INDEPENDENT AND RIGOROUS ASSESSMENT OF STANDARD AND REFINED METHODOLOGIES FOR GPS/IMU SYSTEM CALIBRATION IN AERIAL PHOTOGRAMMETRY

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ABSTRACT:

The paper concerns selected results from the PhD thesis regarding calibration of GPS/IMU systems and quality of direct georeferencing in photogrammetry. Thanks to Pavia's Test Site (PTS) and to a complex structure of flights which were acquired above it, it is possible to perform rigorous and independent validation of results. This means: the possibility of calibrating on one flight and validating on another, totally independent; the usage of disjoint sets of points for calibration and for assessing the results of direct georeferencing. Issues are also investigated such as short term time stability of calibration and reestimation of camera focal length.

1. INTRODUCTION

The thesis concerns direct photogrammetry and in particular some aspects of calibration strategies and procedures as well as result assessments.
A preliminary careful reading of reference bibliography, both at national and international level, allowed a definition of the state of the art of the technique. In this first phase of the work problems connected with direct georeferencing (DG) were faced through the study of several project reports and papers. The main goal of this approach was to analyze and understand the new aspects introduced with inertial systems. This analysis also allowed a comprehension of which problems had already been faced and totally or partially solved and, last but not least, to recognize which issues are still open.
The investigation described above was also useful as a point of reference for the planning and the creation of an ad hoc test-site and of an ad hoc data-set of flights. The realization of Pavia's Test Site (PTS) started at the end of the 90's in order to become a support for different purposes such as GPS survey, traditional photogrammetry and laser scanning acquisitions. During the last few years, several phogrammetric data-sets were also acquired with the aid of inertial systems. These data, even if useful for some analyses, weren't sufficient for a deep and rigorous assessment of direct photogrammetry. To fill this lack, the test-site was enlarged with new ground points (both artificial and natural) and with new flights.
As mentioned above, one of the main goals of the thesis was the analysis of calibration strategies and procedures. To achieve this purpose, a detailed study of the reference systems involved and of their mathematical relations was realized. This investigation was conducted for a double aim: to better understand the results of the calibrations performed with the commercial software and to realize a self-written program for the re-estimation of the calibration parameters.
The second goal of the thesis is the assessment of calibrations in terms of accuracy and of presence of residual parallaxes.
In order to better evaluate the results coming from DG, several traditional aerial triangulations (AT) were performed, one for each of the six blocks involved. This approach allowed the determination of the potentiality of the data and to assess the DG by the comparison between the AT accuracy results and those coming from direct sensor orientation (DSO).
Moreover, two step procedure was chosen for the calibrations and the ATs, calculated in this phase, were also used for this purpose.
Calibrations were performed both with commercial software and with a self-written one. Nevertheless, within the thesis, only results obtained with the latter were shown. This choice guaranteed the risk of an incorrect interpretation of results.
The next step was the validation of the performed calibrations. Different strategies were adopted to evaluate the final accuracy of calibration parameters. To take advantage of the data-set structure, some independent validation approaches can be realized. For instance, it is possible to calibrate with one block and to apply the obtained parameters to another block flown at a different altitude; moreover the same parameters can be applied to a similar block (same altitude) but flown on another day. This approach allows the assessment of the quality of calibration parameters and the detection of the presence of possible systematic errors. All the validations were performed with specific programs written in Matlab language.
Finally, taking into account the results of the validations, a further analysis on calibrations was performed focusing the attention on the re-estimation of focal length. Taking advantage of the presence of three flight heights, focal length was re-estimated and new calibrations were performed.
Finally, some conclusions on direct photogrammetry and sensor calibration were drawn.
As mentioned above, most of the elaborations contained within the thesis, were performed with specific programs purposely written in Matlab language. The author of the thesis ad of the present paper had only contributed to drawing up a few modules.

2. PAVIA'S TEST SITE

Between 2003 and 2005 a national project in inertial positioning in photogrammetry was realized and was concluded. The project leader was Riccardo Galetto from the University of Pavia and the title of the project was "Integrated Inertial Positioning Systems in Aerial Photogrammetry".
The aim of the project was to investigate almost all the features of inertial positioning: sensor calibration; precision and accuracy; direct sensor orientation (DSO) versus integrated sensor orientation (ISO); stability of calibration; influence of

bad GPS constellation and/or cycle slips; local reduction of parallaxes.
The structure of the project was defined after careful examination of the well known OEEPE test "Integrated sensor orientation". Between the two projects there was affinity, concerning the fundamental methodology which was followed. There was continuity too, because the results of OEEPE test were chosen as a starting point for the Italian project and its further aims were to widen the sampling and to solve problems which had not been tackled in the European one.
On the other hand there were also differences between the two projects. First of all the data examined in the Italian test was marked by a broader range of heterogeneity: for instance cameras with 150 and 300 mm focal length were used. Besides that, several photogrammetry scales were taken into consideration, chosen from those more commonly used in Italy for large and medium scale surveys, 1:5000, 1:8000 and 1:18000.
Finally, both artificial and natural ground points were used as photogrammetric control points. Artificial ones obviously allow for a better collimation and an enhanced accuracy, which however is not completely realistic, that is to say that the accuracy is not comparable to that which can be obtained by common cartographic production. The usage of natural points allowed for more realistic estimations of the accuracy level of the direct photogrammetric process in its industrial application.

Pavia's Test Site

Pavia's Test Site (PTS) has many relevant features which have been developed since 1999, according to the needs of the ongoing researches. Some features were created to fully support the execution of the above described project.

The AGCPs set

The first set of ground control points is constituted by 169 artificial ones which are white squares of 35 cm (Figure 2.1). They homogeneously cover the whole test site, which is 6 x 4.5 km2.
Two different types of target were created: markers directly painted on the ground and markers painted on metallic supports. Most of them belonged to the first category and they were mainly realized on roads or other flat concrete structures.

Figure 2.1 Distribution of the AGCPs over the PTS

When this was not possible, in rural parts of the test site, the latter target was installed.
The aerial images which were acquired over Pavia had scales 1:5000, 1:8000 and 1:18000, which are generally used in Italy to produce maps at the scales 1:1000, 1:2000 and 1:10000. The size of the markers was carefully tuned in order to have optimal vision on aerial images whose scale is in the range 1:5000-1:8000. Nevertheless, the markers were usually visible on the 1:18000 images, although with difficulty.

