DIRECT EXTERIOR ORIENTATION OF AIRBORNE SENSORS - AN ACCURACY INVESTIGATION OF AN INTEGRATED GPS/INERTIAL SYSTEM

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ABSTRACT

By 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), many applications can be realized more efficiently and economically due to the reduction or elimination of required ground control and tie point information. Within this article a well controlled test comparing standard aerial triangulation and point determination with direct georeferencing is described to demonstrate the potential and accuracy of a commercially available integrated GPS/Inertial system.

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, this georeferencing processing 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 center of each image can be estimated as one group of the unknown parameters within a least-squares adjustment.

In the past 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 pushbroom scanners for the direct digital acquisition of photogrammetric imagery. A number of systems like the DPA (Kaltenecker, Müller and Hofmann (1994)), the WAAC (Sandau and Eckert (1996)), or the HRSC camera (Wewel, Scholten, Neukum and Albertz (1998)) consist of linear CCD arrays which are oriented perpendicular to the flight direction of the aircraft. As a result of the aircraft motion this configuration generates imagery by scanning the terrain surface strips (pushbroom principle).

For this application the use of direct georeferencing is indispensable in order to enable an operational and effective data processing. Due to the high dynamics of an airborne environment the exterior orientation is required for each scan line at very high frequencies in the order of 200Hz. This can only be realized by the direct measurement of the exterior orientation applying an integrated system consisting of receivers of the Global Positioning System (GPS) and a strap-down Inertial Measurement Unit (IMU).

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 significantly reduced 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 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 imagery is advantageous compared to aerial triangulation even if the additional costs of the IMU are considered. Firstly, 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. The second advantage of applying direct georeferencing is the removal of 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. Thirdly, problems of image matching which is 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 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 a commercially available integrated GPS/Inertial system was applied. After a short review on the integration of GPS/Inertial for direct georeferencing in the next section, the test flight design will be described in section 3, followed by the presentation of the practical results in section 4. In order to profit from the advantages of both techniques, the integration of GPS/Inertial processing and aerial triangulation is another point of major interest. A short outlook will be given in the concluding part of the paper.

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 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, a positioning accuracy up to 10 cm is possible for airborne cinematic environments with remote-master receiver separation below 30 km. 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 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 accuracy of IMU is 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 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 the spatial offsets between the different sensor components have to be applied. 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 computation of 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. As far as there are no rotations between IMU and imaging sensor these angles should remain constant.

2.2 Sensor Configuration

The tested integrated GPS/Inertial system is the POS/DG 310 developed by Applanix Corp. of Markham, ON Canada (Scherzinger (1997)). It 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 PosProc 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.

2.3 Software Configuration

For our test the integration of the GPS/Inertial raw data was done using the Applanix PosProc software. This software performs an optimal integration of the GPS observations and the IMU measurements. First the mechanization of the IMU data and the integration with the update information from GPS is realized in a Kalman filter approach. In a second step a smoothing computes a blended solution from the data obtained in the previous step. A further key function of the system is the in-air alignment capability, avoiding a long static initialization period prior to the flight. The initial alignment is 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 integrated GPS/Inertial system for the direct measurement of exterior orientation, a photo flight was carried out over 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.

Aerial imagery was captured at a flying height of 1000m and 2000m above ground, resulting in two different image scales of 1:6000 and 1:13000. 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 1:13000 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 1:6000 scale imagery was acquired once, followed by the two identical 1:13000 blocks and the second 1:6000 flight. Overall, 104 images were captured in a period of 1.5h. Table 1 shows the sequence of data capture during the test flight in chronological order. The aircraft trajectory is depicted in Figure 1.

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), two stations in Stuttgart (25km), one in Karlsruhe (40km), Frankfurt (130km), München (210km), Bonn (230km) and finally Hannover (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 the photo flights. Therefore, the in-air alignment manoeuver could not be used for the initial alignment of this particular reference station.

