INTEGRATED SENSOR ORIENTATION AT ICC, MATHEMATICAL MODELS AND EXPERIENCES

R. Alamús, A. Baron, J. Talaya
Institut Cartogràfic de Catalunya, Spain

ABSTRACT

The Institut Cartogràfic de Catalunya (ICC) has been involved in integrated sensor orientation for several years, since the integration of an INS to a line scanner sensor (CASI) in 1997, up to the acquisition of an orientation system that has been installed on a photogrammetric camera in 2000.

On the paper the mathematical models used for the assimilation of the GPS/IMU data in a general adjustment procedure will be explained, especially focusing on the determination of the auxiliary parameters needed for directed georeferencing such as boresight misalignment, camera selfcalibration or linear drift parameters. A tentative combination of GPS/IMU and aerial triangulation, currently under study, will also be explained.

Then the experiences of ICC on the integration of GPS/INS data for sensor orientation, together with the work carried out with the OEEPE experiment will be presented.

1 INTRODUCTION

Direct orientation of aerial photogrammetric images is an emergent technology that is gaining ground to the conventional aerial triangulation. However, direct orientation is not just the combination of GPS and IMU observations; a successful 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… should be determined in order to allow a direct georeferencing. The robustness of the image orientation is a critical issue on a production environment; the ICC has been studying different mathematical models and workflows for a robust determination of the auxiliary parameters.

2 MATHEMATICAL MODEL FOR GPS/IMU SENSOR ORIENTATION

A traditional way for defining the orientation of an aerial photograph has been providing the exterior orientation parameters through the photograph projection centre position (x,y,z) and the angles that define its attitude (ω,ϕ,κ). The integration of GPS and inertial observations allows the determination of the inertial sensor position and attitude. The results of the GPS/IMU integration should be related to the exterior orientation parameters together with some auxiliary parameters through a mathematical model. At the ICC two different models have been studied, a geocentric model that is less intuitive on the results analysis, and a UTM model that is more intuitive, and therefore more suitable in a production environment. Both models have been implemented in the ICC GeoTeX/ACX software, [2].

2.1 General description

As stated above, a correct orientation of photogrammetric images implies the correct determination of some auxiliary parameters that are needed in order to propagate the orientation observations measured by the IMU and GPS sensors to the image sensor [4], [6]. Those auxiliary parameters can be divided as camera dependent (nodal distance, camera calibration parameters), mounting dependent (antenna offset, boresight misalignment matrix) or mission dependent (camera selfcalibration parameters, drift parameters). The camera dependent and mounting dependent can be well determined in a calibration flight, however special attention has to be paid to the stability of those parameters, in particular to the boresight misalignment matrix. In the models used at the ICC two groups of drift parameters are implemented, the traditional drift parameters for the GPS observations and a set of drift parameters for the IMU observations. If there are enough satellites in view, the distance to the reference station is not very high and the IMU observations have a very good quality the GPS/IMU integration have the capability to provide position and angular information without drifts, however our experience shows that in a production environment position and angular drift parameters still play a significant role on the orientation of the images.

2.2 Geocentric case

The photogrammetric observations are modelled in the usual way through collinearity equations whose image rotation matrix is parameterised in terms of (ω,ϕ,κ). Concerning the GPS aerial control observations the model used is, [3]:

$$\begin{pmatrix} X_{GPS} \\ Y_{GPS} \\ Z_{GPS} \end{pmatrix} = \begin{pmatrix} X_{DT} \\ Y_{DT} \\ Z_{DT} \end{pmatrix} + (1+\mu_{DT})\, R_{DT} \left(\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + T(\lambda,\varphi)\, R^{j}(\omega\phi\kappa) \begin{pmatrix} X_a^j \\ Y_a^j \\ Z_a^j \end{pmatrix} \right) + \begin{pmatrix} X_s \\ Y_s \\ Z_s \end{pmatrix} + \begin{pmatrix} V_{xs} \\ V_{ys} \\ V_{zs} \end{pmatrix} (t^j - t_0)$$

where

X_{DT} , Y_{DT} , Z_{DT} ,μ_{DT} , R_{DT} are the translation, scale and rotation matrix which defines the datum transfer (it is usually set to the identity transformation).

T is the matrix to transform from a local level frame to an ECEF frame.

X, Y, Z are the geocentric coordinates of the projection centre

X_a, Y_a, Z_a are the antenna offset parameters.

