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Performance of GPS/Inertial Solutions in Photogrammetry

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ABSTRACT

Within the last five years extensive research was done using integrated GPS/inertial systems for the direct georeferencing of airborne sensors for high-end applications. Pushed by the development and practical use of digital sensor systems, originally started with laser scanner systems and followed by imaging multi-line pushbroom scanners, direct georeferencing offers the only way for an efficient sensor orientation process. Nonetheless, even for standard frame based camera systems, digital or analogue, the use of direct orientation measurements is useful in especially in – from a photogrammetric point of view – unfavourable applications like corridor surveys or single model orientation. In the ideal case using direct exterior orientation elements with sufficient accuracy image orientation without any ground control is possible. Within this paper the basic principles of GPS/inertial systems and integration are summed up and the use of integrated systems in airborne environments is discussed, where the main emphasis is laid on the combination with standard analogue frame cameras. The empirical results of different well controlled test flights are used to illustrate the today's performance of direct georeferencing based on high-end integrated systems. Additionally, a combined GPS/inertial-AT or integrated sensor orientation approach is presented which allows the in-situ calibration of certain system parameters even without ground control and therefore provides highest flexibility to overcome the most limiting factor of direct georeferencing: uncorrected errors in the overall system calibration. Finally, the use of directly measured exterior orientations in model orientation and DEM generation is investigated.

1. INTRODUCTION

GPS/inertial integration and its application for sensor orientation is a subject discussed in several papers within the last three Photogrammetric Weeks. Re-reading these articles again the continuous evolution from first integrated systems developed in research projects to the today's commercial off-the-shelf high-end systems for direct georeferencing is clearly visible. Starting in 1995 Schwarz (1995) gave a substantial contribution on the principle of GPS/inertial integration and the design considerations for integrated systems in airborne environments. Two years later this topic was picked up in the one day Phowo tutorial entitled "GPS/INS in photogrammetry" again and in Cramer (1997) empirical test results using experimental integrated systems were presented for the orientation of airborne analogue frame cameras and digital line scanners. Again, two years later the first commercial GPS/inertial systems for high-end applications were available (Lithoupolous 1999) and since then the main focus was laid on the extensive quality testing of such systems in standard airborne environments. The result of such a well controlled test was given in Cramer (1999), where Neukum (1999) presented the quasi operational use of a commercial GPS/inertial system in combination with a multi-line pushbroom airborne camera. Additionally, during the last Photogrammetric Week an international test on integrated sensor orientation using GPS/inertial systems was initiated by the European Organisation for Experimental Photogrammetric Research (OEEPE). Besides practical issues for optimal system integration one main topic of this still ongoing test is laid on the question if and under which conditions direct georeferencing based on integrated GPS/inertial systems is a substitute for classical aerial triangulation. As one can see the question "Will aerial triangulation become obsolete?" reflecting the future role of integrated systems in the photogrammetric workflow is still in dispute. This gives the motivation to discuss the current status of the performance of GPS/inertial solutions for airborne photogrammetric use again.

2. GPS/INERTIAL INTEGRATION AND SENSOR ORIENTATION

2.1. GPS/inertial integration

The benefits of GPS/inertial integration are well known in the meantime: Since both sensor systems are of almost complementary error behaviour the ideal combination will provide not only higher positioning, velocity and attitude accuracy but also a significant increase in reliability, as both systems are supporting each other: The inertial system can help GPS by providing accurate initial position and velocity information after signal loss of lock. Even during satellite outages where the number of visible satellites drops below four INS will provide continuous trajectory information. On the other hand the high absolute performance from GPS can help the inertial navigation system with accurate estimates on the current behaviour of its error statistics. In Kalman filtering used in traditional navigation approaches the internal INS errors are modelled as gyro drifts and accelerometer offsets. These sensor specific errors are estimated together with additional error states describing the navigation errors in position, velocity and attitude. In more enhanced approaches the 15 state error model mentioned before is refined with e.g. gyro and accelerometer scale factors, time variable drifts and error terms describing the non-orthogonality of the inertial sensor axes. Using integrated GPS/inertial systems for high-quality direct georeferencing, models consisting of 15-25 error states are generally used.

2.2. Sensor georeferencing

With the availability of integrated GPS/inertial systems of sufficient accuracy the direct measurement of the fully exterior orientation of any sensor during data recording becomes feasible, which offers an interesting alternative to the standard indirect approach of image orientation based on classical aerial triangulation. Unfortunately, since the GPS/inertial orientation module is physically separated from the sensor to be oriented translational offsets and rotations are existent and have to be considered in addition to the correct time alignment between the different sensor components. Except for the additional misalignment correction (so-called boresight alignment) between inertial sensor axes and corresponding image coordinate frame the correction of time and spatial eccentricities is similar to the general practice in GPS-supported aerial triangulation, where the lever arm has to be determined to reduce the GPS position related to the antenna phase centre on top of the aircraft's fuselage to the desired camera perspective centre. Most likely, the lever arm components between the GPS antenna, the centre of the inertial measurement unit and the camera perspective centre are measured a priori and the appropriate translational offsets are already considered during GPS/inertial data processing. Therefore, the final positioning information from GPS/inertial integration mostly directly refers to the camera perspective centre. Taking this assumption into account the general equation for direct georeferencing which transforms points from the sensor or imaging frame P to the corresponding points defined in a local cartesian object coordinate frame L is given as follows (Equation (1)).