Action	Start time	End time
Static alignment	9:40h	09:48h
Start in Münster	9:57h	
In-air alignment	11:00h	11:13h
Image flight 1:6000	11:23h	11:27h
Image flight 1:13000	11:36h	12:01h
Image flight 1:13000	12:26h	12:52h
Image flight 1:6000	13:00h	13:05h
Landing in Stuttgart	13:16h	
Static alignment	13:18h	13:25h

Table 1, Sequence of data acquisition

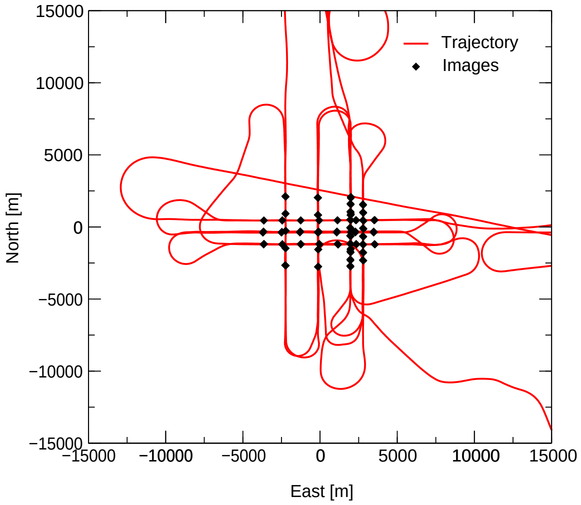

Figure 1, Aircraft trajectory, Vaihingen/Enz (17.12.99)

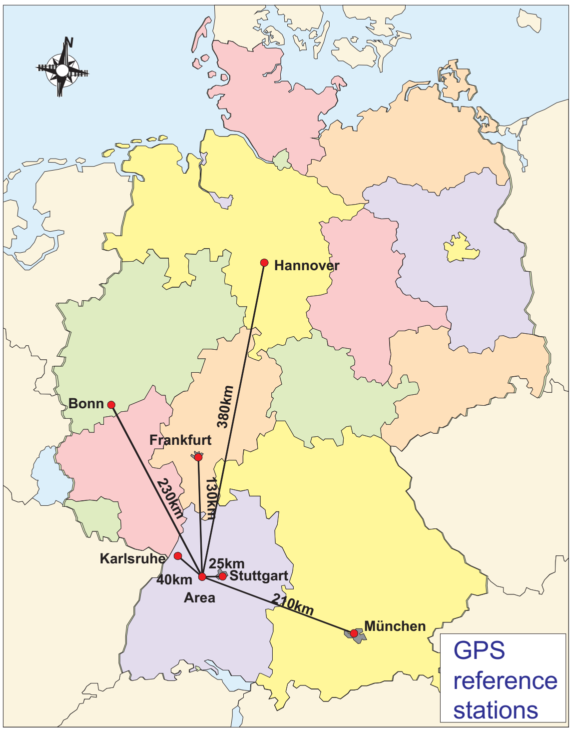

Figure 2, GPS reference stations for Stuttgart test area

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.

3.1 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 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 1:13000). For the 1:6000 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 1:13000 images. For the 1:6000 block the attiudes 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 at least two times 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 by the AT with standard deviations of less than 10cm for the horizontal and the vertical coordinates. Those points are used as check points for testing the overall performance of direct georeferencing for photogrammetric point determination.

3.2 Comparison of georeferencing for different GPS baselines

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 the limiting factor for the overall accuracy of direct georeferencing. This was our motivation to perform a more thorough investigation of the system accuracy which can be obtained for different GPS baselines.

During carrier phase differential positioning fast ambiguity solutions, also known as OTF (on the fly) methods provide continuos GPS trajectories by correctly restoring the ambiguity values. Still, these approaches realized in a number of software systems do not give always successful solutions if the distance between roving and stationary GPS receivers is large. It is understood, more or less, to remain within distances of 50km, preferably 30km, in order to be safe. For economic reasons baselines of up to several 100km would be highly desirable. Tests on fast ambiguity solutions for airborne kinematic GPS positioning, examining the effects of different baselines have already been reported (Ackermann (1996)). We want to continue this work by examining the effects of larger baselines for systems which are capable of direct georeferencing. For this reason the data of 8 different base stations with distances varying from 0 km to 380 km were acquired for the processing of the test data as depicted in Figure 2.

4 TEST RESULTS

4.1 Interior accuracy

As a first step the different solutions of the GPS trajectories for the available baselines which were computed using the GrafNav Software, version 5.06 (Waypoint Consulting) were compared. The GPS trajectory calculated using the Stuttgart-LVA master station served as reference solution. Despite the large variations of the baseline distances 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 internal accuracy for the velocities is in the range of 2-8cm/s. The maximum position differences do not exceed 50cm, the velocity differences do not exceed 60cm/s. Nevertheless, the Karlsruhe solution (40km baseline) performs much worse. Due to radio interference problems, the GPS data were corrupted and could not be processed properly. Therefore, this baseline is excluded from further processing.