X_s, Y_s, Z_s, V_{xs}, V_{ys}, V_{zs} are the linear drift parameters (position, velocity).

t^j is time when the photograph was taken.

t_0 is the auxiliary reference time.

The IMU data (attitude observations) are modelled as:

$$R_{Roll,Pitch,Heading} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} R\ (\omega\phi\kappa) \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} R_{mis}^{t}$$

defining :

$$L_{i,j} := R_{Roll,Pitch,Heading}$$

we have :

$$\begin{aligned} \text{Roll} &= \arctan(L_{3,2}, L_{3,3}) && + DR_0 + DR_1 (t^j - t_0) \\ \text{Pitch} &= \arcsin(-L_{3,1}) && + DP_0 + DP_1 (t^j - t_0) \\ \text{Heading} &= \arctan(L_{2,1}, L_{1,1}) && + DH_0 + DH_1 (t^j - t_0) \end{aligned}$$

where

$R_{Roll,Pitch,Heading}$ is the direction cosine matrix defining the relative orientation of the IMU body frame to the local level frame defined by the sequence of rotations of roll, pitch and heading.

R_{mis} is the fixed direction cosine matrix defining the boresight misalignment matrix.

DR_0, DP_0, DH_0 are the offset of roll, pitch and heading

DR_1, DP_1, DH_1 are the drift of roll, pitch and heading

t^j is time when the photograph was taken.

t_0 is the auxiliary reference time.

2.3 Map projection case

The photogrammetric observations are modelled in the usual way through collinearity equations whose image rotation matrix is parametrized in terms of (ω,ϕ,κ). Concerning the GPS aerial control observations the model used is:

$$\begin{pmatrix} X_{GPS} \\ Y_{GPS} \\ H_{GPS} \end{pmatrix} = \begin{pmatrix} X_{DT} \\ Y_{DT} \\ H_{DT} \end{pmatrix} + (1+\mu_{DT})\, R_{DT} \left(\begin{pmatrix} X_{UTM} \\ Y_{UTM} \\ H \end{pmatrix} + R\,(\mu^j)\, R^j\,(\omega\phi\kappa) \begin{pmatrix} X_a^j \\ Y_a^j \\ Z_a^j \end{pmatrix} \right) + \begin{pmatrix} X_s \\ Y_s \\ H_s \end{pmatrix} + \begin{pmatrix} V_{xs} \\ V_{ys} \\ V_{Hs} \end{pmatrix} (t^j - t_0)$$

where

X_{DT} , Y_{DT} , H_{DT} ,μ_{DT} , R_{DT} are the translation, scale and rotation matrix which defines the datum transfer (it is usually set to the identity transformation).
X_{UTM}, Y_{UTM}, H are the projected coordinates of the projection centre
X_a, Y_a, Z_a are the antenna offset parameters.
X_s, Y_s, H_s, V_{xs}, V_{ys}, V_{Hs} are the linear drift parameters (position, velocity).
t^j is time when the photograph was taken.
t_0 is the auxiliary reference time.

$R\,(\mu^j)$ is $\begin{pmatrix} \mu^j & 0 & 0 \\ 0 & \mu^j & 0 \\ 0 & 0 & 1 \end{pmatrix}$ and μ^j is a scale factor depending on map projection scale factor and flight altitude.

The IMU data (attitude observations) are modelled as:

$$R_{Roll,Pitch,Heading} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} T^t(\lambda,\varphi)\, J_{geo}^{gc}\, J_{utm}^{geo}\, R\,(\mu^j)\, R\,(\omega\phi\kappa) \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} R_{mis}^t$$

defining :

$$L_{i,j} := R_{Roll,Pitch,Heading}$$

then:

Roll = arctan ($L_{3,2}$, $L_{3,3}$) + DR_0 + DR_1 $(t^j - t_0)$
Pitch = arcsin (- $L_{3,1}$) + DP_0 + DP_1 $(t^j - t_0)$
Heading = arctan ($L_{2,1}$, $L_{1,1}$) + DH_0 + DH_1 $(t^j - t_0)$

where

$R_{Roll,Pitch,Heading}$ is the direction cosine matrix defining the relative orientation of the IMU body frame to the local level frame defined by the sequence of rotations roll, pitch and heading.

