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THE SISA/0: ICC EXPERIENCES IN AIRBORNE SENSOR INTEGRATION.

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PURPOSE

This paper describes the work carried out at the ICC in the implementation of an Integrated System of Airborne Sensors (SISA) and discusses a number of results obtained in the orientation and self-calibration of the CASI multispectral scanner.
Since 1993, ICC owns a CASI multispectral scanner, the original orientation system was not accurate enough for mosaicking the images and general fusion with orthoimages. In order to use the CASI as a mapping tool, the ICC decided to implement a SISA. The SISA is an integrated system of airborne (imagery, position, attitude,...) sensors and algorithms that can be used to obtain correct georeferentiation of the CASI imagery.
Due to the weak geometry of the line sensors, the orientation parameters have to be obtained directly. A Litton LTN 101 FLAGSHIP INS carries out the attitude determination, the positioning subsystem relies on a GPS-derived trajectory and a robust procedure for synchronising the INS, CASI and the GPS sensors has been developed. The CASI hardware was modified due to the need to allow for the scan line synchronisation.
For the normalisation process, the ICC has developed software to ensure the correct time tag of the recorded data (inertial, scan lines,...) and determine the trajectory and attitude of the airborne platform. The SISA has been designed to integrate any airborne sensor (laser scanner, radar,...) having minimum synchronisation requirements; to date, it has also been used in one gravimetric flight.
In the test flights presented, the misalignment matrix (between the imagery sensor and the attitude sensor) has been computed together with certain calibration parameters in a bundle adjustment using the GeoTeX.

1. INTRODUCTION

Since 1993, ICC has operated a CASI system for airborne remote sensing projects.
Due to the weakness of the 1-line sensor geometry, the orientation parameters should be determined using direct methods that lean on the use of GPS and inertial systems.
For mapping purposes, it is necessary to attain orientation accuracies that allow further mosaicking and image fusion accuracy below 1 - 2 pixels.
Usually pixel size on CASI projects goes from 2.5 m to 10 m, thus requiring improved precision of the position and synchronisation procedure. Attitude determination precision is dependent on the instantaneous field of view (IFOV) of a single pixel, which is 5 arcminutes in the current configuration of the CASI.

2. CASI SYSTEM: INITIAL APPROACH

In the initial configuration the CASI system was equipped with an imaging subsystem, an attitude subsystem and collects data from a GPS receiver (position subsystem).
The imaging subsystem (the CASI sensor) is a push-broom linear scanner based on a matrix CCD, which allows collection of up to 19 spectral bands, selected from 288 spectral samples in the range of 430 nm to 950 nm and 512 spatial samples.
The position subsystem collects the data from a GPS receiver.
The attitude subsystem is based on SPERRY VG-14A dual axis gyroscopes for pitch and roll. Heading is computed from the GPS derived flight path (track) which is only a rough approximation of the sensor heading; the best that can be obtained is the determination of a mean crab (the difference between track and sensor heading). The CASI records all the raw data (GPS code, phase, gyroscope readings and images) for each scan line and subsequently writes them as a time tagged record onto an 8-mm digital tape. The attitude subsystem is not enough accurate to allow mosaicking CASI images or general fusion with other orthoimages [4]. Root mean squares of residuals of roll and pitch are 0.24° and 0.13° respectively (i.e. 2.75 pixels and 1.5 pixels) in dynamic mode. The lack

of a heading sensor is a major handicap because it is not possible to recover a posteriori all the variations in crab, even though it is possible to compute a mean crab per strip in a bundle adjustment.
The synchronisation procedure is manual and is not robust. Synchronisation errors lie in a wrong time tag for each single line of the CASI causing the effect of a displacement of the position in the trajectory, it is a wrong position for each line even though the GPS trajectory is correctly computed.

