SENSOR INTEGRATION AND CALIBRATION OF DIGITAL AIRBORNE THREE-LINE CAMERA SYSTEMS

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ABSTRACT

The determination of the exterior orientation parameters is an essential pre-requisite for the evaluation of any imagery from terrestrial, airborne or satellite based sensors. Normally, this georeferencing processing is solved indirectly by using a number of well known ground control points and their corresponding image coordinates. Using a mathematical model for the relation between image and object space the exterior orientations can be calculated and the local image coordinates are related to the global ground coordinate system. In principle this approach can be applied for georeferencing of push-broom line scanner imagery, but this process is highly inefficient. Due to the large number of unknowns a large number of tie and control points is necessary for orientation determination. To allow an operational processing the direct measurement of exterior orientation using GPS and INS and additional information is inevitable. Within this article the geometric processing of high resolution line scanner imagery is described and the test results from different airborne test flights flown in 1998 are given.

KURZFASSUNG

Die Bestimmung der Parameter der äußeren Orientierung ist eine wichtige Voraussetzung für die Auswertung terrestrischer, luft- oder weltraumgestützter Bilddaten. Normalerweise wird diese Georeferenzierung indirekt durch die Verwendung bekannter Paßpunktinformationen am Boden und die Messung der zugehörigen Bildkoordinaten gelöst. Unter Verwendung eines mathematischen Modells für die die Beziehung zwischen Bild- und Objektraum können die äußeren Orientierungen berechnet und die lokalen Bildkoordinaten in Bezug zu dem globalen Geländekoordinatensystem gebracht werden. Prinzipiell ist dieser Ansatz der Georefernzierung auch auf Pushbroom–Zeilenscanner–Daten übertragbar, allerdings ist dieser Prozeß hochgradig ineffizient. Wegen der hohen Anzahl von Unbekannten wird für die Orientierungsbestimmung eine große Zahl von Verknüpfungs- und Paßpunkten benötigt. Im Hinblick auf eine operationelle Verarbeitung der Daten ist daher die direkte Messung der äußeren Orientierung mittels GPS, INS und weiteren Sensoren unvermeidbar. In diesem Artikel werden die geometrische Auswertung hochaufgelöster Zeilenscanner–Daten beschrieben und die Ergebnisse verschiedener 1998 durchgeführter Testflüge vorgestellt.

1 INTRODUCTION

Up to now the analogue acquisition of image data prevents photogrammetry to become a fully digital, towards real time mapping system. Todays systems for digital airborne image acquisition can be split into frame and push-broom systems. Despite the ongoing progress in the development of airborne frame cameras it still seems to take some more years to replace the large format film based cameras with equivalently sized digital frame systems. The maximum resolution of digital frame sensors available is about 9000 $\times$ 9000 pixel. Assuming 10μm pixel size, this sensor covers about 80cm^2, which is still significantly less compared to the standard photogrammetric analogue image format of 23 $\times$ 23cm^2. Today, digital systems using the line scanning geometry are the only imaging sensors that can compete with digitized aerial photos in terms of acquired area and image resolution.

These line scanners can be expanded to multi-line sensors providing stereoscopic and multi-spectral data simultaneously. These are enormous advantages compared to traditional analogue data. Unfortunately line scanning systems are affected by one major fact: Georeferencing of image data is more complex compared to standard aerial triangulation. Although the traditional indirect approach using ground control points for the determination of the exterior orientation of the images works for airborne sensors, this process is highly inefficient. For line scanner systems a direct processing strategy utilizing direct measurements of the exterior orientation provided by satellite (GPS) and inertial navigation system (INS) is necessary for operational and efficient data evaluation. Even though direct georeferencing is no must for digital frame cameras a GPS/INS component is also included in some systems (Toth, 1998).

Within this article the integration of GPS, INS and line scanning imagery for the georeferencing of a digital airborne line camera system is shown. Following a short discussion of different approaches of georeferencing of image data the combined approach using GPS, INS and measurements from image space in an extended aerial triangulation process is described (section 3). Compared to the stand-alone GPS/INS integration the combination with image observations increases the reliability of the whole sensor system. Remaining systematic effects can be modeled using additional parameters similar to self-calibration. Furthermore, the photogrammetric constraints are used to eliminate the systematic INS error effects significantly. The influence of the different error types which are introduced with the different sensors are shown. Special focus is given on the effects caused by systematic INS errors. The influence of these errors is shown in some simulations (section 4). In the last part the functionality of the combined aerial triangulation algorithmn is presented. The practical results of different testflights using different camera systems over a well known testfield close to Stuttgart/Germany with more than 150 signalized check points on the ground are given.

2 PRINCIPLES OF GEOREFERENCING OF IMAGERY

The determination of the exterior orientations is a major task in the evaluation procedure of image data and can be done using different orientation methods. These methods can be classified in indirect- or direct approaches and are applicable for traditional frame (digital/analogue) or line imagery. Table 1 gives a short overview of the different approaches most commonly used for the orientation of the image data.

Sensor-type	Approach	
	indirect	direct
frame	Aerial Triangulation (AT)	GPS/INS-Integration
line	AT + kinematic model	GPS/INS-Integration

Table 1: Different orientation approaches for imagery

2.1 Indirect method

In classical photogrammetry using full frame imagery (analogue or digital) the georeferencing problem is solved indirect using ground control and applying geometric constraints between image points and object points. For single image data this procedure is done by spatial resection, which can be generalized to an aerial triangulation (AT) for multiple images. Within this adjustment the photogrammetric collinearity and coplanarity equations are used to connect neighbouring images via tie points and to relate the local model coordinates to the global coordinate system. The exterior orientation parameters for the perspective centre of each image are estimated as one group of the unknown parameters in the adjustment.