R_{mis} is the fixed direction cosine matrix defining the boresight misalignment matrix.
DR_0, DP_0, DH_0 are the drift of roll, pitch and heading
DR_1, DP_1, DH_1 are the velocity drift of roll, pitch and heading
t^j is time when the photograph was taken.
t_0 is the auxiliary reference time.

3 ICC EXPERIENCES

3.1 *First Experiments*

ICC started its experiences on GPS/IMU integration for direct georeferencing with a first successful experiment in 1997. Two projects were done, one block (Linyola) flown at a photo scale 1:32000 containing 80 photos distributed in 5 parallel strips and two cross strips (figure 1) and one linear mapping project (Guissona) consisting in 42 photos flown in 5 strips at a photo scale 1:5000 (figure 2).

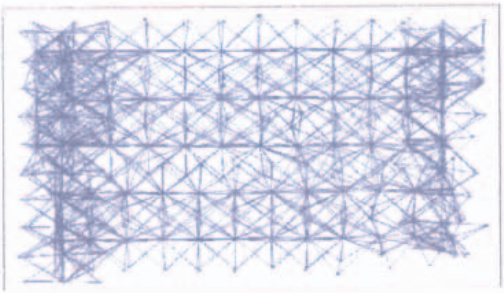

Figure 1: Linyola[1]

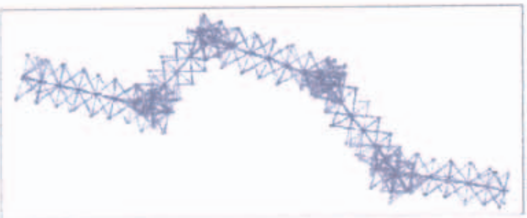

Figure 2: Guissona[1]

The comparison of the photogrammetric points coordinates derived from the classical aerialtriangulation with the ones obtained using direct georeferencing can be seen in table 1, it has to be mentioned that some systematic error on the GPS trajectory were removed by using drift parameters.

Block	X (m)	Y (m)	H (m)
Linyola (1:32000)	0.58	0.65	0.67
Guissona (1 : 5000)	0.12	0.22	0.13

Table 1: RMS of the difference between AT points and points obtained by direct georeferencing

3.2 Operational system for Direct Georeferencing

In late 2000 ICC started to operate an Applanix system in a production environment. In order to define an acceptable workflow for a production environment two blocks at flight scale 1:60000 have been flown with the Applanix system and aerotriangulated. The first one (figure 1) had 255 photos in 6 strips in east/west direction and 3 more in north/south direction, while the second one (figure 2) had 368 photos in 11 east/west direction, 5 in north/west direction and 3 following the coast

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[1] In this plots, photogrammetric observations are shown. Each blue line represents the connection between a projection centre of a photo and a tie point measured in the photo. So, the start of a blue segment represents a tie point and the end represents the photo projection centre in which the tie point has been measured.

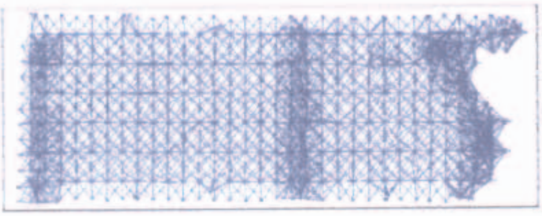


Figure 3: block 1[1]

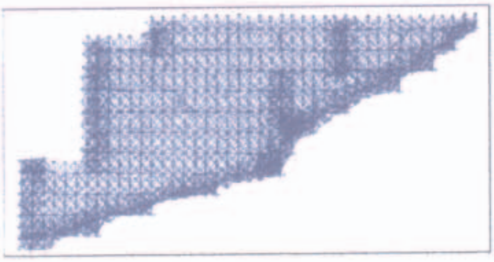


Figure 4: block 2[1]

Thus, once the blocks were aerotriangulated, a calibration adjustment using all information available (photogrammetric, ground control points, GPS and attitude observations) was made in order to compute the boresight misalignment matrix, the camera selfcalibration parameters and to see the attitude residuals. The results obtained in these adjustments were:

	ω	(σ_ω)	φ	(σ_φ)	κ	(σ_κ)
Block 1	0° 4' 25.57"	(2.12")	-0° 1' 52.35"	(1.63")	180° 1' 14.64"	(1.53")
Block 2	0° 4' 22.71"	(1.57")	-0° 1' 54.70"	(1.27")	180° 1' 31.28"	(1.20")

Table 2: boresight misalignment matrices adjusted for each block and standard deviations

Both blocks were flown in 7 days and as it can be observed, the values obtained are equivalents in roll and pitch angles. Only in heading the difference is statistically significant. The reason for such difference can be the drift observed on the heading observations (see figures 5 and 6).