Figure 2.5 Aerial visibility for 150 mm camera and 1:18000 scale

Figure 2.6 Aerial visibility for 150 mm camera and 1:8000 scale

Figure 2.7 Aerial visibility for 150 mm camera and 1:5000 scale

In the previous images, it is possible compare the markers visibility for 150 mm focal length cameras and for the three flight heights.
The AGCPs were measured with GPS in the fast-static mode, using three fixed receivers, set up on vertices of the GPS network, forming an equilateral triangle. The relative redundancy of the adjustment was therefore three, and results were very good, as Table 2.1 shows.

	min [cm]	max [cm]	mean [cm]	sqm [cm]
e	0.16	0.80	0.437	0.134
n	0.16	0.73	0.321	0.094
u	0.33	1.50	0.895	0.246

Table 2.1 Mean statistical parameters of standard deviation σ of the AGCPs, referred to a local Cartesian coordinate system

The NGCPs set

Even though the AGCPs play a key role in the project, the creation of a smaller set of natural GCPs was decided on, because they are visible in images acquired before the creation of AGCPs. Moreover, another interesting point is the estimation of the attainable precision on natural points, which are usually less well defined than artificial ones. To date, there are 62 well distributed NGCPs (Figure 2.8).

Figure 2.8 Distribution of the NGCPs over the PTS

The points were carefully chosen in order to avoid perspective effects, as far as possible, because they must be visible on many different images. For this reason, features belonging to flat surfaces such as roads, courts, etc. were chosen.
As for the AGCP set, the previous images compare the visibility of natural point at the three different flight heights for the 150 mm camera.

Figure 2.1 Aerial visibility for 150 mmcamera and 1:18000 scale

Figure 2.2 Aerial visibility for 150 mm camera and 1:8000 scale

Figure 2.3 Aerial visibility for 150 mm camera and 1:5000 scale

NGCPs were measured with GPS in the fast-static mode, with the same schema used for AGCPs. The relative redundancy of the adjustment was three, and the results were quite good, as the Table 2.2 shows.

	min [cm]	max [cm]	mean [cm]	sqm [cm]
e	0.17	0.76	0.392	0.146
n	0.14	0.79	0.326	0.150
u	0.41	1.49	0.831	0.313

Table 2.2 Mean statistical parameters of standard deviation σ of the NGCPs, referred to a local Cartesian coordinate system

Flights performed over PTS within the frame of the project

During last years many photogrammetric flights were acquired over the city of Pavia, both with traditional and inertial supported techniques.
Four different flights were specially designed and performed over the test site, by the Italian company CGR, whose planes were equipped with Applanix POS/AV 510 sensors. Two of them were acquired with a camera whose focal length was 300 mm, while the others were taken with a 150 mm camera.
The flights were composed of a certain number of blocks, flown at different heights and characterized by the scales 1:5000, 1:8000 and 1:18000. As previously stated, these image scales are usually used in Italy to produce maps respectively at the scales 1:1000, 1:2000 and 1:10000.

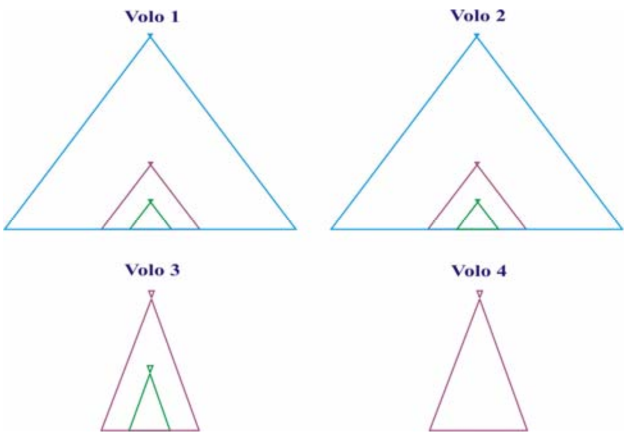

Figure 2.10 Graphical summary of the flights

Flights are usually distinguished between calibration and test flights, in the direct photogrammetry literature. The first are used to calibrate the sensor, while the second are used to assess precision and quality. They should be as independent as possible. In the Italian test, the choice to perform complex flights was taken to give the possibility of following several different strategies for calibration and testing. Moreover, the blocks have a complex structure themselves, to fulfil the need of independent estimation of calibration parameters. Another motivation for such a complex structure is to allow intrinsic quality assessment, that is without external control measurements. Figure 2.10 shows a summary of the flights performed.
Flights 1 and 2 were acquired with a Wild RC30 camera, equipped with a 150 mm lens. They are composed of three blocks whose structure is shown in Figure 2.11, Figure 2.12 and Figure 2.12.
Block 1:5000 has three ordinary parallel strips covering a part of the test site, flown in an East-West direction. The first strip, once completed, is immediately re-flown in reverse. There are two cross strips, at the head and tail of the block; each of them is re-flown in reverse at the end. The along-track overlapping is 60%, while the across-track one is 30%. The number of images taken is around 140.

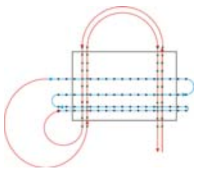

Figure 2.4 Structure of the 1:5000 block

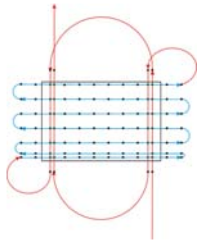

Figure 2.5 Structure of the 1:8000 block

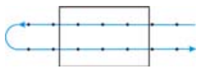

Figure 2.6 Structure of the 1:18000 block

The 1:8000 block 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 re-flown in reverse at the end. The along-track overlapping is 60%, as is the across-track. The number of images is around 130.
The 1:18000 block has a very simple structure and is constituted by only two strips flown in the East-West direction, with the 60/60 overlapping. The number of images taken is around 20.
Flights 3 and 4 were acquired with a Wild RC30 camera, equipped with a 300 mm lens. Their structure is similar to that of flights 1 and 2, but not the same. Indeed, no images at the 1:18000 scale were acquired, because this would have required a high-altitude flight, and good results were not guaranteed.
Flight 3 is composed of the 1:5000 and 1:8000 blocks, having the structure described above. Flight 4 is composed only of the 1:8000 block.
Finally, Table 2.3 summarizes the main parameters of the flights.