In principle this approach can be transferred directly from frame to line imagery acquired by a digital push-broom scanning system. For push-broom systems each image consists of one line in general, using multi-line scanners two or more image lines are recorded simultaneously, therefore the image consists of several image lines (e.g. within the stereo module of the DPA system three pan-chromatic CCD lines are used for data recording). Compared to frame sensors the image geometry of line scanners is much weaker and the orientation parameters have to be reconstructed for each line image. Assuming a line scanner with a data rate of 200Hz yields in 1200 unknowns within one second for the position (X_0, Y_0, Z_0) and attitudes $(\omega, \varphi, \kappa)$ of the camera. However, there is not enough information available to estimate this large amount of unknowns in an adjustment procedure. Therefore, the exterior orientations are determined explicitly for distinct points of time only, the so-called orientation points. The trajectory of the sensor during the time intervals between these points is interpolated using an appropriate kinematic model for the sensor platform (AT + kinematic model). This approach reduces the numbers of unknowns significantly and can be applied very well for space borne sensors (Kornus et al., 1998).

Due to the high dynamics of an airborne environment the system has to be expanded with an INS for the measurement of the short term movements. Using a kinematic model is replaced by an INS that measures the position and attitude data for each image line directly. Although the INS now provides direct measurements of the sensor orientations and these data are introduced in the adjustment, the orientation determination is mainly based on the photogrammetric constraints used to determine the orientation points and therefore this approach still belongs to the indirect methods of image orientation. For airborne scanning systems the potential of this approach is shown e.g. in (Hofmann et al., 1993), (Heipke et al., 1994).

2.2 Direct method

First attempts of direct measurement of exterior orientation in the field of photogrammetry were done since the early thirties of this century. Driving force of these investigations was the aim to significantly reduce the need of ground control. At that time most of these attempts were limited due to their accuracies and the lack of operationality.

With the advent of the global satellite navigation systems (e.g. GPS) and the reduced costs of inertial navigation systems (INS) this situation changed tremendously. GPS offers the possibility to determine position and velocity informations at a very high absolute accuracy. The accuracy level is dependent on the processing approach (absolute, differential), the used type of observables (pseudorange-, doppler-, phase-measurements) and the actual satellite geometry. To obtain highest accuracy the differential phase observations are used. Solving the ambiguities correctly and assuming a reasonable satellite geometry, positioning accuracies up to 10cm are possible for airborne kinematic environments with remote-master receiver separation below 30km. Typical accuracies for the velocity determination are at the level of a few cm/s (Cannon, 1994).

The principle of inertial navigation is based on the measurements of linear accelerations and rotational rate increments of a body relative to an inertial coordinate frame. The actual position, velocity and attitude informations are obtained from an integration process. Starting with an initial alignment to get the initial position, velocity and attitudes, the first integration of the angular rates and linear accelerations gives attitude and velocity information. After a second integration step the position informations are available. Due to these integrations the accuracies of INS are not constant but time dependent. Due to the quality of the used inertial sensors, the accuracy is very high for short time spans but degrades with time caused by accumulating errors within the integration process. Additional errors are introduced from errors in the initial alignment.

To reduce the systematic errors the INS has to be supported by additional data. In the high dynamic airborne environment only GPS can meet these requirements, therefore GPS is an ideal sensor for integration with inertial data. Due to the complementary error behaviour, the high long term stability of the GPS measurements can be used for bounding the growing INS errors. Traditionally, this GPS/INS integration is realized in a Kalman filtering approach. Within this process the GPS position and velocity information is used to determine the errors of the chosen error states. For medium to high quality INS a 15-state error model, consisting of 9 navigation errors (position, velocity, attitude) and 6 sensor specific error terms (gyro drift, accelerometer bias) can be sufficient for many cases (Skaloud and Schwarz, 1998). Additional error terms can be introduced due to the physical offsets between the GPS antenna and the INS.

Several tests have shown the high potential of these integrated GPS/INS systems for georeferencing of image data. Especially in the last years, these systems have been tested extensively for the orientation of airborne analogue or digital frame cameras as well as for digital line scanners (table 1). Comparing the exterior orientations from GPS/INS with reference values from aerial triangulation, accuracies of camera positions of 10-15cm and attitude accuracies up to 15 arc sec were achieved for the measured orientation parameters. Using the position and attitudes directly measured from GPS/INS for the orientation of a standard photogrammetric wide-angle camera and recalculating image points by spatial forward intersection of image rays, accuracies on the ground of less than 20cm for the horizontal and less than 30cm for the vertical coordinates could be obtained from a flying height of 2000m above ground (Wewel et al., 1998), (Hutton and Lithopoulos, 1998).

The positions and orientations from GPS/INS do not refer to the perspective centre of the imaging sensor directly. Caused by translational and rotational offsets, the GPS antenna and the centre of the inertial system are displaced from the camera. Additionally, the attitudes from GPS/INS are calculated from the rotation of the INS body frame defined by the INS sensor axes to the local level frame. The INS axes do not coincide with the image coordinate frame. These offsets have to be taken into account before applying the orientations for the georeferencing of the imagery. The translational offsets are determined using conventional terrestrial survey methods after installation of the system in the aircraft used for the photo flights. The rotational offsets between the INS sensor axes and the camera coordinate system cannot be observed via conventional survey methods. Therefore, these rotational offset or misalignment angles between the INS and camera system have to be determined with in-flight calibration using a small number of tie and control points. Nevertheless, if there are no relative movements between the different sensor components, these offsets should remain constant for several survey campaigns. There is some ongoing work to prove the stability of these displacements over a longer period of time.