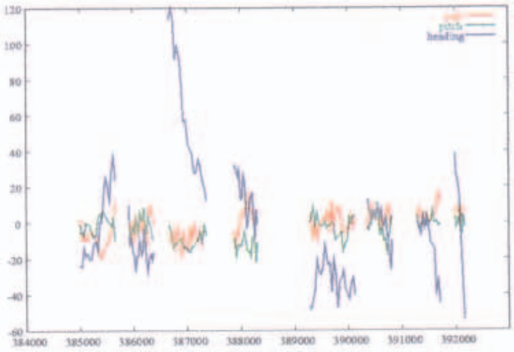


Figure 5: angular residuals 21.09.00 (arc-sec)

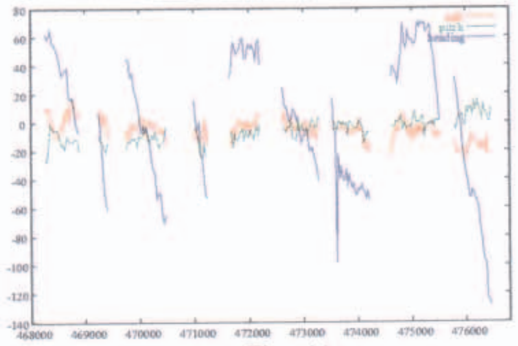


Figure 6: angular residuals 22.09.00 (arc-sec)

From these values it can be seen that roll and pitch accuracies are good enough, but the heading angle residuals are showing a systematic behaviour and can rise as big as 2 arc-minutes. So, according to our experience and at least when flying long photo lines, the heading determination is not accurate enough for robust direct orientation. Therefore, it is necessary to aerotriangulate some photographs for allowing the estimation of a heading drift, in order to correct the systematic errors.

Different configurations using regular sub-blocks for obtaining a robust configuration in order to compute the heading drift and, at the same time, saving a great part of AT were studied. The configuration that showed a good performance consists in measuring tie points in only one model at the beginning and at the end of each strip as shown in figure 7.

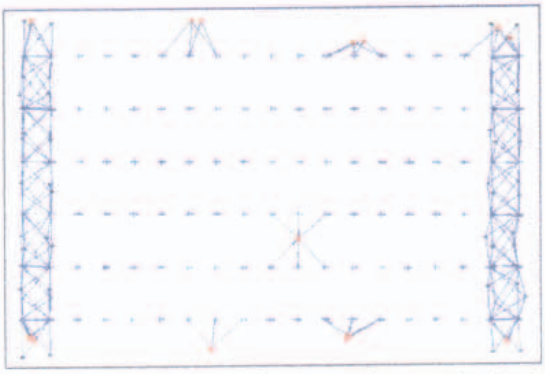
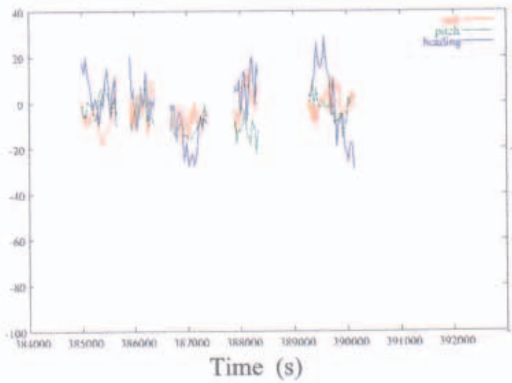


Figure 7: configuration chosen to orient regular blocks[2]

Using this configuration the camera parameters and heading drift can be estimated and so this angular drift corrects the high heading residuals. The angular residuals of this adjustment are shown in figures 8 and 9. As can be seen in figure 9 after applying the angular drift parameters there are still some isolated peaks on the heading residuals, those peaks are reported also in other experiments and can only be identified by measuring some tie points or by a visual determination of the parallax. Those effects can be a problem for stereo plotting and are a serious handicap on the robustness of the method.



