EXPERIMENTAL TESTS ON THE BENEFITS OF A MORE RIGOROUS MODEL IN IMU/GPS SYSTEM CALIBRATION

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Commission III, WG III/1

KEY WORDS: Orientation, System, Calibration, GPS/INS, Integration, Adjustment.

ABSTRACT:

System calibration is required in integrated IMU/GPS systems to account for the spatial offset and misalignment between IMU, GPS and camera frames; synchronization is to be maintained, to predict IMU/GPS position and orientation data at the mid-exposure time of the images. To this aim, measurement on the ground, complemented by a calibration flight over a test field, are performed. Depending on the mathematical model, a two steps or a single step procedure may be used to recover the calibration parameters. In the former, parameters are computed as a weighted average of the discrepancies between the exterior orientation (EO) parameters of the images derived from block adjustment and those computed from the IMU/GPS data, in the latter parameters are explicitly inserted in the collinearity equations and the IMU/GPS data are considered as pseudo-observed quantities, replacing EO parameters as unknowns in the block adjustment. Results of their application to a calibration test field over the town of Pavia are discussed.

1. INTRODUCTION

1.1 A national research program on IMU/GPS systems

Integrated on-board positioning and orientation systems composed by an Inertial Measurement Unit (IMU) and one or more GPS receivers allow direct georeferencing of images in aerial photogrammetry. For sale since a few years, their acceptance in map production is still hindered in Italy by the lack of technical prescriptions, required for their use in projects financed by state or regional map agencies. In spring 2003, under a national research project aiming at preparing technical prescriptions and guidelines for use of IMU/GPS systems in aerial photogrammetry, 4 flights have been executed over a test field established in Pavia (Italy). Scanned images as well as GPS and IMU processed data were later distributed to the research units, all coming from institutes of photogrammetry in eight Italian universities. Data processing is still underway, to measure the large amount of images acquired and to perform the various accuracy checks scheduled within the project goals. The end of the of data analysis is foreseen for October 2004.
Although every unit may focus also on specific objectives, the common project goals were set as follows:

- determination of the accuracy and long term stability of the GPS/IMU system calibration parameters;
- development of methods to eliminate residual parallaxes without resorting to aerial triangulation;
- development of internal quality control methods in order to check the reliability of GPS/IMU data, without resorting to aerial triangulation;
- analysis of the main commercial photogrammetric software in order to check their functionality related to direct georeferencing with GPS/IMU data;
- proposal of guidelines for the execution and testing of airborne photogrammetric flights using on-board GPS/INS systems.

The specific goal of the research unit the authors are members of and the subject of this paper is the development of calibration methods for the integrated IMU/GPS system. More information on the test characteristics and goals are presented in (Casella and Galetto, 2003); in the following, a short description is given anyway to clarify the presentation of the results of the calibration methods.

1.2 Characteristics of the test blocks

Four different flights have been performed with an Applanix POS/AV 510 over the test site by Compagnia Generale Ripreseaeree, based in Parma (Italy). In the first two, the Wild RC30 camera mounted a focal length of 300 mm, while in the others a 150 mm lens was used. Each flight resulted one or more blocks, flown at different heights: image scale are 1:5000, 1:8000 and 1:18000, i.e. the image scales normally used in Italy to produce maps respectively at the scales 1:1000, 1:2000 and 1:10000.
Flights 1 and 2 have been executed two days apart with a 150 mm lens. They are composed of three blocks each. The **1:5000 block** (about 140 images overall) has three ordinary parallel strips covering a part of the test site, flown in East-West direction. The first strip, once completed, is immediately flown in reverse. There are two cross strips, at the head and tail of the block; each of them is flown in reverse at the end. The forward overlap is 60%, while the sidelap is 30%.
The **1:8000 block** (about 160 images) has seven ordinary parallel strips covering the whole test site, flown in the East-West direction. The first one is flown back and forth. There are two cross strips, at the head and tail of the block; each of them is flown back (at the end) and forth (at the beginning). The across-track overlapping is 60%, as well as the across-track.
The **1:18000 block** (about 20 images) has a very simple structure and is constituted by two strips flown in the East-West direction, with 60/60 overlap.

