ON THE ACCURACY AND PERFORMANCE OF THE GEOMÒBIL SYSTEM

R. Alamús, A.Baron, E.Bosch, J.Casacuberta, J.Miranda, M.Pla, S.Sànchez, A.Serra, J.Talaya

Institut Cartogràfic de Catalunya (ICC), Parc de Montjuïc, E-08038 Barcelona
(ralamus, abaron, ebosch, jcasacuberta, miranda, mpla, santis, aserra, talaya)@icc.es

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ABSTRACT:

The GEOMÒBIL is a Land Based Mobile Mapping System (LBMMS) developed by the ICC. It is a modular system that allows the direct orientation of any sensor mounted on a roof platform. The GEOMÒBIL system is composed of the following subsystems: orientation subsystem, image subsystem, laser ranging subsystem, synchronization subsystem, power and environmental control subsystem and data extraction software subsystem.

After a brief description of the GEOMÒBIL system, the paper focuses on the calibration and performance of the GEOMÒBIL image subsystem. It describes the calibration of the CCD (Coupled-Charged Device), cameras used (camera calibration) and the calibration of the boresight parameters (eccentricity and misalignment of the image sensors with reference to the GPS/IMU reference frame). The accuracy and stability of the boresight camera calibration are also discussed. In order to evaluate the accuracy and performance of the system, several missions have been carried out under different configurations and environments. An operator has measured elements in the images by using data extraction software developed by the ICC as part of the GEOMÒBIL system. The results of the campaigns in terms of the accuracy and performance of the GEOMÒBIL are discussed and conclusions are drawn.

Finally, the paper gives a brief description of the future developments related to the integration of new sensors into the GEOMÒBIL platform. In particular, a terrestrial laser scanner has recently been installed and the first results are presented.

1. INTRODUCTION

The GEOMÒBIL is the multi-sensor land based platform developed at the ICC. It can acquire data from different sensors. Up to now two CCD monochrome digital cameras and a terrestrial laser system, which are operated simultaneously with a direct orientation subsystem and are accurately synchronized to GPS time, have been integrated into the system.

In addition to being a geographic data acquisition system, the GEOMÒBIL is a system for acquiring and georeferencing sensors and a software package for extracting information from acquired data.

Based on a platform able to integrate any sensor and a direct reference subsystem, the GEOMÒBIL system is meant to be a tool capable of acquiring geographic data with cartographic accuracy requirements in a production environment.

2. GEOMÒBIL SYSTEM

With the objective of developing an LB-MMS flexible enough to integrate several sensors for acquiring data of cartographic interest, the ICC started the GEOMÒBIL project, which, at this first stage, integrates the positioning and orientation subsystems, algorithms and sensors required to determine coordinates of observed elements applying photogrammetric techniques. In order to transfer the different reference frames, the system is equipped with a rigid structure where the image/laser sensors, orientation and positioning subsystems are physically installed. To begin with, two digital cameras that form stereoscopic models in the zone of interest are employed. The zone of interest is defined to be at a 10m distance from the vehicle along track and a 10m distance wide across track in order to acquire all the elements in the photographs, such as horizontal and vertical road signs. The integration platform is mounted on a vehicle that equips other auxiliary subsystems for the continuous operation of the system, like air conditioning, electrical power and other subsystems. Operator security and attenuation of the disturbing vibrations present in mobile environments are also included.

Figure 1: GEOMÒBIL System.

The GEOMÒBIL system has been divided into the following subsystems:

- *Orientation:* handles the absolute temporal and geometric reference frames.
- *Integration Platform:* is a rigid physical base for the transference of the geometric reference frame of all the installed sensors.
- *Image Sensor:* handles scene configuration, sensor geometry and parameters.

- *Image Acquisition:* handles the exposure synchronization and control, image acquisition and storage.
- *Synchronization:* creates the temporal reference frame coherently transferable to all sensors.
- *Power and Environment Control:* guarantees power supply and stabilizes the operational environment conditions for all the sensors.

Apart from the subsystems installed on the vehicle that run during data (orientation, synchronization, image and laser ranging) acquisition, the GEOMÒBIL system is made up of a sensor calibration procedure and data extraction software.

2.1 Orientation subsystem

The orientation subsystem is responsible for georeferencing the photographs taken by the GEOMÒBIL. Thus, it provides the coordinates (position) and the angles (attitude) of their projection centers. This subsystem is based on an Applanix system, which is specially designed for land vehicle applications and is integrated in the GEOMÒBIL. This system is basically composed of:

- An IMU (Inertial Measurement Unit), a sensor that provides measurements of accelerations and angular velocities.
- Two sets of GPS antenna-receivers, one of double frequency to provide observations of the position and velocity, and the other one of single frequency to improve the heading angle determination. This system is called GAMS (GPS Azimuth Measurement System).
- A DMI (Distance Measurement Indicator), a sensor directly installed on one of the vehicle's rear wheels which provides information of the distance traveled.
- A POS Computer System, which contains the core of the system, IMU and DMI interfaces, two GPS receivers and a removable PC-card disk drive where data is stored.
- A POSPac, software for processing GPS data and integrating the GPS solution with the observations of the other sensors.

