the hardware level, where the hardware components of the systems are combined in one ‘black’ box and interface, is not treated here. This approach for example offers advantages in the reacquisition of satellite signals after loss of lock but due to the hardware integration it is almost impossible to modifiy the system for applications different to the ones it was designed for. Therefore, the second approach to run the hardware units independently and combine the output of both systems on the software level is commonly used. It can be divided in a centralized and decentralized filtering approach.

In the first strategy the GPS and INS components are tied together in one filter. The integration is done on the raw measurement data level of both sub-systems instead of the position and velocity level. In general, this centralized approach is straightforward from the processing point of view, GPS data from

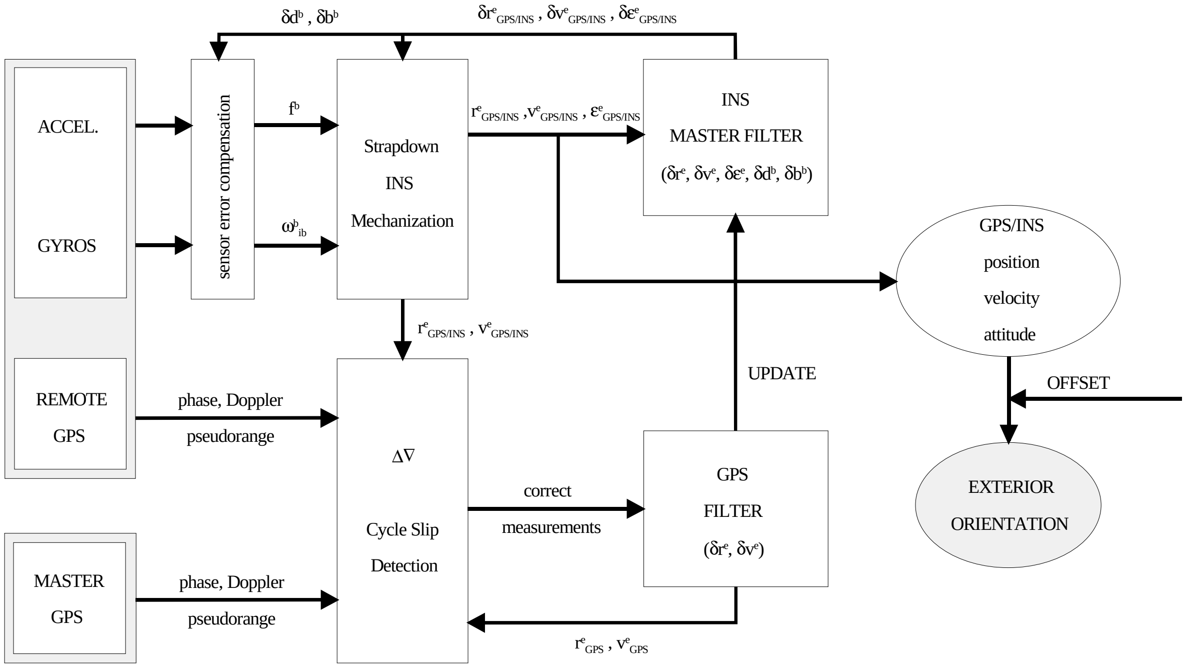

Figure 3: Decentralized Kalman filter for GPS/INS integration.

less than four satellites can be used for update, but this strategy is not flexible enough for the combination with other sensors, because the whole master filter has to be recomputed for adding an additional sensor. To overcome this problem a decentralized approach can be chosen. In contrary to the centralized filter the data of the subsystems is preprocessed in local filters and their results are feeded in the global master filter. This integration provides high flexibility to add other sensors without modifying the whole master filter, and it is more reliable since blunders of the different subsystems can be detected before all data is combined in the master filter. Most of the time, the filters are running separately. Nevertheless, periodically the output of one filter is used as pseudo-measurement to update the other filter. Depending on the way the different filters interact, different designs for the decentralized approach are possible. They are called fully-decentralized, sub-decentralized or cascaded filter. For more details about this and the correct mathematical formulation of the Kalman filtering equations see for example Wei & Schwarz (1990b), Škaloud (1995), Gelb (1974).

The whole complexity of a decentralized Kalman filter for GPS/INS integration is shown in Figure 3 (Škaloud et al., 1996). Two filters, a local filter for processing the GPS data and the master filter for the INS data, are working in parallel. The double differenced pseudorange, phase and phase rate observations form the measurement vector of the GPS filter. Within this filter optimal estimations for the 6 GPS error states (position errors δr_x^e, δr_y^e, δr_z^e and velocity errors δv_x^e, δv_y^e, δv_z^e) are done. The estimated position and velocity from GPS is used as pseudo-measurement for updating the INS master filter. The state vector of this master filter consists of 15 error states: 9 navigation errors (position δr_x^e, δr_y^e, δr_z^e, velocity δv_x^e, δv_y^e, δv_z^e and misalignment $\delta \varepsilon_x^e$, $\delta \varepsilon_y^e$, $\delta \varepsilon_z^e$) and 6 error terms describing the systematic INS sensor errors given in the INS body frame (accelerometer bias δb_x^b, δb_y^b, δb_z^b and gyro drift δd_x^b, δd_y^b, δd_z^b). The updated INS error states are fed back to correct the INS raw measurements and to aid the strap-down INS data mechanization following the flowchart given in Figure 2. Hence, the output data from mechanization is not only from INS but from integrated GPS/INS observations. The position and velocity informations are used to detect and correct possible cycle slips in the GPS observations. After applying the correction terms for the constant spatial and rotational offsets as described in section 1 the exterior orientation is obtained.