The quality of the integrated GPS/INS positions and attitudes is highly correlated with the quality of the updating information from GPS. Even though the INS informations can be used to bridge short GPS outages or to detect small cycle slips of the carrier phase measurements, the overall performance will degrade if the GPS position and velocity update informations are of minor quality for a longer time interval. The inertial data can only be used to detect GPS short term failures. The correction of long term systematic errors is not possible. Especially in case of photogrammetric applications where the distance between remote and master receiver can be very large due to operational reasons, at least constant offsets for GPS positions have to be expected resulting from insufficient modeling of the atmospheric errors. Additionally, errors might be introduced from incorrect datum parameters for datum shift, remaining systematic effects from the imaging sensor or – quite simple – erroneous reference coordinates of the master station. Within the standard approach of GPS supported aerial triangulation these remaining systematic errors are introduced as additional unknowns and compensated in the bundle block adjustment. Such an approach is not possible for the “simple” GPS/INS integration using a Kalman filter, as far as no informations from image space are used. In other words, every error that is not modeled in the dynamic model of the filter will introduce errors in the georeferencing process.

3 COMBINING GPS AND INS WITH AERIAL TRIANGULATION

Similar to GPS supported aerial triangulation an integrated approach should be applied for the georeferencing of imagery by combining and utilizing as many informations from different sensors as possible, i.e. GPS, INS, and informations from image space. This approach should

- enable a control of the georeferencing process by increasing the reliability of the whole system.
- allow an operational processing in terms of
  - the number of required tie and control points, which should be less or equal compared to standard aerial triangulation with full frame imagery.
  - the potential of an automated processing.
- enable a self-calibration of the camera.
- provide a higher accuracy compared to direct georeferencing by GPS/INS integration, particularly if only data for the single image strips are available.

The general idea is to perform an aerotriangulation of imagery in order to correct the position and attitude, which are provided from the GPS/INS module. Similar to the approach proposed by (Gibson, 1994), these terms contain INS error terms, as well as parameters for system calibration resulting from the physical offsets of the different sensors. Although the algorithmn was developed for the evaluation of line scanner imagery, the data of traditional frame sensors combined with a GPS/inertial module can be processed in the same way.

3.1 GPS/INS data processing

In contrary to the GPS/INS processing proposed i.e. by (Schwarz, 1995), (Skaloud, 1995), (Sherzinger, 1997) within the algorithm presented here, no Kalman filter is used. Originally, this algorithm was designed for processing of the data from the DPA sensor system – a three line push-broom scanner, that will be described in more detail in section 5 –, where inertial data are available only during the acquisition of image strips due to hardware restrictions. The lack of a continuous INS data trajectory prevents the standard Kalman approach starting with a static initial alignment for position and attitude. Therefore, the initial alignment has to be done in-flight, during the motion of the aircraft. Usually, this in-flight alignment is obtained from gyrocompassing (mainly for roll and pitch) and the combination of GPS derived velocities to the inertial measurements during aircraft maneuvers, which are performed to provoke accelerations in all directions (mainly for heading). As there are almost no accelerations during the image strips, this method is not applicable to determine the initial attitudes, in especially the heading angle.

Therefore the basic concept of the algorithm, which is presented in figure 1 is as follows. First a strap-down INS mechanization is performed, which is supported by the GPS measurements. If there is no additional information available the initial offsets (accelerometer bias, gyro bias) of the inertial sensor are assumed to be zero for the first mechanization step of the INS data. The initial position and velocity are obtained from GPS. Assuming a normal flight, the initial orientation of the system will be close to zero for the roll ω and pitch angle φ. The initial heading κ is obtained from GPS. Using the estimated initial alignment and the sensor offsets, the mechanization is done, whereas the INS derived positions are updated via GPS at every GPS measurement epoch.

After integration the parameters of exterior orientation (position X_i, Y_i, Z_i, attitude $\omega_i, \varphi_i, \kappa_i$) are available for every measurement epoch i. The positioning accuracy is mainly dependent on the accuracy of the GPS positioning. The attitudes are mainly corrupted by a constant offset $\omega_0, \varphi_0, \kappa_0$ due to the incorrect initial alignment. Additionally, there are some drift errors $\omega_1, \varphi_1, \kappa_1$ caused by remaining sensor offsets. These errors have to be determined and corrected (equation 1) to obtain corrected attitudes $\bar{\omega}_i, \bar{\varphi}_i, \bar{\kappa}_i$ and to get highest accuracies for the georeferencing.

$$\begin{aligned} \bar{\omega}_i &= \omega_i + \omega_0 + \omega_1 \cdot t \\ \bar{\varphi}_i &= \varphi_i + \varphi_0 + \varphi_1 \cdot t \\ \bar{\kappa}_i &= \kappa_i + \kappa_0 + \kappa_1 \cdot t \end{aligned} \tag{1}$$

Equation 1 is a simplification of the true error behaviour. Additional errors introduced due to the correlations between the attitudes are not considered here. The effects caused by correlations are described in section 4 in more detail. Nevertheless, applying this error model in an iterative process of a combined aerial triangulation, the best solution will be obtained after a few iteration steps.

In addition to the INS error terms, the orientations are affected by the unknown misalignment $\delta\omega, \delta\varphi, \delta\kappa$ between the INS body b and the image coordinate frame p.