Flights 3 and 4 have been executed about 3 weeks apart, with a 300 mm lens. Their structure is similar to that of flights 1 and 2, but the 1:18000 scale block is missing, because there was no practical point in acquiring images at that scale with this lens. Flight 3 is composed of the 1:5000 and 1:8000 blocks, with the structure described above. Flight 4 is composed only of the 1:8000 block.
The images (the total number of images is close to 1000) have been scanned with a pixel size of 14 microns.

1.3 Test field and Ground Control Points

A test field 6 x 4.5 km wide was set up in the city and its surroundings, which includes either artificial targets (AGCP) and natural points (NGCP). The GCPs have been measured with GPS in fast static mode, using three fixed receivers, set up on vertices of a pre-existing GPS network. To point out and eliminate possible setup errors, all points have been measured twice some months later. The estimated inner accuracy of the network is better than 1.5 cm.
The AGCP set consist of 169 artificial square targets either metal plates fixed to ground or painted, 35 x 35 cm wide, homogeneously distributed. The size of the markers has been chosen in order to be optimal for images in the scale range 1:5000 – 1:8000. Most of the markers have been painted on paved roads or flat concrete structures.
A smaller set (62 points) of natural GCPs was also available.

1.4 Reference data for calibration

The research unit of the authors of this paper took care of the measurement and analysis of the block flown at image scale 1:8000 with a 300 mm focal length. The block is made of 11 strips, 7 flown in East-West direction and 4 across the block. The cross strips are flown twice on the same line but in reverse; one of the East-West strips is also flown twice. To provide calibration data and reference data to check the results, a manual AT was measured. It is planned within the project to interchange the different flights in order to have independent calibration and test data. At the time of writing, tough, no other 300 mm block was available, so we decided to used the same block for both purposes. On the 144 images, 466 tie and pass points have been measured manually with the software GDS (Geosoft – Italy). Besides, 199 GCP have also been measured: 154 AGCPs and 45 NGCPs; out of the AGCPs set, 35 points have been used as control in block adjustment. Therefore, overall 164 check points were available (figure 1).
The reference system used in the adjustment is a local tangential frame, with origin at the ellipsoid and y axis in the meridian plane. The bundle block adjustment and the calibration of the IMU/GPS system have been performed with the program Calge of the Politecnico di Milano (Forlani and Pinto, 1994).
In order to verify the accuracy of the AT and the stability of the solution, two different configurations for ground control have been used. In the former, 35 GCP distributed along the block edges and on the overlap between strips; the latter, with only 4 ground control points at the block corners. No additional parameters were used.
Fixing the exterior orientation (EO) of the images to the values computed from the previous adjustment, the coordinates of the 164 available check points (119 artificial, 45 natural) were determined by forward intersection. Table 2 summarizes the statistics of the forward intersection.

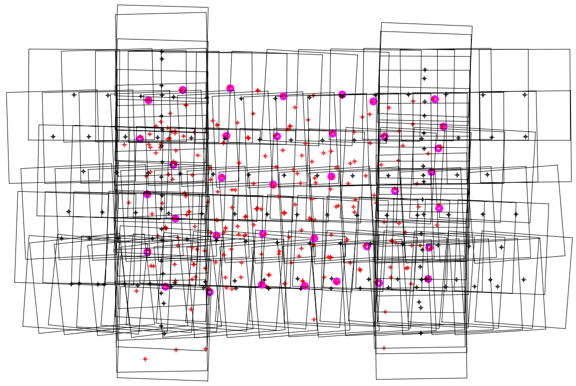

Figure 1 – Plot of the 1:8.000 scale block with location of control (large pink dots) and check points (red dots)

Block control configuration	σ_0 [μm]	RMS AGCPs (cm)			RMS NGCPs (cm)		
		X	Y	Z	X	Y	Z
AT “35 AGCP”	5.7	2.3	2.3	6.9	5.5	9.3	13.6
AT4 “4 GCP”	5.7	3.4	3.2	44.9	4.9	10.7	40.3

Table 2 - Forward intersection: accuracy of the EO from the AT measured on the check points.