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5. TEST RESULTS

The performance of direct exterior orientation of airborne sensors using an integrated GPS/INS system has been tested several times from the Institute for Photogrammetry. The results of two testflights are presented in this section. The first test was done in 1995 and was jointly conducted by the University of Calgary, Department of Geomatics and the IfP. In this large scale photogrammetry test over a well surveyed test field in the open brown coal pit mine area close to Cologne, the potential of a ‘standard’ decentralized filtering approach for GPS/INS integration is proved. The second test was performed within the scope of evaluating the digital airborne three CCD line scanner DPA (Digital Photogrammetric Assembly (Hahn et al., 1996)) in October 1996. Again, external reference measurements for the evaluation of the GPS/INS performance are obtained from photogrammetry (medium scale). In contrary to the common Kalman filtering approach using GPS and INS only and realized in the first test the georeferencing is done in two steps: Approximate GPS/INS exterior orientations are determined for each image strip first and afterwards, these orientations are calibrated utilizing the stereo capability of the imaging sensor. This approach is necessary due to special hardware constraints. During the test INS angular rates and linear accelerations are only available for the short and straight image strips and not for the whole flight trajectory. Hence, no initial alignment at the beginning of the mission is possible and the in-flight alignment of the INS for each image strip is realized using photogrammetric constraints. In both test campaignes similar geodetic GPS receivers providing double differenced phase observations and INS of medium accuracy class are used.

During the first test 168 aerial images in cross pattern were captured with a flying height of about 900 m above ground using a wide-angle Zeiss-RMK-A camera. With 80% forward and 60% side overlap they form the highly redundant photogrammetric block. For a sub-set of 77 centre located images the parameters of exterior orientation are determined using inverse photogrammetry. For the evaluation of the performance of the direct determined exterior orientation from GPS/INS the orientations from photogrammetry are used as reference. It has to be mentioned that these values are estimated values only and might be different from the actual camera station and orientation at time of exposure. Due to the fact that they are estimated as free unknown parameters in the bundle adjustment process they are affected by remaining systematic errors of the exterior and the inner orientation. The theoretical position accuracy of the perspective centres from bundle adjustment is about 3 cm (STD) in horizontal and 2 cm (STD) in vertical direction. The mean accuracy of the orientation angles is about 2 milli-degree (mdeg) in roll and pitch and 1 mdeg in yaw. The results of the comparision between GPS/INS exterior orientation and the orientation parameters from photogrammetry are depicted in Figures 4 and 5 for the positioning and attitude accuracy, respectively. The position accuracy is mainly dependent on the quality of the GPS positioning. Due to a poor satellite geometry during the testflight the differences between GPS/INS and photogrammetric positions are quite large. Their rms values are about 15 cm horizontally and 20 cm vertically, which is large for a 10 km baseline between master and remote station. The differences between the orientation parameters are given in Figure 5 for the three angles roll, pitch and yaw. The errors in yaw are randomly distributed with standard deviations (STD) of 0.015 deg. For the roll and pitch angle they are about 0.03 deg (STD) and there are still some remaining time dependent systematic error effects. This indicates that the systematic errors in the integrated GPS/INS attitudes are not completely eliminated by GPS updates for roll and pitch. These might be caused by the insufficient satellite geometry or unmodelled effects due to aircraft dynamics. More detailed explanations concerning these problems can be found in Škaloud et al. (1996).

The second flight for testing GPS/INS exterior orientation took place over a well controlled testfield 30 km north of Stuttgart. Originally, this testfield was established to investigate the geometric potential of the airborne 3 CCD line scanner DPA. During the test in October 1996 36 photogrammetric images in cross pattern were taken (Zeiss RMK-Top camera, wide angle) with standard overlap and processed

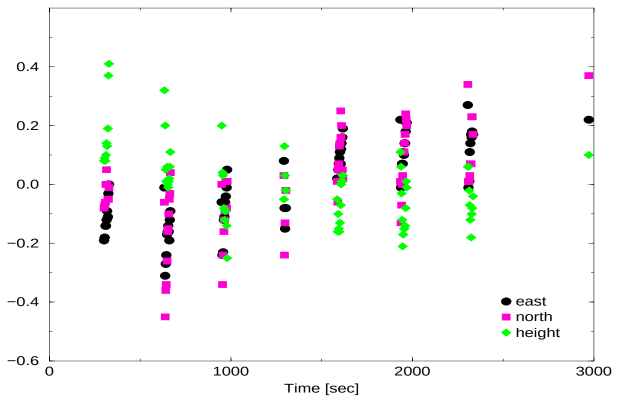

Figure 4: GPS/INS position accuracy, in [m] (Test 1995).