$$\begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix}_L = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}_L + \lambda \cdot R_B^L(\omega, \varphi, \kappa) \cdot \Delta R_P^B(\Delta\omega, \Delta\varphi, \Delta\kappa) \cdot \begin{bmatrix} x_p \\ y_p \\ -f \end{bmatrix}_P \tag{1}$$

This equation is based on the well known spatial similarity transformation also used for standard indirect image orientation supplemented with an additional rotation matrix ΔR_P^B as a function of the boresight alignment angles $\Delta\omega, \Delta\varphi, \Delta\kappa$ rotating the image vector ($x_p, y_p, -f$)^T from the photo coordinates P to the body-frame system B. The rotation is necessary since the directly measured orientation angles refer to the body-frame system defined by the inertial sensor axes and not to the image coordinate system. This is different from the indirect approach. Although a first raw alignment of both coordinate frames is tried during system installation manually, misorientations – typically in the size of a few tenth of a degree – remain and have to be compensated numerically during boresight correction. The final rotation angles ω, φ, κ are derived from the GPS/inertial attitude data. After R_B^L rotation and subsequent scaling of the image vector the translation (X_0, Y_0, Z_0)^T based on the reduced and transformed GPS/inertial position measurements results in the final object point coordinates. This modified spatial similarity transformation describes the basic mathematical model not only for direct georeferencing but also for a general combined GPS/inertial-AT approach for image orientation. Similar to standard aerial triangulation the modified model may be expanded with additional unknowns to allow the overall system calibration which will be illustrated in more details in Section 2.4.

2.3. Coordinate frames and attitude transformation

Within the previous sub-section one major point was not considered: The orientation angles from GPS/inertial are not comparable to the photogrammetric angles ω, φ, κ and therefore cannot be used to build up the R_B^L matrix directly. Since INS and integrated GPS/inertial systems originally were designed for navigation purposes the computed attitudes are interpreted as navigation angles roll r, pitch p, yaw y. At a certain epoch t_i these navigation angles are obtained from a matrix $R_B^{N(t_i)}$ at time t_i rotating the inertial body frame to the so-called navigation frame N which is a local system whose origin is located in the centre of the inertial sensor axes triad. Since the INS is moving relatively to the earth's surface this local frame is not constant but moving with time, therefore the x-axis of this local navigation frame always points to the local north direction where the z-axis follows the local plumb line pointing down and the y-axis completes the right hand frame. In contrary to this, the photogrammetric image orientation angles from indirect image orientation based on the collinearity equation are obtained from a transformation between the sensor frame (photo coordinates) and a fixed cartesian earth related local system normally defined as an east-north-up coordinate system. The origin of this local frame is given with its geographic coordinates Λ_0, Φ_0 and therefore clearly differs from the moving local navigation frame. Hence, the conversion of navigation angles is necessary to enable the image orientation based on the equation mentioned above.

One possible way to transform the navigation angles to photogrammetric attitudes is realized via the cartesian earth-centred earth-fixed coordinate system to connect the time variable local navigation frame $N(t_i)$ with moving origin (time varying position Λ_i, Φ_i), and the fixed photogrammetric local coordinate system L. Now, the following Equation (2)

$$R_B^L(\omega,\varphi,\kappa) = R_{N(t_0)}^L(\pi,0,-\frac{\pi}{2}) \cdot R_E^{N(t_o)}(\Lambda_0,\Phi_0) \cdot R_{N(t_i)}^E(\Lambda_i,\Phi_i) \cdot R_B^{N(t_i)}(r,p,y) \qquad (2)$$

is found defining the transformation from the observed navigation angles r, p, y to the photogrammetric angles ω, φ, κ. The rotation matrix $R_{N(t_0)}^L$ is obtained from the composed two elementary rotations $R_1(\pi) \cdot R_3(-\pi/2)$ to align the different axes directions between the local navigation system N and the photogrammetric local frame L. In case the axes directions between inertial body frame B and imaging coordinate frame P do not coincide an additional correction matrix R_P^B similar to the axes alignment rotation before has to be considered at the right end of the matrix product. A slightly different solution to this transformation problem and additional information on the definition of the different coordinate frames is given in Bäumker & Heimes (2001).

2.4. System calibration

One inherent problem in image orientation is the overall system calibration. Any discrepancies between the assumed mathematical model used in the orientation process and the true physical reality during image exposure will cause errors in object point determination. This problem appears in traditional indirect as well as in direct image orientation but in the second approach based on GPS/inertial measurements system calibration gains in importance significantly. In classical aerial triangulation additional parameters like mathematical polynomials (e.g. Ebner 1976, Grün 1978) or – alternatively – physical relevant parameters (e.g. Brown 1971, originally designed for use in terrestrial photogrammetry) are used to fit the physical process of image formation with the assumed mathematical model of central perspective. For direct georeferencing especially the modelling of the interior geometry of the imaging sensor is of major importance since GPS/inertial now provides direct measurements of the true physical camera position and orientation during exposure whereas in bundle adjustment the exterior orientations are estimated values only. Although these values are optimal values from an adjustment point of view they might differ significantly from the physically valid parameters due to the strong correlation with the interior orientation of the camera and the additional parameters for self-calibration. Due to the perfect correlation between camera focal length and vertical component a small difference of about 20μm between assumed focal length from lab-calibration and true focal length during camera exposure for example will result in a systematic height offset of about 20cm for 1:10000 image scale. Besides the already mentioned parameters for self-calibration and boresight alignment calibration, additional corrections for subsequent correction of directly measured positioning or attitude data are considered. This is similar to standard GPS-supported aerial triangulation where additional constant offsets or linear drifts are used to compensate systematic errors in the GPS positions – if present. Therefore, Equation (1) is completed like follows (Equation (3)),

