ICC experiences on Inertial / GPS sensor orientation

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Abstract

In the last few years the photogrammetric community is accepting the use of direct orientation for photogrammetric projects. The orientation of other Earth observation sensors (LIDAR, spectral sensors…) also relies on GPS/INS integration. Direct orientation aims at the elimination of the aerial triangulation process and measurements of ground control points in order to implement fast orientation workflows and to reduce costs. However, in real life projects several issues can disturb direct georeferencing: instability of the system calibration (misalignment matrix and selfcalibration parameters), drifts in the angular observations, mounting problems and GPS positioning errors. These problems have to be addressed in order to obtain a reliable sensor orientation.

This paper will be focused on the experience of the Institut Cartogràfic de Catalunya (ICC) on the field of GPS/INS integration during the last 3 years. The different workflows adopted by the ICC to overcome the reliability problems are based either on direct georeferencing supported by a minimal aerial triangulation configuration or on the combination of GPS/INS observations and automatic aerial triangulation. Both methods improve the robustness and reliability of photogrammetric projects. Some experiences in LIDAR orientation will also be presented.

1. Introduction

Inertial/GPS combination is an emergent technology for sensor orientation that is gaining acceptation by the photogrammetric community. However, direct orientation is not just the combination of GPS and IMU observations; a successful and reliable orientation depends also on the correct determination of all the elements that participate on the transformation from the image space to the object space. Those elements such as the boresight misalignment matrix, nodal distance, antennas offset, drift parameters, etc. must be determined in order to perform direct sensor orientation. The robustness of sensor orientation is a critical issue in real live projects. ICC has been studying different mathematical models, workflows and techniques combination for a robust determination of all parameters involved in direct sensor orientation.

2. Inertial/GPS camera orientation

According to the experience of ICC in the use of direct orientation for photogrammetric projects, several issues have been identified as critical ones, mainly due to the lack of redundancy and low reliability. In this section, some results obtained by ICC in the use of direct orientation data are presented and these problematic points are commented.

In order to evaluate the quality of the GPS/INS data, camera positions and attitudes were calculated at exposure times and introduced into a bundle block adjustment (with classical aerial triangulation and ground control point distribution) as direct observations of the external orientation parameters with low weights. The estimated residuals reflect the somewhat empirical accuracy of the external orientation parameters deduced from GPS/INS measurements. The results of that kind of evaluation are reported in following sections.

2.1. Drifts

Drifts affecting IMU gyroscopes can be estimated and corrected during the integration of the GPS and IMU data. Since is not clear but, whether the dynamic of the airplane within the strips does not allow a correct determination of the gyros drifts or an IMU calibration problem, sometimes the attitude observations of the photographs delivered by the GPS/Inertial integration process can be affected by a drift pattern, mainly in the heading angle.

The first blocks processed by ICC showed a similar pattern. Figures 1 and 2 illustrate the residuals of the angular observations of each photograph obtained for two of these blocks, one at 1:60000 and the other one at 1:32000 flight scale.

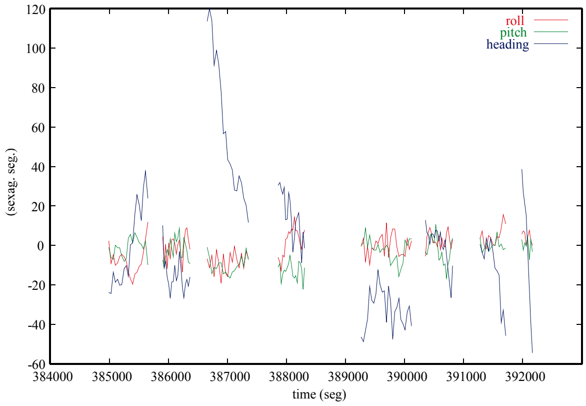

Figure 1: Angular residuals for 1:60000 block

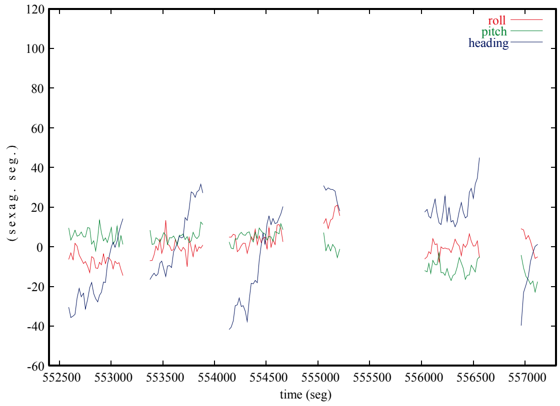

Figure 2: Angular residuals for 1:32000 block

The statistics of these angular residuals are summarized in the following tables:

1:60000 block

	std. dv.	RMS
Roll	9.8 ”	9.8 ”
Pitch	9.2 ”	9.2 ”
Heading	40.7 ”	40.7 ”

1:32000 block

	std. dv.	RMS
Roll	6.6 ”	6.6 ”
Pitch	8.4 ”	8.4 ”
Heading	21.4 ”	21.4 ”

As it can be observed in both figures, roll and pitch observations give good residuals, with values below 20 arc-seconds in the worst case (1 pixel at 15 microns corresponds to 17.6 arc-seconds). Despite these good statistics, a slight drift behaviour can be observed. This drift pattern is more obvious observing the heading angular residuals. They show a strong drift in each strip, with values that can reach 120 arc-seconds.

This pattern in the heading angle has to be corrected in order to avoid that these large residuals affect the orientation of the block. ICC has introduced a new drift parameter for the three angles, which are described in the following equations:

$$Roll = Roll_{DG} + DR_0 + DR_1(t^j - t_0) \quad (1)$$

$$Pitch = Pitch_{DG} + DP_0 + DP_1(t^j - t_0) \quad (2)$$

$$Heading = Heading_{DG} + DH_0 + DH_1(t^j - t_0)\,. \quad (3)$$

Where t^j is the time exposure of the photo and t_0 mean time of the strip.

Introducing the estimation of these parameters in the bundle block adjustment of both blocks, the new angular residuals obtained are those presented in figures 3 and 4.

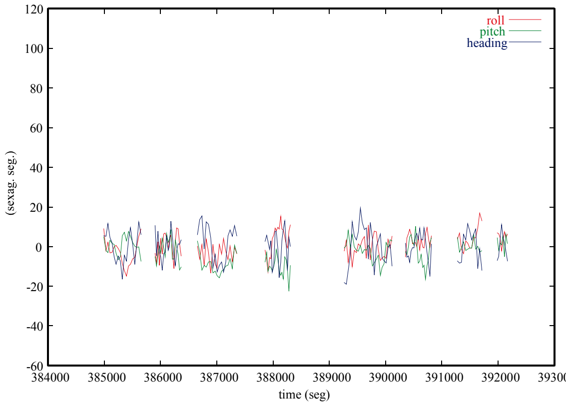

Figure 3: Angular residuals for 1:60000 block using drift parameters

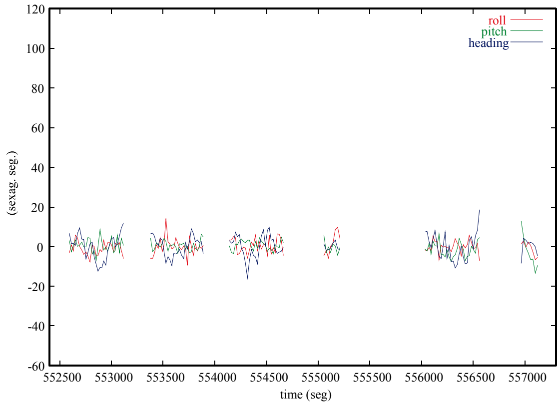

Figure 4: Angular residuals for 1:32000 block using drift parameters

The statistics of these angular residuals are summarized in the following tables:

1:60000 block

	std. dv.	RMS
Roll	7.9 ”	7.9 ”
Pitch	7.4 ”	7.4 ”
Heading	9.6 ”	9.6 ”

1:32000 block

	std. dv.	RMS
Roll	3.7 ”	3.7 ”
Pitch	3.7 ”	3.7 ”
Heading	5.8 ”	5.8 ”

Figures 3 and 4, as well as their statistics, show that the estimated drift parameters have addressed the drift behaviour and the high heading angle residuals shown in figures 1 and 2. The attitude residuals for the three angles obtained in this case show excellent values (below 10 arc-seconds RMS).

As it is shown in this section, it is possible that the GPS/Inertial integration does not correct all drift affecting the IMU gyroscopes. Then, for a robust orientation, the remaining drift has to be estimated and corrected. Some additional information (photogrammetric tie points) must be observed to estimate the drift pattern and improve the residuals obtained.