3. THE SISA SYSTEM

As a conclusion from our experience with the CASI scanner, it was necessary to design and construct a complete orientation and synchronisation system. This system (called SISA, stands for Sistema Integrat de Sensors Aerotransportats, Integrated System of Airborne Sensors) provides a more robust synchronisation interface for the new ICC-CASI system, a more accurate attitude subsystem and a position subsystem (an interface to the GPS receiver).
This system must not only provide the orientation and synchronisation subsystem for the CASI sensor. It must also be flexible enough to be able to integrate data from other sensors (for example, metric or digital cameras, laser scanners, airborne radar,...), which must meet minimum synchronisation requirements.
The SISA is the system used to integrate the GPS data, the IMU data and to provide a synchronisation procedure for the entire set of sensors. The current configuration of the SISA provides an interface to the attitude subsystem (LTN 101), an interface to a dual frequency GPS receiver and a robust procedure for synchronising the attitude sensor (INS) and the imaging sensor (CASI) to GPS time.
The interface to the attitude subsystem consists of collecting the data from the INS/IMU and synchronising this data to GPS time.
As the CASIrecords the image data by itself, the interface of the SISA to the CASI is simply the time synchronisation of the CASI lines to GPS time.
The interface to the position subsystem consists of collecting the data from the GPS receiver and providing the reference frame for synchronisation.

3.1 Attitude subsystem

In 1996, the ICC bought a LTN 101 FLAGSHIP INS (Inertial Navigation System) which contains a highly accurate IMU (Inertial Measurement Unit). This INS is the core of the new attitude subsystem.

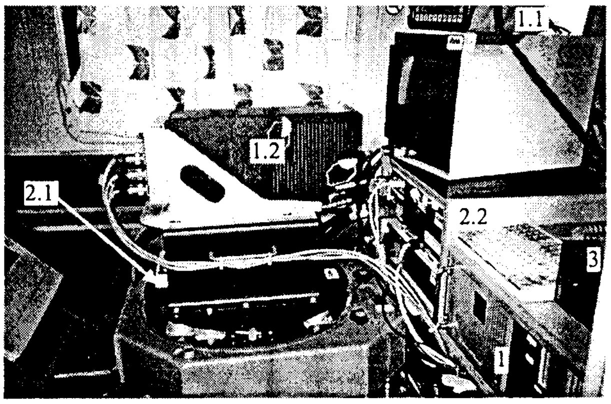

Figure 1: Assembly of the whole system: SISA (1) –GPS receiver Ashtech Z-12 (1.1), and INS LTN 101 (1.2)–, the CASI (2.1 CASI head sensor, 2.2 control unit) and CCNS-4 navigation system (3) in the Partenavia P-68 Observer.

The Litton LTN 101 is a medium accuracy navigation grade strapdown inertial reference unit. Its IMU integrates three dual frequency zero-lock RLG (Ring Laser Gyro) gyroscopes and three silicon linear accelerometers. The IMU components were hand-picked by Litton for the ICC according to long-term stability criteria.
The interface to the IMU can be realized through the ARINC 429 industry standard or through the Litton's propietary FLAGCAL/DART SW/HW interface provided to ICC.

3.2 Position subsystem

The position subsystem provides an interface to a GPS dual frequency receiver which is also used as a reference for the synchronisation subsystem.

3.3 Navigation subsystem

The whole system is operated with the CCNS-4 Navigation system, which is used to plan and help in navigating the CASI flights.

3.4 Imaging subsystem

The current imaging subsystem is the CASI sensor. However, any *imaging* sensor (laser scanner, digital cameras,...) could be used that meets minimum synchronisation requirements. To date, the SISA has also been used in one gravimetric flight.

3.5 Synchronisation subsystem

The design of the synchronisation procedure has been designed taking into account the synchronisation requirements of the INS.
The LTN 101 is only able to interface to a GPS receiver through the ARINC 429 protocol but, in order to have acces to the raw INS data, the ARINC 429 interface was not used. Since the LTN 101 is able to detect a pulse and embed it in its data, the synchronisation procedure is based on the generation of a sequence of pulses.