$$\begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} = \begin{bmatrix} X'_0 \\ Y'_0 \\ Z'_0 \end{bmatrix} + \sum_{i=0}^{n} \begin{bmatrix} a_i \\ b_i \\ b_i \end{bmatrix} \cdot \ t^i \qquad \begin{bmatrix} \omega \\ \varphi \\ \kappa \end{bmatrix} = \begin{bmatrix} \omega' \\ \varphi' \\ \kappa' \end{bmatrix} + \sum_{i=0}^{n} \begin{bmatrix} u_i \\ v_i \\ w_i \end{bmatrix} \cdot \ t^i \tag{3}$$

where t^i denotes the time and (a_i, b_i, c_i), (u_i, v_i, w_i) are the terms for position and attitude correction, respectively. The index n determines the order of the correction polynomial. Such offsets or linear correction terms are introduced to eliminate remaining influences of systematic positioning and attitude offsets or first order effects if necessary. Although such errors should not be expected for high quality integrated systems, unfavourable GPS satellite constellations during data acquisition, longer base lines or – very simple – errors in the GPS reference station coordinates or antenna phase centre correction can cause errors in the integrated positions. Additionally, if the quality of the GPS data is not sufficient to completely eliminate the internal systematic inertial errors this will affect the quality of GPS/inertial attitude determination. This scenario shows the relevance of the correction terms given in Equation (3). Under ideal circumstances, if optimal GPS/inertial data are available, the unknowns (u_0, v_0, w_0) are used to estimate the boresight alignment angles. In case Equation (1) is expanded with low order correction polynomials given in Equation (3) the boresight alignment can be replaced with the attitude offset correction since both values are redundant and non separable from the $R_B^L \cdot \Delta R_P^B$ rotation matrix product. Equations (1) and (3) are the basic mathematical formulas to realize a combined GPS/inertial bundle adjustment. In combination with the usual additional parameter sets (preferable modelled as physical relevant and interpretable parameters as proposed by Brown) such a general approach provides the best opportunity for an optimal overall system calibration. The potential of such a combined or integrated approach of sensor orientation is discussed in Section 4.

3. PERFORMANCE OF DIRECT SENSOR ORIENTATION

The investigation of the accuracy performance of integrated GPS/inertial systems for direct sensor orientation was one major topic of research during the last years. In especially at the Institute for Photogrammetry (ifp) extensive test flights were done since 1998 to evaluate the potential and accuracy performance of GPS/inertial systems, where the main focus was laid on the combination of commercial high-end systems with standard analogue aerial frame cameras. Since the images were captured over a well surveyed test site close to Stuttgart (Vaihingen/Enz, size 7km x 5km), the standard method of aerial triangulation was applied to provide independent values for comparison with the exterior orientations from GPS/inertial. Nonetheless, one has to be very careful calling these values reference values since they are estimated values highly correlated with the interior orientation of the camera or non-corrected systematic errors in the model and might differ from the true physical orientation parameters as already mentioned. Therefore, the overall system quality is obtained from check point analysis, where object points are re-calculated using spatial forward intersection based on the known exterior orientations from GPS/inertial and compared to their pre-surveyed reference coordinates. Within this spatial intersection the directly measured exterior orientations are handled as fixed values, i.e. with very small standard deviations $\rightarrow 0$. Before direct georeferencing is performed the boresight alignment is determined from analyzing the attitude differences at a certain number of camera stations. Since for the ifp test flights no spatially separated calibration test site was available this boresight calibration was done within the actual test area which might result in slightly too optimistic accuracy numbers. Generally the calibration site is different from the desired mission area. This topic is discussed in Section 4.

Within the ifp test flights the two only currently available commercial high-end GPS/inertial systems were tested under similar airborne environments. During the first campaign in December 1998 the POS/AV 510 DG – formerly called POS/DG 310 – from Applanix, Canada (Reid & Lithopoulos 1998) was flown, about 15 months later in June 2000 a similar test was done using the AEROcontrol IId system from IGI, Germany (Kremer 2001). Both systems were also used within the OEEPE test as described in more details in Heipke et al. (2001). Since the test configurations and results from the Vaihingen/Enz test flights are already published in detail (Cramer 1999, Cramer et al. 2000, Cramer 2001) only the main results and conclusions are summed up here.

- The tests have shown, that for medium image scales (1:13000, wide-angle camera), the obtained accuracy (RMS) in object space is about 5-20cm for the horizontal and 10-25cm for the vertical component. Using large scale imagery from lower flying heights above ground (1:6000, wide-angle camera) results in slightly better object point quality. The accuracy numbers mentioned above are obtained from the Vaihingen/Enz test site and are reconfirmed with similar results from the OEEPE flight data. Most likely, both independently checked GPS/inertial systems provided quite similar accuracy performance.
- The quality of object point coordinates from direct georeferencing is dependent on the number of image rays used for object point determination. A large image overlap providing a strong block geometry positively influences the point accuracy since multiple image rays can compensate remaining errors in the orientation parameters. From the object point accuracy

mentioned above the higher accuracy bound corresponds to blocks with high overlaps where the lower accuracy should be expected from object point determination from 2-3 folded points from single flight strips.