3.2 Combined aerial triangulation

Similar to the Kalman filter concept, the errors are grouped in an error state vector. This vector includes the navigation errors, the sensor noise terms and can be expanded by additional calibration terms. After mechanization the error terms are updated using the values estimated in the aerotriangulation step. Within this aerial triangulation the photogrammetric coplanarity (relative orientation) and collinearity (absolute orientation) are used for the estimation of the error terms. For reasons of simplification and flexibility the collinearity equation will be utilized in the following.

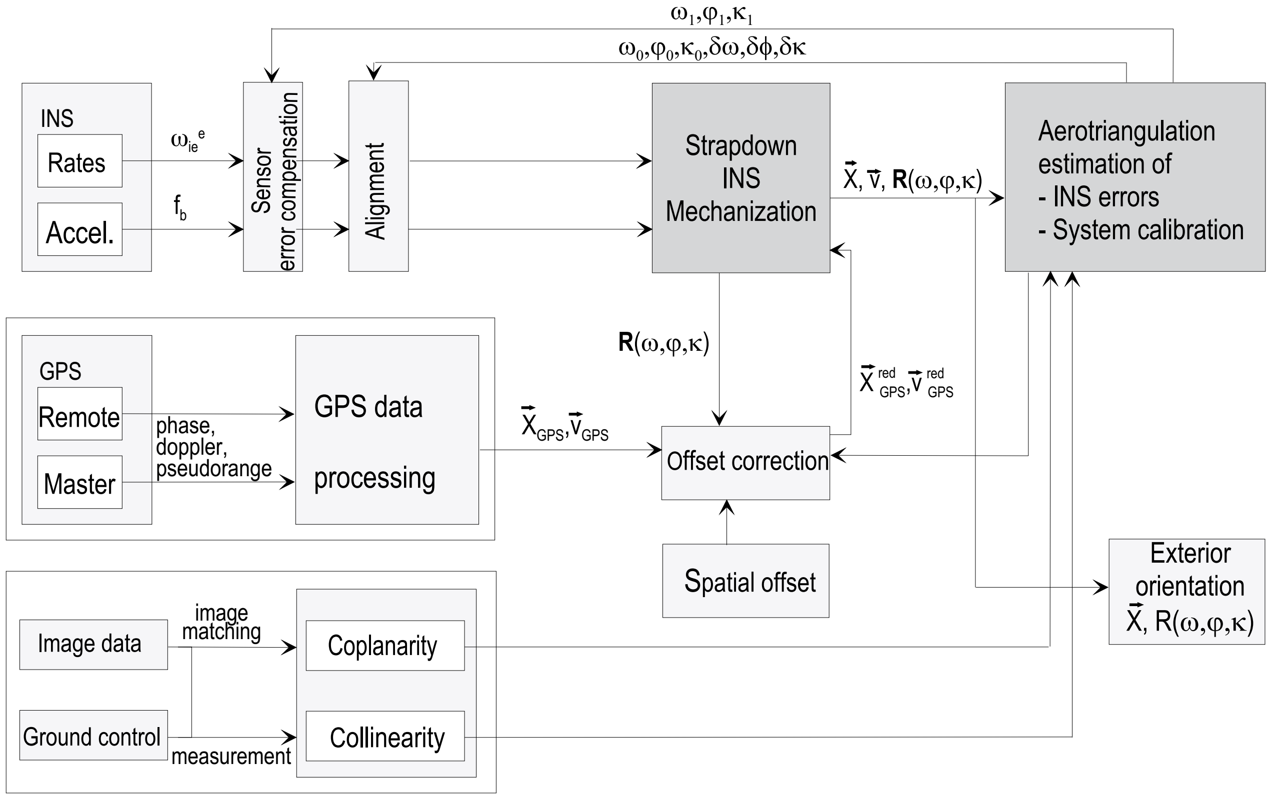

Figure 1: Workflow of georeferencing.

To take the different error terms into account, the standard collinearity equation

$$\vec{X}^m = \vec{X}_0^m + \lambda\, \mathbf{R}_p^m \cdot \vec{x}^p \qquad (2)$$

where

$\vec{X}_0^m = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}$ coordinates of perspective centre denoted in the mapping frame m

$\vec{X}^m = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$ coordinates of object points given in the mapping frame m

$\mathbf{R}_p^m = \mathbf{R}_p^m(\omega, \varphi, \kappa)$ rotation matrix from image p to mapping frame m

$\vec{x}^p = \begin{pmatrix} x' \\ y' \\ -c \end{pmatrix}$ coordinates of image point given in image frame p

λ scaling factor

has to be modified as follows:

$$\vec{X}^m = \vec{X}_0^m + \mathbf{R}_b^m \cdot [\lambda\, \mathbf{R}_p^m \cdot \vec{x}^p + \Delta\vec{X}_{cam}^b - \Delta\vec{X}_{GPS}^b] \qquad (3)$$

where

$\vec{X}_0^m = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}$ coordinates of the phase centre of the GPS antenna denoted in mapping frame m

$\vec{X}^m = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$ coordinates of object points given in the mapping frame m

$\Delta\vec{X}_{cam}^b = \begin{pmatrix} \Delta X_{cam} \\ \Delta Y_{cam} \\ \Delta Z_{cam} \end{pmatrix}$ offset between INS and perspective centre of imaging sensor given in body frame b

$\Delta\vec{X}_{GPS}^b = \begin{pmatrix} \Delta X_{GPS} \\ \Delta Y_{GPS} \\ \Delta Z_{GPS} \end{pmatrix}$ offset between GPS antenna and perspective centre of imaging sensor given in body frame b

