ACCURACY ANALYSIS OF MODULAR AERIAL DIGITAL SYSTEM SAAPI IN PROJECTS OF LARGE AREAS

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ABSTRACT:

With the recent developments in the technology of optical digital sensors, the use of professional digital frame cameras emerged as an alternative for aerial photogrammetric applications. The main reasons are their flexibility and cost effectiveness, when compared to film cameras and high-end digital systems. There are some models of cameras with 50, 60 and 80 megapixels, which provide ground coverage near to photogrammetric film cameras. These cameras can also be integrated to GPS/INS systems, with specially designed mechanic mounts and electronics devices that can control all components of the aerial mapping system. Several custom designed systems have been used worldwide with suitable results for mapping applications. This paper presents the results obtained with SAAPI system in two huge projects: the digital mapping of Bahia State (600.000 km^2 with a GSD of 80 cm) and Santa Catarina State (97.000 km^2 with a GSD of 39 cm), both in Brazil. In order to assess the geometric accuracy of this mapping system some results obtained with SAAPI in these projects are presented, using INPHO-MATCH-T for DTM generation. The experiments were carried out to assess the accuracy achieved in the object space coordinates when considering self calibrating bundle adjustment with direct georeferencing. Moreover, orthophotos, DSM and DTM products were generated and analysed. It was verified that suitable accuracy was achieved, aorund 1 to 1.5 GSD in the final products.

1. INTRODUCTION

The use of digital cameras for photogrammetric applications, especially in aerial mapping is a recognized trend due the advances in sensor resolution and other hardware and software components. Nowadays, there are some models of cameras with 50, 60 and 80 megapixels, with advantages, when compared to film cameras and high-end digital systems, because of their flexibility and cost effectiveness

Compared to classic film cameras (230 x 230 mm format) or high-end digital systems, professional digital frame cameras have smaller ground coverage area, although this scenario is rapidly changing with advances in sensor resolution. On the other hand, the professional digital cameras allow the development of lightweight and in-house integrated aerial photogrammetric systems with very attractive costs.

Due to this favourable cost/benefit ratio several custom designed systems have been used worldwide with excellent results for mapping applications, as DigiCam (IGI), DSS (Digital Sensor System – Applanix) and SAAPI (Lightweight Airborne Image Acquisition System - Engemap). Others independents systems based on this category of camera for different photogrammetric applications were previously implemented, as showed in Mostafa and Schwarz (2000), Habib et al. (2002), Roig et al. (2006) and Petrie (2009).

Within this context, this paper presents the geometric results achieved for large blocks of images acquired by SAAPI, in order to assess the geometric accuracy of this category of mapping system.

2. SAAPI SYSTEM

The SAAPI system (Lightweight Airborne Image Acquisition System) was developed by Engemap Company in Brazil, with UNESP partnership and FAPESP (The State of São Paulo Research Foundation) funding in the first phase of the project. This system is composed by an acquisition platform, control and power units (Figure 1).

The main features of the system are:

- RGB and Infrared professional digital cameras with same spatial and radiometric resolution;
- Direct Georeferencing system (GPS/INS);
- Specific rigid housing for the cameras;
- Autonomous system of triggering, high precision data synchronization, logging and storage in SSD (Solid State Disk);
- Software for automatic flight plan generation (SAAPI-PV), real time navigation and system control (SAAPI-NC), and flight post processing data (SAAPI-PP);
- Modular design that allows high flexibility for installing the system in different aircrafts, mainly in small aerial platforms.

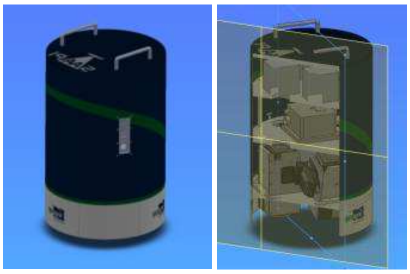

Figure 1. SAAPI system.

The technical specifications of the cameras that compose the SAAPI acquisition platform are given in Table 1.

Focal length	50 mm (optional 35mm)
Pixel size	6 µm
Radiometric resolution	8/16 bit
Spectral bands (two cameras)	RGB and IR
Image frame	8176 x 6132 pixels (50 megapixels) or 8956 x 6708 pixels (60 megapixels)
Sensor size	49 x 36.9 mm
Camera field of view (along/across track)	46°/59°

Table 1. Technical specifications of the cameras in SAAPI system.