3.5.1 CASI modifications

Following requirements specified by the ICC, ITRES modified the CASI hardware to allow the use of different IMUs (the LTN 101 in particular) and an external independent time synchronisation of the CASI frames. In the original CASI configuration, the CCD array is attached to the sensor platform through a vibration isolation mount. Its purpose is to protect sensor electronics against strong accelerations produced by the aircraft dynamics. The attitude subsystem is attached to the sensor platform. Due to this design the attitude sensor was not able to be rigidly attached to the CCD generating differences between the measured attitude by the attitude subsystem and the attitude of the CCD. That is why ICC asked to replace the original isolation mount with a global one which isolates the CASI-IMU assembly. This new assembly has to allow installation of the IMU sensor as close and rigidly to the CASI sensor head as possible.
As CASI generates a frame identifier – which is sent to the SISA through a RS-232 asynchronous port – which is not suitable for synchronisation purposes ITRES was asked to generate one pulse per frame (ppf) in order to synchronise CASI images. The ppf is generated at the mid-time exposure (m), as shown in Figure 2.

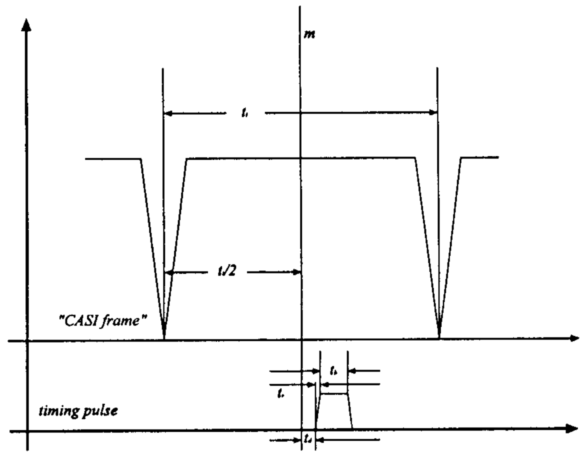

Figure 2: Pulse per frame requirements.

3.5.2 Synchronisation procedure

The GPS pps (pulse per second) gives the time reference frame to the entire system. On one hand, SISA records the pps. On the other hand, SISA sends the pps to the INS, which embeds the pulse in the record received by the INS. Thus, each pps has a corresponding INS record. As the pps sequence is generated at 1 Hz frequency, GPS time for the corresponding INS record is known with an ambiguity of 1 second (the fraction of a second that the pps has been detected is known but not the full second) so a smart procedure is implemented on the SISA. The SISA, instead of sending a GPS pps every second, filters the pps generating a pseudorandom sequence of pulses to send to the INS. Since some of the GPS receivers on the market do not allow for synchronisation of more than 1 event per second and the CASI usually records images at frequencies from 10 Hz to 60 Hz (depending on the amount of data to be collected and the flying speed), it is not possible to synchronise every single ppf of the CASI (this is every single scan line). Thus, it is necessary to filter the ppf to synchronise it as an event by the GPS receiver.
The SISA receives the GPS pps and the CASI ppf and frame header. This information is filtered, generating a new sequence of pulses; this is the synchronisation sequence. This sequence of pulses is sent to the IMU sensor and the GPS receiver, which time tags each pulse received in GPS time. The SISA collects the time of the synchronisation pulses. Figure 3 shows the data flow in the synchronisation and IMU/INS data and GPS data collection process.
The synchronisation procedure has two operating modes; the first one synchronises INS data to GPS time while the CASI sensor is not operative; the second one synchronises CASI frames and INS data to GPS time.
At the beginning of the flight, only the GPS receiver and the INS sensor are switched on. The method to synchronise INS to GPS time is based on the gener-

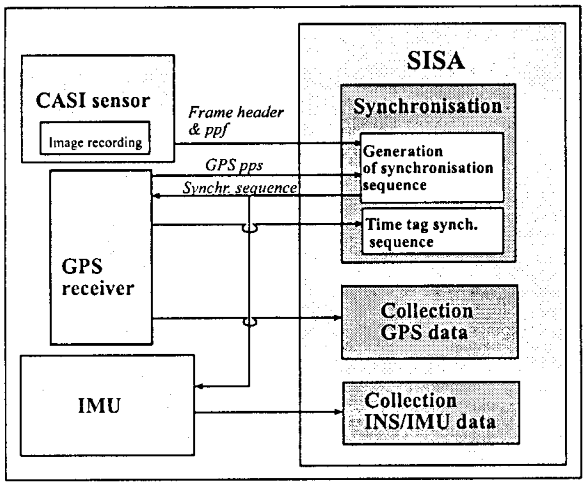

Figure 3: Synchronisation procedure and data flow.