$\mathbf{R}_b^m = \mathbf{R}_p^m(\bar{\omega}, \bar{\varphi}, \bar{\kappa})$ rotation matrix from INS body b to mapping frame m

$\mathbf{R}_p^b = \mathbf{R}_p^b(\delta\omega, \delta\varphi, \delta\kappa)$ rotation matrix from camera frame p to INS body frame b

$\vec{x}^p = \begin{pmatrix} x' \\ y' \\ -c \end{pmatrix}$ coordinates of image point given in image frame p

λ scaling factor

Equation 3 gives the complete mathematical model for the direct georeferencing of the image data. The different error states mentioned in section 3.1 are integrated in the extended collinearity equation. Setting up this equation for each ground control point or tie point allows the estimation of the unknown INS errors $\omega_0, \varphi_0, \kappa_0, \omega_1, \varphi_1, \kappa_1$ and the misalignment $\delta\omega, \delta\varphi, \delta\kappa$ between the INS body b and image coordinate frame p. After estimating the unknowns in the combined aerial triangulation, the results are fed back to the mechanization to improve the starting values significantly. Using these corrected parameters the mechanization of the INS data is repeated, and the improved exterior orientations are used as input for a second adjustment process. Therefore, the combined evaluation of GPS, INS and image data consists of two major parts: The strap-down INS mechanization and the subsequent aerotriangulation for error estimation. The whole process is performed iteratively until the final solution is reached.

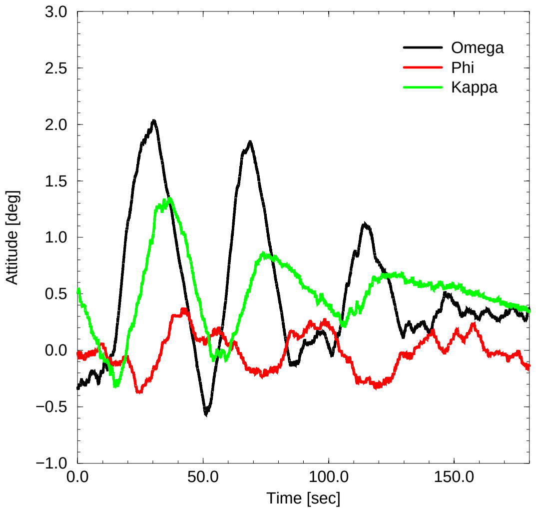

Figure 2: Attitude variation during a photogrammetric strip

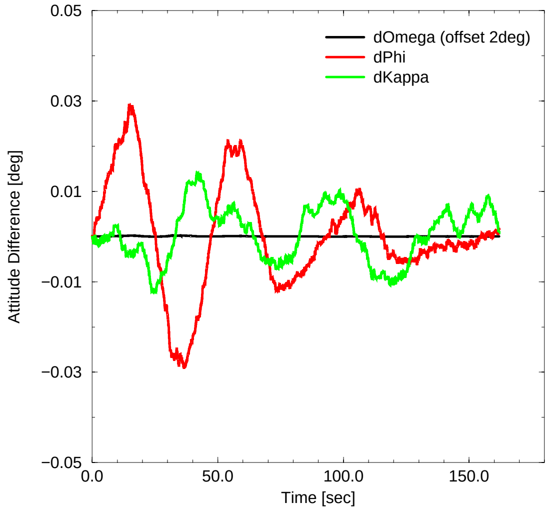

Figure 3: Attitude differences caused by wrong initial alignment (alignment error $\Delta\omega_0$=2°)

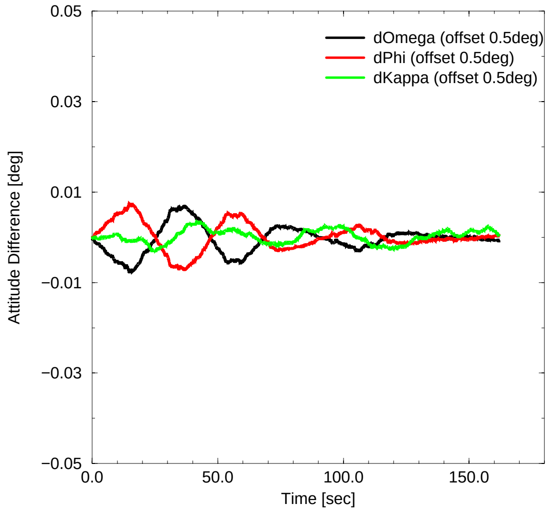

Figure 4: Attitude differences caused by wrong initial alignment (alignment error $\Delta\omega_0$=0.5°,$\Delta\varphi_0$=0.5°, $\Delta\kappa_0$=0.5°)

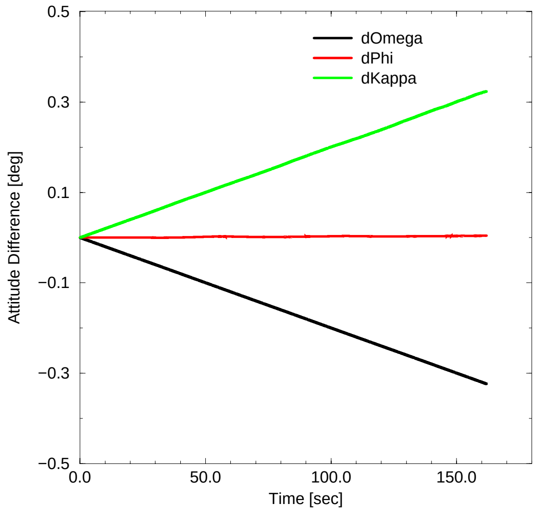

Figure 5: Attitude differences caused by remaining sensor drifts (drift error $\Delta\omega_1$=+0.002°/sec, $\Delta\kappa_1$=-0.002°/sec)