As expected, also because of the normal focal length, the error in elevation increases significantly with 4 GCP only, but accuracy in X,Y is only slightly affected, witnessing the inner consistency of the block. The estimate for sigma naught is about half a pixel, which is reasonable for manual measurements on digital images and is unchanged with less control. The accuracy of the NGCPs is about half of that provided by AGCPs.

2. IMU/GPS SYSTEM CALIBRATION

2.1 Introductory remarks

A system calibration is required to account for the spatial offsets and misalignment between IMU, GPS and camera frames; moreover, reference to a common time scale is to be maintained, to allow the interpolation of the IMU/GPS navigation data to the mid-exposure time of the images.
The spatial offsets IMU-camera can be best obtained by theodolite measurement, with an accuracy in the order of a centimeter; an alternative is to include them in the functional model, perhaps as nuisance parameters, together with the misalignment angles. Misalignment angles cannot be measured directly to the necessary accuracy, so they are obtained by minimizing the differences from the exterior orientation provided by a standard photogrammetric solution and that measured by the IMU/GPS sensor.
This calibration problem, which is common also to mobile mapping system (El-Sheimy, 1996) to our best knowledge has been first addressed in aerial photogrammetry by the University of Calgary group (Skaloud et al, 1994). Since, several authors (Skaloud, 1999; Kruck, 2001; Cramer and Stallman, 2002; Mostafa, 2002) have proposed variations or alternatives to this original approach. Calibration techniques can be grouped under two broad categories, the so called two-steps and one-step methods (see also Skaloud, 2003 for a review on this specific

subject and Heipke, 2002); both are shortly addressed in the next paragraphs.
Just to roughly summarize, it is so far acknowledged that in operational terms both approaches lead to accuracies more or less comparable on the ground; one-step methods require less ground control or, with less reliability, none at all.
There are still some open issues, though. From a theoretical standpoint, the lack of information on the covariance matrix of the IMU/GPS solution (usually not provided by the proprietary processing software) still prevents to specify correctly the stochastic model in both approaches; from a more operational standpoint, how often should the calibration procedure be repeated and what is the minimum reliable block configuration to calibrate successfully, though several papers have been published on the subject, has not yet being practically translated in technical recommendations and an operational procedure.

2.2 Previous work on this topic

One of the major efforts up today towards clarifying the performance of IMU/GPS systems has been the OEEPE test "Integrated Sensor Orientation" (Heipke et al, 2002). Within the test activities, the authors used a "two-step" calibration procedure (Forlani, Pinto 2002) which modifies, as far as the stochastic model is concerned, the method proposed in (Skaloud, 1999). Later on, a 1-step procedure has been also implemented (Pinto, Forlani, 2002), looking for the minimum reliable configuration for the calibration block, especially in terms of number of GCP necessary.
In the following we present an improved 2-step method, based on a more realistic stochastic model, again after a proposal by (Skaloud, 2003). By applying all methods to the Pavia dataset we try to find out whether this more complex model yields benefits in terms of accuracy of the calibration compare to the others; beside, we check how the performance of the various approaches changes with changing calibration block configuration.

2.3 The "two-steps" procedure

Let's start from the collinearity equation:

$$r_i^L = r_j^L + R_c^L s_i r_i^c \qquad (1)$$

where: r_i^L = position of point i in object space, a cartesian system L conveniently located in the block area;
r_i^c = image coordinates of point i in camera frame c;
r_j^L, R_c^L, s_i = EO parameters of image j (position of the projection centre, rotation matrix from c to L), scale factor for image point i.

Let assume the IMU/GPS positions be referred to the projection centre and the IMU angles providing the rotation from IMU (the body frame b) to L; r_i^L can be also obtained as:

$$r_i^L = r_{j\,IMU/GPS}^L + R_b^L \left[s_i R_c^b r_i^c + a^b \right] \qquad (2)$$

where: $r_{j\,IMU/GPS}^L$ = IMU/GPS-derived position of the projection centre of image j, in the local frame L;
R_b^L = rotation matrix from body frame b to L frame;
R_c^b, a^b = calibration parameters: rotation matrix from c to b frame; offset between the IMU/GPS-derived and the photogrammetrically-derived perspective centre position in the b frame.