Of course these good GPS results will have to be verified for different conditions, still the result is very encouraging. For our test data in principle each reference station that provides undisturbed GPS data can be used for the further processing. The expected strong dependency of the achievable accuracy on the distance to the GPS reference station could not be verified.

In the second processing step the GPS/Inertial data were integrated applying the PosProc software of Applanix Corporation. The software combines the pre-computed results of the GPS processing (position and velocities) and the IMU data within a Kalman filter. In our configuration the following parameters were estimated:

Base length [km]	RMS [cm]		Max. Dev. [cm]	
	Hor.	Vert.	Hor.	Vert.
0	5.7	9.4	36.5	17.8
25	1.8	8.5	7.9	13.5
130	5.8	17.1	14.7	39.0
210	11.2	21.9	26.1	47.0
230	12.2	8.1	18.0	22.6
380	10.4	12.1	19.7	25.3

Table 2, Internal differences of GPS/Inertial positions

Base length [km]	RMS [$\cdot 10^{-3}$ °]			Max. Dev. [$\cdot 10^{-3}$ °]		
	ω	φ	κ	ω	φ	κ
0	0.4	4.1	4.3	3.5	56.3	30.4
25	<0.1	<0.1	0.3	0.3	0.5	0.8
130	0.1	0.2	0.9	0.8	1.8	2.4
210	0.3	0.4	1.2	1.8	2.4	3.3
230	0.2	0.3	0.7	1.4	1.3	2.2
380	0.1	0.2	1.0	0.7	1.2	2.8

Table 3, Internal differences of GPS/Inertial orientations

- navigation errors (3 position errors, 3 velocity errors, 3 alignment errors)
- 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 error of the GPS trajectory used to update the Kalman filter (3 positions, 3 velocities) was modelled as a first order Gauss-Markov process.

To check the accuracy between the different solutions the position and attitude differences were calculated. The internal differences of the solutions for available baselines are depicted in Tables 2 and 3. Within the tables the solution using the GPS master station Stuttgart-LVA located at a distance of 25km to the test area served as reference again.

As shown before the different GPS trajectories fit to each other very well. For this reason the solutions of GPS/Inertial integration provided by the Kalman filtering and smoothing are also very consistent. The RMS values for the positions are in the range of 1dm and 2dm for horizontal and vertical components, respectively. For the attitude differences, these values are between 0.0001°-0.001°. 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 (see Table 2 and 3).

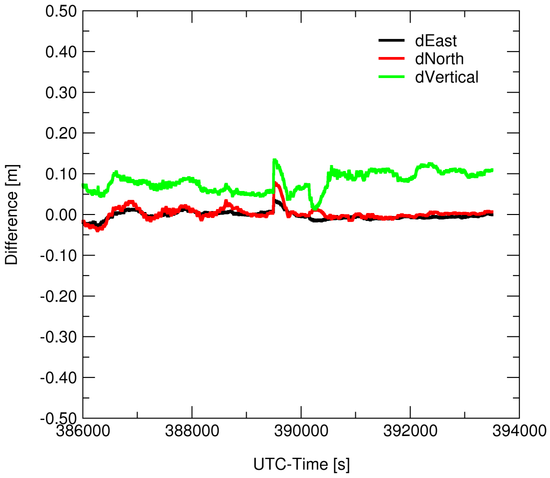

Figure 3, GPS/Inertial position differences
(Stuttgart-LVA - Stuttgart-Uni)

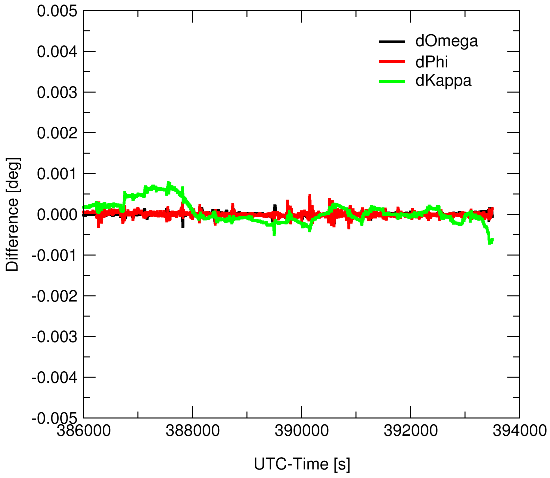

Figure 4, GPS/Inertial attitude differences
(Stuttgart-LVA - Stuttgart-Uni)

