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Direct Geocoding - is Aerial Triangulation Obsolete?

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ABSTRACT

By direct geocoding or direct georeferencing, i.e. the direct measurement of the exterior orientation of an imaging sensor using an integrated system consisting of receivers of the Global Positioning System (GPS) and a strap-down Inertial Measurement Unit (IMU), required ground control and tie point information could be reduced or eliminated significantly. Using integrated GPS/inertial systems many applications can be realized more efficiently and economically. In principle, aerial triangulation will become obsolete if the exterior orientations are obtained directly with sufficient accuracy and if there are no errors in the calibration of the multi-sensor system (GPS, IMU and imaging sensor). This article describes a well controlled airborne test to investigate the potential and accuracy of a commercially available integrated GPS/inertial system (POS/DG310 from Applanix, Canada). Within this test standard aerial triangulation is used as reference for direct georeferencing. The empirical accuracy of direct georeferencing obtained from this test might help to answer the question, whether aerial triangulation will become obsolete in future or not.

1. INTRODUCTION

The determination of the exterior orientation parameters is an essential pre-requisite for the geometric evaluation of any kind of imagery from terrestrial, airborne or satellite based sensors. Traditionally, the geocoding or georeferencing is solved indirectly applying a number of well known ground control points and their corresponding image coordinates. Using a mathematical model for the transformation between object and image space the exterior orientations can be calculated in order to relate the local image coordinates to the global ground coordinate system. In classical photogrammetry this task is solved with spatial resection for single images, an approach, which is generalized to an aerial triangulation (AT) for multiple images. The photogrammetric collinearity equations are applied to connect neighbouring images via tie points and to relate the local model coordinates to the global reference coordinate system via control points. Therefore, exterior orientation parameters for the perspective centre of each image can be estimated as one group of unknowns within a least-squares adjustment.

In the last years the use of direct georeferencing, i.e. the direct measurement of the exterior orientation of an imaging sensor for photogrammetric applications, has been mainly stimulated by the development of airborne push-broom scanners for the direct digital acquisition of photogrammetric imagery (e.g. Kaltenecker, Müller and Hofmann (1994)), Sandau and Eckert (1996), Wewel, Scholten, Neukum and Albertz (1998)). For line scanner systems a direct processing strategy utilizing direct measurements of the exterior orientation provided by satellite and inertial navigation system is inevitable for an efficient data evaluation. For full frame cameras the use of direct georeferencing is less obvious. Nevertheless, a GPS/inertial component is also included in current systems for digital image acquisition (Toth (1998)). Since direct georeferencing is no must for digital frame cameras, there are mainly operational reasons for applying this technique for that kind of imagery. In general, two types of observations are required for aerial triangulation: control points, where image points and their corresponding terrain coordinates have to be provided, and tie points, where image coordinates of homologous points are measured in overlapping images. To rationalize the process of aerial triangulation the required number of control points can be reduced significantly by the application of a GPS based aerial triangulation, which integrates GPS measured camera stations into the adjustment. The required tie points can be provided automatically by image matching, which enables the point transfer during automatic aerial

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triangulation. Both techniques are state-of-the-art and realized by a number of systems, hence there should be no need for direct georeferencing of airborne full frame imagery.
Still there are a number of applications, where the direct georeferencing of standard aerial frame imagery is advantageous compared to aerial triangulation even if the additional costs of the IMU are considered:

- Direct georeferencing enables a faster acquisition of the exterior orientation, since the computational burden for automatic aerial triangulation is higher compared to the effort for GPS/inertial integration.
- Direct georeferencing removes limitations to the flight path during image acquisition. Continuous absolute GPS trajectories, as obtainable by OTF methods, would in principle permit an aerial triangulation without ground control points. For that purpose a certain number of images has to be captured in the well known photogrammetric block configuration. However, this flight configuration can be disadvantageous, if only small areas have to be captured or if a linear flight path is aspired for tasks like the supervision of power lines or the image acquisition at coast lines.
- Additional problems of image matching required for automatic aerial triangulation are avoided if direct georeferencing is applied. Image matching can be very difficult or even impossible at some areas. Cases critical for matching during aerial triangulation are steep slopes, no texture, forests, large water bodies, large scale urban regions or moving shadows. Additionally, the availability of approximate tie points is very critical for matching. Depending on the shape of the terrain, GPS camera stations and a DTM can be required to provide these approximations (Käser, Eidenbenz and Baltsavias (1998)). Even though techniques like automatic aerial triangulation have reached a very mature state, the use of direct georeferencing and therefore the knowledge of the image orientation parameters can be advantageous for a number of applications.