ation of a sequence of pseudorandom pulses from the GPS pps to the INS. These sequences are generated using the algorithm used by tapped feedback shift registers (algorithms used in the code generation of the GPS signal structure). This algorithm generates a sequence of pulses that are sent to the INS and time tagged by the SISA. This procedure enables synchronisation of every 15-second block of INS data during the entire flight to GPS time with no time ambiguity.
Once the CASI system is switched on and begins to record data, the synchronisation procedure switches to the second mode. This mode filters the pulses generated by the CASI (at a much higher frequency than the GPS receiver) and only 1 of every n pulses is sent to the INS and time tagged by the GPS receiver. This procedure allows synchronisation of every single line of a CASI image.
As soon as the CASI sensor is switched off, the synchronisation procedure switches to the first mode.

4. OPERATING PROCEDURE

Before switching on the aeroplane engines, the SISA collects data during 10 minutes approximately. In this period of time, a fine alignment of the INS is carried out and a long enough synchronisation sequence is collected to synchronise (in post-process) the INS data to GPS time before CASI begins to record images. This alignment is done with the engines off in order to take out the vibrations due to the engines in the alignment process. Afterwards, the flight starts and follows a normal operation.

5. DATA PROCESSING

The acquisition system is complemented with software (to process the GPS data and synchronise the INS data and CASI scan lines to GPS time).

5.1 GPS data processing

The GPS data was processed using TraDer. TraDer is a GPS processing software developed at ICC for the determination of GPS trajectories using either code observations (Garrotxa) or phase observations (Bellmunt). TraDer is capable of using a network of GPS reference stations for a robust estimation of the ambiguities and a precise determination of the flight path.

5.2 INS data processing

The INS does the alignment on the initial data taken with the aeroplanes engines off. Afterwards, the INS computes the attitude of the entire flight, which is interpolated at each scan line.
Although the accuracies of the INS are sufficient for the CASI orientation, the kernel of an IMU/INS data processing software has been used with comparable results. Such a software will be necessary with sensors requiring higher accuracies.

5.3 Synchronisation

The information recorded by the synchronisation procedure is used to time tag every CASI line and INS record.
The pseudorandom sequence of pulses is stored by the SISA as a sequence of corresponding time tags. The INS has embedded the sequence of pulses in its records. In the INS data synchronisation, the pseudorandom sequence of pulses is extracted from the INS records and matched with the sequence of time tags stored by the SISA. This procedure enables resolution of time ambiguity and every line is time tagged correctly.
In the case of the CASI, the synchronisation time is propagated from the few synchronised lines to the whole CASI image.

5.4 Bundle adjustment

Due to the mounting or features of the sensor geometry, there are some global parameters that affect the entire flight. Depending on the mounting, a misalignment matrix parameter set has to be taken into account. Depending on the sensor geometry, self-calibration parameters have to be considered. In the case of the CASI, there is no geometric laboratory calibration so self-calibration parameters are required. To carry out the determination of these parameters, tie and ground points are identified in the images and a bundle block adjustment is done to determine the matrix misalignment. The block adjustment is done using GeoTeX [2].

5.4.1 Misalignment matrix

As there is an angular misalignment between the axis of the reference system of the CASI head sensor and the axis of the reference system of the INS, it is necessary to compute this misalignment matrix between the image reference system (the one related to the CASI) and the IRS.

5.4.2 Self-calibration

No laboratory geometric calibration is available so it is necessary to compute variations on nominal sensor parameters (focal length and principal point co-ordinates in the image reference system). Due to the weakness of the CASI geometry only focal length and principal point distances are adjusted.

6. ANALYSIS OF CASI ORIENTATION

This section discusses the results of the Garrotxa and Bellmunt flights.