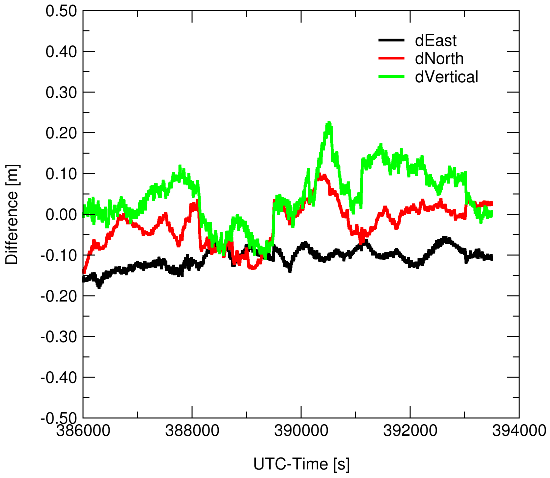

Figure 5, GPS/Inertial position differences
(Stuttgart-LVA - Bonn)

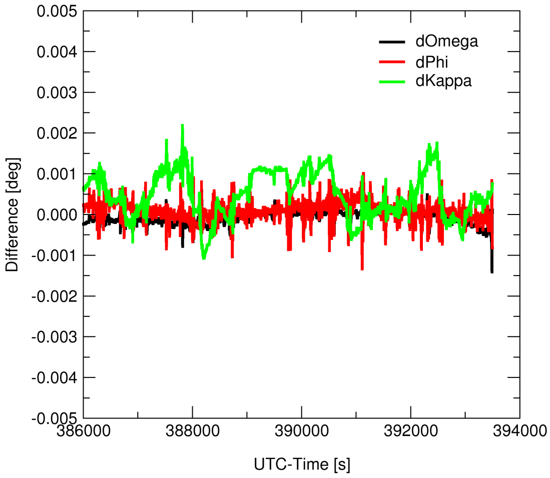

Figure 6, GPS/Inertial attitude differences
(Stuttgart-LVA - Bonn)

As an example, Figures 3 and 4 depict the position and attitude differences for the aircraft trajectories computed from Stuttgart-LVA and Stuttgart-Uni. As the baseline length to the testsite is about 25km for both stations and the distance between the GPS master stations is only within a few hundreds of meters, both solutions should provide the same position and attitude information, theoretically. As it can be seen, the position differences are quite small, their accuracy is about 1cm (STD) for the horizontal and 2cm (STD) for the vertical coordinates. Nevertheless, a significant offset of about 10cm can be seen in the vertical component. This was due to some erroneous antenna phase centre corrections. Additionally, sharp jumps of about 10cm size are visible. They are due to different GPS ambiguity solutions for the two baselines. Similar jumps can be seen in the Stuttgart-LVA - Bonn difference plot (Figure 5). 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 PosProc 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 small cycle slips properly.

Compared to the position variations the attitude differences are very small. The maximum deviations are below 0.001° for the 25km baseline difference. Even for the 230km long baseline they did not exceed 0.0025° (Figure 6). Such an attitude error of about $2.5 \cdot 10^{-3}$ ° will result in an error in object space well below 10cm assuming a flying height of 2000m above ground. Comparing this attitude error effect to the maximum position deviations of about 2dm for the 230km base, the influence caused by position errors is factor twice larger. Similar effects can be seen for the other baselines, too (Tables 2,3). This result verifies the statement mentioned in Section 3.2, that GPS positioning accuracy seems to be the limiting factor for the overall GPS/Inertial exterior orientation performance. Nevertheless, it has to be proven with the absolute accuracy tests, comparing the GPS/Inertial exterior orientations to the reference values from photogrammetry.

4.2 Exterior accuracy

One main condition before using the GPS/Inertial orientations for any sensors to be oriented is the precise time alignment between the different sensors. 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 up to now, the time offset was estimated comparing the perspective centres from photogrammetry to the coordinates from POS/DG. Dividing the absolute value of the displacement vector by the actual aircraft velocity gives an approximation for the time offset between GPS/Inertial orientation module and camera system. Using this method a time delay of about 53msec could be determined with a RMS value of 2msec. The following exterior accuracy tests were performed using this 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. Therefore, this offset will be reconfirmed by measuring the length of the pulse using appropriate electronic devices in future.