Several aerial surveying projects were successfully performed by Engemap Company in the latest years with the SAAPI system, including urban and environmental mapping, highways, power lines and pipeline applications. These projects include cartographic mapping in different scales, from 1:10.000 (GSD of 60-80 cm) to 1:1.000 (GSD of 10-15 cm). In the section 4, it will be presented some results from two mapping projects in large areas that are being carried out by Engemap Company in Brazil using the SAAPI: Bahia and Santa Catarina states.

3. BACKGROUND

In general, camera calibration is performed before aerial surveying and the IOP (Interior Orientation Parameters) are usually estimated by laboratory methods or field methods, including close range camera calibration. These parameters are constrained in bundle block triangulation, with the image coordinates being a priori corrected for the systematic errors (lens distortion, photogrammetric refraction and, less common, affine deformation). This solution leads to a more simplified bundle adjustment model, with less parameter to be estimated, avoiding the high correlations between the estimated IOP and EOP (Exterior Orientation Parameter)

The camera IOP (focal length, principal point coordinates, lens distortions coefficients, affine deformations) can be estimated during the bundle block adjustment based on the collinearity equations including additional parameters that can be written expanding the collinearity equations. Even knowing that the use of additional parameters can result in high correlations between parameters, it is important to consider the differences in the environmental conditions between the calibration field and the flight area. Moreover, the operation and the handling of the cameras during the flight projects can modify the inner geometry of the cameras (depending on the optical and sensor stability of the camera model) and this changes can affects the bundle reconstruction.

Generally, polynomial models were used as additional parameters in bundle block adjustment. In this approach the focal length and the principal point coordinates are constrained with its a priori calibrated values and polynomial coefficients aims at to absorb the residual systematic errors related to the lens distortion, shrinkage and other non modeled deformations. The process in which these models are used is generally known as *self calibration* and was developed in the seventies. Nevertheless, some authors argue that this term should be related to the camera calibration with a minimum set of constraints and even without ground control and that a better term should be in-situ or on-the-job calibration (Clarke and Fryer, 1998). Examples of groups of additional parameters are Ebner, Brown and Grun models (Muray et al, 1984; Mikhail et al, 2001; Clarke and Fryer, 1998).

It is of crucial important to analyze the correct use of these additional parameters groups for digital cameras, since that many errors existing in analog film cameras, like shrinkage or errors due to comparator measurements are not observed in digital sensors. In order to investigate this subject, some experiments using LPS (Leica Photogrammetry Suite) software, which triangulation module was set to use additional parameters, were carried out. Images collected with a 39 MP Hasselblad digital camera were used. In the performed experiments it was verified that using only the radial lens distortion provided better results on the object space reconstruction than the polynomial models (Brown, Ebner, Bauer and Jacobsen). Details of these tests are presented in Ruy et al (2008).

In this context the experiments presented in this paper were carried out with bundle block adjustment performed by the INPHO package software (Match-AT, Match-T) with blocks of images acquired by SAAPI system. In these experiments, for each block of image, the camera calibration parameters were computed using a small sub-block, with dense control point distribution, and the entire block of images were processed with different control point configurations. Moreover, the DSM accuracy is also assessed.

4. EXPERIMENTAL ASSESSMENT

The accuracy assessment of the system will performed with data produced by SAAPI system in two mapping projects of large areas: Bahia and Santa Catarina States (Figure 2), which are two of the largest mapping projects in Brazil. The features of these projects are:

Bahia state mapping:

- Area (approximated): 600000 km^2;
- Image resolution (GSD): 80 cm
- Products: DSM (Digital Surface Model) and Orthomosaics at 1:10.000 scale.
- Accuracy specifications: altimetry (RMSE) – better than 1.8 m; planimetry – better than 3.0 m.

Santa Catarina state mapping:

- Area (approximated): 97000 km^2;
- Image resolution (GSD): 40 cm (RGB and IR);

- Products: DSM (Digital Surface Model), DTM (Digital Terrain Model), Orthomosaics and hydrography restitution at 1:10.000 scale.
- Accuracy specifications (RMSE): planimetry and altimetry – better than 1.0 m.

Figure 2. Geographic location of the Bahia and Santa Catarina state mapping projects.