The Garrotxa block was flown on 23 July, 1998. It is a block of 14 strips which are alternatively flown from North to South and from South to North. The main parameters of the block are given in Table 1. GPS code observations and INS attitude observations are used for aerial control. As the raw pixel size is 3.5 m × 3.5 m, the GPS code solution has enough accuracy (1 m RMS) for our purposes. In addition to the aerial control, 111 ground points and 96 check points were identified and measured from 1:25000 digital orthophoto maps whose pixel size is 2.5 m. Heights were obtained from ICC's countrywide elevation database. Accuracy of the orthophoto maps used is about 2.5 m and accuracy of the elevation database is better than 2 m (1-σ level in both cases). 97 of the ground points have only 1 photogrammetric observation, these points are identified on the block borders, the rest of ground points are identified in 2 images and situated inside the block. Check points are uniformly distributed inside the block.

Sensor type	*CASI 501*
focal length	9.33 mm
flying h.ab.ground	2160 m
airplane speed	263 km/h
strip overlap	50 %
length	17500 m
width	21500 m
time between lines	48 ms
pixel size	3.5m × 3.5m
no. N - S strips	14
no. transversal strips	0
total no. of strips	14
no. of photo obs.	469
no. of ground points	111
no. of check points	96
no. of aerial control bias sets	none
no. of misalignemnt matrix sets	1
no. of selfcalibration parameter sets	1

Table 1: Garrotxa block, main parameters.

In the dataset described, the root mean square of the residuals at the check points gives: 4.7 m along-flight, 4.4 m across-flight (horizontal) and 2 m in height. When translated into pixel units, this gives: 1.26, 1.34 and 0.6, respectively. The precision of the check points' co-ordinates is about 2.5 m for the horizontal components and the solution is constrained to the ground truth for the vertical component.
RMS on photogrammetric residuals gives 7.1 μm (0.47 pixel) across-flight and 6.5 μm (0.43 pixel) along-flight.
The consistency on mosaicked images has been checked; RMS differences on matched points in overlap areas of CASI images are better than 1 pixel.

The Bellmunt block was flown on 19 August, 1998. It is a block of 7 strips; 5 are flown alternatively from North to South and from South to North and 2 are transversal strips. The main parameters of the block are given in Table 2. GPS phase observations and

INS attitude observations are used for aerial control. 39 ground points and 36 check points were identified and measured from 1:5000 digital orthophoto maps whose pixel size is 0.5 m. Heights were obtained from ICC's countrywide elevation database. Accuracy of the used orthophoto maps is about 1 m and accuracy of the elevation database is better than 2 m (1-σ level in both cases). 27 of the ground points have only 1 photogrammetric observation, these points are identified on the block borders, the rest of the ground points are identified in 2 images and situated inside the block. Check points are uniformly distributed inside the block.

In the dataset described, the root mean square of the residuals at the check points gives: 1.7 m along-flight, 2.3 m across-flight (horizontal) and 2 m in height. When translated into pixel units, this gives: 1.7, 2.3 and 2, respectively. The precision of the check points' co-ordinates is about 1 m for the horizontal components and that the solution is constrained to the ground truth for the vertical component.

RMS on photogrammetric residuals gives 7.1 μm (0.47 pixel) across-flight and 5.3 μm (0.35 pixel) along-flight.

Sensor type	*CASI 501*
focal length	9.33 mm
flying h.ab.ground	659 m
airplane speed	426 km/h
strip overlap	50 %
length	5446 m
width	2270 m
time between lines	16 ms
pixel size	$1m \times 1m$
no. N - S strips	5
no. transversal strips	2
total no. of strips	7
no. of photo obs.	204
no. of ground points	39
no. of check points	36
no. of aerial control bias sets	none
no. of misalignemnt matrix sets	1
no. of selfcalibration parameter sets	1

Table 2: Bellmunt block, main parameters.

In the Bellmunt block, check point accuracy is 1 pixel (horizontal) and 2 pixel (vertical). This fact has to be considered in the comparison of the precision of the check points in the Garrotxa block, which is relatively higher; check point accuracy is 0.71 pixel (horizontal) and 0.6 pixel (vertical).