- The overall system quality is mainly dependent on the correct overall system calibration, including the orientation module and the imaging component. In this case especially the vertical component seems to be critical. In several test flights systematic and, moreover, scale dependent offsets in the vertical coordinate of object points were present, which might be due to small inconsistencies between the assumed camera focal length from calibration and the true focal length during the flight. Additionally, uncorrected influences of refraction will cause the same systematic effects. Besides the essential boresight alignment calibration the precise determination of these effects is mandatory before the system is used for direct georeferencing, otherwise they will affect the system performance significantly. Most likely, this calibration will be determined within a small calibration block and then used for the subsequent test areas, unfortunately the stability of system calibration over a longer time period and the quality of calibration transfer between calibration site and mission area is not proven yet and is under current investigation. Nonetheless, in an ideal scenario the calibration should be performed in the mission area directly, preferable without any ground control. Such an in-situ calibration results not only in significant cost savings since no additional effort for flight and data processing is necessary for the calibration blocks, also the optimal calibration parameters valid for the desired test area could be determined.

4. PERFORMANCE OF INTEGRATED SENSOR ORIENTATION

The combined georeferencing using AT and integrated GPS/inertial exterior orientation measurements is based on the mathematical formulas given in Equations (1) and (3). As already pointed out, this model is expanded with additional parameter sets used for self-calibration like in traditional aerial triangulation. This approach provides highest flexibility for system calibration and combined object point determination. The potential and requirements are illustrated within the following example and compared to standard AT and direct georeferencing.

4.1. Test data set

To show the potential of combined GPS/INS-AT for system calibration and point determination the results of one of the calibration blocks from the OEEPE test data sets are depicted in the following. This medium scale (1:10000) image block consists of 5 strips, two of them flown twice. Altogether 85 images (60% long and side overlap, wide-angle camera) were captured during the flight using an analogue aerial camera. For direct georeferencing high quality GPS/inertial data are available, where the boresight angles have been corrected already. Within this paper the results from the GPS/inertial data provided by the Applanix POS/AV system are given only. For quality tests the coordinates of 13 well distributed independent object points with a positioning accuracy of 1cm were available. These points were used for the estimation of the overall exterior system performance. Within the empirical tests object point determination is done in different versions. The results of the several test runs are given in Table 1 and discussed in the following.

4.2. Results from aerial triangulation

Following the rule of thumb (Kraus 1990) the theoretical accuracy to be expected from aerial triangulation assuming a wide-angle camera and signalized points is in the range of $\sigma_{X,Y} = \pm 4\mu m$ (in image scale) and $\sigma_Z = \pm 0.005\%$ of flying height above ground corresponding to an object point

#	Configuration (+ additional parameters)	GCP/ ChP	$\hat{\sigma}_0$ [μm]	RMS [cm]			Max.Dev. [cm]		
				ΔX	ΔY	ΔZ	ΔX	ΔY	ΔZ
1a	GPS-AT	4/9	6.5	5.6	4.8	21.0	9.6	7.9	31.7
1b	GPS-AT + self-calibrat. (SC)	4/9	4.7	4.2	5.3	9.0	8.3	10.3	18.4
2a	DG	0/13	23.0	16.6	18.6	23.2	29.0	37.7	44.9
2b	DG + boresight alignm. (BA)	0/13	10.8	9.0	7.8	23.0	16.4	16.8	39.5
2c	DG + SC (no focal length c)	0/13	9.7	8.9	7.3	19.9	13.6	12.9	39.6
2d	DG + c, x_p, y_p	1/12	9.8	8.8	7.1	13.7	12.9	13.3	30.8
2e	DG + SC	1/12	9.7	8.6	7.2	13.2	13.5	12.8	29.9
3a	GPS/INS-AT	0/13	6.4	8.2	7.8	18.2	13.3	20.5	30.1
3b	GPS/INS-AT + BA	0/13	6.4	7.6	7.4	18.5	13.3	19.4	29.0
3c	GPS/INS-AT + SC (no c)	0/13	5.4	5.2	6.5	16.5	10.5	15.6	23.9
3d	GPS/INS-AT + c, x_p, y_p	1/12	5.9	6.1	6.1	7.4	13.5	12.6	16.1
3e	GPS/INS-AT + SC	1/12	5.4	5.5	7.3	6.0	10.7	16.4	9.9

Table 1: Accuracy of object point determination (OEEPE test, block Cali10, Applanix POS/AV).

quality of 4cm (horizontal) and 8cm (vertical). For the chosen test data set these theoretical values are verified from the empirical accuracy based on a GPS-supported AT (Version #1a). Nonetheless, the aspired vertical accuracy is worse since a systematic offset about 20cm in the height component affects the accuracy significantly. This error corresponds for example to a change in camera focal length of 20μm and is compensated if appropriate additional unknowns are introduced into the adjustment. Applying an additional self-calibration using the physically interpretable additional parameter set proposed by Brown (1971) the vertical accuracy is in the aspired range (Version #1b, Figure 1). Since there is a perfect correlation between focal length and vertical component similar results are obtained if an additional height offset ΔZ is considered instead of focal length correction Δc. This shows quite clearly that if the data of one image scale corresponding to one flying height are available only, the error source cannot be separated between these two effects. Nevertheless, from further analysis of the 1:5000 image scale blocks from the OEEPE test material a scale dependent variation of the vertical offset is indicated. Since such an effect should be quite unusual for GPS positioning this systematic is caused most likely from the imaging component, due to focal length variations as shown before or non-corrected influences of refraction. Similar scale dependent height variations are already known from earlier test material for example the Vaihingen/Enz test data (Cramer, 1999).