In the "two-step" procedure the EO elements obtained by a standard ground-controlled bundle block adjustment are compared with the EO elements measured by the IMU/GPS data in the same flight. The calibration parameters (besides the misalignment angles in the matrix R_c^b, an offset a^b between the IMU/GPS solution and the photogrammetric solution for the camera projection centres was considered) are estimated as a weighted average of the discrepancies between the EO of the block adjustment and those provided by INS/GPS.
Since no information is available for the latter, only AT results are used to get a weighted average of a_x, a_y, a_z, ω, ϕ, κ; the weights are derived from the standard deviations of the EO parameters estimated in the AT. This should yield a more consistent result, since whenever block geometry is weaker (e.g. on the border strips) the EO elements, which may be biased and poorly determined, will count less for the determination of the calibration parameters. Correlations between EO elements arising from block adjustment have been neglected.
The effectiveness of this weighting procedure was reflected in "OEEPE test" (1:5000 block) where RMS on check points computed by direct georeferencing, were in the order of 7 cm for N, E and 12 cm for elevations.

2.4 The "one-step" procedure

Comparing (1) and (2), the EO of image j is computed as:

$$r_j^L = r^L_{IMU/GPS} + R_b^L a^b$$
$$R_c^L = R_b^L R_c^b = R_G^L R_{lj}^G R_b^{lj} R_c^b \qquad (3)$$

where: R_b^{lj} = rotation from b to lj (the navigation system) measured by IMU;
R_{lj}^G = rotation from lj to the geocentric frame G;
R_G^L = rotation from object frame L to the G frame.

We therefore substitute $r^L_{IMU/GPS} + R_b^L a^b$ for r_j^L and the product $R_G^L R_{lj}^G R_b^{lj} R_c^b$ for R_c^L in the collinearity equations, removing the dependence on EO parameters. The modified equations are then linearized with respect to the components of the vector a^b, the angles ω, ϕ, κ of R_c^b, the components of $r^L_{IMU/GPS}$ and finally with respect to the ground coordinates of the tie points. The functional model for the block adjustment is complemented by the pseudo-observation equation of each IMU/GPS data (either positions and angles) and the pseudo-observation equation of the coordinates of the GCP. This is the base of the "one-step" calibration procedure.
As far as the stochastic model is concerned, due to lack of information (in terms of a variance-covariance matrix of the solution) from the IMU/GPS data processing, often considered a proprietary information, we assign positions and angles accuracies according to manufacturer's specifications, therefore neglecting correlations arising from pre-processing.

2.5 An improved "two-steps" method

In a recent paper (Skaloud and Schaer, 2003) discuss the correctness of the one-step and two-steps procedures. Since the two methods are equivalent if the variance covariance matrices are correctly propagated, Skaloud favours the two-steps because its implementation is easier: at least the EO variances should be part of the standard output of any bundle adjustment program, while including IMU/GPS observations with time dependent correlations in a one-step bundle software would be difficult. The importance of properly accounting for the temporal correlation arising from the Kalman filtering of the combined IMU/GPS solution is stressed, to avoid biased mean values and too optimistic accuracy estimates from the calibration. Restricting the functional model of calibration to the misalignment angles, he argues that correlations between different updates in the KF solution can be modelled by an exponentially decaying function:

$$\rho(t, t+\Delta t) = e^{\frac{-\Delta t^2}{T^2}} \quad (4)$$

where T is the bias variation correlation time of the gyroscopes and Δt the time interval between two images.

Following his suggestion, we further extended our two-step model to account for a more complete stochastic model, on the AT side as well as on the IMU/GPS side.