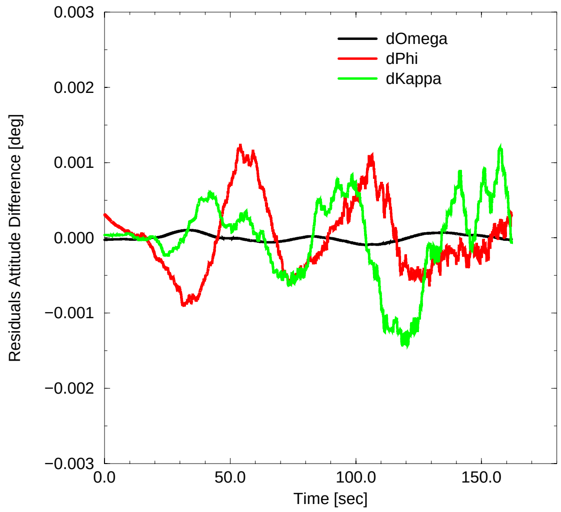

Figure 6: Residuals after linear drift regression

4 EFFECT OF INS ERRORS

The iteration, i.e. the repeated mechanization of the INS raw data, is an important step within the presented algorithm for georeferencing. To illustrate this, the influence of non corrected errors on the obtained attitudes is shown in the next figures. Due to the presented algorithm, the following investigations are focused on the effects of wrong initial attitudes and remaining sensor drifts.

Figure 2 is a plot of the attitude variations of an airborne sensor flying a photogrammetric strip of about 10km length. The attitude data shown here are obtained from an inertial system. In a second step the INS data of the same interval are mechanized again, but an error of 2° for the initial roll angle ω_0 is introduced, additionally. Figure 3 shows the obtained differences between the erroneous attitudes and the true solution from figure 2. The difference curve for the roll angle is shifted by 2°. It is quite obvious, that not only the ω-angle, which is shifted by this constant offset now, is influenced by this misalignment error, but also the pitch and heading angles are affected. Due to the wrong alignment in the roll component, parts of the sensor movements are sensed by the wrong sensor axes. This results in differences in the attitudes, which are highly correlated with the movement of the aircraft. The attitude difference $\Delta\varphi$

(pitch) corresponds to the -κ-movement (heading), the difference $\Delta\kappa$ to the pitch angle (φ), respectively. The maximum errors occur in the first part of the flight line, where the sensor dynamics are higher compared to the second half of the strip. For the $\Delta\varphi$ angle they are in the range of $\pm$0.03°. Applying initial alignment errors for all sensor axes, i.e. initial errors in the size of $\Delta\omega_0$=0.5°, $\Delta\varphi_0$=0.5° and $\Delta\kappa_0$=0.5°, the attitude differences from all sensor axes are correlated with the sensor movement (figure 4). Due to the reduced size of the introduced errors (2° compared to 0.5°) the maximum variations in attitude differences are reduced by a factor of four compared to the variations depicted in figure 3, which shows that the error size is dependent on the size of the misalignment errors. It is quite obvious that if the inertial data integration starts with the correct initial attitudes, the correlation errors due to the wrong alignment are zero.

The influence of remaining sensor drifts on the attitudes is shown in figure 5. Assuming non corrected gyro drift values of about 0.002°/sec for the roll and -0.002°/sec for the heading, the INS data are integrated and compared to the given true values from figure 2. The differences are depicted in figure 5. They seem to be linear, but after linear drift regression the residuals show some remaining effects, that are again correlated with the sensor movements (figure 6). The size of the variations is within a 0.002° interval for this data set, which is well below the error budget caused by wrong initial attitude angles.

The figures 3-6 show the influence of systematic INS errors – wrong initial alignment and remaining sensor drifts – for attitude determination. Due to the misalignment errors, the obtained attitudes are shifted from their true values. Remaining sensor offsets – gyro drift – cause linear drift errors of the obtained attitudes. Additionally, errors due to correlations between the different sensor axes are introduced in both cases. The size of these correlation errors depends on the size of the remaining sensor errors and the dynamic range of the sensor movement. The correlation errors are the limiting factor for the georeferencing process, because these error terms are not modeled in the sensor model given in equation 1. Therefore, it is essential to determine especially the initial alignment as precise as possible, to eliminate the correlation errors. This can only be done in an iterative process, because the first assumption for the initial alignment is erroneous and the obtained attitudes are falsified by these correlations. Using the improved values from the estimation procedure will improve the quality of the GPS/INS data integration, due to minimizing the influence of sensor correlation. Finally, the data are only falsified by the modeled sensor errors and then the best solution for the georeferencing is obtained.