One crucial point during the application of direct georeferencing is the accuracy and reliability obtainable by such a system. In order to demonstrate the potential of direct georeferencing for airborne cameras an accuracy investigation of an integrated GPS/inertial system is presented within this article. For that purpose a test comparing standard aerial triangulation and point determination by direct georeferencing is described. During the test the commercially available integrated GPS/inertial system POS/DG310 developed by Applanix Corp. of Markham, ON Canada (Scherzinger (1997), Reid and Lithopoulos (1998)) was applied. After a short review on the integration of GPS/inertial data for direct georeferencing in the next section, the test flight design will be described in section 3, followed by the presentation of the test results in sections 4 and 5. As the GPS/inertial data were processed using different master stations with different baseline length, in the first step the internal accuracy is calculated. Afterwards the GPS/inertial results are compared to the absolute references from AT to get the absolute accuracy results.

2. GPS/INERTIAL INTEGRATION

Direct georeferencing is based on the combination of GPS and inertial measurements. GPS offers the possibility to determine position and velocity information at a very high absolute accuracy. The accuracy level is dependent on the processing approach (absolute, differential), the used type of observable (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, a positioning accuracy up to 10cm is possible for airborne kinematic environments with remote-master receiver separation below 30km. The typical accuracy for the velocity determination is 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 information is obtained from an integration process. Starting with an initial alignment to get the initial position, velocity and attitude, the first integration of the angular rates and linear accelerations gives attitude and velocity information. After a second integration step the position information is available. Due to these integration steps the accuracy of IMU is not constant but time dependent. Depending on 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 (Schwarz (1995)). Additional errors are introduced from errors in the initial alignment.

To reduce the systematic errors the IMU 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 IMU errors. Traditionally, this GPS/inertial 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) might 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 IMU.

2.1. Misalignment calibration

To relate the position and orientation data provided by the GPS/inertial system to the perspective centre of the camera spatial and time eccentricities between the different sensor components have to be removed. The spatial shift between the sensor components can usually be measured using a conventional terrestrial survey. Since the physical IMU sensor axes are not aligned to the image coordinate frame the misalignment has to be determined additionally in order to use the attitudes from the IMU for the georeferencing of the photogrammetric image data. This misalignment can be determined by computing the mean differences between the image orientations from AT and the GPS/inertial attitudes for one or several images. The GPS/inertial attitudes are corrected by these offset angles and used for the orientation of the images. Calibrating the misalignment once these angles should remain constant as far as there are no relative rotations between IMU and imaging sensor. The precise time alignment is realized by the exchange of synchronization signals, mostly. These pulses relate the different sensors to a common time scale which is given by the global GPS time, normally. The time alignment has to be realized with an accuracy well below 1msec. Assuming an aircraft velocity of about 70m/s, a timing error of 1msec will cause an error in position of about 1dm, which is almost the accuracy to be expected from GPS.

2.2. Sensor Configuration

The tested integrated GPS/inertial system POS/DG310 consists of four main components: A dual frequency carrier phase embedded GPS receiver (Novatel Millennium), a six degree of freedom IMU (Litton LR86), the POS Computer System (PCS) and the POSPac software for post-processing. Additional GPS receivers located on the ground were used as master stations. Several master stations with various baseline lengths were installed to investigate the influence of different GPS baselines on the quality of the integrated GPS/inertial position and attitude information. For the tests the Litton LR86 IMU was rigidly mounted on a Zeiss RMK Top15 aerial camera. The GPS antenna was centred above the camera on top of the fuselage of the aircraft.

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2.3. Software Configuration

For our test the integration of the GPS/inertial raw data was done using the Applanix POSPac software. The processing realized in the POSPac software is divided into two major parts. First, the GPS data evaluation is done separately using the GrafNav GPS Software, version 5.06 (Waypoint Consulting). Within this software the GPS differential phase observations are calculated using the implemented OTF methods for correctly resolving the ambiguities. The position and velocity information from GPS is then used as update information for the GPS/inertial integration process. Within this step an optimal integration of the GPS results and the IMU measurements is obtained. This integration is realized in a Kalman filter approach. In a second step a smoothing computes a blended solution from the data obtained in the Kalman filtering to obtain a best estimated trajectory from GPS/inertial data. In our configuration the following 25 parameters were estimated during the filtering:

- navigation errors (3 position errors, 3 velocity errors, 4 alignment errors (using a modified error model for the κ-angle estimation (Scherzinger (1996)))
- short term IMU errors, modelled as first order Gauss-Markov process (3 accelerometer drifts, 3 accelerometer scale factor drifts, 3 gyro drifts, 3 gyro scale factor drifts)
- long term biased IMU errors (3 gyro offsets)

The errors in the GPS trajectory used to update the Kalman filter were modelled as a first order Gauss-Markov process.
The initial alignment between the IMU body frame and the global earth related coordinate system was obtained from the in-air alignment, avoiding a long static initialization period prior to the flight. This alignment can be obtained on the flight from gyrocompassing and the combination of GPS derived velocities to the inertial measurements during aircraft manoeuvres, which are performed to provoke accelerations in all directions. After processing, position, velocity and attitude data from POS/DG are continuously available for the complete trajectory with a data rate of 50Hz.