4.1 Experiments with Bahia data

The Bahia project is a large aerial survey project (600000 km^2) that is being developed by Engemap Company since 2009. The image block used in this study is located in south-west part of Bahia state in Brazil, as showed in Figure 3.

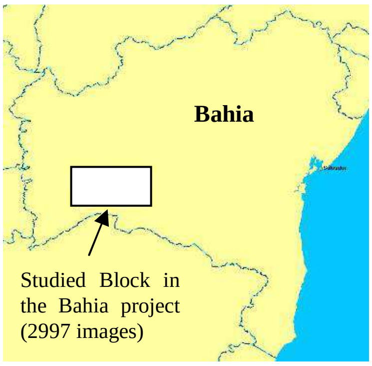

Figure 3. Geographic location of the studied block of images in Bahia.

A set of experiments with bundle block adjustment with this image block in Bahia state are presented. This block is composed by 2997 images distributed in 48 strips. The flight height was 4670 m, resulting in a GSD (Ground Sample Distance) of 80 cm.

Moreover, DTM accuracy analysis for this project, based on the quality control performed independently by the official Cartographic Army agency in Brazil - DSG (Geographic Service Division) will be presented and discussed.

4.1.1 *Bundle Block adjustment*

For this block the processing and analysis were carried out with 127 GCPs (Ground Control Points) and 26 check points. The tie points were automatically measured in the INPHO Match-AT software, with a rigorous quality control. It was used the EO parameters provided by GPS/INS (Novatel SPAN-CPT). The GPS/INS shift/drift model error was used to absorb systematic residual errors in the camera positions due to the block dimensions and consequently variation of the distance between the aircraft and GNSS base station.

In this work it is also assessed an approach that performs the calibration in a sub-block with dense control points distribution (See marked area in Figure 4). The IOP estimated in this sub-block were then used in the whole block, with a reduced set of GCP. Figure 4 shows the complete block of images related to the Bahia project as well as the ground control and check point distribution. In the left-up region it is showed the sub-block with dense GCP distribution, used for in-situ calibration.

Figure 4. Full block (2997 images) with control (127 points) and check points (26 points) distribution and a sub-block with control and check points distribution (marked with blue).

In order to assess the approach that uses a sub-block for computing the IOP, a calibration trial using 344 images (area marked in blue, in Figure 4) and 154 control points was carried out with the Match-AT INPHO software (In-Block module). The computed parameters and estimated standard deviations are presented in Table 2.

***f* (mm)**	35.645 ± 0.003
***x_0* (mm)**	-0.065 ± 0.002
***y_0* (mm)**	0.176 ± 0.002
***K_1* (mm^{-2})**	-7.167 x10^{-05} ± 2.710 x10^{-08}
***K_2* (mm^{-4})**	5.958 x10^{-08} ± 6.501 x10^{-11}
***K_3* (mm^{-6})**	-8.315 x10^{-12} ± 4.821 x10^{-14}
***P_1* (mm^{-2})**	-5.729 x10^{-06} ± 5.433 x10^{-08}
***P_2* (mm^{-2})**	3.795 x10^{-07} ± 5.511 x10^{-08}

Table 2. IOP parameters and their estimated standard deviations computed with on-the-job calibration using a sub-block of 344 images.

After that, four experiments with the complete block (2997 images) and different number of control points were performed:

A. With all control points (127 points);
B. With 79 control points;
C. With 41 control points;
D. With 18 control points.

For all these tests, the same set of 26 check points were used, to assess the 3D reconstruction accuracy in each experiment. Table 3 presents the RMSE (Root Mean Square Error) in this set of check points for each experiment. In the last column of this table it is presented the expected accuracy (σ_e) of the object space coordinates for the block of images using well known error propagation formulas. This theoretical accuracy is computed as a function of the measured point error, the block definition and the geometry of the acquisition, as defined in

Krauss and Waldhaus (1993). This expected accuracy is only used as a reference value for the object space reconstruction.

		Experiment				σ_e
		A	**B**	**C**	**D**	
RMSE (m) Check Points	**X**	0.405	0.414	0.432	0.521	1.290
	Y	0.428	0.434	0.445	0.465	1.290
	Z	0.753	0.774	0.714	0.812	2.420
RMSE (GSD) Check Points	**X**	0.5	0.5	0.5	0.6	1.6
	Y	0.5	0.5	0.6	0.6	1.6
	Z	0.9	1.0	1.0	1.0	3.0

Table 3. RMSE values of the discrepancies in the check points for the Bahia full block (2997 images).