6.1 Orientation

In the early stages of GPS aerial triangulation, ambiguities were solved approximately. Errors in ambiguity determination (in the GPS data process) cause position errors which are modeled using aerial control bias parameters. As the GPS path is computed using code (Garrotxa) or solving robustly ambiguities using phase observations (Bellmunt), no aerial control bias sets are needed.

According to the LTN 101's accuracy, attitude residuals are not significant in the orientation of the CASI sensor, but Figures 4 and 5, specially ω in Figure 4, show systematic residuals, which might be caused by the INS. The root mean square (RMS) of the attitude residuals gives 18.7 arcseconds for ω, 22.5 arcseconds for φ and 4.5 arcseconds for κ in the Garrotxa block; in the Bellmunt block, 17.7 arcseconds for ω, 21.2 arcseconds for φ and 3.9 arcseconds for κ. There are no significant differences in RMS at attitude residuals.

RMS on GPS positioning are 0.35 m, 0.54 m and 0.38 m for X,Y and Z in the Garrotxa block and 0.031 m, 0.047 m and 0.033 m in the Bellmunt block. The main reason of the differences is the fact that the GPS trajectory was computed using code in the Garrotxa block and phase in the Bellmunt block.

6.2 Stability of misalignment matrix and self-calibration parameters

In both blocks, separately and independently, matrix misalignment and self-calibration parameters have been adjusted in a photogrammetric bundle adjustment.

The Garrotxa block was flown on the ICC Cessna Citation while the Bellmunt block was flown on the Partenavia-68 Observer so the whole system was taken off from the aeroplane. In particular, the INS was detached from the mount where the CASI head sensor is installed (see Figure 1), and mounted again on a different aeroplane.

Both groups of parameters are highly correlated; displacements on principal point are highly correlated with ω and φ angles of the misalignment matrix –

	Garrotxa	Bellmunt
ω	$0^\circ\ 29'\ 2''$	$0^\circ\ 27'\ 49''$
φ	$0^\circ\ 0'\ -2''$	$0^\circ\ 0'\ -6''$
κ	$0^\circ\ -1'\ 14''$	$0^\circ\ -5'\ 28''$
δf	$0.6496\,mm$	$0.6318\,mm$
δx_0	$12.74\,\mu m$	$10.75\,\mu m$
δy_0	$64.52\,\mu m$	$62.17\,\mu m$

Table 3: Adjusted values for matrix misalignment (ω, φ and κ) and self-calibration (δf, δx_0 and δy_0) parameters in the Garrotxa and Bellmunt blocks.

	Garrotxa	Bellmunt
σ_ω	$345'' \simeq 1.15\,p$	$370'' \simeq 1.23\,p$
σ_φ	$512'' \simeq 1.70\,p$	$496'' \simeq 1.65\,p$
σ_κ	$56'' \simeq 0.19\,p$	$94'' \simeq 0.31\,p$
$\sigma_{\delta f}$	$0.003\,mm$	$0.010\,mm$
$\sigma_{\delta x_0}$	$24.83\,\mu m \simeq 1.66\,p$	$24.02\,\mu m \simeq 1.60\,p$
$\sigma_{\delta y_0}$	$17.73\,\mu m \simeq 1.18\,p$	$18.67\,\mu m \simeq 1.24\,p$

Table 4: Adjusted standard deviation for matrix misalignment (ω, φ and κ) and self-calibration (δf, δx_0 and δy_0) parameters in the Garrotxa and Bellmunt blocks.(Equivalence in pixels is denoted by p.)

across-flight principal point displacement (δy_0) is correlated to ω and along-flight (δx_0) to φ-. Therefore, given the weak geometry of the 1-line sensors, the bad B/H (base-to-height) ratio for the CASI and the low redundancy in the photogrammetric observations, determination of matrix misalignment and self-calibration parameters was not possible until surface control was introduced into the adjustment.
In spite of the differences in the mounting, the results shown in Table 3 prove that CASI-INS assembly is very stable. ω and φ angles are not significantly different in both flights, differences are within the parameters' theoretical standard deviation (see Table 4) and are smaller than the pixel size (IFOV 5 arcminutes).