3. TESTFLIGHT DESIGN

In order to evaluate the performance of the GPS/inertial system for the direct measurement of exterior orientation, a photo flight was carried out over a well surveyed testfield close to Stuttgart in December 1998. The test site had an extension of 7km x 5km, a number of 78 signalized ground control points were available. Additionally, 64 non signalized tie points were obtained from AT. Aerial imagery was captured at a flying height of 1000m and 2000m above ground, resulting in two different image scales of 1:6 000 and 1:13 000. The large scale imagery was captured in the eastern part of the test site. Two strips each consisting of 8 images with 60% forward and 30% side overlap were acquired. The 1:13 000 block covered the whole test area by 3 long image strips and 3 cross strips. Both blocks were captured twice in order to enlarge the flying time. After the in-air alignment the 1:6 000 scale imagery was acquired first, followed by the two identical 1:13 000 blocks and the second 1:6 000 flight. Overall, 104 images were captured in a period of 1.5h.
Additionally, static GPS data were acquired using several master stations with different baseline length, to check for any systematic errors caused by the varying baseline length. The different master stations were located in the test site (Vaihingen/Enz (V)), two stations in Stuttgart (25km, Stuttgart-Uni (S1) and Stuttgart-LVA (S2)), one in Karlsruhe (K) (40km), Frankfurt (F) (130km), München (M) (210km), Bonn (B) (230km) and finally Hannover (H) (380km). The different master stations covered the flight interval at least from the in-air alignment manoeuver till landing in Stuttgart, except of the Vaihingen station. Due to logistic problems this receiver was switched on just before the beginning of the photo flights. Therefore, the in-air alignment manoeuver could not

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be used for the initial alignment of this particular reference station. For the direct georeferencing evaluated in the following part of the paper the results of the in-air alignment were applied. This approach is most relevant for practical applications since the in-air alignment, which provides the initial attitudes of the system, can be performed just before approaching the test area, and no additional data capture on the ground is required. The static alignment of the GPS/inertial system at the beginning and end of the flight was only performed in order to provide additional reference data.

Applying the standard method of aerial triangulation, reference values for the exterior orientations directly measured by the POS/DG system were provided for each camera air station. During AT the terrain coordinates of 32 signalized points captured by static GPS baseline measurements were used as control points. The theoretical standard deviations of the orientation parameters determined by aerial triangulation are in the range of 8cm for the horizontal components of the camera perspective centres and 4cm for the vertical component (image scale 1:13 000). For the 1:6 000 photogrammetric block these values are about 2.5cm and 1.5cm for horizontal and vertical coordinates, respectively. The attitude accuracy is about $\sigma_\omega = \sigma_\varphi = 9$ arc sec and $\sigma_\kappa = 4$ arc sec for the 1:13 000 images. For the 1:6 000 block the attitudes could be obtained with an accuracy of about $\sigma_\omega = \sigma_\varphi = 6$ arc sec and $\sigma_\kappa = 3$ arc sec. This accuracy should be better than the values to be expected from the integrated GPS/inertial system and therefore they can be used as reference values. The remaining signalized points as well as additional tie points on the ground were obtained from AT with theoretical standard deviations in the range of 5cm for the horizontal and the vertical coordinates. Those points are used as check points for testing the overall performance of direct georeferencing for object point determination.

4. TEST RESULTS

4.1. Interior accuracy

As mentioned above, during GPS/inertial integration the GPS data is applied for correction of the systematic IMU errors. For this reason the accuracy of the GPS positioning and velocity is one limiting factor for the overall accuracy of direct georeferencing. This was the motivation to perform a more thorough investigation of the system accuracy which can be obtained for different GPS baselines.

Therefore, as a first step the different solutions of the GPS trajectories for the different master stations obtained from the GrafNav GPS processing were compared to determine the internal accuracy of the different trajectories. The GPS trajectory calculated from the Stuttgart-LVA (S2) master station served as reference solution. The statistics for the positioning differences are given in Table 1. Despite the large variations of the baseline distances the different trajectories are very consistent. The differences of the obtained GPS positions were only in the order of <10cm (RMS) for the horizontal and <20cm (RMS) for the vertical components. The maximum position differences do not exceed 55cm, even for the S2-H baseline. There are some systematic offsets visible, mostly in the vertical components. For the V and S1 station for example they are due to erroneous antenna phase centre corrections. For the longer baselines they might be caused by uncorrected atmospheric effects or some inconsistencies in the reference station coordinates. Nevertheless, the Karlsruhe solution (S2-K) performs much worse. Due to radio interference problems, the GPS data were corrupted and could not be processed properly. Therefore, this baseline has to be excluded from further processing. Of course these good GPS results have to be verified for different testflight conditions and different software, still the result is very encouraging. The expected strong dependency of the achievable accuracy on the distance to the GPS reference