The functional model is again provided by equations (3), written in a slightly different way:

$$r_{AT}^{L} = r^{L}_{IMU/GPS} + R_b^{L}\, a^b$$
$$R_c^{L}{}_{AT} = R_G^{L}\, R_{lj}^{G}\, R_b^{lj}\, R_c^{b} = R_c^{L}{}_{IMU/GPS} \quad (5)$$

to stress that r_{AT}^{L} is the perspective centre position as computed by the AT and the product of the four rotation matrices on the right side yields the image attitude from IMU measurements.

For each image of the calibration block, we have 12 therefore observed quantities: $(X,Y,Z)_{AT}$, $(X,Y,Z)_{IMU/GPS}$, $(\omega, \phi, \kappa)_{AT}$ and $(\omega, \phi, \kappa)_{IMU/GPS}$.

We write three equations for the projection centre position and three for the attitude angles. Unlike (Bäumker and Heimes, 2001 and Skaloud and Schaer, 2003), out of the nine elements of R_c^L (both AT and IMU/GPS) we just take r_{12}, r_{23} and r_{13} (the elements corresponding to ω, ϕ, κ in case of small rotations) to have truly independent information, since each rotation matrix depends originally on just three computed attitude values.

From a general L.S. model with condition equations and observation equations:

$$D\,y = A\,x + d \quad (6)$$

where y and x are the expected values of the observations, we linearize (5) with respect to the observations as well as with respect to the unknowns. The matrix D in (6) is therefore the Jacobian with respect to the observations and the matrix A is the Jacobian with respect to the unknowns (the design matrix).

As far as the stochastic model is concerned, the covariance matrix of the observations is in principle a block diagonal matrix made of two blocks only, one representing the covariance matrix of the bundle adjustment, the other the covariance matrix of the Kalman filtering for the IMU/GPS solution. To keep things reasonably simple (thought no optimization of the computation has yet been performed) we only considered the 6x6 diagonal blocks referring to the EO parameters of each image from the bundle block. As far as the IMU/GPS observations are concerned, we followed the model suggested by Skaloud, considering time correlations for IMU/GPS positions and attitudes to be modelled by (4). Since we didn't have actual estimates for the variances from the KF nor specific information on the quality of the GPS data acquired during the calibration flight, we simply used the accuracies stated by the manufacturer for the IMU (8 mgon for pitch and roll, 10 mgon for yaw) and 6 cm in E,N and 10 cm in elevation for the GPS positions.

3. EXPERIMENTAL RESULTS

3.1 Calibration parameters

As mentioned previously, no attention has been paid yet to speed up computing time for the computation of the LS solution; the computational burden, though, increases significantly with the number of images in the calibration block. This has still prevented, at the time of writing, to compute the estimates of the new method using all images (see Table 3). With a smaller number of calibration images, using just four strips (2 perpendicular, flown twice in reverse, 5 GCP – figure 6) this has been possible (see Table 4).

Calibration method	a^b [cm]			R_c^b [deg]		
	Ex	Ey	Ez	ω	ϕ	κ
"two-steps"	-18.7	-5.0	27.5	180.6665	-0.1365	179.9778
"one-step"	-20.3	-6.9	23.2	180.6675	-0.1360	179.9778

Table 3 - Estimates for the calibration parameters from the whole block, with both methods

Calibration method	a^b [cm]			R_c^b [deg]		
	ex	ey	Ez	ω	ϕ	κ
"two-steps"	-11.7	-1.2	39.5	180.6664	-0.1377	179.9791
"one-step"	-19.5	-7.0	29.6	180.6678	-0.1359	179.9790
"two-steps w.corr."	-11.2	-2.5	33.4	180.6716	-0.1379	179.9779

Table 4 - Estimates for the calibration parameters from 4 strips, with both methods.

As it is apparent, estimates for the misalignment angles do agree much more compare to offsets. Differences are better than 2 mgon for the same dataset (and much more for k, whose accuracy is the highest). Differences in offsets are not significant statistically, tough.