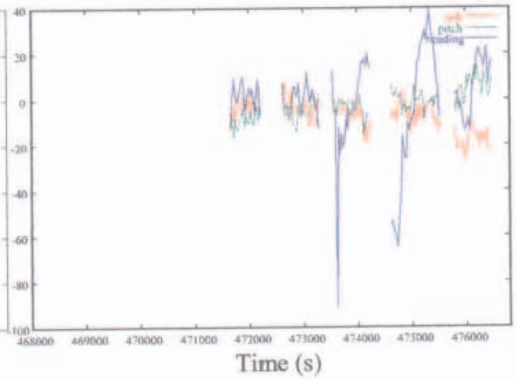


Figure 8: angular residuals 21.09.00 (arc-sec)

Figure 9: angular residuals 22.09.00 (arc-sec)

To check the accuracies on the ground given by the exterior orientation obtained using this configuration, a forward intersection adjustment was computed. The ground coordinates points obtained have been compared with those given by the AT of each blocks.

The differences obtained are similar for both blocks and quite good. Following the differences for block 1 are plotted:

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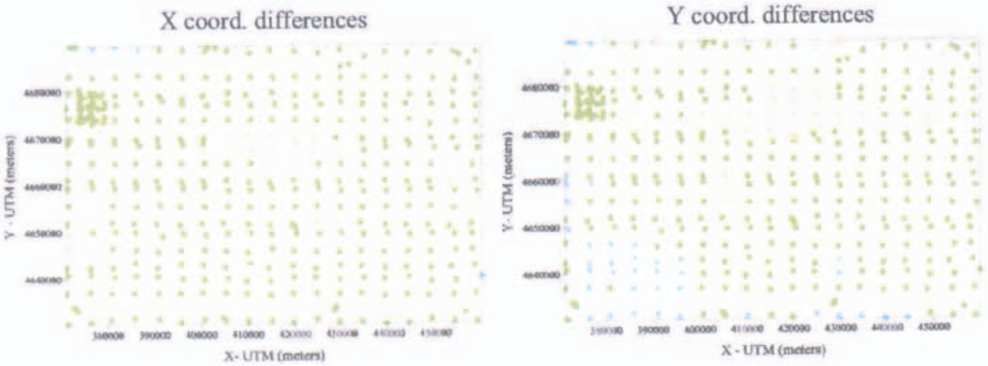
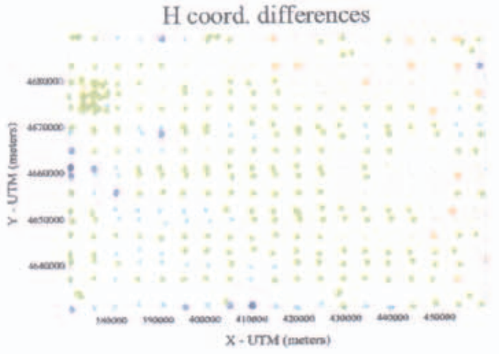
[2] Each cross represents a photo projection centre. Blue lines represent the connection between a photo projection centre and a tie point measured in the photo. Red points represent ground control points observed in a photo.





Distribution of differences in % of total points

	X	Y	H
● -5.00 to -2.25 m	0.0%	0.0%	0.0%
● -2.25 to -1.50 m	0.0%	0.0%	3.5%
● -1.50 to -0.75 m	5.8%	6.3%	16.9%
● -0.75 to 0.75 m	92.9%	84.1%	62.5%
0.75 to 1.50 m	1.3%	9.6%	14.1%
1.50 to 2.25 m	0.0%	0.0%	2.5%
2.25 to 5.00 m	0.0%	0.0%	0.5%

Figure 10: differences on ground coordinates in X_{UTM}, Y_{UTM} and H between AT points and points obtained by configuration chosen

Another aspect that has to be considered is if the configuration chosen allows the estimation of the camera focal length and the principal point corrections. The values for this parameters obtained in the calibration adjustment and those obtained on the proposed configuration are statistically equivalent.

3.3 Stability of the boresight calibration

Efficiency of direct orientation depends on a good knowledge of the geometric relationship between the involved sensors (boresight misalignment matrix). The determination of the misalignment matrix is done though a well controlled calibration flight. It is important to use an updated misalignment matrix to get acceptable results, however, calibration are very expensive and time consuming. So it is very important to study the stability of the misalignment matrix and perform calibration flighst every certain period.