2.2. Blunders

In some photogrammetric blocks ICC has detected that some attitude observations show really large and isolated residuals that don’t follow any pattern. Figures 5 and 6 show the attitude residuals obtained in two different 1:22000 flight scale blocks.

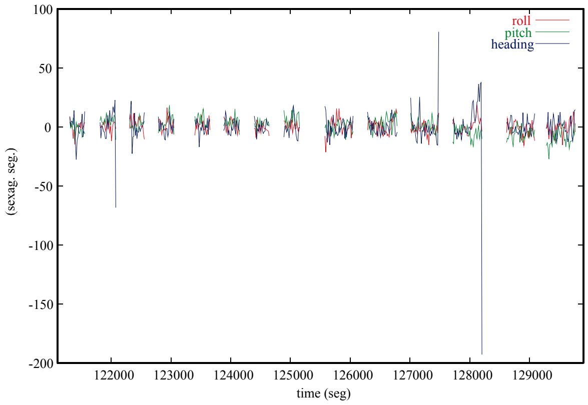

Figure 5: Angular residuals for 1:2200 block using drift parameters

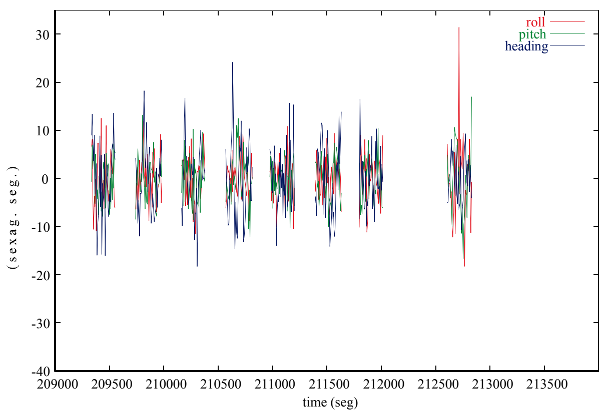

Figure 6: Angular residuals for 1:22000 block using drift parameters

In the left-hand figure, large heading residuals in the last photograph of three strips are obtained. Of course, these residual values (from 100 to 200 arc-seconds) make impossible the use of these angles to orient the photographs. In the right-hand figure, a roll residual has a value greater then 30 arc-seconds. Roll and pitch blunders don’t appear as often as heading outliers and are not as large as them, but they also have to be detected for a reliable orientation.

Likely, these blunders in the attitude observations are not really outliers of the orientations given by the GPS/Inertial integration, but a bad transfer of these orientations between IMU and camera reference frames. It is well known that the installation stability of the IMU in the camera body can be a source of many problems. In fact, new mountings of the IMU inside the lens cone are being studied to improve the robustness of the mounting. Moreover, no blunders are observed in the new generation of digital cameras with the IMU well integrated in the camera body. Then, a fully integrated IMU sensor installation inside the camera is recommended to avoid outliers in photographs' attitudes.

2.3. Stability of the misalignment matrix

It is essential, that the relation between the position and orientation data provided by the GPS/INS system (referred to the IMU body frame) and the camera reference frame is accurately determined and that the stability of this relation is ensured. It may be quite difficult to establish a guidance about how and how often this misalignment has to be calibrated, taken into account the high cost of a flight calibration.

Following table shows the misalignment matrices computed by ICC in several flights.

	ω σ_ω	φ σ_φ	κ σ_κ
1:60000 (09-09-2000)	0º 4' 26" (2.1")	-0º 1' 52" (1.6")	180º 1' 15" (1.5")
1:60000 (10-09-2000)	0º 4' 23" (1.6")	-0º 1' 54" (1.6")	180º 1' 31" (1.2")
1:5000-8000 (25-05-2001)*	0º 2' 18" (2.5")	-0º 3' 42" (1.6")	180º 5' 34" (3.1")
1:32000 (26-05-2001)	0º 2' 14" (1.9")	-0º 3' 23" (1.6")	180º 5' 23" (1.3")
1:22000 (28-05-2001)	**0º 2' 02" (1.2")**	**-0º 3' 38" (1.6")**	**180º 5' 34" (1.0")**
1:22000 (07-06-2001)	**0º 5' 24" (1.3")**	**-0º 3' 09" (1.2")**	**180º 5' 27" (1.1")**
1:22000 (19-06-2001)	**0º 3' 08" (5.3")**	**-0º 3' 19" (3.6")**	**180º 5' 17" (3.2")**

Table 1: misalignment matrices computed by ICC for different flight campaigns
(* IMU was discharged from the camera between 21.09.2000 and 25.05.2001)

As it can be observed, changes of 10-15 arc-seconds in the kappa angle component and 15-20 arc-seconds in the pitch angle component occur nearly in all flight sessions. Roll component may be more stable except for the jump of 2-3 arc-minutes observed between 28-05-2001, 07-06-2001 and 19-06-2001.