Like any system that combines inertial and GPS observations at a high level of integration, GPS derived trajectories are used to correct and calibrate the drifts of IMU gyros and accelerometers so that the position and velocity errors derived from inertial sensors are minimized. However, the main drawbacks for terrestrial navigation are the presence of obstacles on the road, like bridges or tunnels, which interrupt totally or partially the acquisition of GPS observations during some time interval, and the existence of areas where most of the GPS satellites signals are blocked by terrain conditions, like urban areas with high buildings, forest zones, etc. In these areas without GPS coverage or with a very poor constellation, position and velocity are calculated from IMU observations, whose errors only depend on the distance traveled since during the GPS signal outage DMI observations are used.

In order to obtain the position and attitude of photographs from the position and angles provided by the orientation subsystem, it is important to fix the relation between all the reference frames of the orientation process. For this reason, the relationship between the IMU, cameras and GPS must be totally stable.

2.2 Integration Platform

The integration platform is the structure where the different sensors are mounted for their operation. This platform must be sufficiently stable for the precise transference of reference frames. Two basic requirements must be considered, namely that the platform must have a maximum physical space at the top of the van, and the geometry of the platform must be totally stable in order to transfer the global reference frame (computed from the GPS/IMU data) to any sensor installed on the platform. This implies high immunity to deformations. The design of the platform was studied [3] and several options were analyzed. The optimal solution is based on an irregular mesh system with diagonal reinforcements, as can be seen in figure 2. This structure is equipped with equidistant anchorage points so that different sensors can be easily distributed.

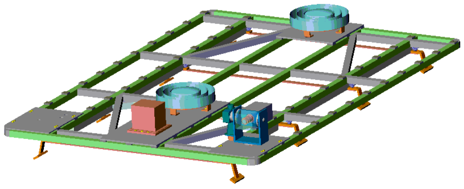


Figure 2: Integration Platform simulation with the diagonal reinforcements.

As explained above, the biggest constraint in the design of the platform and the anchorage system for the sensors has been the stability requirements. The maximum deformations tolerated between the reference center of the absolute frame (IMU) and the reference center of the relative frame (Camera) are 1mm in displacement and 70 arc seconds in rotation.

2.3 Image sensor subsystem

The subsystem design has been driven by two main requirements: to acquire images of at least 1Mpix and to get 10m stereoscopic overlap at a 10 m distance from the van (about 100 m^2). The selected image size is a compromise between image resolution and data storage and management. The stereo overlap requirement is conditioned by two factors: getting the maximum stereoscopic overlap free of obstacles (between the vehicle and the objects of interest) and preserving a B/D ratio (stereoscopic base – object distance) as good as possible (see figure 3). Table 1 summarizes the image sensor subsystem characteristics.

No. Píxels	1024x1024
Píxel size	12 µm
Focal length	10.2 mm
FOV	62.13º
IFOV	3 min. 38 sec.
Stereoscopic overlap @10 m	10.55 m
Precision@10 m (across-track)	0.8 cm
Precision@10 m (along-track)	5.6 cm

Table 1: technical features of on-board image sensors.

Figure 3 shows some significant photogrammetric figures. Notice the dependency of the along-track photogrammetric precision on pixel size and B/D ratio versus the dependency of the across-track photogrammetric precision on pixel size only.

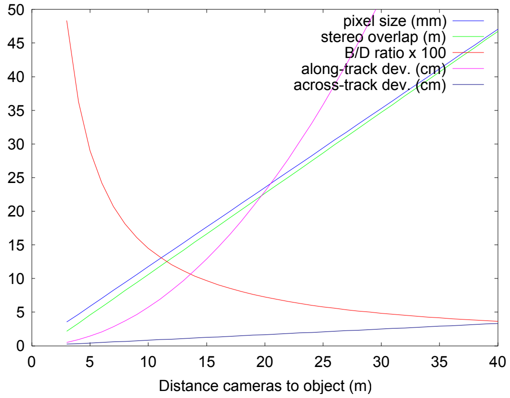


Figure 3: Relationship between distance (units in m) and photogrammetric precision (units in cm) across and along-track (along-track precision strongly depends on B/D ratio), stereo overlap (units in m), pixel size (units in mm) and B/D ratio (B/D ratio times 100).