Differences on κ are in the order of 5 arcminutes (1 pixel) and are consistent with the weaker stability of the mount in the flight direction; the INS is attached to the ICC-INS platform using a tray that is fixed to the platform using 3 screws, 1 in the front part of the tray and 2 in the rear part. The CASI head sensor is attached to the platform base using 6 screws. Thus, these particularities of the platform could account for the difference in κ.
The standard deviation of κ is higher than ω and φ. The better precision of κ is because no high correlation with other parameters is found. It is also important to note that precision on ω and δy_0 is of the same order (1.1 pixel in the Garrotxa block and 1.2 pixel in the Bellmunt block) and precision on φ and δx_0 is of the same order as well (1.7 pixel in the Garrotxa block and 1.6 pixel in the Bellmunt block). The precision on the determination of ω, φ and principal point depends on the accuracy of the ground control, surface control, photogrammetric observations and the model used in the description of the calibration parameters.

The variation on focal length is about 7% of its nominal value in both blocks. No correlation with other parameters has been detected. When focal length is set to its nominal value (9.33 mm), the adjusted orientation parameter is shifted upwards approx. 7% of the flying height (148 m in Garrotxa and 50 m in Bellmunt). The magnitude of these differences do not correspond to any error in the GPS data process or GPS antena eccentricity so it must be due to the CASI's inner geometry.

7. CONCLUSIONS

As the results of the analysis of the Garrotxa and Bellmunt blocks show, the original goal of the SISA system has been successfully reached.
The solution adopted, the SISA, solves the two weaker points of the initial CASI orientation system: attitude and synchronisation subsystems. However, the good results are due not only to a good attitude subsystem and a robust synchronisation procedure, but also to a stable platform that allows rigid attachment of the CASI and the INS. If stability cannot be guaranteed, it will be necessary to determine misalignment matrix parameters on each flight (or every few flights).
Direct methods for orientation require a good knowledge of the geometric relationships between all the sensors involved and the inner geometry (calibration) of the imaging sensor (CASI or other system).
In the orientation of sensors, which require lower ac-

curacy than that provided by the inertial sensors, the INS solution is enough for attitude determination and no GPS integration is needed.

To fully exploit direct method capabilities, laboratory calibration of the imaging sensor as well as a good knowledge of the geometric relationships between sensors are needed.

8. ACKNOWLEDGEMENTS

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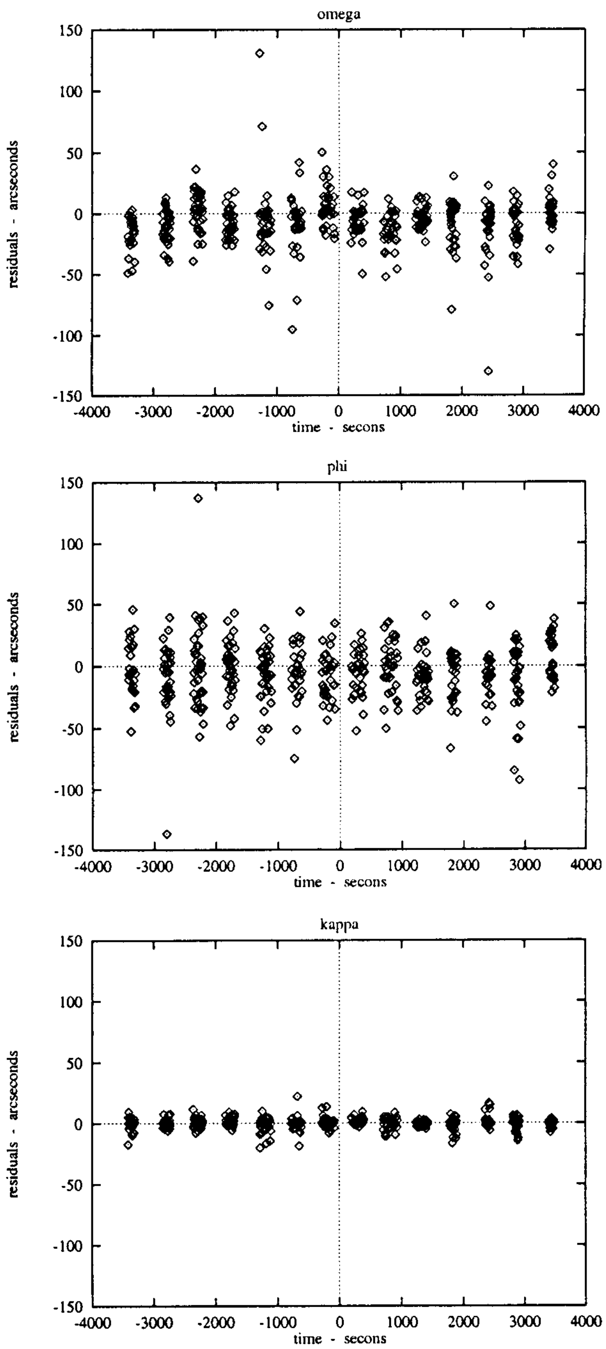