From the results shown in table 1, it would be too costly to perform a system calibration flight often enough to detect these changes, because they appear nearly every day. The optimal solution would be to have some additional information that allows for the estimation of the misalignment matrix every flight.

2.4. Camera selfcalibration parameters

Another important issue to be taken into account is the selfcalibration of the camera. It is well known that some camera calibration parameters (like focal length or principal point position) can suffer some distortions depending on external conditions such as pressure, temperature, flight altitude, etc. [2].

As an example, table 2 shows the values of the focal length distortion (for the same lens) estimated in two different flights of the same month.

Flight date	Flight scale	Focal length distortion
01.07.1999	1:32000	-19 µm
25.07.1999	1:40000	-4 µm

Table 2: focal length distortion for two different flights

Of course, these changes in camera selfcalibration parameters are not reflected in the camera calibration certificate, and can produce errors in direct georeferencing of several centimeters.

One possibility to address this problem would be a detailed study on the impact of atmospheric and flight conditions on the camera parameters, but this task is quite difficult due to the high casuistic and variability of these conditions as well as due to all correlations existing between them. An easier way would be the estimation of these distortions in each flight using additional information given by some photogrammetric measurements.

2.5. Increasing robustness

All issues presented in the last section affect the orientation of photogrammetric blocks and show that the robustness of direct orientation has to be increased. These problems have to be addressed in order to achieve a reliable sensor orientation. As explained before, it is necessary to estimate additional parameters that correct and absorb the effects described previously: angular drifts in the attitude of the photographs, instability of the misalignment matrix and changes in the camera parameters due to environmental influences. It is also important to have enough redundancy to detect some errors and outliers in position and attitude observations given by GPS/INS system.

2.5.1. Minimal aerial triangulation

For all reasons previously presented, it is not recommended to renounce on the observations of all tie points for a reliable sensor orientation. One option that ICC is using in photogrammetric blocks orientation consists in measuring a minimal aerial triangulation configuration and some ground control points. This allows for the estimation and detection of all issues and errors that affect direct georeferencing.

As an example, figures 7 and 8 show the photogrammetric measurements of a full aerial triangulated block (figure 7) and those of one of the minimal aerial triangulation configuration suggested (figure 8).

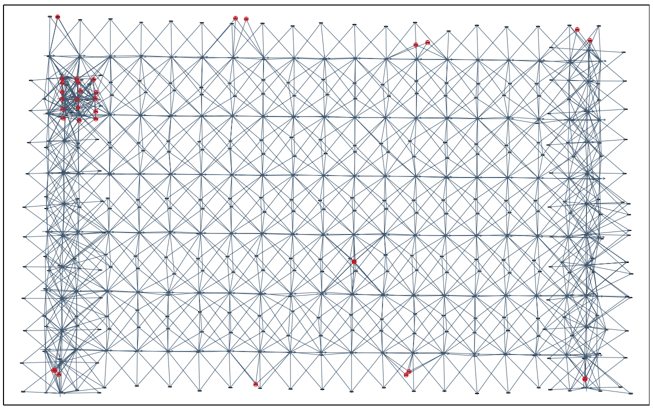

Figure 7: photogrammetric observations in a fully aerotriangulated block

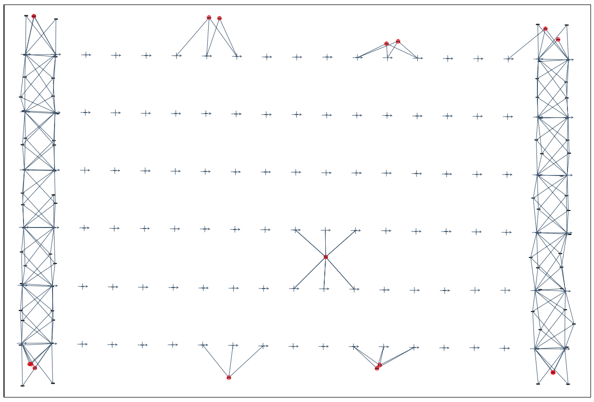

Figure 8: photogrammetric observations using minimal configuration

Despite the use of photogrammetric observations implies additional costs in the orientation, it considerably increases the robustness and reliability and, definitely, the accuracy of the orientation obtained. Beyond that, calibration flights are not longer necessary.