2.4 Image acquisition subsystem

The image acquisition subsystem selects photo parameters, generates the trigger pulse and handles data. In order to freeze the stereo scene, both cameras are synchronized at the time of image capture. The photographs are taken by the image acquisition subsystem, which generates a pulse train (trigger) at a frequency depending on the traveled distance or at a given constant frequency.

If the acquisition frequency is configured spatially, the trigger period depends on the distance covered by the van and partially on road turns. This required information is obtained from vehicle speed and heading, continuously provided by the orientation subsystem. A typical spatial period would be 10 meters or a turn higher than 60 degrees, which corresponds to the camera field of view.

The hardware components of the image acquisition subsystem are two Frame Grabbers, one Counter/Timer and two removable disks, all of which are managed by a Control PC. A Frame Grabber, required to control the digital cameras, is the interface between the cameras and the acquisition software. The Counter/Timer is a device for generating pulse trains used to trigger the camera and to synchronize the timeboard. The software components of the image acquisition subsystem are integrated in the general GEOMÒBIL software application that is in charge of the hardware equipment configuration, acquisition control, GPS time synchronization process and system status displaying.

The data storage capacity of the system has been evaluated to be higher than 100 Gbytes. Considering that a GEOMÒBIL survey session can last seven hours at 1 Mbyte image size, driving at a 72 Km/h vehicle speed and with a spatial acquisition frequency of 10 meters/image, a minimum storage capacity of 101 Gbytes is needed per session. Hence, the system storage capacity is composed of two removable 73.4 Gbytes disks. If necessary, the disks can be exchanged to increase the storage capacity. According to the current hardware configuration and to the data recording rate of disks, a maximum of four pairs of images per second can be taken by the system. This number is enough to cover the requirements of the system, and can be easily enhanced by using larger and faster disks as soon as they are available.

2.5 Synchronization subsystem

The synchronization subsystem aims to synchronize in a common temporal reference (GPS time) all the sensors integrated in the GEOMÒBIL (GPS/IMU/Image sensors/laser). This subsystem integrates a timeboard and handles different synchronism signals: PPS, Trigger and Resync.

The timeboard is a device that allows timetagging of received TTL signals with 20 ns resolution. Thus, all the received signals are precisely referenced to the temporal reference system defined by the timeboard. However, the requirement is to synchronize the sensors in a global temporal reference (GPS time). Therefore, the synchronization subsystem process is divided into two steps, namely initialization and data synchronization.

The goal of the initialization process is to establish the difference between GPS time and timeboard start time, which is defined as the instant when the timeboard resets its internal time to zero and starts working. In this initialization step, T_0 is defined as the result of the subtraction between synchronism or the GPS-timetagged *Resync* pulse and the same pulse but timetagged by the timeboard. During subsystem operation, the drift of the timeboard internal clock is also monitored and corrected using the 1PPS signal provided by the GPS.

2.6 Sensor Calibration Procedure

A sensor calibration protocol must be defined for each sensor on board of the GEOMÒBIL.

In general, a sensor calibration protocol is divided into two sets of calibration procedures: the sensor inner parameter calibration (if needed), and the relationship between all the sensors on the platform, in particular the relative orientation of the two cameras and the boresight calibration of the sensor in relation to the orientation subsystem.

In the case of digital CCD cameras, calibration comprises the calibration of optical parameters —focal length, principal point and lens distortion— and the relative orientation of the cameras and boresight calibration; that is, determination of the eccentricity vector and the misalignment matrix between the image reference system (defined by each camera) and the inertial reference system (defined by the GEOMÒBIL orientation subsystem).

In the case of the laser scanner, only boresight calibration is performed.

2.7 GEOMÒBIL: data extraction software

The data extraction software assists the interactive digitization of features for creating, updating or revising georeferenced data. The system allows the point measurement on the images obtained with the GEOMÒBIL, and the classification of the feature attributes according their semantic contents.

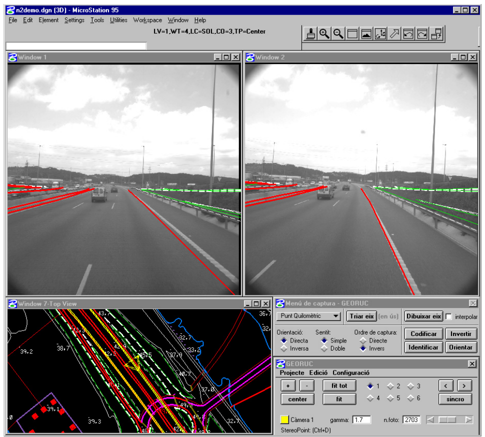
The original idea, to use a stereo environment that allowed superimposition of vector data, based in the photogrammetric model obtained from the orientation data of two images, was considered too expensive and the actual system is not stereo. For each pair, each image is visualized in a view and the operator should identify the point to be measured in both images. Vector data can be superimposed on top of the images.