The experiments were performed with the IOP computed in the sub-block (344 images) and presented in Table 2 in order to assess this "dual-block" approach.

By analyzing Table 3 it can be verified that when the number of GCPs was reduced seven times (experiment D), the quality of the solution in the object space was still maintained, when compared to the experiment A that used all the GCPs. The accuracy in the 3D reconstruction was around 1/2 GSD in planimetry and one GSD in altimetry. These results indicate that both the direct georeferencing system and the calibration strategy are working properly.

For the analysis of the experiments presented in this work it was verified that the IOPs computed in the sub-block can be successfully applied to the complete block with a considerable reduction in the number of GCP, provided that a suitable direct georeferencing system is used. In this case it was verified that a bridging distance of 20 bases and one control point at every 8 flights strips are enough to achieve and guarantee the quality of the solution.

4.1.2 *DSM analysis*

The main product of the Bahia project that is being generated by Engemap Company is the DSM of the entire Bahia state with 5 m of resolution. Figure 5 shows an example of DSM generated with MATCH-T software, for the studied area.

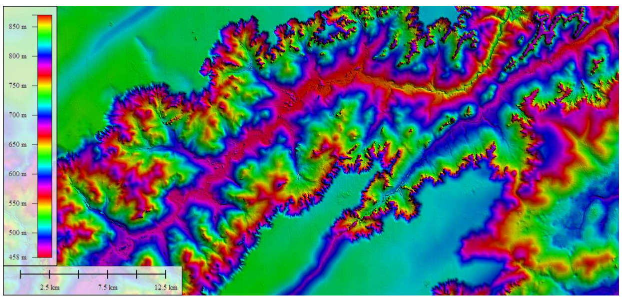

Figure 5. Example of DSM generated for the Bahia project.

The quality control of the products is being independently performed by the official Cartographic Army agency in Brazil - DSG (Geographic Service Division). For this DSM resolution (5 m) the project specifications establishes that 90% of the altitude values of measured points on the final product must have error less than 2.5 m and the RMS errors have to be less than 1.8 m, when compared to the independent check points collected in the field.

A set of 12712 check points, collected and analysed by DSG agency was available for DSM quality control. These points represent 759 topographic maps in scale 1:25.000 which correspond to 165445 km^2 of area in the west part of the Bahia state. Figure 6 shows the point distribution and Table 4 one summary of DSM quality control analysis performed by the Brazilian Army.

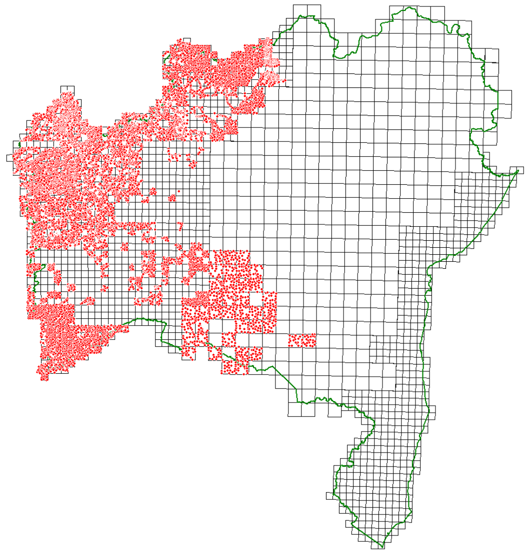

Figure 6. Check points (12712 points) distribution in the Bahia state area for the DSM quality control.

	Max. (m)	Min. (m)	Average (m)	RMSE (m)	RMSE (GSD)
Error	2.805	0.005	0.946	1.164	1.4

Table 4. Results of the quality control of DSM model for Bahia project (12712 points analyzed).

Considering the results presented in Table 4 it can be seen that the accuracy of the DSM is clearly compatible with the project specifications. The maximum individual error was 2.8 m, 97% of the analyzed points had errors less than 2.5 m and the RMSE error was around 1.1 m.

By definition, the DSM is related to the visible surface of the terrain and the absolute altitude or elevation of the points above the terrain.