4.3. Results from direct georeferencing

In the second step the point determination is repeated using direct georeferencing (DG, Version #2a, Figure 2) where the GPS/inertial exterior orientations are used as fixed parameters and the object point coordinates are obtained from forward intersection only. The accuracy obtained from DG is about 15-20cm which should be expected for such medium scale blocks. The difference vectors at every single check point are depicted in Figure 2. Since no adjustment is performed the obtained $\hat{\sigma}_0$ is worse compared to standard AT, indicating that the image rays do not intersect in object space due to remaining errors in the exterior orientations or the mathematical model. To estimate the influence of such present errors the object point determination is repeated introducing additional unknowns in the mathematical model. The additional introduction of boresight correction parameters (BA, Version #2b) and the refinement of system self-calibration (SC, Version #2c) results in a significant increase in $\hat{\sigma}_0$ by a factor of 2. Now the horizontal quality from check points is well below 1dm. This shows the potential of the general expanded mathematical model for in-site system refinement. In the ideal case no additional flights for calibration are necessary because the estimation of boresight angles and the camera calibration can be realized in the test site directly even without knowledge of any ground control. Nevertheless, such an efficient in-site calibration is only possible for image blocks providing strong geometry and with meandering flight directions. This are some limitations for the flight planning, but even more important, the following has to be taken into account: Not all errors can be corrected without ground control. In especially constant shifts in the GPS/inertial positioning and offsets in the height component due to sub-optimal camera calibration have to be mentioned in this context. In standard airborne photogrammetric applications, where image data of one area are available in one certain image scale mostly, the refinement of the camera focal length is not possible without ground information due to the poor intersection geometry of image rays. Therefore the focal length c (Version #2c) was excluded from the self-calibration parameter set. Quite clearly, this shows the limits of direct georeferencing. If the system conditions between calibration and mission flight significantly change and position or height offsets are introduced due to any reason, the compensation of such systematic errors is only possible if at least one single GCP is available in the test area. In other words, such errors are non-detectable without any check points in the mission area and therefore will deteriorate the accuracy significantly, especially if an object accuracy in the sub-decimetre range is aspired. From a reliability point of view such a situation has to be avoided strictly. This indirectly gives an answer to one of the main motivations for direct georeferencing whether sensor orientation without any check points is really desirable. With one check point that can be introduced as ground control point – if necessary – these systematic errors are compensated. In our case one point located in the middle of the block was used to model the height offset within a refined interior orientation of the camera which increases the vertical accuracy up to 13cm (RMS). Comparing the results from Versions #2d and #2e no significant differences are seen which indicates that the three interior orientation parameters are sufficient to model the systematic effects. Nevertheless, it has to be mentioned that for the final two versions the term DG in its narrower sense is not correctly any more, since the results are obtained with the use of one ground control point now.

4.4. Results from combined GPS/inertial-AT or integrated sensor orientation

Within the final test runs (Versions #3a - #3e) the same calculations from Versions #2a - #2e are repeated again, but one major difference is applied: The GPS/inertial orientations are not used as fixed values any more but appropriate standard deviations are introduced in the adjustment procedure. This approach is similar to the general strategy used in GPS-supported AT where the directly measured coordinates from GPS are used with certain standard deviations corresponding to their expected accuracy. Typically, values of 5-10cm are introduced for the quality of the GPS positioning. Within the data set presented here corresponding standard deviations for GPS/inertial positioning and attitude of 5cm and 0.003deg are introduced, respectively. These values are derived from the comparison to the exterior orientations from standard AT and therefore should represent a realistic estimation of the expected positioning and attitude accuracy. Taking these standard deviations into account the exterior orientations are no fixed values any longer and corrections are estimated within the adjustment. The difference to the DG versions presented before is quite obvious: The reached values for $\hat{\sigma}_0$ are enhanced significantly. Consequently, the empirical accuracy from check point analysis is improved. In especially in Version #3a (Figure 3) the large difference to the RMS values from DG (Version #2a, Figure 2) is visible: the horizontal accuracy increases by a factor of two, although no additional parameters are introduced. The strong image geometry provided from standard frame cameras positively influences the quality of object point determination. The quality of the intersection of image rays in object space is improved since remaining tensions are interpreted as remaining errors in the orientation parameters. Additionally, the comparison of Figures 3 and 2 shows the interesting fact that the existing systematic errors are more clearly visible in Version #3a. Besides the almost constant height offset a horizontal shift in north-west direction seems to be existent. Assuming the exterior orientation as error free and constant, all tensions are projected into the object point determination resulting in a more disturbed difference vector plot. The introduction of additional corrections for the boresight angles and an additional self-calibration (without focal length correction) further improves the accuracy and compensates parts of the error budget. Nevertheless, similar to the previous results the existent vertical offset can only be eliminated with the usage of at least one ground control point which has been done in the final two versions. The best overall accuracy in the range of 6cm (RMS) for all three coordinate components is obtained when all self-calibration parameters are introduced in the adjustment approach (Version #3e, Figure 4). Although the results are only based on one GCP the accuracy is almost similar to the accuracy from GPS-supported AT as calculated in Version #1b and seen in Figure 1.