3. THE AERIAL TRIANGULATIONS PERFORMED

The aerial triangulation (AT) is a well-known procedure that was studied in depth during the last decades by different research groups. The goal of this section is not to add new contributions to this technique. Nevertheless, in order to analyse, in a strict way, the direct orientation approach it is important to know very well the potentiality of the data-set used.
In other word, to understand how good are the results of DSO it is necessary to compare those results with those determined in a better way. AT is the best technique to determine the EO parameters of a block; by comparison with the EO parameters coming from the DSO, it is possible to evaluate the potential of the direct photogrammetry.
A 2-step technique was chosen for calibration: the EO parameters coming from the GPS/IMU system and those coming from an AT calculation are compared. The differences

Flight	Date	Scale	Date	Focal length	Relative flight height	Overlappings	Stripes number	Images number
1	14/5/2003	1:5000	14/05/03	150 mm	750 m	60/30	8	139
		1:8000	14/05/03	150 mm	1200 m	60/60	11	131
		1:18000	14/05/03	150 mm	2700 m	60/60	2	19
2	16/05/03	1:5000	16/05/03	150 mm	750 m	60/30	8	135
		1:8000	16/05/03	150 mm	1200 m	60/60	11	128
		1:18000	16/05/03	150 mm	2700 m	60/60	2	15
3	06/04/03	1:5000	06/04/03	300 mm	1500 m	60/30	8	146
		1:8000	06/04/03	300 mm	2400 m	60/60	11	145
4	17/03/03	1:8000	17/03/03	300 mm	2400 m	60/60	11	135

Table 2.3 Summary of the performed flights

between the two sets can be considered as an estimation of the calibration parameters.
The results for flight 1 and flight 2 will be presented, both flown with a 150 mm camera. These flights, that have the most complete structure, allowed us to perform different strategies for calibration and test.

On the ATs and on the analysis performed

For space reason, in the paper will be discussed only the results in terms of accuracy on CKPs. This analysis has the goal to verify if the CKP's coordinates, obtained with photogrammetric stereo-plotting, are close to their true values (obtained via GPS survey). This comparison allows the evaluation of the quality of external orientation parameters. As mentioned at the begin of this section, the results of ATs can be considered as a touchstone for the evaluation of all the following elaborations presented within the note.
The performed ATs and their following evaluations involved different software.
The observations were realized with Socet Set-Orima software that was used only as an instrument for measuring the point coordinates. The aerial triangulations were performed with BLUH, which is a scientific software written by Karsten Jacobsen of the University of Hannover (Germany). Several strategies were adopted during aerial triangulation. The final choice, whose results were used for the following study phases, has these characteristics:

- aerial triangulation realized in a local cartesian system to avoid the introduction of errors depending on cartographic deformation;
- the image coordinates were corrected for radial distortion and atmospheric refraction;
- 35 GCPs well distributed on the test-site were used for the computation;
- control and check points rigorously divided; no check points were introduced into AT computation. They were used exclusively for results analysis.

Finally the evaluation of the EOs determined with the ATs was realized with programs purposely written in Matlab.
The determination of CKP coordinates was done with a single model approach; this choice was dictated by the will to work in a more realistic scenario. In a productive environment the stereo-plotting operations are usually done with a single model approach instead of a multi-rays determination.
It is important to underline that all the results that will be shown in this section as well as in the following ones, have all been obtained using the same set of CKP image coordinates (acquired during the point collimations made with Socet Set). All the differences in the results that will be analyzed, are exclusively due to the different EO parameters.
Moreover a set of specific programs allows an extraction from the whole data-set of measurements, a sub-set of them. In particular the data-set that contains all the points plotted exclusively on the longitudinal models will be reported in the present note. Due to the high overlapping between images, some points are visible even in two models instead of the traditional one. This sub-set will be called *along*.

The accuracy of the performed ATs

From now on, flight 1 will be indicated with "pv1" and flight 2 with "pv2". For instance, "pv1.5000" stands for flight 1, block flown at the 1:5000 image scale.
Table 3.3 shows for each block (column #1) the mean and the rmse for the three components east (e), north (n) and up (u). Columns #2 and #3 show the number of points and the number of observations involved in the analysis.

Block	N. pts	N. obs	Mean [m]			Rmse [m]		
			e	n	u	e	n	u
pv1 5000	167	623	-0.007	0.005	0.012	0.039	0.037	0.056
pv1 8000	193	1139	0.006	-0.006	0.010	0.046	0.055	0.088
pv1 18000	132	341	0.016	-0.014	-0.021	0.096	0.105	0.165
pv2 5000	147	570	-0.005	-0.006	0.012	0.054	0.055	0.077
pv2 8000	185	1068	0.007	0.004	-0.011	0.051	0.057	0.101
pv2 18000	159	382	0.009	0.029	-0.048	0.087	0.115	0.214

Table 3.3 Accuracy for the data-set along

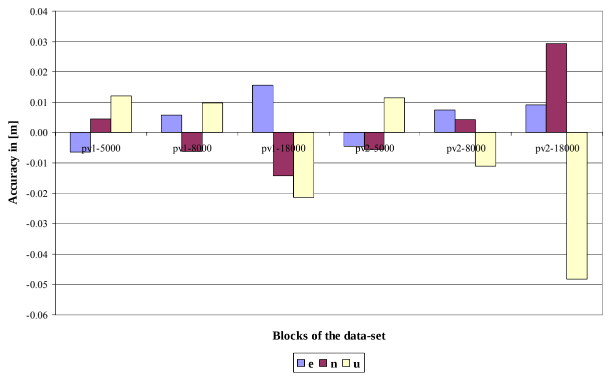

Figure 3.1 Mean accuracy for the data-set along

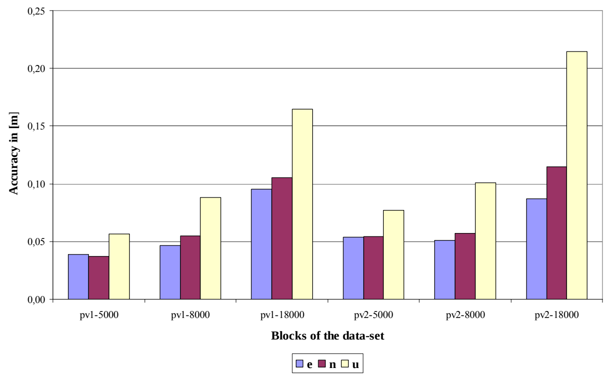

Figure 3.2 Rmse of the accuracy for the data-set along

The following two images show the same information in graphic form; Figure 3.1 shows the results of the data-set along in terms of mean accuracy for the three component e, n and up and for each block and the Figure 3.2 shows the same results in terms of rmse.
Considering, at first, the mean value, No systematic errors are revealed especially in the two lower block (1:5000 and 1:8000).
Examining the rmse trend for all blocks, it is evident that the accuracy gets worse passing from 5000 to 18000 block. The results of the two flights are almost equivalent even if pv2 shows a larger error in the up component.
Nevertheless, the planimetric components keep substantially less than one decimetre also for the higher block and the up component is, at worst, around 20 cm.
It is also interesting to observe that the 5000 and the 8000 blocks show, astonishingly, similar results, especially for the pv2 flight. In other words, there is not a gain passing from a lower to an higher block.
This phenomenon could derive from the size of the artificial markers. The dimension of the AGCP set was optimized for flight at the 1:8000 scale and these markers appear a bit larger in the lower block. This oversize could influence the manual collimations of the operator (the instrumental mark is to small for the dimension of the artificial markers) and the final accuracy results. The marker size creates a sort of accuracy ceiling that cannot allow a greater accuracy.