The exterior accuracy is tested comparing the positions and orientations of the camera air stations provided from POS/DG to the results obtained from aerial triangulation. In order to relate both values, the spatial and rotational offsets between camera and IMU - determined during misalignment calibration - were applied and the camera exposure times were interpolated into the 50Hz GPS/Inertial trajectory using a third-order polynomial. The misalignment angles were corrected using the mean values from the attitude differences at the 32 1:6000 images.

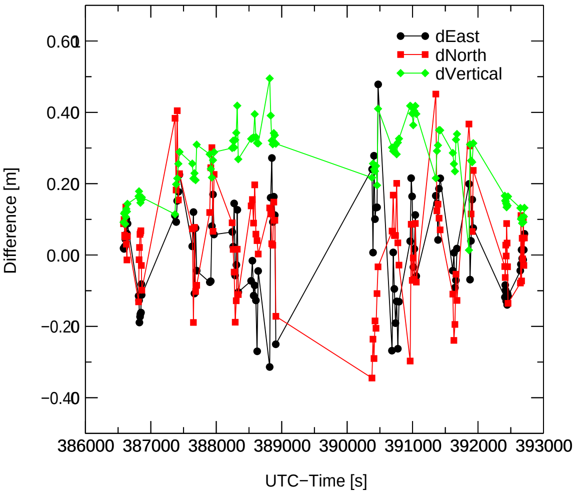

Figure 7, Position variations of direct georeferencing compared to aerial triangulation at camera air stations

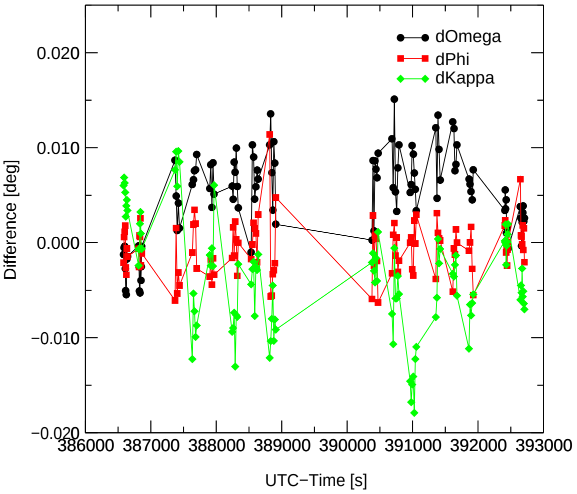

Figure 8, Attitude variations of direct georeferencing compared to aerial triangulation at camera air stations

Image scale	Statistical parameter	Value [cm]		
		dEast	dNorth.	dVertical
6000	RMS	9.9	7.1	13.5
6000	Max.Dev.	18.9	13.5	17.8
6000	Mean	-5.0	1.4	13.2
6000	Std.Dev.	8.5	6.9	2.6
13000	RMS	15.1	17.5	30.8
13000	Max.Dev.	47.8	45.1	49.2
13000	Mean	3.3	4.0	30.0
13000	Std.Dev.	14.7	17.0	7.4

Table 4, Absolute accuracy of GPS/Inertial positions (Stuttgart-LVA, 25km)

Image scale	Statistical parameter	Value [$\cdot 10^{-3}$ °]		
		$d\omega$	$d\varphi$	$d\kappa$
6000	RMS	3.0	2.0	3.9
6000	Max.Dev.	5.6	6.7	7.0
6000	Mean	0.0	0.0	0.0
6000	Std.Dev.	3.0	2.0	3.9
13000	RMS	7.8	3.2	7.7
13000	Max.Dev.	15.1	11.4	17.9
13000	Mean	7.1	-0.9	-5.1
13000	Std.Dev.	3.2	3.0	5.8

Table 5, Absolute accuracy of GPS/Inertial attitudes (Stuttgart-LVA, 25km)

Using the two 1:13000 and 1:6000 image flights, the accuracy could be obtained from 72 and 32 discrete camera air stations. The POS/DG exterior orientations were calculated from the Stuttgart-LVA GPS/Inertial trajectory. The 104 differences for positions and attitudes are given in Figures 7, 8. The corresponding statistical values are listed in Tables 4 and 5. As the reference values from photogrammetry are dependent on the image scale, the statistical values (RMS, Max.Dev., Mean, Std.Dev.) are calculated for the 1:13000 and 1:6000 image block, seperately.