As explained on the previous section the stability of the boresight misalignment matrix has been studied on two independent flights, the time period between the first and the last flight was just 20 days and the misalignment matrix was found the be stable, more studies will be carried out when more blocks with GPS/IMU data will available.

Since 1998 ICC is operating a CASI (Compact Airborne Spectographic Imager) and orienting its images by using a GPS/INS system Although the orientation of this sensor is much less demanding that a photogrammetric sensor, [the IFOV (Instantaneous Field Of View) of one CASI pixel is about 300 arcsec while the IFOV of one photo pixel scanned at 15 microns is about 20"] ICC has been studying the stability of the boresight misalignment between the CASI sensor and the INS system, the results are presented on the following table.

Block	ω (σ_ω)	φ (σ_φ)	κ (σ_κ)	Date
Garrotxa	0° 5'54''(33'')	0° 4'59''(35'')	-0° 1'38''(57'')	1998.07.23
Benifallet	0° 3'36''(50'')	0° 0' 1''(54'')	-0° 4' 2''(165'')	1998.08.04
Bellmunt	0° 5'31''(37'')	0° 5'24''(37'')	-0° 5'24''(96'')	1998.08.19
Paris 1	-0°15'35''(35'')	-0°18'57''(38'')	-0°30' 3''(84'')	2000.04.07
Paris 2	-0°16'30''(35'')	-0°21'24''(36'')	-0°27' 7''(87'')	2000.04.25
Paris 3	-0°15'37''(31'')	-0°22'45''(33'')	-0°36'38''(88'')	2000.05.06
Paris 4	-0°16'24''(37'')	-0°18'15''(36'')	-0°34'22''(104'')	2000.06.02

Table 3: adjusted boresight calibration parameters for several blocks (CASI sensor)

Table 3 shows the results concerning the stability of the boresight (note that the misalignment matrix has been expressed with the ω,φ and κ parameterisation). For these flights it was carried out a bundle block adjustment per flight in order to compute the boresight misalignment matrix. In Garrotxa, Benifallet and Bellmunt blocks the CASI-INS platform was detached between flights and moved from an airplane to another, despite these changes the matrix is fairly stable (specially considering that the IFOV of the sensor is about 5 arc-minutes). Before Paris flights the CASI sensor was upgraded, this explains differences in the boresight calibration due to modifications on the sensor electronics. Adjusted values for κ shows larger differences up to 7 arc-minutes. Due to the narrow FOV of the sensor and the not so accurate available control κ was not possible to determine better (for a deeper discussion on the orientation of the CASI see [1]).

4 OEEPE EXPERIMENT

The ICC has participated in the OEEPE Test Integrated Sensor Orientation, whose purpose was to investigate integrated sensor orientation using GPS and IMU in comparison and in combination with aerial triangulation [5].

Two sets of GPS/IMU data from two different companies were provided, both of them describing the same configuration of a calibration block flown at scales 1:5000 and 1:10000. The goal of the calibration flight was to estimate, though a combined adjustment, the auxiliary parameters needed for a correct direct georeferencing. At ICC the auxiliary parameters adjusted were: boresight misalignment matrix, antenna offset and camera selfcalibration.

4.1 Determination of the boresight misalignment matrix

The boresight misalignment matrices obtained for each company are:

	ω (σ_ω)	φ (σ_φ)	κ (σ_κ)
company 1	0° 5' 26.101" (1.35")	-0° 0' 31.896" (1.33")	0° 3' 36.160" (1.53")
company 2	0° 6' 56.990" (2.11")	0° 3' 16.028" (2.08")	179° 49' 21.521" (1.20")

Table 4: boresight misalignment matrices adjusted and their standard deviations

Analysing these results, it can be commented that it was possible to perform a good determination of the boresight misalignment in both cases. This says that the configuration of the block is robust enough to allow the determination of the relation between the camera system and the IMU system. It can be observed that the standard deviations for company 2 are a little worse that for company 1. This can be partially explained by a poorer quality of the photogrammetric observations from company 2 block. In fact, the RMS of the photogrammetric residuals obtained in the adjustments have been:

	x image coordinate	y image coordinate
company 1	3.6 μ	3.7 μ
company 2	4.0 μ	4.2 μ

Table 5 : RMS of photogrammetric residuals for each company

4.2 Determination of the antenna offset

The antenna offset, between the camera and the GPS, antenna can be precisely measured using topographic techniques, however, in the calibration flight adjustment done by ICC a correction to the nominal value was also computed. When interpreting the corrections to the nominal antenna offset it has to be kept in mind the strong correlation between its components and other system parameters. (the flight direction component of the antenna offset is highly correlated with an error in the synchronization of the photographs and the height component has the same effect that an error in the nodal distance used in the computations).