4. THE CALIBRATIONS PERFORMED

As described in previous paragraph, the ATs were calculated with BLUH, while the all the following steps, calibration, direct orientation of the images and validation, were executed with specifically written Matlab procedures.
Calibrations were performed with a two-step procedure and the D and M vectors were determined by taking the simple arithmetic average of the differences between the AT-determined EOs and the directly measured ones, once they were converted to the same reference system.
In the paragraph, the calibrations performed within the thesis will be illustrated and discussed, focusing attention on the stability of the estimated parameters.

Single block calibration

IMU system calibration was performed six times, once for each of the considered blocks. The calibration parameters were obtained using the two step procedure formulas and using the AT orientations described in paragraph 3. Both lever arms and boresight misalignments were calculated.
Table 4.1 summarizes the results obtained for lever arms: the second column shows the number of the images used; the next three columns contain the lever arm values, indicated with D (Delta), as they measure an offset; the last three columns indicate their standard deviations.
Table 4.2 summarizes the similar results for boresight misalignments: the second column shows again the number of the images used; the next three columns contain the boresight values, indicated with M and the last three columns indicate their standard deviations.
Analyzing these two tables it is possible to observe that the calibrations performed on the 1:18000 blocks are less reliable than the others, due to the reduced number of the images used.
Generally speaking the misalignment estimation is very good, as figures are very often below the threshold indicated by the manufacturer, and rather stable from one calibration to another.
Lever arm estimation is less stable. In principle, if there weren't any systematic components, all the six lines of columns 3-5 of Table 4.1 should contain the same values and more precisely should be null.

Block	N. img	D_x [m]	D_y [m]	D_z [m]	σ_{Dx} [m]	σ_{Dy} [m]	σ_{Dz} [m]
pv1.5000	80	-0.174	-0.048	-0.146	0.053	0.064	0.034
pv1.8000	76	-0.134	-0.113	-0.220	0.075	0.081	0.031
pv1.18000	8	0.027	-0.076	-0.400	0.101	0.092	0.050
pv2.5000	84	-0.166	-0.015	-0.154	0.086	0.098	0.040
pv2.8000	77	-0.173	-0.041	-0.156	0.094	0.105	0.034
pv2.18000	8	-0.215	0.028	-0.292	0.203	0.182	0.110

Table 4.1 Summary of results obtained for the six performed calibrations - lever arms

Block	N. img	M_x [grad]	M_y [grad]	M_z [grad]	σ_{Mx} [grad]	σ_{My} [grad]	σ_{Mz} [grad]
pv1.5000	80	-0.7227	0.1521	-0.0614	0.0075	0.0042	0.0049
pv1.8000	76	-0.7204	0.1553	-0.0609	0.0044	0.0039	0.0041
pv1.18000	8	-0.7253	0.1586	-0.0633	0.0024	0.0039	0.0029
pv2.5000	84	-0.7253	0.1522	-0.0605	0.0082	0.0053	0.0059
pv2.8000	77	-0.7240	0.1546	-0.0617	0.0047	0.0044	0.0040
pv2.18000	8	-0.7238	0.1570	-0.0672	0.0024	0.0071	0.0033

Table 4.2 Summary of results obtained for the six performed calibrations - boresight misalignments

In order to understand better the last assertion, it is opportune to make a consideration. Some producers usually suggest to companies to first determine the lever arms via topographic survey. The company, that acquired the images of our data-set, followed this procedure. So, they had performed a pre-processing phase where lever arms were taken into account to transform the raw GPS and IMU measurements and directly referred them to the camera system. In other words, the position information, given by the integrated system, was directly referred to the projection centre so that the IMU origin was virtually coincidental with the camera centre.
So, in theory, the lever arm data coming from calibration should be null or negligible. Unfortunately, they aren't and, on the contrary, they assume significant values in particular if the D values were compared with their sigma.
But, as it will be discussed within next paragraphs, at least one systematic error is present, due to the miscalibrated focal length. This bias is absorbed in the Dz estimation during calibration therefore, being the effects of the uncalibrated focal length depending on flight height, they were shown in a variation of Dz values between different flight heights. More precisely, the Dz absolute values increase with the altitude. To take into account the effects of this systematic error, the calibration procedure virtually moves the projection centres downward.
In the same way, the presence of significant values in Dx and Dy components could be interpreted as attempts to reabsorb the presence of systematic errors in the planimetric component. These biases could be connected with a miscalibration in the position of principal point or with a problem in data time-recording.
Nevertheless, variations between different flights having the same height and structure are not, in principle, to be expected. The observed differences could be due to random errors, which are present of course, but these differences could be more

realistically due to different environmental conditions that could cause, for instance, a different focal length variation.
The causes and the effects of these lever arms as well as the final accuracy induced from the calculated calibration parameters will be subject of the next paragraph.

5. CALIBRATION ASSESSMENT OF DSO: RESULTS AND VALIDATIONS

To assess the accuracy, it was decided to follow the same practical approach that would be used by a company. Some accuracy analyses were conducted using the above reported calibration parameters. The aim of this evaluation is both the quantification of the precision achievable with direct georeferencing and the analysis of the presence of systematic errors.
The analyses conducted can be subdivided into three categories:

- Homogenous validations: the parameters were applied to the same block that was used to determine them;
- Cross-validation within the same flight: a set of parameters was used to calibrate all the blocks of a flight;
- Homogeneous validation with different flight: a set of parameters was used to calibrate a block flown at the same altitude but belonging to a different flight.

One of the main aims of the paragraph is independent validation of results. This means that a set of CKPs totally unused in previous stages of the workflow was used for accuracy analysis. Moreover, the availability of three different blocks, at three different altitude, and flights flown on two different days allowed several independent validations to be performed
For space reason, the paper will show the validation results only in terms of accuracy for the along data-set.