Diff.	RMS [cm]			Max.Dev. [cm]			Mean [cm]			STD [cm]		
	East	North	Vert.	East	North	Vert.	East	North	Vert.	East	North	Vert.
S2-V	2.5	4.1	12.9	5.6	11.2	22.2	-1.8	-2.4	12.1	1.7	3.3	4.4
S2-S1	1.0	1.6	8.5	3.6	8.2	13.9	-0.2	0.3	8.1	0.9	1.5	2.4
S2-K	26.4	21.3	31.9	84.6	442.9	10419.0	-19.2	-18.1	-13.8	18.2	11.6	28.7
S2-F	2.8	5.1	17.2	6.8	15.3	39.9	-2.2	-1.5	15.8	1.8	4.9	7.4
S2-M	9.6	6.1	22.0	28.9	17.1	52.2	-6.0	-1.1	19.2	7.5	6.0	10.7
S2-B	10.9	5.6	8.2	18.6	15.2	24.0	-10.7	-2.2	4.5	2.4	5.1	6.8
S2-H	6.2	8.2	12.1	16.9	20.4	26.2	-4.2	-4.7	-9.7	4.6	6.8	7.2

Table 1: Internal accuracy of GPS trajectories (position).

Diff.	Position						Attitude					
	RMS [cm]			Max.Dev. [cm]			RMS [10^{-3} °]			Max.Dev. [10^{-3} °]		
	East	North	Vert.	East	North	Vert.	ω	φ	κ	ω	φ	κ
S2-V	1.9	4.1	9.4	4.5	36.5	17.8	0.4	4.1	4.3	3.5	56.6	30.4
S2-S1	1.0	1.5	8.5	3.6	7.9	13.5	<0.1	<0.1	0.3	0.3	0.5	0.8
S2-F	2.8	5.1	17.2	6.5	14.7	39.0	0.1	0.2	0.9	0.8	1.8	2.4
S2-M	9.5	6.0	21.9	26.1	16.1	47.0	0.3	0.4	1.2	1.8	2.4	3.3
S2-B	10.9	5.5	8.1	18.0	14.3	22.6	0.2	0.3	0.7	1.4	1.3	2.2
S2-H	6.2	8.3	12.1	16.6	19.7	25.3	0.1	0.2	1.0	0.7	1.2	2.8

Table 2: Internal accuracy of GPS/inertial trajectories (position and attitude).

station could not be verified. Similar results for absolute kinematic GPS positioning in an airborne environment could be found in Ackermann (1996).

To check the internal accuracy of the GPS/inertial trajectories, similar tests were performed with the trajectories obtained from the POSPac software. The position and attitude differences between the different solutions were calculated. The Stuttgart-LVA (S2) GPS/inertial trajectory served as reference again. The internal differences of the solutions for the baselines are depicted in Table 2. As shown in Table 1 the different GPS trajectories fit to each other very well. For this reason the solutions of GPS/inertial integration provided from Kalman filtering and smoothing are also very consistent. The RMS values for the positions are more or less the same compared to Table 1. For the attitude differences these values are between 0.0001°-0.001° for all stations except one. Due to the lack of GPS data for the in-air alignment manoeuver for the Vaihingen baseline it took more time for the attitudes to converge to the same accuracy level. This is the reason for the larger RMS values and maximum deviations for the Vaihingen GPS/inertial trajectory.

As an example, Figures 1 and 2 depict the position and attitude differences for the aircraft trajectories computed from Stuttgart-LVA and Bonn. As it can be seen, the position differences are small, the RMS values are about 10cm. Nevertheless, a significant offset of about 10cm in the east coordinate exists. Additionally, sharp jumps of about 10cm size are visible. They are due to different GPS ambiguity solutions for the two baselines. Within the GPS/inertial integration long term GPS errors (like constant offsets) could not be detected in general. In case of the chosen integration approach implemented in the POSPac software, using processed GPS data for updating the Kalman filter without any feedback to the raw GPS observations, it seems to be difficult to detect and correct some cycle slips properly. Compared to the position variations the attitude differences are small. Even for this 230km long baseline they did not exceed 0.0025°. Such an attitude error of about 9 arc sec results in an error in object space well below 10cm assuming a flying height of 2000m above ground. Comparing this error to the maximum position deviations of about 2dm, the influence caused by position errors is factor twice larger. Similar effects can be seen