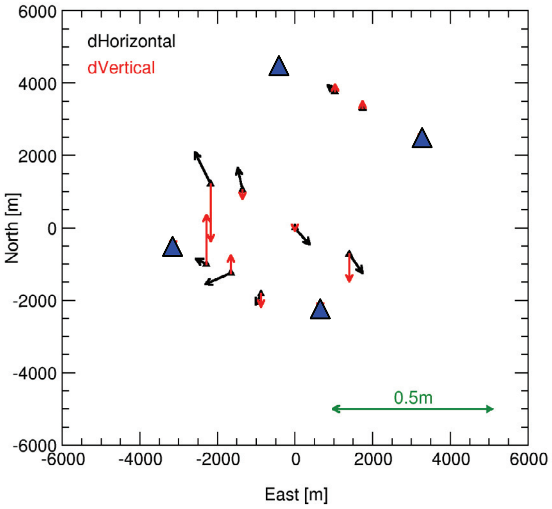

Figure 1: Residuals after GPS-supported AT with self-calibration, 4 GCP (Version #1b).

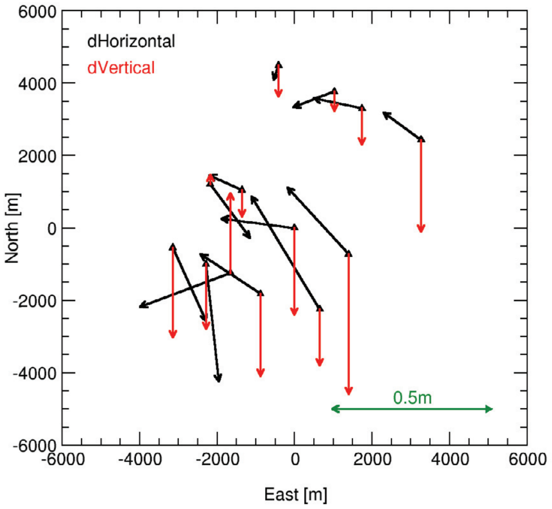

Figure 2: Residuals after direct georeferencing, fixed exterior orientation (EO, Version #2a).

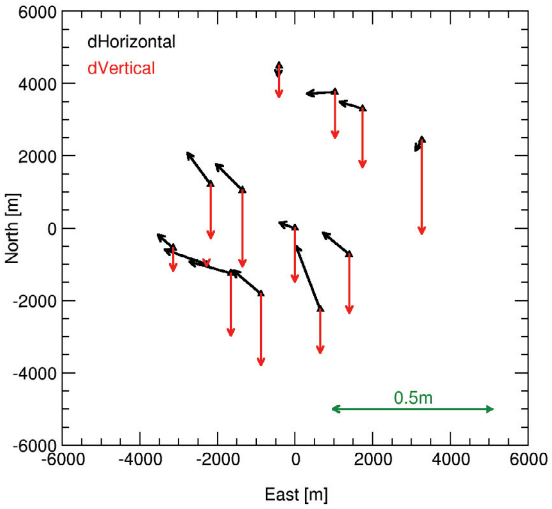

Figure 3: Residuals after GPS/inertial-AT, EO with Std.Dev. (Version #3a).

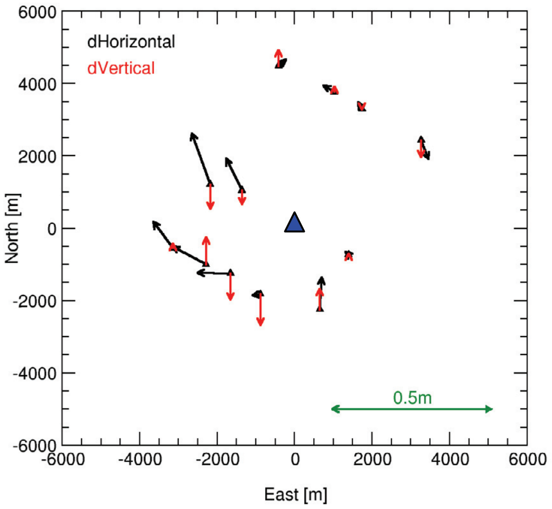

Figure 4: GPS/inertial-AT with self-calibration, 1 GCP, EO with Std.Dev. (Version #3e).

From the results obtained in the integrated or combined GPS/inertial-AT approach the following conclusions can be drawn, showing the possible application fields of GPS/inertial technology in aerial photogrammetry. These conclusions have to be seen in addition to the statements already given at the end of Section 3.

- The quality of object point determination increases if appropriate standard deviations are assumed for the GPS/inertial exterior orientations. The strong image geometry of standard frame cameras compensates remaining errors in the exterior orientation parameters.
- The overall sensor system calibration is a quite demanding task, therefore an in-site calibration is realized in a combined GPS/inertial-AT approach. The exclusive and a priori correction of the three boresight angles does not seem to be sufficient in some cases. The additional use of self-calibration and/or additional boresight refinement parameters yields in better results. This negative influence of non-corrected systematic errors is not only valid for the orientation based on GPS/inertial data but also for traditional AT.
- Using the combined GPS/inertial AT the alignment of boresight angles and sub-sets of the additional self-calibration parameters can be determined within the test area even without ground control if certain requirements related to the flight planning and block geometry are fulfilled.
- Constant position shifts and vertical offsets are the most critical errors since they are non detectable without any check point information. In case such errors occur after system calibration and no ground control is available in the mission area they will decrease the object point accuracy.
- Using an overall sensor system optimally calibrated for the mission area realized with an combined GPS/inertial AT – based on a minimum number of ground control, if necessary – the obtained object point quality is quite similar to the results from GPS-supported or standard AT.