The one step method proved much more difficult to handle to reach convergence with respect to the OEEPE test where it was first applied. Indeed, unless the values of the two-step methods are used as approximations, at the first iteration the offset parameters can jump to meters. In the following iterations, though, angles converge more quickly. Correlations between offset and misalignment were also found higher than in the OEEPE test data, though they also strongly depend on the accuracy of the pseudo-observation on IMU/GPS data. Despite this problem, the one-step solution is the most coherent overall across the two calibration datasets.

3.2 Discrepancies at the check points

Different sets of calibration parameters have been obtained for each of the three methods, by varying the calibration block configuration either in terms of number and type of strips as well as of ground control provided. Each calibration dataset has been applied to the IMU/GPS data of the whole block to get the correct EO parameters. Then the coordinates of the 164 check points have been computed by forward intersection, so the results are directly comparable with those of the manual Aerial Triangulation and with the reference values from the terrestrial GPS network.

Table 5 shows the RMS on the check points for the calibration computed over the whole block.

11 strip, (144 photo)	σ_0 [µm]	RMS AGCPs (cm)			RMS NGCPs (cm)		
		X	Y	Z	X	Y	Z
"two-step"	9.4	5.2	10.9	9.5	8.2	8.7	16.9
"one-step"	9.5	5.2	10.8	8.4	8.2	8.7	14.0

Table 5 - RMS on the artificial (119) and natural (45) GCP for the calibration parameters estimated from the whole block.

As it is apparent, no true differences in ground point accuracy can be traced between the two methods; only a small improvement seem to emerge as far as elevations are concerned. With respect to the reference AT, direct georeferencing is about half as accurate in terms of sigma naught and for the horizontal, while elevation is just 50% worse than AT. Differences between AGCPs and NGCPs are now smaller.

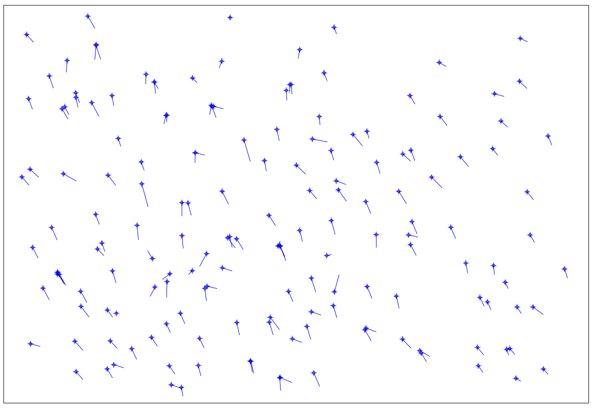

Figure 6 - Systematic component (10 cm) in Y direction

Decomposing the RMS, the standard deviations are much the same as for AT, but a systematic component (10 cm in Y, 4 cm in X) is now present in the RMS (see Figure 6), while it was insignificant in the AT; this applies also to the results of all subsequent calibration datasets. We are still investigating why this happened.

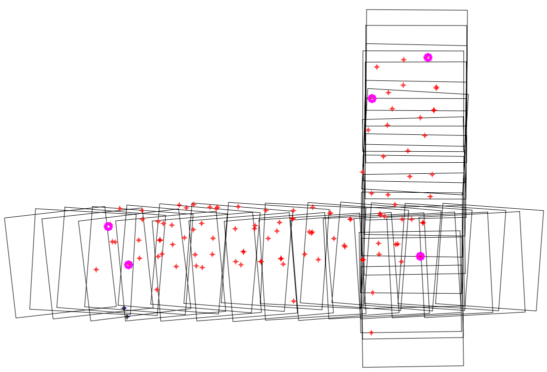

Figure 7 - Calibration block made of 4 strips, 5 GCP

A possible explanation may arise from inconsistencies between the GPS solution for the flight and the GPS solution for the ground network. Although the ground reference stations for the flight were the same used in the network, maybe processing of the kinematic data didn't result in a high accuracy solution. Because of the block design, any systematic error in the GPS solution cannot be adsorbed by the offset parameters and will show up on the ground.

In a second set of tests, smaller sections of the block have been used: 4 strips (two East-West and two Nort-South, flown twice) with 51 images and 5 GCP (see Figure 7); two strips (East-West, flown twice) with 21 images and 4 GCP (see Figure 8).