The results of the DSM quality control indicate that there was a small tendency in the values (see the average column in Table 4). This tendency was mainly positive, because the values of heights measured on the DSM are higher than the corresponding ones obtained by the geodetic instruments in field (check points). This bias can be explained, in part, by the smoothing effect of DSM due to buildings, trees and others entities above the terrain artefacts. Then, if the check points are collected near to these features a difference in the DSM model can be expected in the quality analysis.

4.2 Experiments with Santa Catarina data

Santa Catarina is an aerial survey project (97000 km^2) that is being developed by Engemap Company since 2010. The bundle block adjustment experiments were performed with a block composed by 5723 images distributed in 69 strips that corresponds to 10016 km^2. This block is located in a south part of the state, as showed in Figure 7. The flight height was about 3300 m, resulting in a GSD (Ground Sample Distance) of 40 cm.

The DSM accuracy analysis for this block was done by Engemap and will be presented in this section.

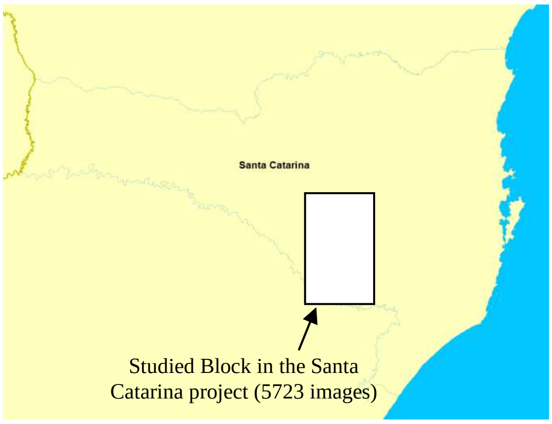

Figure 7. Geographic location of the studied block of images in Santa Catarina.

4.2.1 *Bundle Block adjustment*

For processing and analysis of this block 328 GCPs (Ground Control Points) and 52 check points were available. The tie points were automatically measured in the INPHO Match-AT software, with a rigorous quality control. The EO parameters were provided by GPS/INS (Novatel SPAN-CPT). The GPS/INS shift/drift model error and a polynomial self-calibration model were used to absorb systematic residual errors due the block dimension.

A. With all control points (328 points);
B. With 144 control points (edge and center of the block);
C. With 19 control points;
D. Without control points (only with Direct Georeferencing).

The camera was previously calibrated using the calibration field located in Assis city, in July 2010, three months before the flights in Santa Catarina. The flight over the calibration field was performed with four across strips in two different altitudes. The IOP (Table 5) were computed using the Match-AT INPHO software (In-Block module) with 28 images, 13 control points and perspective center constraints.

f (mm)	50.213 ± 0.010
x_0 (mm)	-0.017 ± 0.003
y_0 (mm)	0.012 ± 0.003
K_1 (mm^{-2})	-3.001 $x10^{-07}$ ± 9.810 $x10^{-08}$
K_2 (mm^{-4})	-1.367 $x10^{-09}$ ± 2.421 $x10^{-10}$
K_3 (mm^{-6})	1.613 $x10^{-12}$ ± 1.803 $x10^{-13}$
P_1 (mm^{-2})	-1.368 $x10^{-07}$ ± 1.800 $x10^{-07}$
P_2 (mm^{-2})	-2.951 $x10^{-07}$ ± 1.531 $x10^{-07}$

Table 5. IOP parameters and their estimated standard deviations.

In all tests, the same set of 52 check points were used in the assessment of the 3D reconstruction quality in each situation. Table 6 presents the RMSE (Root Mean Square Error) in the check points for each experiment and the expected accuracy (σ_e) of the object space coordinates for the block of images, as presented in the Bahia experiments.

		Experiment				σ_e
		A	**B**	**C**	**D**	
RMSE (m) Check Points	**X**	0,379	0,401	0,406	0,411	0.468
	Y	0,263	0,253	0,307	0,325	0.468
	Z	0,527	0,524	0,528	0,541	1.349
RMSE (GSD) Check Points	**X**	0,9	1,0	1,0	1,0	1.2
	Y	0,7	0,6	0,8	0,8	1.2
	Z	1,3	1,3	1,3	1,4	3.4

Table 6. RMS values of the discrepancies in the check points for the Santa Catarina block.