5. DEM GENERATION

Up to now the main focus in GPS/inertial performance tests was laid on the estimation of the overall and absolute system quality obtained and quantified from the empirical check point residuals. Nonetheless, major photogrammetric tasks still are in the field of stereo plotting and automatic DEM generation from stereo models where the results from AT – especially the estimated exterior orientations – in the traditional way serve as input data for the single model orientation. In contrary to the absolute system quality now the relative performance is of interest and the question whether the short term quality of the directly measured GPS/inertial exterior orientations is good enough to generate parallax-free stereo models has to be responded. The current work at ifp is focussed on this topic and first results are given in the following.

The typical accuracy of direct georeferencing based on fixed orientation elements for image blocks reaches values about 15-30µm in image space as shown above and verified for example from the results from the OEEPE test. Since a certain amount of this value can be interpreted a remaining y-parallax such a high $\hat{\sigma}_0$ will prevent stereo measuring capabilities. Nevertheless, the situation changes if only single models or single strips are taken into account. A typical example is shown in Figure 5, where the differences between the GPS/inertial attitudes and the orientation angles from standard AT are depicted for two parallel flight lines (image scale 1:6500, flying height 1000m). These data are part of the Vaihingen/Enz test June 2000, where the IGI AEROcontrol integrated GPS/inertial system was flown in combination with an analogue airborne camera (Cramer 2001).

As it can be seen from Figure 5 there is a large jump in the heading angle differences between the two different strips. If this jump is interpreted as an error in the GPS/inertial attitude determination such non-corrected systematic will induce high $\hat{\sigma}_0$ values if points from both strips are used for object point determination. But concentrating on the differences between neighbouring images within one single strip only, the attitude variations are significant smaller.

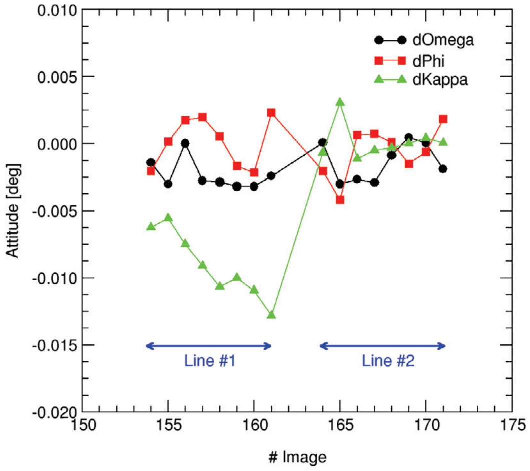

Figure 5: Differences between attitudes from GPS/inertial and AT (Vaihingen/Enz test).

To estimate the influence of orientation errors on the subsequent DEM generation from stereo images a synthetic stereo pair was simulated (assumed image scale 1:10000, wide-angle camera) where both images consist of the same radiometric information. This synthetic image pair was generated to provide optimal requirements for the automatic point transfer, otherwise the influence of remaining errors in the exterior orientations on the generated DEM is superimposed with effects from erroneous image matching. Thus, the automatic point matching within this stereo pair reconstructed from correct exterior orientation parameters should result in an exact horizontal plane in object space since all image points provide the same and constant x-parallax. In the next step additional errors in the exterior orientations are introduced and the image matching is repeated. To get realistic values for the orientation errors the differences in the exterior orientation parameters between neighbouring images are analyzed. Within this example the exterior orientation of the first image was falsified by the following numbers: ΔEast=2cm, ΔNorth=8cm, ΔVertical=12cm, $\Delta\omega$=0.0003deg, $\Delta\varphi$=0.005deg, $\Delta\kappa$=-0.004deg. The values correspond to the orientation differences between the images #165 and #166 from the test data set depicted in Figure 5 and will result in certain y-parallaxes if the automatic image matching is repeated on this mis-oriented stereo pair. In our case the subsequent image matching based on the Match-T program (Krzystek 1991) reaches a theoretical 3D point height accuracy of 18cm and an estimated internal height accuracy of the interpolated DEM points of about 3cm. From the internal Match-T classification about 43% of the matched points are classified as regular grid points within the accuracy bounds. The remaining points are classified as so-called lower redundancy points where less than 4 points are used for mesh interpolation or the obtained height accuracy of the interpolated DEM point is below the selected accuracy bound. Although significant y-parallaxes due to orientation errors are present within the images the automatic image matching seems to deliver reasonable results. Nevertheless, this internal accuracy does not necessarily reflect the exterior quality of the obtained surface model. Therefore the resulting surface model obtained from Match-T is shown in Figure 6 together with the true surface plane to be expected from correct matching based on non-erroneous orientation parameters. As one can see the obtained surface shows systematic differences compared to the expected horizontal plane, that can be divided into a global and a local systematic error effect. The global effect more or less represents the model deformation due to the introduced errors in the exterior orientation of the first image. These systematic and well known effects from the theory of relative orientation can also be estimated from the mathematical relation known from relative orientation, where the influence of orientation errors on the obtained height deformation is expressed (Kraus 1990). As a first approximation the obtained surface can be described as a plane that shows a negative systematic shift compared to the true horizontal plane and additionally is tilted from south-east to north-west. The size of the vertical errors vary from approximately -1dm to -4dm. Besides this global and low-frequency systematic error representing the influence of model deformation additional higher-frequency local errors are seen as a topography on the surface. For example in the south-eastern part of the model a raise in the heights of about 15cm is clearly visible.