Figure 4: Residuals for ω, φ and κ. Each group of points corresponds to 1 strip of the Garrotxa block. (1 pixel $\simeq$ 300 arcseconds)

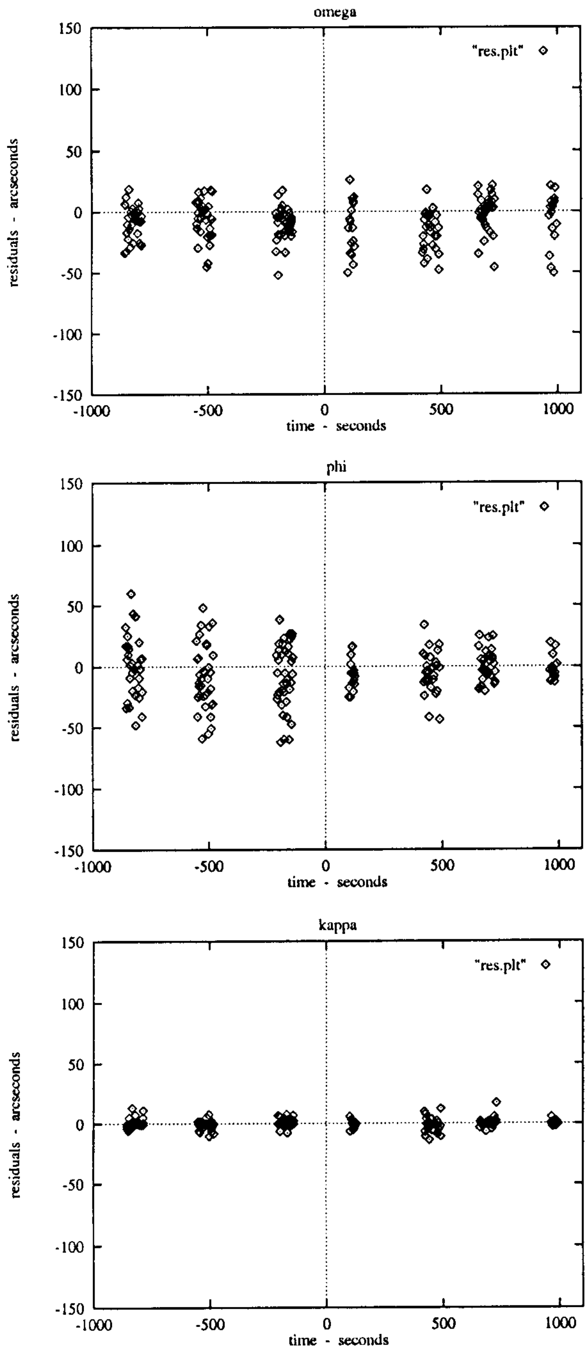

Figure 5: Residuals for ω, φ and κ. Each group of points corresponds to 1 strip of the Bellmunt block. (1 pixel $\simeq$ 300 arcseconds)