As one can see from Figure 7 and Table 4, the RMS values in camera positions are about 15cm horizontally and 30cm vertically for the 1:13000 scale and about 10cm and 15cm for the 1:6000 images, respectively. Nevertheless, there is a significant offset visible in the vertical coordinate. This offset is not constant but differs with the image scale. The size of this offset is about 30cm for the 1:13000 photos and about 13cm for the 1:6000 image scale which is more or less of the same ratio as between the two image scales. Therefore, this offset might be caused by variations in the interior orientation of the photogrammetric camera although such errors are quite unusual due to the stable geometry of the camera frame. Our investigations showed, that an induced error in the focal length of the camera of about 20μm will cause the detected errors in the vertical component of the persepective centres. Reducing these systematic offsets in the coordinates, the standard deviations come down to 7cm and 3cm for the 1:13000 and 1:6000 images. This is most likely what one can expect from the photogrammetric reference values.

The RMS values for the camera attitudes are within 10 arc sec, 7 arc sec, 14 arc sec (1:6000) and about 28 arc sec, 12 arc sec, and 28 arc sec (1:13000) for omega, phi and kappa, respectively (Table 5, Figure 8). As the mean offset from the 1:6000 camera stations was used for the misalignment determination the RMS values are better than the accuracy for the 1:13000 image block. In especially, in the ω and κ component significant offsets of about $7 \cdot 10^{-3}$ ° and $-5 \cdot 10^{-3}$ ° are visible for the 1:13000 image scale. Taking these offsets into consideration, the standard deviation for the omega and kappa angle come down to about 12 arc sec and 20 arc sec which is approximately of the same size than for the 1:6000 images. This shows that the correct determination of the misalignment is a very demanding task and has to be solved as precise as possible. Any errors in the misalignment between IMU and camera will cause errors in object point determination using the GPS/Inertial orientations for direct georeferencing. Nevertheless, correcting the systematic position and attitude shifts, the position and attitude differences are randomly distributed and no time dependent effects are visible. Within the available time period of about 1.5h the systematic IMU error effects could be eliminated by the frequent updates from the GPS observations very effectively.

To assess the overall georeferencing performance of the complete sensor system the terrain coordinates of the signalized points could be determined by spatial intersection applying their corresponding image coordinates and the exterior orientation from by direct georeferencing. This corresponds to a photogrammetric point determination, where aerial triangulation is replaced by direct georeferencing. These results are presently being calculated and will be presented during the workshop.

5 CONCLUSION

Within this paper the first results of a well controlled airborne testflight could be given. Although the evaluation of the test data is in its first stage, the presented internal and exterior accuracy show the great potential of direct georeferencing using a commercially available integrated GPS/Inertial system in combination with a high quality aerial camera. The results are confirmed by a similar test, which was flown in February 1998 over a test field near Cologne. Within this test an accuracy of direct georeferencing for point determination of about 2dm from an altitude of 2000m could be achieved. This accuracy is sufficient for many applications. The order of magnitude corresponds to the theoretical accuracy of photogrammetric point determination by standard aerial triangulation (Kraus (1991)). For our test configuration a theoretical value of $\sigma_{X,Y}$ = 8cm and σ_Z = 20cm can be expected. In our opinion the results of direct georeferencing are comparable to the results of aerial triangulation from a technical point of view, so there are mainly economic reasons for a user to use AT or 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 GPS trajectory as shown in Section 4.1. Since GPS is the only sensor, which can be influenced (and disturbed) from external sources this can become a problem for some applications. Additionally, if direct georeferencing is applied, the proper calibration of the imaging sensor becomes an issue of major importance also (Section 4.2). In our current work we are aiming on the integration of GPS/Inertial and aerial triangulation in one software system, which represents the most flexible approach of georeferencing. The main goal during the combination is the control of the whole process by increasing the reliability of the system, the possibility for self-calibration of the camera, which is inevitable for highest accuracy demands, and the control (and determination) of additional calibration parameters for the GPS/Inertial system, for example the misalignment estimation between IMU and camera, or the correction of long term errors caused by constant shifts in the GPS trajectory.

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