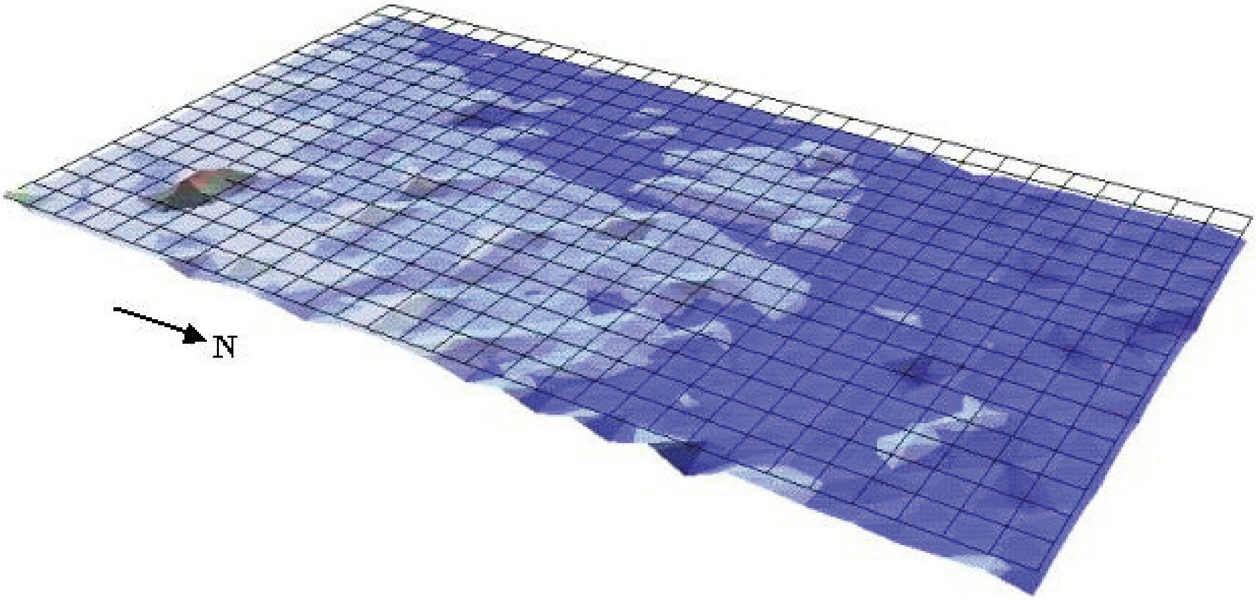

Figure 6: DEM from automatic image matching based on mis-oriented synthetic stereo model.

Such vertical errors correspond to errors in the automatic image matching which shows the negative effect of the existent parallaxes. Besides the height errors horizontal deformations are present (non-visible from Figure 6). Further detailed analysis proves that the horizontal displacement errors mainly occur in a star-shaped form pointing in north, north-east direction in the northern half and in south, south-east direction in the southern part of the model. The maximum horizontal errors are in the range of approximately 2dm and therefore quite similar to the mean height offset.
These first and preliminary tests are only based on simulations with a synthetic stereo pair, where the orientation of one image is falsified by a certain amount, which should correspond to an orientation error that can be expected within two subsequently measured GPS/inertial orientation parameter sets. The results have shown that for this specific test data set the DEM generation from stereo models based on automatic image matching obtains acceptable results, although remaining orientation errors are present. Nevertheless, the generated surface model is superimposed with the model deformations. This effect has to be taken into account, if no ground control is available. Alternatively a certain portion of the model deformation can be eliminated with an additional absolute orientation process which is similar to the procedure in relative/absolute image orientation. Further work has to be focussed on the effect and size of height errors due to incorrect automatic point matching. In this case in especially the robustness of the automatic image matching on remaining orientation errors has to be determined. Based on more detailed future investigations recommendations on maximum tolerances for the orientation errors resulting in errors in the surface model should be given for different configurations and image scales, finally.

6. CONCLUSIONS

The extensive tests performed in the last years have shown that the GPS/inertial technology is mature for practical use in operational environments. The obtained accuracy based on GPS/inertial data still has remaining potential of improvement. Especially the refinement of the integrated sensor orientation software where the GPS/inertial data are introduced and processed plays a significant role for the obtained overall system quality from imaging and orientation component. Today the integration of direct exterior orientation measurements in the photogrammetric reconstruction process is done on the GPS/inertial positions and attitude level. Nevertheless, in future "true" integrated processing software approaches might be available directly based on the GPS phase measurements and the inertial angular rates and linear accelerations. Within such an integrated evaluation the photogrammetric constraints are used to support the GPS/inertial data processing. Such an approach, similar to the centralized Kalman filtering in GPS/inertial integration, will result in higher overall system reliability and accuracy. To resume, in future, GPS/inertial technology will be used in all parts of the photogrammetric reconstruction process. GPS/inertial systems will become a standard tool for airborne image orientation. The acceptance of this technology will be pushed by the growing use of new digital airborne sensors with their need for a very flexible and fast data evaluation.

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