In Table 6 it can be verified that the number of control points did not influenced the 3D reconstruction, due the quality of direct georeferencing and camera calibration parameters. The accuracy in the 3D reconstruction for all experiments was around one GSD in planimetry and slightly more than one GSD in altimetry.

The experiment D was done without control points and its solution was similar to the results obtained in the experiment A that uses 328 control points.

For the analysis of the experiments it was verified that the IOPs previously computed in the calibration field were good enough to guarantee the quality of the 3D solution. It was necessary to include a polynomial self-calibration model available in the INPHO software in a bundle block adjustment due to the block dimensions and systematic residual errors.

4.2.2 *DSM analysis*

The DSM that is being generated by Engemap Company in the Santa Catarina project has 5 m of resolution. Figure 8 shows an example of DSM generated with MATCH-T software, for the studied area.

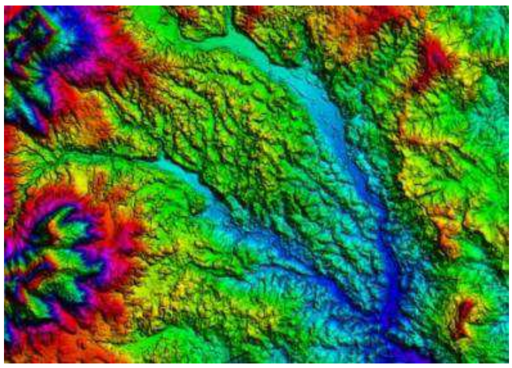

Figure 8. Example of DSM generated for the Santa Catarina project.

The quality control of the products of Santa Catarina is being performed by internal Quality Control Department in Engemap Company, with client inspection. According to the technical specifications of this project the quality of the DSM and DTM has to be better than 1.0 m (RMSE). For the quality control analysis a set of 49 check points was used, distributed over the block (10016 km^2). Figure 9 shows the point distribution and Table 7 presents the results of the DSM analysis.

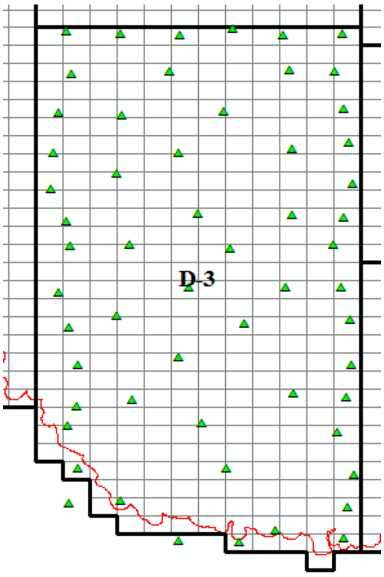

Figure 9. Check points (49 points) distribution in the Santa Catarina state area for the DSM quality control.

	Max. (m)	Min. (m)	Average (m)	RMSE (m)	RMSE (GSD)
Error	1.372	0.008	0.305	0.755	1.9

Table 7. Results of the quality control of DSM model for Santa Catarina project (49 points analyzed).

By analyzing the results presented in Table 7 it can be seen that the accuracy of the DSM is compatible with the project specifications, as occurred in Bahia project. The maximum individual error was 1.3 m and the RMS error was around 0.7 m.

5. CONCLUSIONS

This paper presented an outline of the SAAPI system that is a digital acquisition platform for photogrammetric applications. This system is composed by professional digital frame cameras in a modular design, with flexibility and light-weight, which can be installed in different kinds of aircrafts and helicopters and can be used for fast mapping production.

The results obtained with bundle block adjustment and the DSM quality control showed that this type of digital acquisition system can be successfully used for mapping projects, provided that rigorous photogrammetric processing workflow is used.

The projects dimensions being developed using a modular aerial mapping system is a remarkable feature that have to be highlighted. These are two major mapping projects of aerial photogrammetry in Brazil and the quality of images and products shows the potentiality of these systems. The quality control of these projects is being conducted independently by official Brazilian Cartography agencies.

One limitation of the digital professional frame cameras are the sensor resolution and coverage area, which results in an increase of the number of images and measured points in the photogrammetric projects. Nowadays this limitation is becoming irrelevant due to the new sensors resolution (50-60-80 mpixels), the GPS/INS integration and high performance photogrammetric software available, like INPHO package that allowed the fully automation and fast processing of the photogrammetric products.

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7. ACKNOWLEDGEMENTS

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