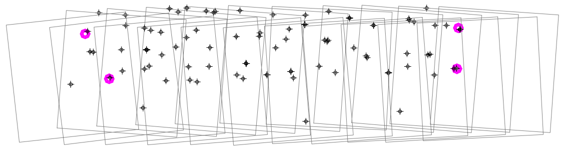

Figure 8 - Calibration block with two strips, 4 GCP

The picture emerging from this table (table 9) is less clear. There are hints that the one-step leads to somehow better results in elevation. This may be simply due to the inner strength of the one-step solution, which is less sensitive to poor ground control, because the pseudo observations of the IMU/GPS data manage to prevent excessive block deformations (which are mainly in elevations, with the 300 mm lens). The extended two-steps does not improve the accuracy of the standard two-step except in one case. On the other hand, sigma naught, which is fairly independent of block configuration in all cases with the other two methods, is always worse.

4 cross strips, (51 photos) + 5 GCP	σ_0 [µm]	RMS AGCPs (cm)			RMS NGCPs (cm)		
		X	Y	Z	X	Y	Z
"two-step"	9.8	5.1	10.9	18.8	8.1	8.7	27.3
"one-step"	9.9	5.1	10.8	11.3	8.1	8.7	19.0
"two-step" w. corr	19.2	5.3	12.0	18.4	8.4	9.4	25.8
2 strips, (21 photos) + 4 GCP							
"two-step"	10.0	5.2	10.9	30.4	8.2	8.8	39.0
"one-step"	10.1	5.2	10.8	9.4	8.3	8.7	12.0
"two-step" w. corr	13.3	5.3	12.0	18.4	8.4	9.4	25.8

Table 9 - RMS on the artificial (119) and natural (45) GCP for the calibration parameters estimated from.

The last series of test was performed with the one-step method only and with the minimum ground control necessary, by varying the number of images. As reported in (Pinto et Forlani, 2002), we found in previous simulations that just one GCP may suffice, unlike "two-steps" where a standard control is necessary for the AT; result are shown in table 10.
The results of previous simulations are basically confirmed also in this case: while the horizontal accuracy remain the same with decreasing block size and block strength (and does not get any worse for the same block with more GCP), there is a clear deterioration of the accuracy in elevation.

"one-step" with 1 GCP	σ_0 [μm]	RMS AGCPs (cm)			RMS NGCPs (cm)		
		X	Y	Z	X	Y	Z
11 strips	9.4	5.2	10.9	10.4	8.3	8.7	18.1
4 cross strips	9.8	5.2	10.9	16.4	8.1	8.7	24.8
2 strips	10.0	5.2	10.9	18.7	8.3	8.7	27.2

Table 10 - RMS on the artificial (119) and natural (45) GCP for the calibration parameters estimated with one-step and 1 GCP only.

4. CONCLUSION

The preliminary results of two calibration methods for IMU/GPS systems applied to a 1:8000 block flown over the testfield of Pavia have been presented. Although it should be stressed that analysis of the large amount of data collected in the framework of the national research project COFIN 2002 is just at the beginning, the advantages of one-step method already emerged in other test seem to be confirmed and stand on a minimal control on the ground and on an equivalent if not better accuracy compare to the two-steps method. As far as the refined model for the two-steps method, we could not verify yet any improvement (nor we found biases in the one-step solution). We hope to get soon more detail on the GPS solution to possibly adjust to the actual values at least of the variances of GPS positions, which may be misjudged (see the systematic discrepancies on the horizontal components at the check points) and to extend the analysis to the other blocks to find out whether these conclusions get more support or not.

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Acknowledgements

This work has been financed in the framework of the National Research Program COFIN 2002 by the Ministry of the University and Scientific Research of Italy. Thanks go to proff. Galetto e Casella of the Pavia University for coordinating the project and making available the reference coordinates of the GCP. Compagnia Generale Ripreseaeree di Parma (Italy) is acknowledged for processing and providing image and IMU/GPS data.