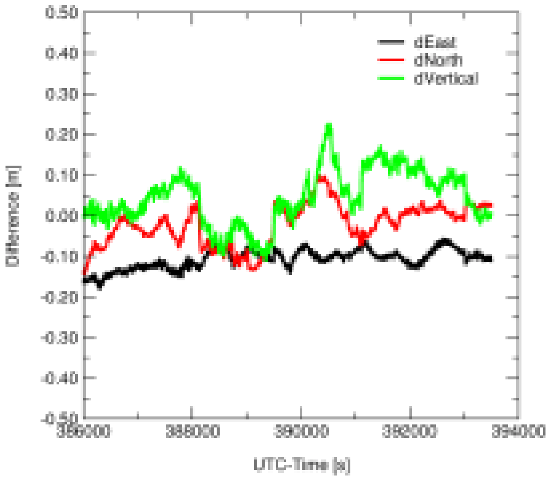

Figure 1: GPS/inertial position differences (Stuttgart-LVA - Bonn).

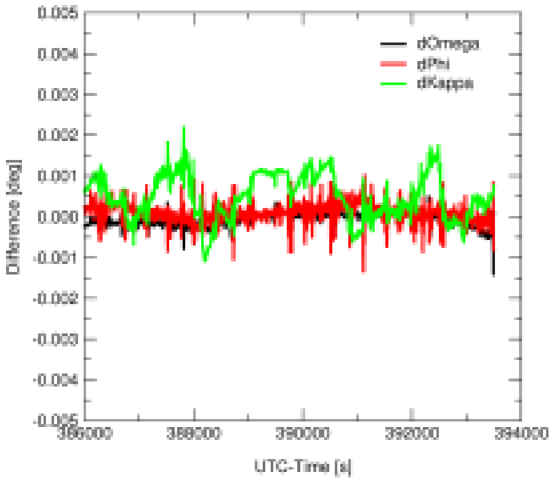

Figure 2: GPS/inertial attitude differences (Stuttgart-LVA - Bonn).

for the other baselines, too. From this point, the GPS positioning accuracy seems to be the limiting factor for the overall GPS/inertial exterior orientation performance.

4.2. Exterior accuracy

All accuracy values computed till now are obtained from internal differences between the GPS or GPS/inertial solutions. To get absolute numbers, the orientation values have to be compared to the reference data from AT. Before starting these comparisons the precise time alignment between the GPS/inertial sensors and the photogrammetric camera has to be guaranteed. In our case the RMK midexposure TTL pulse was a high-low signal where the falling edge (beginning of pulse) is synchronized with the maximum opening of the camera shutter. This pulse was send to the POS/DG via the flight management and navigation system installed in the aircraft. Unfortunately, the POS/DG was sensitive to the rising edge (end of pulse) of the TTL signal, therefore the recorded trigger times have to be corrected by the length of the pulse to obtain the correct exterior orientations for the photogrammetric images. As the pulse length could not be measured directly, the time offset was estimated comparing the perspective centres from photogrammetry to the coordinates from POS/DG. Dividing the length of the displacement vector with the actual aircraft velocity an approximation for the time offset between the GPS/inertial orientation module and camera system is obtained. Using this method, a time delay of about 53msec could be determined with a RMS value of 2msec. Therefore, the following absolute accuracy tests were performed using this estimated time offset. Nevertheless, one has to keep in mind, that the 53msec value is only an estimation for the time delay and remaining systematic effects from photogrammetry are directly projected into this estimation.

Utilizing the corrected trigger times, the camera air stations were interpolated into the 50Hz GPS/inertial trajectory solution calculated from the reference station Stuttgart-LVA using a third-order polynomial. In order to relate orientation and camera module, the spatial and rotational offsets were applied. The spatial offsets were known from terrestrial measurements. The misalignment angles $\Delta\omega$, $\Delta\varphi$, $\Delta\kappa$ between camera and IMU have to be calibrated from the differences between the exterior orientations from AT and direct georeferencing. From theory, the misalignment should remain constant as far as there are no relative movements between the sensor components. Therefore, the angles are estimated for each strip separately to check the consistency of the

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estimated values. For the four 1:6 000 flight lines, the values for the misalignment angles are differing in the range of 0.005°, 0.002° and 0.011° for roll, pitch and heading, respectively. The mean value is about 0.003°, -0.028° and -0.083°. Calculating the angles from 7 and 5 images for each of the twelve 1:13 000 flight lines, values in the range of $0.007° < \Delta\omega < 0.013°$, $-0.032° < \Delta\varphi < -0.028°$, $-0.098° < \Delta\kappa < -0.075°$ with mean values of 0.010°, -0.029° and -0.088° are obtained. These variations are depicted in Figure 3, where the flight lines 1-12 correspond to the 1:13 000 strips and the last four lines to the 1:6 000 strips. The differences between the estimated values for both image scales are quite obvious, especially for the roll and heading. The misalignment is not constant, but depends on the chosen references from AT used for calibration. In order to get best results for the accuracy tests and direct georeferencing the misalignment parameters have to be calibrated for each image scale, separately.