2.5.2. Combination with automatic matching

In order to improve the reliability of photographs orientation, ICC is also working in the integration of GPS/IMU orientation with automatic aerial triangulation. The automatic measurements of tie points between photographs will provide the necessary redundancy for estimating the additional parameters explained in sections 2.1 to 2.4 at a very low cost. First tests with Match-AT [Sigle and Heuchel, 2001] of the German Inpho Company showed highly promising results. A block with 463 photos of scale 1:22000, digitized at 14 microns pixel size, with 65% end and side lap was automatically matched and triangulated in approximately 18 hours (Pentium IV, 2GHz, all data on local IDE disks). Using GPS/IMU observations and also an existing digital terrain model (grid width: 60m) as initial information, the program yielded 8697 well distributed points, as can be seen from the block section depicted in figure 9. Using the direct orientation as initial information the matching can be executed even without any knowledge of ground control points, i.e. tie point observations can be provided directly after photo scanning in two subsequent automatic processes without any measurement activity in between. At the moment a big part of the saved time is spent to check and verify the automatically generated results and also to complete measurements, where the image matching process failed (e.g. in areas of poor image contrast). The next step will be to study if the combination with the GPS/IMU observations provides enough redundancy for a robust orientation without the need of re-observing remaining weak matching areas. Thus, direct orientation and automatic matching processes will control each other and assure the reliability of the photograph orientation process.

Figure 9: Result of automated aerial triangulation with Inpho's software package Match-AT

3. Inertial/GPS Lidar orientation

LIDAR has become a recognized and widely used mean to generate high quality DTMs. Since 2001, ICC is operating an Optech ALTM 3025 LIDAR system, which is capable to emit 25000 pulses per second from altitudes up to 3000 m above ground. It is directly orientated by an Applanix POS AV system and a GPS base station on ground. To minimize GPS errors the base station is supposed to be located within 25 km distance to the aircraft and the laser operation also is restricted to GPS time windows with at least 6 locked satellites and a PDOP smaller than 4.

LIDAR systems measure the time between the emission and the reception of the reflected laser pulse. Using the speed of light as a constant these time measures combined with the POS AV position and orientation data can be transformed into accurately georeferenced X, Y and Z coordinates. Two different time measures related to the first and the last echo of the emitted laser pulse result in two different ground points representing the first hit (e.g. at the tree canopy) and the last hit of the laser shot (e.g. on the ground). Thus, the data set yields two point clouds, one representing more or less the surface and the other the terrain.

For rigorous direct orientation the boresight between the laser body reference frame, the IMU reference frame and the phase center of the GPS antenna needs to be known. The values are measured during laboratory calibration by the manufacturer and after mounting the system in the aircraft the first time.

The use of direct orientation for the Lidar sensor suffers the same weakness than the use of direct orientation for photogrammetric blocks (mainly stability of the misalignment matrix and sensor calibration). As the geometry of the Lidar sensor is very weak these parameters are regularly checked in costly calibration flights over a large building and over a flat surface (airport runway).

Figure 10 shows the in-flight calibrated pitch and roll angles obtained from recent calibration flights. Larger variations of these angles (as happened for pitch between the calibration flights in November 2002 and March 2003) reflect a real change in the orientation between the laser body and the IMU reference frame, which were caused by (unknown) external forces (hard landing or shock during mounting or transporting the system). The variation of the vertical offsets is mainly caused by GPS positioning errors (figure 11). The in-flight calibrated values vary within +/- 15 cm, although the trajectories were computed to an estimated accuracy better than 10 cm. That proves that even in well-preplanned flights (> 6 satellites, PDOP<4, reference station <25 km) significant errors in the computed trajectory (that propagates directly to the sensor observations) are usual. It was also observed that the values changed at a high frequency that even single flight lines of the same day were affected by different vertical offsets (see figure 13).