Homogeneous validations within the same flight

Homogeneous validations were performed for the six considered flights. Accuracy has been studied by the comparison of the CKP coordinates calculated in a photogrammetric way with those surveyed in a topographic way (and considered the true ones). The comparison was made for each CKP and for each determination: a CKP can be compared in different models and then a CKP could be stereoplotted many times.
The term homogeneous was chosen because calibration and validation are calculated on the same flight, as, for instance, columns 1 and 2 of Table 5.1 show.
This method is not representative of the usual daily working procedures, at least for Italian companies, but it allows the best accuracy which is attainable with DG to be defined. Moreover, this approach allows the understanding of some dynamics involved in calibration procedures.
Comparing Table 5.1 and Table 3.3, it can be noticed that DG accuracies are not too far from those coming from AT, in this homogeneous situation. Of course there is a worsening of the results but their sizes remain close to the accuracy obtained using the error theory in the normal case.
Focusing attention on the mean value of the altimetric component (column #3 of Table 5.1), it is possible to notice that no systematic errors appear, especially for the two lower blocks.
It is well-known that the focal length printed in the camera certificate is incorrect because it was estimated not in operational conditions but in the laboratory. It is also known that AT absorbs this error virtually by moving the projection centres while DG can not. In direct photogrammetry this problem appears as an error in the up component.

Calibra-tion.	Valida-tion	N. pts	N. obs	Mean [m]			Rmse [m]		
				e	n	u	e	n	u
pv1 5000	pv1 5000	167	623	0.054	-0.027	0.013	0.078	0.070	0.112
pv1 8000	pv1 8000	193	1139	0.055	-0.051	0.002	0.081	0.088	0.109
pv1 18000	pv1 18000	132	341	0.100	-0.068	0.065	0.147	0.154	0.228
pv2 5000	pv2 5000	147	570	0.085	-0.006	0.001	0.112	0.075	0.097
pv2 8000	pv2 8000	185	1068	0.097	-0.032	-0.007	0.112	0.080	0.109
pv2 18000	pv2 18000	159	382	0.182	-0.102	-0.142	0.207	0.176	0.321

Table 5.1 Accuracy for the data-set along - homogenous validation

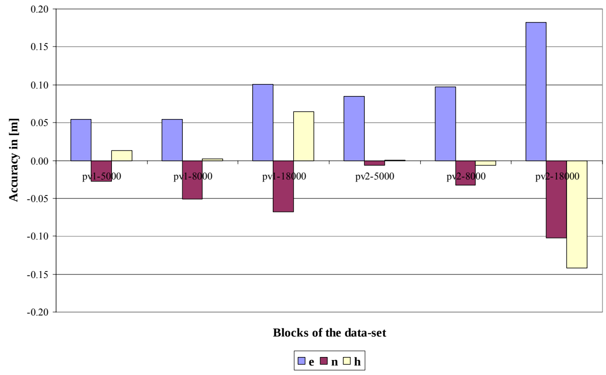

Figure 5.1 Mean accuracy for the data-set along - homogenous validation

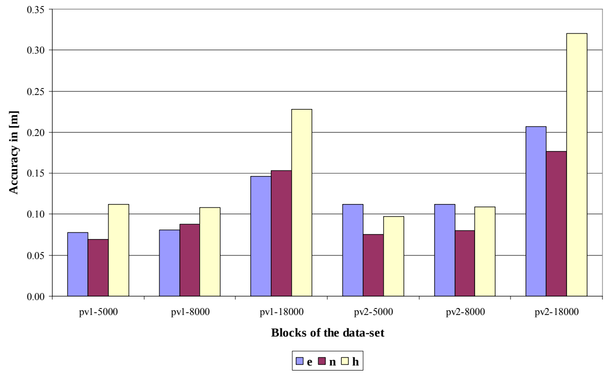

Figure 5.2 Rmse of the accuracy for the data-set along - homogenous validation

Usually to take into account this aspect, a re-estimation of inner camera parameters, and in particular, of focal length is advisable. To realize this re-estimation at least two blocks flown at two different altitudes are needed. This method is not usually applied by the company because it requires additional time and money.
But, analysing the results in the homogeneous validation and taking into account the considerations expressed at the end of previous paragraph, it can be observed that the estimated lever arms can be considered as substitute of focal length re-estimation.
As Table 5.1 shows, the application of these lever arms, in the homogeneous case, allows for the reduction of elimination of systematic errors in the up component, reaching the same accuracy level of ATs. Moreover, it is interesting to notice that although the mean values remain more or less the same, the rmse values are reduced. In other words, the accidental errors are reduced.

Cross validation within the same flight

Cross validation was also performed within the same flight. That means that a set of parameters, determined for a block, was used to calibrate the other two blocks of the same flight.
Several combinations can be realized using both flights. In the next paragraphs the results of flight pv1 using the calibrations obtained for 1:5000 and 1:8000 scales will be presented. These results exemplify the behaviour of the data-set.
Results are summarized in Table 5.2 where columns #1 and #2 report the blocks which reference calibration and validation. For instance, the first line means that the parameters obtained from the pv1.5000 block was applied to the same block for validation; the second line means that the same set of parameters (pv1.5000) was applied to block pv1.8000; and so on. As shown the cross-combination was realized within the same flight.
It is also important to underline that rows #1 and #5 of Table 5.2 must contain the same values as rows #1 and #2 of Table 5.1 because they fall also in the homogenous validation case.
Passing from a homogeneous calibration to a heterogeneous one, random errors maintain approximately the same size in general but sometimes planimetric components are increased by up to 50%. Concerning systematic errors, an increase of the up component is clearly visible: this highlights that the focal length value used, taken from the camera calibration report, is significantly different from the true one.