Before using the GPS/inertial orientations for object point determination the absolute accuracy of the exterior orientations is calculated from 72 and 32 camera air stations respectively. The obtained results are listed in Table 3. As the theoretical accuracy of the reference values from AT is dependent on the image scale and – for the attitude differences – two sets of misalignment angles were applied, the statistics (RMS, Max.Dev., Mean, Std.Dev.) are given separately for the 1: 13 000 and 1:6 000 image block. As one can see from Table 3, the RMS values in camera positions are about 15cm horizontally and 30cm vertically for the 1:13 000 scale and about 10cm and 15cm for the 1:6 000 images respectively. Nevertheless, there is a significant offset in the vertical coordinate. The size of this offset is correlated with the image scale. It is about 30cm for the 1:13 000 photos and about 13cm for the 1:6 000 image scale. This is more or less the same ratio as between the two image scales. Therefore this offset is most likely due to errors in the calibration of the photogrammetric camera (focal length) and not caused by errors in the GPS/inertial orientation parameters. Although such errors should be quite unusual due to the stable geometry of the camera frame, similar effects are reported in Grün, Cocard and Eidenbenz (1993). Utilizing the GPS/inertial positions as direct measurements of the camera stations in a GPS supported AT and introducing additional correction terms for the interior orientation of the camera, the interior orientation parameters are estimated significantly. The focal length is corrected by 20µm. This systematic error induces the errors in the vertical component of the perspective centres. Usually, this effect is not visible, because it will be compensated as soon as additional offset and drift parameters are introduced in the GPS supported AT. Nevertheless, correcting this systematic error the deviations in height are about 5cm and 10cm for the 1:6 000 and 1:13 000 image blocks, respectively. This is most likely what one can expect from the photogrammetric reference values.

Image scale	Statistical value	Position [cm]			Attitude [10^{-3} °]		
		East	North	Vert.	ω	φ	κ
6000	RMS	9.9	7.1	13.5	3.0	2.0	3.9
6000	Max.Dev.	18.9	13.5	17.8	5.6	6.7	7.0
6000	Mean	-5.0	1.4	13.2	0.0	0.0	0.0
6000	STD	8.5	6.9	2.6	3.0	2.0	3.9
13000	RMS	15.1	17.5	30.8	3.2	3.0	5.8
13000	Max.Dev.	47.8	45.1	49.2	8.1	12.3	13.8
13000	Mean	3.3	4.0	30.0	0.0	0.0	0.0
13000	STD	14.7	17.0	7.4	3.2	3.0	5.8

Table 3: Absolute accuracy of GPS/inertial exterior orientations compared to AT
(GPS/inertial solution from Stuttgart-LVA, 25km).

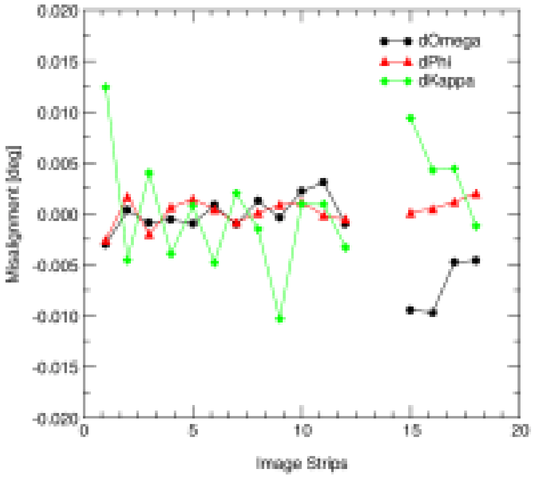

Figure 3: Variation of estimated misalignment from different image strips.

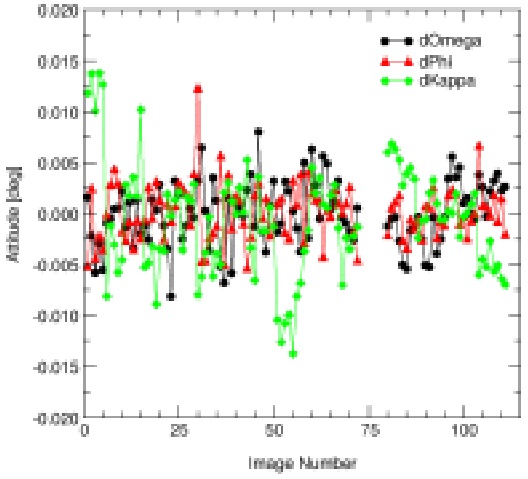

Figure 4: Attitude variations of direct georeferencing compared to AT.