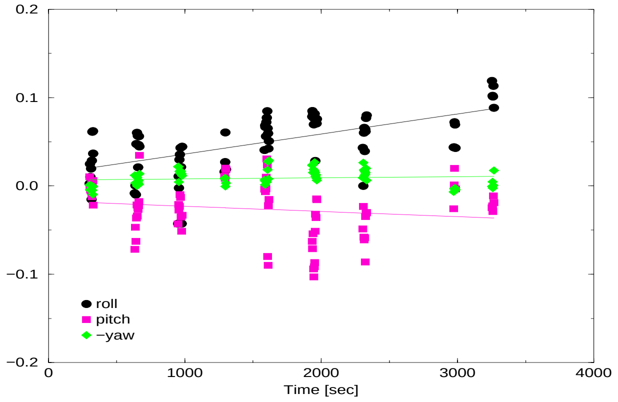

Figure 5: GPS/INS attitude accuracy, in [deg] (Test 1995).

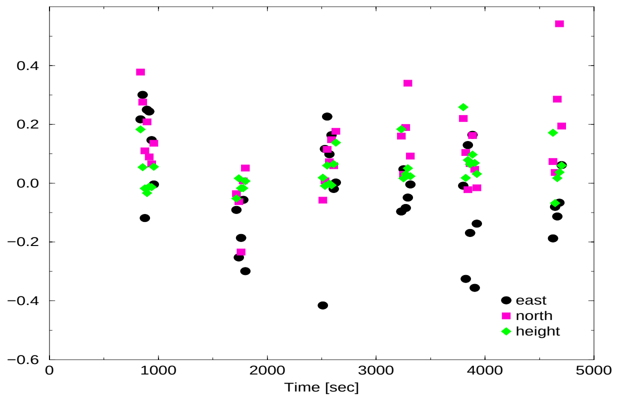

Figure 6: GPS/INS position accuracy, in [m] (Test 1996).

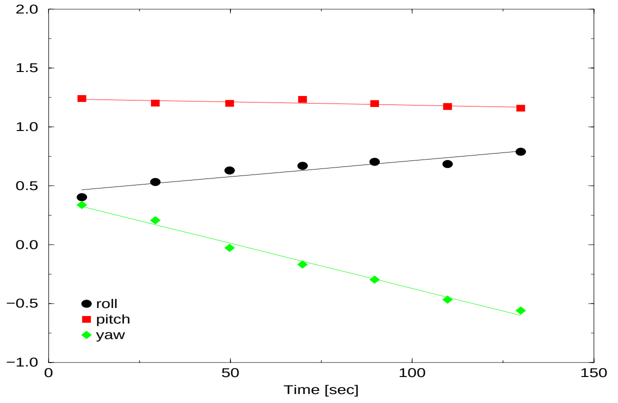

Figure 7: GPS/INS attitude accuracy before photogrammetric calibration, in [deg] (Test 1996, strip 2).

in an aerial triangulation to obtain reference values for exterior orientation. Since the flying height above ground was about 2000 m the accuracy of the estimated reference values for exterior orientation is slightly worse compared to the first test. The theoretical accuracies from bundle adjustment are about 10 cm for the horizontal positions, and 3.5 cm for the vertical component. For the orientation angles these values are 2.2 mdeg, 2.4 mdeg and 1.0 mdeg for roll, pitch and yaw angle, respectively. The results from comparision between GPS/INS and photogrammetric references are given in Figures 6 and 7. For the position differences the rms values are about 13 cm for the east, 15 cm for the north, and 7 cm for the height component, respectively. Again these errors seem to be quite large but as they are following the same error behaviour than the reference positions one can conclude that these values are mainly affected by the insufficient reference for position from bundle adjustment. The true GPS/INS positions are expected to be better than the rms values mentioned before. The evaluated GPS/INS attitudes for one image strip before applying the photogrammetric calibration are illustrated in Figure 7. They are shifted by a certain amount due to the only approximately known initial alignment at the beginning of the image strip and the small constant misalignment between photogrammetry image frame and INS body frame. Additionally, there are some drift effects caused by the remaining sensor offsets. Nevertheless, these errors are systematic following a first order polynomial. In order to fix them the photogrammetric calibration utilizing the stereo capability of the camera is applied. After linear fitting the remaining differences from GPS/INS attitudes and aerial triangulation are in the range of 5 mdeg. The complete test is described in Cramer et al. (1997).

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6. SUMMARY

In this paper a brief introduction in the wide and complex field of GPS/INS integration for direct determination of exterior orientation was given. The benefits of this integration method for accurate position, velocity and attitude determination were shown. For more information, especially concerning the detailed mathematical formulations of the different integration approaches, the interested reader is referred to the given references.
Nevertheless, the important role of direct exterior orientation especially for the georeferencing of digital sensors was pointed out and the high accuracy potential was illustrated presenting the results of two airborne tests. The obtained accuracies are high enough for almost all mapping applications and even the very high demands for photogrammetric data evaluation might be fullfilled in the future.

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