Calibra-tion.	Valida-tion	N. pts	N. obs	Mean [m]			Rmse [m]		
				e	n	u	e	n	u
pv1 5000	pv1 5000	169	1903	0.054	-0.027	0.013	0.078	0.070	0.112
pv1 5000	pv1 8000	195	6007	0.052	-0.051	0.076	0.083	0.092	0.137
pv1 5000	pv1 18000	141	752	0.100	-0.088	0.283	0.193	0.210	0.359
pv1 8000	pv1 5000	169	1914	0.052	-0.027	-0.061	0.080	0.078	0.129
pv1 8000	pv1 8000	195	6029	0.055	-0.051	0.002	0.081	0.088	0.109
pv1 8000	pv1 18000	141	752	0.111	-0.086	0.199	0.156	0.237	0.284

Table 5.2 Accuracy for the data-set along - cross validation

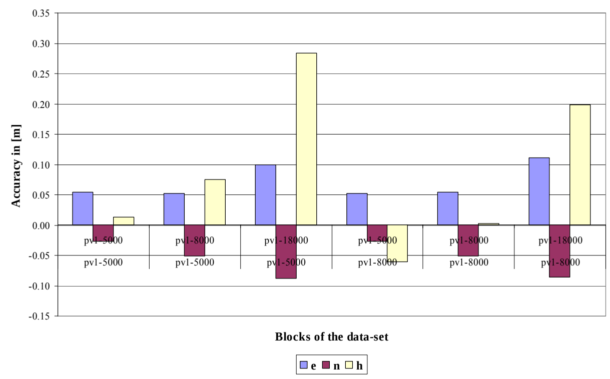

Figure 5.3 Mean accuracy for the data-set along - cross validation

This systematic error is absorbed in the estimation of Dz and, if validation and calibration flights have approximately the same height, miscalibrated focal length is not too disturbing. But this is no longer valid if calibration and validation happen with two different flight heights: a systematic height error is visible, whose size is a function of the difference in height between calibration and validation flights.
Observing the yellow bar (up component) of Figure 5.3, it is possible to see the behaviour described above. Analysing, for instance, the cross validation obtained with the pv1.5000 parameter set: the bar is minimal for the first data-set (which falls in the homogenous case) and progressively becomes higher with the increase of flight height difference.

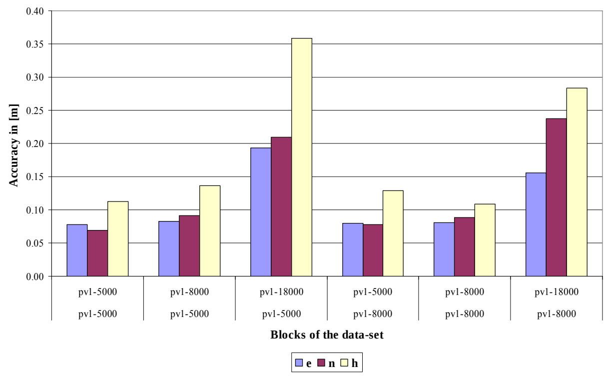

Figure 5.4 Rmse of the accuracy for the data-set along - cross validation

Considering the validation performed with the pv1.8000 parameter set, the applied Dz made an optimal correction for the homogenous case (set #5) but caused an error in the lower and in the higher block. In particular, the applied Dz is an overestimation for the pv1.5000 block and it caused a negative systematic error in final accuracy; on the other hand, Dz is an underestimation for the pv1.18000 block and the effect of incorrect focal length cannot be completely absorbed.

Homogeneous validation with different flights

Homogeneous validation was also performed with different flights. This means that a set of parameters, determined for certain block of a flight, was used to calibrate the block at the same altitude of the second flight.
This assessment was performed in order to evaluate the stability of the parameter set in short term time; the two considered flights were acquired within 48 hours of each other.
Results are summarized in Table 5.3 where columns #1 and #2 report the blocks to which calibration and validation are referred. For instance, the first line means that the parameters obtained from the pv2.5000 block was applied to the similar block (same altitude) of flight pv1. This procedure was applied for each of the six blocks involved.
Comparing these results with those reported in Table 5.1, it is possible to analyze the stability of the calibration parameters.
Analysing the mean values, it is possible to see that the results obtained for the two blocks at 1:5000 scale are comparable with those coming from the homogeneous case within the same flight. In other words, the calibration parameters found for pv2.5000 are optimal also for pv1.5000 and vice versa. In particular the accuracies in the up component remain stable.
Nevertheless, results of 1:8000 and 1:18000 scales show different behaviour: the planimetric components maintain the accuracy but the up component significantly changes. In particular the 1:8000 blocks show worse results for both cases (row #2 and #5); the 1:18000 blocks present smaller errors in absolute value but, in comparison to Table 5.3 and Table 5.1, it can be noticed that the results changed sign. This means that the Dz applied caused an overcorrection. In other words, the calibration parameters determined for 1:8000 and 1:18000 blocks cannot be successfully applied outside the flights for which they were estimated. This behaviour is also clearly visible in Figure 5.5.
Moreover, analysing the Dz values summarized in Table 4.1, it is distinctly visible as the lever arm determined figures, for instance, for the 1:18000 blocks, show significantly different

values. This difference could be caused by a different focal length variation due to different environmental conditions.

Calibra-tion.	Valida-tion	N. pts	N. obs	Mean [m]			Rmse [m]		
				e	n	u	e	n	u
pv2 5000	pv1 5000	167	613	0.054	-0.028	0.007	0.079	0.070	0.112
pv2 8000	pv1 8000	193	1139	0.057	-0.052	0.068	0.086	0.090	0.131
pv2 18000	pv1 18000	132	340	0.114	-0.077	0.162	0.246	0.239	0.267
pv1 5000	pv2 5000	147	570	0.086	-0.006	0.008	0.112	0.075	0.097
pv1 8000	pv2 8000	185	1068	0.096	-0.033	-0.071	0.114	0.083	0.131
pv1 18000	pv2 18000	158	380	0.182	-0.090	-0.233	0.287	0.235	0.369

Table 5.3 Accuracy for the data-set along - homogeneous validation with different flights

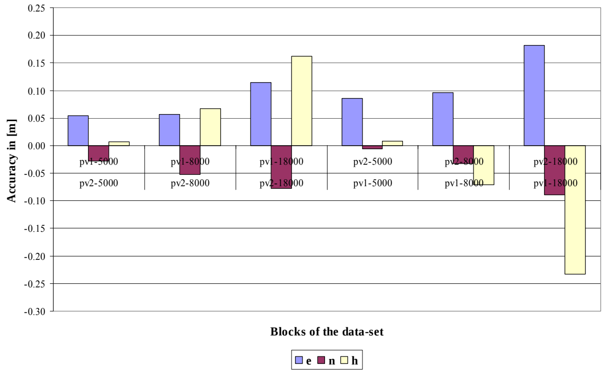

Figure 5.5 Mean accuracy for the data-set along - homogeneous validation with different flights