The attitude variations of direct georeferencing compared to AT are depicted in Figure 4. The RMS values are within 10 arc sec, 7 arc sec, 14 arc sec (1:6 000) and about 11 arc sec, 11 arc sec and 21 arc sec (1:13 000) for ω, φ and κ respectively. As the two misalignment sets were determined from the mean offset from all 1:6 000 and 1: 13 000 camera stations separately, the obtained mean values are zero. The maximum attitude deviations are about 0.006°, 0.007° and 0.007° (1:6 000) and 0.008°, 0.012° and 0.013° (1:13 000). Due to the higher theoretical accuracy of the reference attitudes from AT the accuracy obtained from 1:6 000 images is better compared to the 1:13 000 scale. Nevertheless, one has to keep in mind that one reason for these small RMS numbers is the optimal estimation of the misalignment angles from all images of the block. This shows that the correct misalignment determination is a very demanding task and has to be solved as precise as possible. Remaining errors in the misalignment between IMU and camera will cause errors in object point determination using the GPS/inertial orientations for direct georeferencing.

5. DIRECT GEOREFERENCING

To assess the overall performance of the complete sensor system, terrain coordinates of object points are re-determined by spatial intersection utilizing the corresponding image coordinates and the exterior orientations from direct georeferencing. This corresponds to a photogrammetric point determination, where aerial triangulation is replaced by direct georeferencing. The results from the 1:13 000 image block are presented here. The exterior orientations were obtained from the Stuttgart-LVA GPS/inertial trajectory, corrected by the mean misalignment calculated from all 72 1:13 000 images. In order to check the performance of direct georeferencing, different versions were calculated. The results are depicted in Table 4. In version 1 the 142 object points were re-computed using all 72 images and the interior orientation from lab calibration. The obtained horizontal accuracy is about 8cm - 9cm. The vertical accuracy is worse, due to the significant offset in the z component, caused by the erroneous focal length of the camera. The size of the offset is about 24cm and therefore it is more or less of the same size as the absolute z position differences of the coordinates of the perspective centres detected earlier (see Table 3). This error is directly projected into the accuracy of object point determination. The accuracy in z significantly improves applying the corrected interior orientation parameters for object point determination. Now, the accuracy in

Vers.	Images	Checkpoints	East [cm]		North [cm]		Vertical [cm]	
			RMS	Max.Dev.	RMS	Max.Dev.	RMS	Max.Dev.
1	72	142	7.3	24.8	9.0	33.4	26.7	60.0
2	72	142	5.0	19.5	7.0	30.5	12.1	36.8
3	36	135	6.4	20.0	9.0	31.9	15.7	37.1
4	36	133	9.0	24.9	8.2	30.5	15.0	63.0
5	7	84	15.0	30.8	13.9	47.3	23.9	63.7
6	7	95	7.1	22.8	16.1	35.2	25.2	59.0
7	7	92	9.9	37.6	21.1	70.8	24.9	91.5

Table 4: Accuracy of direct georeferencing (GPS/inertial solution from Stuttgart-LVA, 1:13000 imagery).

height is about 12cm (RMS) and the maximum deviations did not exceed 40cm in all coordinates (version 2). These results could be re-confirmed, processing the two 1:13 000 image blocks separately (versions 3 and 4). From 36 images and 135 and 133 re-computed check points, respectively, similar RMS values for the horizontal and vertical accuracy are obtained. Nevertheless, the maximum deviations are bigger than before. This is due to the fact, that only 15-folded image points (max.) could be used for point determination compared to up to 22 to 30-folded points using all 72 images. This effect becomes more clearly in calculating object points from one image strip only. This was done in versions 5 - 7, where the three long strips of the second 1:13 000 image block were considered separately. The maximum deviations rise up to 30cm - 90cm. Additionally, the RMS values are deteriorated up to 20cm in X, Y and 25cm in height. This might be caused by some remaining systematic in the exterior orientations, for example due to errors in the misalignment estimation.

6. CONCLUSION

Within this paper the results of a well controlled airborne testflight were presented. Although the evaluation of the test data is not finished yet, the presented internal and especially exterior accuracy indicates the great potential of direct georeferencing using the POS/DG GPS/inertial system in combination with a standard photogrammetric aerial camera. The obtained accuracy for object point determination is very high. For the 1:13 000 image block flown in standard cross pattern the order of magnitude corresponds to the theoretical accuracy of photogrammetric point determintion. For such a testflight design theoretical values of $\sigma_{X,Y}$ = 5cm and σ_Z = 10cm should be expected from AT (Kraus (1994)). As the obtained results of direct georeferencing can compete to these theoretical results of AT from a technical point of view, there are mainly economic reasons for a user to use direct georeferencing for his applications.