5 PRACTICAL RESULTS

To test the performance of the presented algorithm for direct georeferencing using GPS, INS in a combined aerial triangulation different test flights over a well surveyed photogrammetric test field using different airborne line scanners and standard photogrammetric cameras were done in 1998. For the georeferencing the systems were equipped with different GPS/INS components: The integrated GPS/inertial system POS/DG provided by Applanix (Sherzinger, 1997) was used for the frame sensor (Zeiss RMK-Top15) and one line scanner (Wewel et al., 1998), a special designed strap-down inertial measurement unit by Sagem and a Trimble 4000SSi differential receiver configuration was combined with the second line scanning system, the "Digital Photogrammetric Assembly (DPA)" camera system. The basic parameters of the camera are listed in table 2. As mentioned before, the inertial system is tightly coupled with the image data recording of the DPA camera. INS data are only recorded simultaneously to the image data acquisition during the image strips. Therefore, the combined AT approach is the only way for processing the DPA data using the direct approach of georeferencing. On the other hand the POS/DG system is a commercially available integrated system, which is in general moreorless independent of the sensor to be oriented. The system uses the "traditional" approach for GPS/INS integration. First, the mechanization of the IMU data and the integration with the update information from GPS (position, velocity) is done in a flexible Kalman filter. In a second step a smoothing computes a blended solution from the data obtained in the previous step to obtain the best estimation for the trajectory of the sensor. The alignment of the system is obtained from an in-flight alignment procedure as described in section 3.1.

Stereo module	
Focal length	80mm
Line array	2×6000 pix/line
Number of lines	3
Pixelsize	10μm
Data resolution	8bit
Convergence angle	$\pm$25°
Spectral range	515 – 780nm
Ground resolution	25cm (h_g=2000m)
Spectral module	
Focal length	40mm
Line array	6000 pix/line
Number of lines	4
Pixelsize	10μm
Data resolution	8bit
Spectral range	440 – 525nm
	520 – 600nm
	610 – 685nm
	770 – 890nm
Ground resolution	50cm (h_g=2000m)

Table 2: Basic DPA camera parameters

For the POS/DG data sets the GPS/INS data could be processed using two different approaches: First, the data processing is done with the Applanix PosPac software using the GPS/inertial data of the whole flight. In a second step, only the GPS and INS data recorded during the image strips are considered, to simulate the data available for the DPA camera, and the processing is done with the iterative method of combined aerial triangulation using the observations from image space together with GPS and INS as described above. Due to the different processing methods comparisons between the two different exterior orientations from Applanix and the combined AT are possible. As the high potential and accuracy of this system was shown e.g. in (Hutton and Lithopoulos, 1998) these comparisons will give a first impression of the performance of the combined AT approach. Additionally the accuracy of direct georeferencing could be checked using the exterior orientation parameters.

The testflights were done over a photogrammetric testfield close to Stuttgart, Germany with more than 150 signalized ground control points available. The reference coordinates from terrestrial GPS static surveys and from aerial triangulation were available with an accuracy better than 5cm. Therefore, these points could serve as references for the accuracy investigations. During the flight tests, data of three flight lines in east-west direction of 10km length were acquired. For the RMK test, the flying height was about 2000m resulting an image scale of 1:13000. The DPA data were recorded at the same flying height. The quadratic ground pixel size was about 25cm $\times$ 25cm. For the second line scanning system, the flying height was about 3000m above ground. Due to the mistuned aircraft velocity the ground pixel size was rectangular, about 20cm in flight and 15cm across flight direction.

5.1 Exterior orientation

Within the figures 7-9 the functionality of the iterative combined approach is shown for the determination of the attitudes for one of

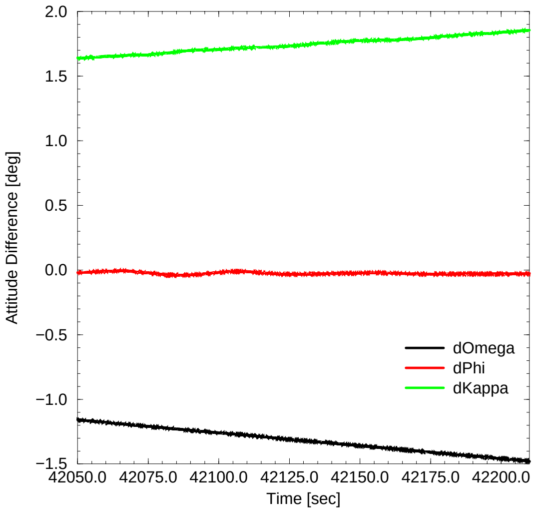

Figure 7: Attitude differences between exterior orientations from GPS/INS (POS/DG) and combined AT (first iteration)

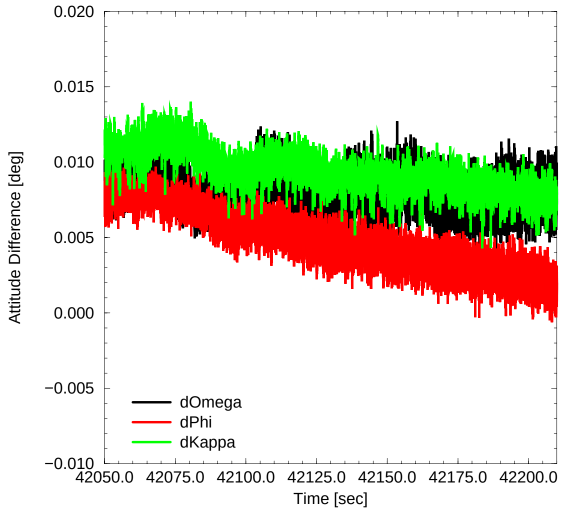

Figure 9: Attitude differences between exterior orientations from GPS/INS (POS/DG) and combined AT (third iteration)