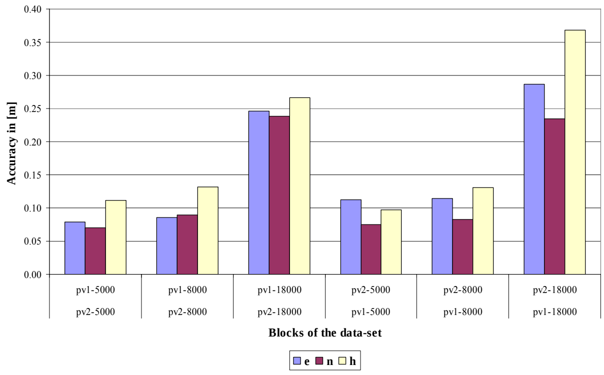

Figure 5.6 Rmse of the accuracy for the data-set along - homogeneous validation with different flights

Some considerations

In this paragraph, a review of some selected results is shown. Applying the parameters obtained in Section 4 to the different blocks following different strategies, different results and different accuracies were achieved.
At the end of the previous section, unexpected values in lever arms were observed in the calibration results. The reason for this behaviour was attributed to the presence of systematic errors and, in particular, for the up component, to the use of an incorrect focal length. Moreover, a variation of the up component of lever arms, depending on the flight heights, was observed. Finally a variability of the estimated parameters, between the two flights, was detected.
In this section, the results of the application of these parameters are evaluated in order to understand their influence on the accuracy of the plotted points.

The analyses conducted were subdivided into three categories: homogenous validations; cross-validation within the same flight; homogeneous validation with different flight.
The accuracy results are, in general, surprisingly good and not so far from those estimated for the normal case.
Analysing the results in terms of systematic errors, the mean values show interesting behaviours. For the homogeneous case, the results are good while for both cross-validation and homogeneous validation with different flights, the final accuracies show the presence of a new systematic error depending, for the up component, on the altitude.

6. RE-ESTIMATION OF FOCAL LENGTH

In the previous sections results of calibration and accuracy assessment were shown, analysing especially the values obtained for the up component.
It is well-known that the focal length (c) reported in the calibration certificate is incorrect. This happens because c is determined in the laboratory under different environmental conditions from those actually present on the plane during acquisition. In particular the different temperature causes a variation between the focal length printed in the certificate and that present during the flight.
Moreover, in section 5, it was assumed that the Dz component of lever arms is able to absorb the effect of an incorrect focal length. To assess this hypothesis and to evaluate if the values obtained for lever arms can be explained in terms of inner orientation re-calibration, a focal length re-estimation was performed.
Noticeably, re-estimated focal length changes with the height therefore it is not strictly correct to assign a unique value to a flight. Nevertheless, this simplification will be used in this chapter, in order to better understand the dynamics involved.
The re-estimation of focal length was performed for both flights pv1 and pv2 using BLUH software.
Focal length corrections were calculated for each block, as AT was performed by jointly adjusting the usual photogrammetric observations as well as the measurements of the camera centre, performed by GPS.
This approach required a careful weighting strategy; a half pixel accuracy was assigned to the photogrammetric observations while to the GCPs, used in the ATs, the precisions supplied by the GPS survey; the accuracy given by the producers was assigned to the camera centres measured by the integrated systems.
Only the results of c re-estimation for flight pv1 will be presented and only the validation results achieved using the 1:8000 block calibration parameters will be shown.

The re-estimated focal length and the new calibration

As mentioned at the beginning of the paragraph a unique value of c corrections was used and applied. Averaging the different results for flight pv1, it was established that the correction to apply to the nominal value of focal length was 30 microns.
This value proves that the focal length actually present during the flight can be significantly different from that reported in the calibration certificate.
Using the new focal length the system calibration was performed again; for block pv1.8000, the results are shown in Table 6.1 and 6.2. the former summarizes the results obtained for lever arms: the second column shows the number of the images used; the next three columns contain the lever arm values, indicated with D (Delta); the last three columns indicate their standard deviations; the latter summarizes the similar results for boresight misalignments: the second column shows

again the number of the images used; the next three columns contain the boresight values, indicated with M and the last three columns indicate their standard deviations.

Flight	Photo	D_x [m]	D_y [m]	D_z [m]	σ_{Dx} [m]	σ_{Dy} [m]	σ_{Dz} [m]
pv1.8000	76	-0.131	-0.111	0.019	0.075	0.080	0.030

Table 6.1 Summary of results obtained for the new performed calibration- lever arms

Flight	Photo	M_x [grad]	M_y [grad]	M_z [grad]	σ_{Mx} [grad]	σ_{My} [grad]	σ_{Mz} [grad]
pv1.8000	76	-0.7204	0.1554	-0.0609	0.0043	0.0040	0.0041

Table 6.2 Summary of results obtained for the new performed calibration - boresight misalignments

Comparing the new calibration parameters with the previously determined ones, contained in the second line of Table 4.1 and Table 4.2, the only significant difference is the value Dz, as expected; boresight misalignments and planimetric components of lever arms don't change.
As previously discussed, the lever arms values shown in section 4 contain the attempt to reabsorb the effects of an incorrect focal length. Now that c was re-estimated and the more precise value was used during AT and calibration phases, the lever arms haven't neutralized this phenomenon yet. Moreover, the new value of Dz can be considered substantially negligible and that no other systematic error is present in the lever arms anymore.

Accuracy assessment

Assessments were performed using the same strategies presented in section 5: homogeneous validation within the same flight, cross-validation and homogeneous validation with different flights. In the following paragraphs, the main results obtained using the new pv1.8000 parameter set will be shown.

Homogeneous validation within the same flight

Table 11.3 and Table 11.4 show the results obtained using the new set of parameters in the homogeneous case for both whole and along data-set. Comparing these results with those summarized in Table 10.1 and Table 10.2, it is possible to notice that the results are the same.

Block	N. pts	N. obs	Mean [m]			Rmse [m]		
			e	n	u	e	n	u
pv1 8000	193	1139	0.055	-0.051	0.002	0.081	0.088	0.108

Table 11.4 Accuracy for the data-set along - homogenous validation

The use of the lever arms set shown in chapter 9, that contains the focal length error reabsorbtion, produces the same accuracy results achieved using a calibration parameter set obtained after a preliminary focal length re-estimation.
In particular, for the data-set used within the thesis, the estimated c variation is optimal for the pv1.8000 block, as the final accuracy shows.

Cross-validation within the same flight

Cross-validations were performed for the three blocks of flight pv1; the results are summarized in Table 11.5 and Table 11.6.
As discussed in the previous paragraph, for the homogeneous case (line #2), nothing changes while, for the pure cross-validation (line #1 and #3), significantly variations appear.