The antenna offsets adjusted, for company 1 shows a displacement of 6.5 cm in flight direction and 10.0 cm in height. For company 2, the values were 7.5 cm in flight direction and 8.3 cm in height. As stated above, it is not possible to know if the height correction of the antenna offset is due to an incorrect measurement of the antenna offset or to the use of a wrong value of the nodal distance. Also, as the block were flown at nearly constant velocity (variation of only 10% were observed) a constant error on the synchronization will show up as a correction of the antenna offset on the flight direction (7 cm correction on the flight direction is equivalent to a synchronization error of about 0.0008 seconds). A block with strips flown at significantly different velocities would help to decorrelate these two error types. Moreover, a parameter modelling a synchronization error cannot be adjusted because the position and attitude observations were only available at the exposures time (time span was 5 seconds for photos at 1:5000 and 10 seconds for photos at 1:10000 approximately). It would be desired to have the data at 200 Hz in order to be able to estimate this parameter.

The best way for determining a correct nodal distance is by doing a laboratory calibration of the lens cone. As the blocks were flown at two different scales (1:5000 and 1:10000), it has to be mentioned that the focal length parameter has been decorrelated from the nodal distance or height component of the antenna offset

4.3 Angular drift parameters

Looking at the angular residuals (figures 11 and 12) obtained in the calibration adjustments for both companies, a systematic behaviour is observed in some strips. So, some problems on the determination of the kappa can be identified for both companies. This confirms the behaviour that has been detected in the blocks at flight scale 1:60000 processed by ICC and explained before. The use of angular drift parameters per strip for correcting the heading behaviour can be helpful.

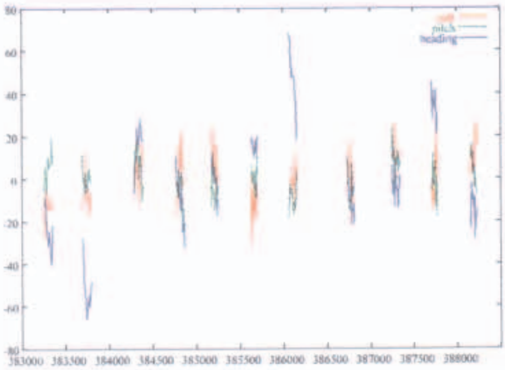


Figure 11: angular residuals obtained for company_1

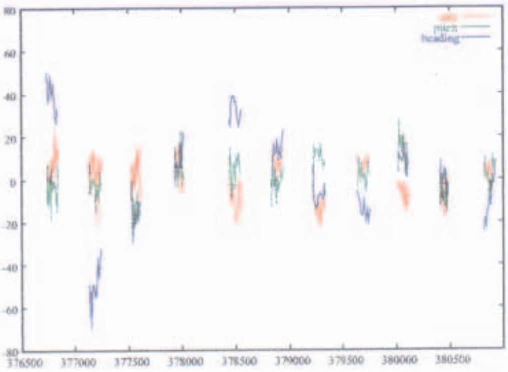


Figure 12: angular residuals obtained for company_2

5 PRACTICAL CONCLUSIONS

Direct georeferencing is showing an acceptable performance, however, there are still some aspects that have to be improved in order to increase the robustness of the technique. The principal aspects to be taken into account in direct georefrencing can be summarized on:

- Calibration flights should be done for a correct determination of all the auxiliary parameters needed on direct georeferencing.
- Studies on the stability of the auxiliary parameters should be carried for determining a recommended recurrence of the calibration flights.
- As the determination of kappa shows sometimes a systematic error that can be corrected using angular drift parameters, minimal aerotriangulation of the block is still necessary to model angular observations errors.
- It is desirable to estimate/calibrate a synchronization offset as well as the nodal distance, this parameters show a high correlation with the flight direction component and the height component of the antenna offset respectively.
- Further studies should be carried out on the integration of GPS/IMU georeferencing and automatic aerotriangulation. This would be helpful to increase the robustness of both methods.

6 REFERENCES

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