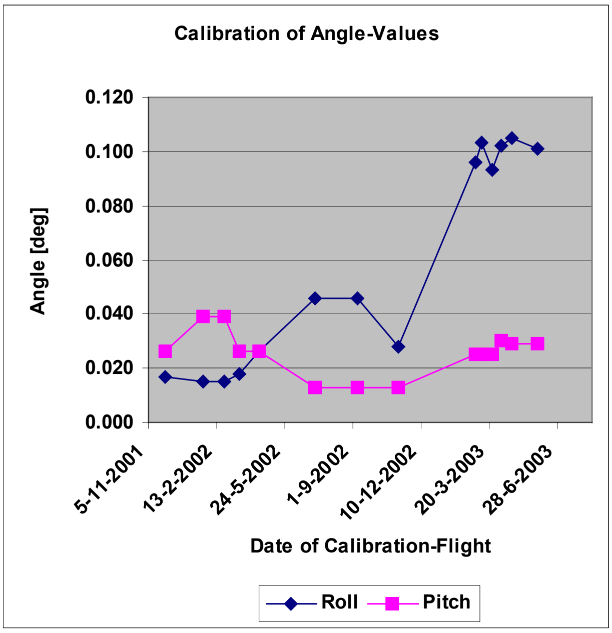

Figure 10: Results of pitch and roll angle calibration

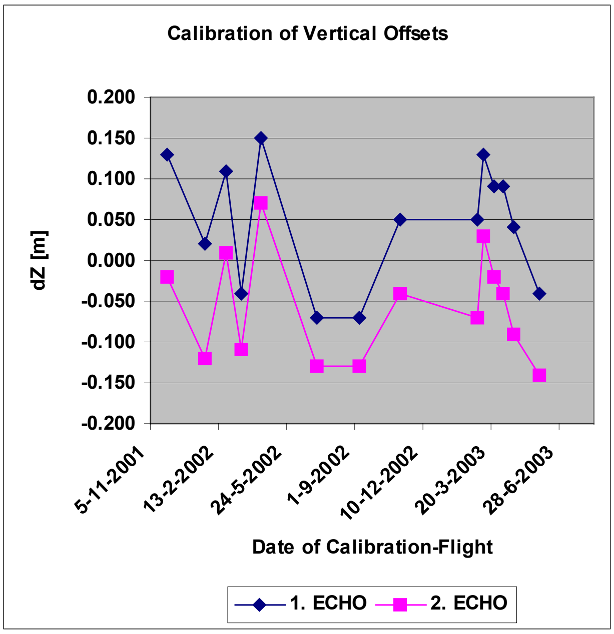

Figure 11 : Results of vertical offset calibration

3.1. Strip adjustment

As explained above, even if daily calibration flights are performed, the limitations of GPS trajectory determination will cause systematic errors that need to be corrected in order to operate a Lidar sensor at very high accuracy. Thus, the ICC has developed an automated laser strip adjustment approach, which estimates and corrects the major part of those systematic vertical errors and allows for reliable DTM generation of wide areas in reasonable time.

The approach was developed and applied in the framework of the "Ter-project", whose objective was to generate a highly accurate DTM of the Eastern Ter river, an area of approximately 200 km^2. It requires a modified block design, which employs additional crossing flight strips and a certain number of **c**ontrol **a**reas (CAs), which depends on the size and the shape of the block. Each data strip must be covered by at least one crossing strip, i.e. for a regular block with all parallel flight strips one crossing strip and one CA is sufficient, while in case of more complicated block shapes more crossing strips may be required. To increase redundancy and confidence of the later adjustment, it is recommended that CAs are covered by a crossing flight strip and longer data strips also are crossed by more than one strip. The latter will reduce errors, introduced by GPS accuracy variation, which might occur during long strips. If the block consists of a series of different regular sub-blocks, as it is the case in the example shown in figure 12, isolated sub-blocks should be fixed by an additional CA. A more detailed description of the model and of the nearly fully automated way of data processing is given in [Kornus and Ruiz, 2003].

In the following only a few results of that project are outlined to illustrate the impact of the mentioned vertical offset on the LIDAR data. They also document the high performance of the LIDAR system and of the applied strip adjustment. Figure 13 shows the result of the strip adjustment executed for the data block depicted in figure 12. It graphically represents the estimated height corrections for the single data strips, day-wise and in chronological order. It shows clearly, that the corrections are affected by systematic errors, which depend both on the day and on the time during the single data session. The zig-zag characteristic of the curves might indicate remaining calibration errors affecting the laser point heights in the order of a few centimetres.