Observing the accuracy results obtained in the up component, it is possible to see an appreciable reduction of systematic height effects. The remaining value is probably due to a residual difference of focal length between the various flight heights.
These results effectively show that the focal length cannot be considered a constant if different flight heights are taken into consideration. A small variation in c between different altitudes is clearly present; if the focal length is re-estimated as a constant, this simplification will directly affect the final accuracy of the up component. Concerning the different results between the whole and the along data-set, the considerations made in chapter 10 are still valid.

Calibra-tion.	Valida-tion	N. pts	N. obs	Mean [m]			Rmse [m]		
				e	n	u	e	n	u
pv1 5000	pv1 5000	167	613	0.051	-0.027	0.026	0.080	0.077	0.118
pv1 8000	pv1 8000	193	1139	0.055	-0.051	0.002	0.081	0.088	0.108
pv1 18000	pv1 18000	132	341	0.110	-0.082	-0.088	0.156	0.240	0.226

Table 11.6 Accuracy for the data-set along - cross-validation

Homogeneous validation with different flights

Finally homogeneous validation with different flights was performed applying the new parameter set obtained for pv1.8000 block to the similar block of flight pv2.
The results are summarized in Table 11.7 and Table 11.8. The results obtained with this new set don't show an appreciable improvement but, rather they show similar values to those reported in Table 10.9 and Table 10.10.
This behaviour indicates that different flight conditions, although the blocks were acquired within few days, can cause significantly differences in final accuracies.
In other words, focal length can significantly change on different days, even if the same flight height is evaluated. This phenomenon is particularly clear, if different periods are considered such as springtime or summertime. The data examined in the thesis shows that this behaviour can happen also within a very short period.

Calibra-tion.	Valida-tion	N. pts	N. obs	Mean [m]			Rmse [m]		
				e	n	u	e	n	u
pv1 8000	pv2 8000	185	1068	0.096	-0.033	-0.068	0.114	0.083	0.130

Table 11.8 Accuracy for the data-set along - homogeneous validation with different flights

7. CONCLUSIONS

A thorough analysis of the state of the art was conducted in order to understand which issues have already been faced and which ones are still open to question. Descriptions of the test-site and the data-set used within the thesis were reported. An overview of the reference systems involved in calibration procedures was given together with the equations that connected them to each other.
Results of performed aerial triangulations, in terms of accuracy and residual parallaxes, were shown in order to evaluate the potentialities of the blocks considered.
Estimated calibration parameters were reported and discussed.
Several combinations of the flights used for calibration and for validation were considered for quality assessment. Moreover, accuracy was evaluated using the nominal focal length and the re-estimated one.
The thesis faced several issues connected with sensor orientations focusing the attention on some aspects of lever arms estimation. In particular, as an end result of the assessment, two considerations can be made:

- a six parameter calibration must always be realized;
- an in-flight calibration should be calculated each time a block is acquired, using a small number of the images taken.

The former assumption is analyzed first. It often happens that only boresight misalignments are taken into account during calibration procedures because lever arms are usually determined previously with topographic survey.

This approach, in theory correct, on the other hand doesn't allow for the management of the presence of some systematic errors that can cause a worsening in final accuracies.

The lever arms estimated in section 4 don't represent the physical relations between the sensors involved but they allow for the reabsorbtion of the effects of some simplifications that are usually introduced in DG. In particular the up component of lever arms reduces considerably the errors induced from the use of an incorrect focal length. To neglect the lever arms can cause deterioration of the final accuracies.

During the EuroCOW meeting in Castelldefels, last January, a similar approach was suggested by one of the most important IMU world producers, the Applanix company.

Up to quite recently, the traditional Applanix calibration software performed only a simple three parameter estimation. Lever arms were taken into account only as pre-measured values. Recently they changed this approach by introducing a new element called *datum shift*.

The main aim of *datum shift*, as the name suggests, is to take into account the errors introduced by the use of a cartographic frame instead of a local tangential one. Nevertheless, if *datum shift* is applied, the estimated value will represent the sum of different error sources; not only the cartographic deformation but also the error induced by the variation of c. In other words, *datum shift* can cover the same role filled by the lever arms within the thesis. In addition, lever arms are able to reabsorb even the effect of datum deformation.

Analysing the in-flight calibration some further considerations can be made.

Traditionally, in the national and international literature, to evaluate the calibration parameters stability means to analyze the mechanical immovability between the involved sensors. Extending the concept of stability to the role filled by focal length in the thesis, a new interpretation of calibration stability can be made. What must be evaluated now is the stability of some error sources such as the value assumed by the focal length.

In particular, within the thesis, some behaviours of c clearly appeared:

- focal length during flight operations can assume values significantly different from those printed in the calibration certificate;
- focal length can also significantly change from one day to another due to the different environmental conditions;
- finally, if a flight is taken at different altitudes, focal length can also considerably change passing from one block to another.

The thesis analysis shows that the focal length actually present during flights is very different to the calibrated one. Moreover cross-validations show the variability of c depending on the altitude. Finally, homogeneous validations with different flights have demonstrated the variability between different days (even in a short period).

The thesis shows that the calibration procedure must be performed for each block considered, if the best accuracies want to be achieved. In any case, it is recommendable to perform the calibration flight at the same height as that used for the production.

Further, during the EuroCOW meeting last January, the Applanix company had also suggested a similar approach. Figure 7.1 shows the calibration scheme suggested by them during the above-mentioned workshop. In particular they recommended the creation of two sub-blocks composed of 3 strips, 5-8 images and a couple of GCPs, in order to determine the parameters.

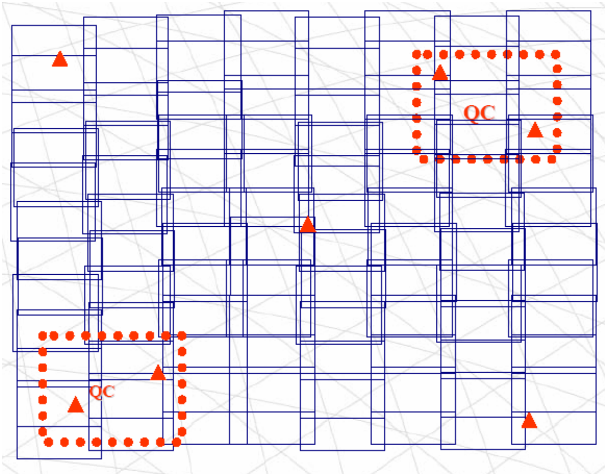

Figure 7.1 Calibration scheme suggested by Applanix

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