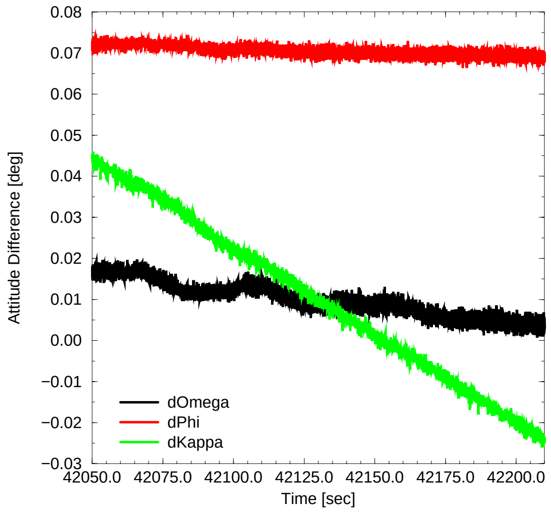

Figure 8: Attitude differences between exterior orientations from GPS/INS (POS/DG) and combined AT (second iteration)

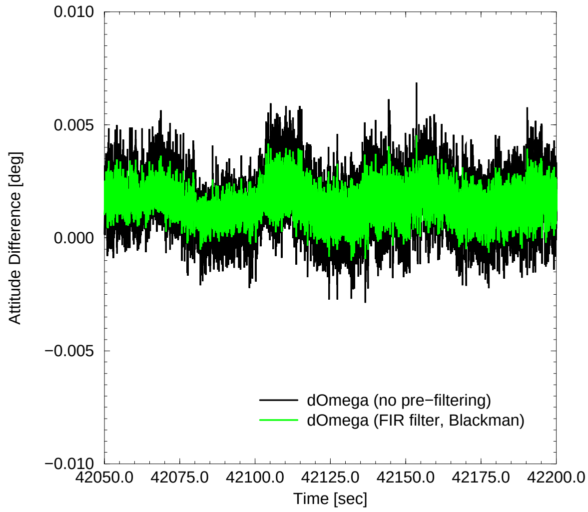

Figure 10: Influence of FIR filtering on attitude differences (roll angle ω)

the long strips exemplarily. The differences between the attitudes from the combined AT to the values obtained from the POS/DG system are depicted in the figures. Figure 7 shows the results after the first iteration step. The remaining attitude offsets in the range of $\Delta\omega_0$=-1.16°,$\Delta\varphi_0$=-0.02°, $\Delta\kappa_0$=1.63° and the linear drift effects due to erroneous drift values for the gyros are clearly visible. Within the second and third iteration (figures 8 and 9) the differences between the two solutions decrease significantly. After three iteration steps the empirical standard deviations of the attitude differences are about 4arc sec, 7arc sec and 5arc sec for the roll, pitch and heading difference, respectively. These remaining differences are mainly caused due to the fact, that for the inertial data used for the combined AT no pre-filtering was applied, to estimate the influence of filtering performed in the Applanix software. Using appropriate filter methods described in the signal processing literature (Oppenheim and Schafer, 1989), for example using optimal Finite Impulse Response (FIR) low pass filters as proposed in (Skaloud and Schwarz, 1998) would reduce the differences again. Figure 10 shows a significant reduction of the differences for the roll angle by a factor of two after low pass filtering using a blackman window with a cut-off frequency of 35Hz compared to the unfiltered data.

The high correspondence of the two orientation parameter sets shows the potential of the combined AT for the georeferencing. After the estimation of the INS error terms given in the error model in equation 1 the obtained attitudes are quite similar. For the short time interval during a photogrammetric image strip the model is sufficient to fully describe the error behaviour of the inertial sensor used.

5.2 Direct georeferencing

Using the determined exterior orientations of the line scanners and the measured image coordinates, corresponding object points on the ground were re-calculated and compared to their reference coordinates. This direct georeferencing gives the overall performance of the whole sensor system because not only the errors in the exterior orientations but the errors in the imaging part (image coordinates, lens distortions, remaining systematic errors) are affecting the quality of point determination in object space, additionally. Before using the exterior orientations for georeferencing, the misalignment angles between the INS and the image coordinate frame and the INS error terms have to be estimated using a few ground control points located in the corners of each image, usually.

Using the exterior orientations from the combined AT, accuracies in the range of one pixel in object space from a flying height of 3000m have been achieved for the first line scanning system. This is very promising. The RMS values calculated were about 20cm for the east component, which corresponds to the flight direction, 10cm for the north coordinate, perpendicular to the flight direction and 15cm for the vertical component. The maximum deviations did not exceed 50cm for the east, 20cm for the north and 50cm for the vertical coordinates.

Unfortunately, applying the combined AT for the processing of the DPA data from the November test flight these good results could not be reproduced. The accuracy of object point determination from DPA stereo imagery is quite worse and in the range of about 1m for the horizontal coordinates and 1.50m for the vertical component, obtained from the flying height of 2000m above ground. These accuracies are quite unsatisfactory. The large errors might be caused by incorrected errors of the DPA inertial system, due to the fact that the IMU was not re-calibrated since the last six years. The spectral analysis of the INS measurements from the 1998 test shows significant differences compared to data from an airborne test flown in 1992. Additional errors are introduced due to unmodelled errors in the inner orientation of the camera, because up to now the additional parameters for self-calibration are not fully implemented in the actual software version. Calculating the combined AT using only the informations from one stereo channel e.g. the nadir channel (spatial resection) the estimated $\hat{\sigma}_0$ in image space is in the range of 1.5 pixel, compared to 2-3 pixel using all three stereo channels.

6 CONCLUSIONS

This article shows the high potential of direct georeferencing for airborne scanner imagery. Although the traditional GPS/INS integration could give very satisfactory results, the integration of all available sensor data in a combined aerial triangulation will give a more reliable and more flexible solution. Especially if the GPS and INS data are available only for a very short time interval, e.g. during the image strips, such an combined approach will allow the strip wise georeferencing of scanner images with a sufficient accuracy.

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