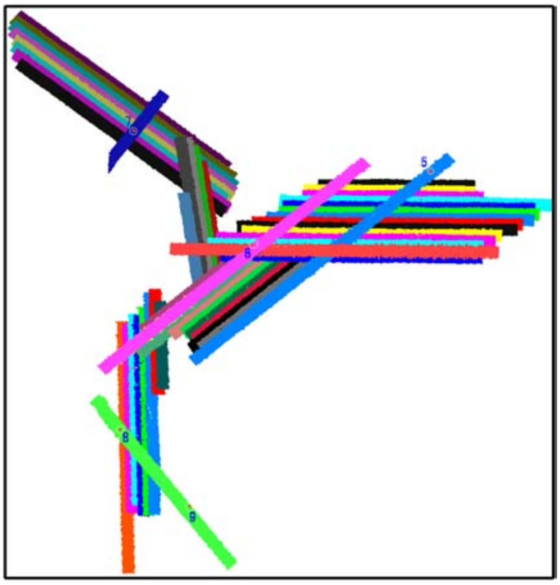

Figure 12: Example of a modified block design with crossing flight strips and five control areas. The size of the circumscribing rectangle is 20x21km.

Airplane	Partenavia P-68C Observer
LIDAR system	ALTM 2025-E
Flying speed	222 km/h
Flying altitude	2,300 m (above ground)
GPS frequency:	1 Hz
INS frequency:	200 Hz
Laser repetition rate:	25,000 Hz
Scan frequency:	42 Hz
Scan width:	± 5º
Swath width:	402 m
Strip side-overlap	50%
Beam divergence:	0.2 mrad
Foot print size:	0.46 m

Table 3: Flight and system parameters

Table 4 contains the statistics of the estimated height corrections. The daily effect is expressed as the respective mean correction (*Mean*), which varies between 10.2 and 18.4 cm. Besides this global effect there also exist variations (*Range*) within the single data sessions of the same order of magnitude. It’s assumed that the major part of those errors is caused by the GPS. After applying the estimated height corrections, the laser points were tile-wise classified and a regular DTM with 1 m grid spacing was produced from the ground-points using the software package TerraScan [Terrasolid, 2002].

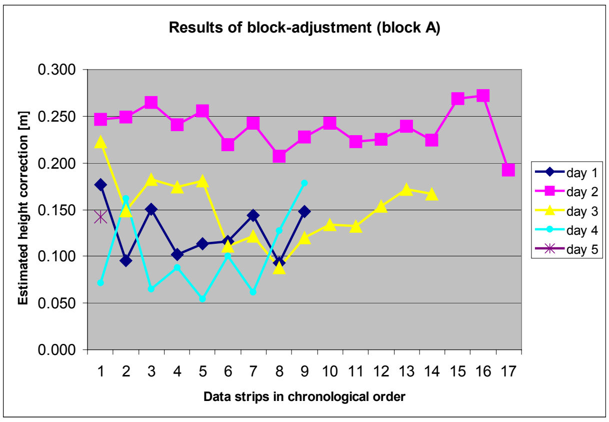

Figure 13: Estimated height corrections for the single data strips

Day	#1	#2	#3	#4	#5	all
# of strips	9	17	14	9	1	50
Min [m]	0.093	0.192	0.088	0.054	0.142	0.050
Max [m]	0.177	0.272	0.223	0.179	0.142	0.270
Range [m]	0.084	0.080	0.134	0.125	0.000	0.220
Mean [m]	0.126	0.237	0.138	0.102	0.142	0.165
Sigma [m]	0.029	0.022	0.030	0.046	-	0.062

Table 4: Statistics of the estimated height corrections

4. Conclusions

The experience of ICC in the field of GPS/IMU integration has been presented in this paper. Several issues identified as potentially problematic have been presented:

- Drifts in the heading angle
- Blunders
- Stability of the misalignment matrix

- Sensor calibration
- GPS trajectory determination systematic errors

All these points must be well controlled in order to have a reliable sensor orientation. The proposed solution for increasing the robustness of sensor orientation is to obtain some additional information (measurements of tie points, lidar cross strips...) in order to be able to model the critical issues or at least to control them.

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