Nevertheless, the main risk of direct georeferencing is the dependency of the results on precise time alignment between the sensor components and a correct absolute GPS trajectory. Since GPS is the only sensor, which can be influenced from external sources and might be affected by remaining systematic errors, i.e. for longer baselines, this can become a problem for some applications. Additionally, if direct georeferencing is used, the proper system calibration becomes an issue of major importance. In this sense system calibration means determination of the spatial and rotational offsets between the sensor components, i.e. the misalignment between IMU and camera frame, and the interior orientation of the camera. Using directly measured orientation parameters for photogrammetric point determination the stability and correctness of the interior orientation of the imaging sensor is mandatory. As shown before, the correct calibration of the sensor system cannot be guaranteed a priory. Any error in the interior orientation elements will deteriorate the accuracy of

object point determination. From this point of view, the integration of the GPS/inertial exterior orientations in a combined AT provides the most flexible approach. This combination allows the control of the whole process by increasing the reliability of the system and gives the possibility for self-calibration of the camera, which is inevitable for highest photogrammetric accuracy demands. Additionally, the misalignment between IMU and camera can be estimated for each image block optimally and long term errors caused by constant shifts in the GPS trajectory are detected and corrected in the adjustment. Although AT is now re-introduced in the georeferencing process, the computational burden is still less compared to traditional AT without GPS/inertial observations. As the perspective centres are already known from GPS/inertial with very high accuracy, only very few points are necessary for the estimation of the additional parameters. Particularly, the time consuming measurement of large number of tie points is not necessary any more.
Will AT become obsolete or not? The test shows, that in principle direct georeferencing can fulfill highest accuracy requirements. From this point traditional aerial triangulation can be replaced by direct georeferencing. Nevertheless, in terms of reliability the combined approach should be recommended - at least to reconfirm the quality of the directly measured orientation parameters.

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8. REFERENCES

Ackermann, F. (1996): Experimental tests on fast ambiguity solutions for airborne kinematic GPS positioning. Proc. ISPRS Congress B6, pp. S1-S6.

Cannon, E. (1994): The use of GPS for GIS georeferencing: status and applications. Proc. ISPRS Congress Comm. IV, pp. 163-172.

Grün, A., Cocard, M. and Kahle, H.-G. (1993): Photogrammetry and kinematic GPS: Results of a high accuracy test. Photogrammetric Engineering and Remote Sensing (PE&RS), Vol. 59, No. 11, pp. 1643-1650.

Kaltenecker, A., Müller, F. and Hofmann, O. (1994): Digital Photogrammetric Assembly (DPA) - An airborne stereo and multispectral imaging and evaluation system. First Internat. Airborne and Remote Sensing Conference, pp. II/117-II/127.

Käser, C., Eidenbenz, C. and Baltsavias, M. (1998): Evaluation and testing of several digital photogrammetric systems for system Acquisition by national mapping agency. Proc. ISPRS Congress Comm. II, pp. 140-148.

Kraus, K. (1994): Photogrammetrie I, 5th edition, Dümmler Verlag.

Reid, D. B. and Lithopoulos, E. (1998): High Precision Pointing System for Airborne Sensors. Proceedings IEEE Position Location and Navigation Symposium (PLANS), pp. 303-308.

Sandau, R. and Eckert, A. (1996): The stereo camera family WAOS/WAAC for spaceborne/ airborne applications. International Archives of Photogrammetry and Remote Sensing, Vol. 31 Part B1, pp. 170-175.

Scherzinger, B. (1996): Inertial navigation error models for large heading uncertainty. Proceedings IEEE Position Location and Navigation Symposium (PLANS), pp. 121-130, April 1996.

Scherzinger, B. (1997): A position and orientation post-processing software package for inertial/GPS integration (POSProc). Proc. International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, pp. 197-204, Banff, Canada.

'Photogrammetric Week '99' D. Fritsch & R. Spiller, Eds., Wichmann Verlag, Heidelberg, 1999.

Schwarz, K.P. (1995): Integrated airborne navigation systems for photogrammetry, in Fritsch/Hobbie (eds.): Photogrammetric Week 1995, Wichmann Verlag, pp. 139-154.

Skaloud, J. and Schwarz, K.P. (1998): Accurate orientation for airborne mapping systems. In Proc. ISPRS Congress, Com. II, pp. 283-290, Cambridge.

Toth, C. (1998): Direct platform orientation of multisensor data acquisition systems. Int. Archives of Photogrammetry and Remote Sensing (IAPRS), 32-4, pp. 629-634.

Wewel, F., Scholten, F., Neukum, G. and Albertz, J. (1998): Digitale Luftbildaufnahme mit der HRSC - Ein Schritt in die Zukunft der Photogrammetrie. Photogrammetrie-Fernerkundung-Geoinformation (PFG), Vol. 6, pp. 337-348.