The system is based in MicroStation 95 and the customization has been developed using MDL language. The system functionality for image and vector visualization, data digitalization and editing or data storing takes advantage of the MicroStation basic tools. As the same tools are used in data compilation, editing and storing for other topographic databases created at the Institut Cartogràfic de Catalunya, data integration can be achieved without any data transformation.

The application allows the reproduction of the path covered by the GEOMÒBIL, visualizing the sequence of images collected by each camera. The path information is obtained from a file with the position (geographic coordinates in a given reference system) and attitude of the projection center for every photo. Another file provides information about the parameters for the cameras (focal length, principal point coordinates, radial distortion and internal orientation).

Each image sequence is visualized in a MicroStation view. The view is configured according to the camera (coordinates and angles of the projection center, coordinates of the principal point, and focal length), and the image is placed in the perpendicular plane to the camera axis at a selected distance of the projection center. This method allows the visualization of georeferenced data on top of the image.

Two views of MicroStation can be used to show the path, the projection centers and the orientation of the visualized images. Vector data and raster images can be also displayed in these views. As no more than eight views can be used in MicroStation, a maximum of six sequences can be visualized during a session.



LV=1,WT=4,LC=SOL,CO=3,TP=Center

Orientació: ◆ Directa ◇ Inversa

Sentit: ◆ Simple ◇ Doble

Ordre de captura: ◇ Directe ◆ Invers

◆ 1 ◇ 2 ◇ 3 ◇ 4 ◇ 5 ◇ 6

Càmera 1 gamma: 1.7 n.foto: 2703

Figure 4: Screen shot of the GEOMÒBIL data extraction software.

The tools for image management allow to advance and to go backwards one image in one or more views, to select one image in one view, to synchronize the images for all the views, and to go to the nearest image to a georeferenced point. The visualization tools, as zoom in, zoom out, center the view to a given point, or fitting the image in the view, have been specially developed for this application, because MicroStation standard visualization tools do not preserve the camera configuration.

The point coordinates are calculated resolving the collinear equations from the position identified in two images. The images can be amplified to facilitate the point identification, and the epipolar line can be visualized, after giving the point in the first image, to identify the same point in the second image. The collinear equations solution is computed in geocentric coordinates to increase the accuracy, and then it is converted to the work reference system.

The coordinates of the calculated point are sent to MicroStation to be processed by the active command as a standard input. Microstation commands and other specific tools can be used to capture new data or to modify existing information. A set of tools has been created to gather elements tied in the roads. They allow to capture the axis of the route, to attribute it with some characteristics (number of rails, tunnel, street...) and to capture attached elements to the road as kilometric points, traffic signs, gas stations or bus stops.

3. GEOMÒBIL IMAGE SUBSYSTEM CALIBRATION

3.1 Camera parameters calibration

Calibration of the optical parameters was carried out at the ICC facilities.

The floor of the ICC exposition room has a regular pattern (as can be seen in image 5). Using classical surveying techniques, a local reference frame was set in the exposition room. The coordinates of six points on the ground in the local reference frame were measured. The position of each camera was computed on up to six different sites around the target area on a balcony situated at 8.40 meters above the target area. From each of these sites both cameras were operated to image the target area.

Figure 5: setting of the camera calibration site.

Up to 471 points were identified in the images of the target area, with in a total amount of 4165 photogrammetric observations (average of 347 photogrammetric observations per image). Six of the 471 points are the six measured points mentioned above. These six points become six full control points. The other 465 are vertical control points at height zero (in the local reference frame). Moreover, due to the regular pattern and distribution of points, a distance restriction between the adjacent points of the 471 point network was imposed.

A Bundle Block Adjustment was carried out in the above conditions using GeoTex software (Colomina et al. 1992). Focal length and the principal point parameters were adjusted. At a first stage, no corrections for lens distortion were taken into account.

In a second step, a polynomial of 5th order was adjusted in order to remove the lens radial distortion. Figure 5 shows the radial component of the photogrammetric residuals against the distance to the principal point and adjusted polynomials for the right and left cameras.

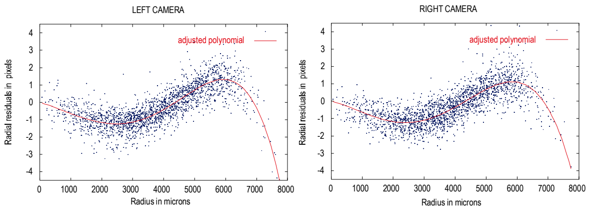


Figure 6: radial distortion calibration: adjusted polynomials for lens radial distortions for right and left cameras.

Notice that no significant differences were found between the radial lens distortion of each camera. As a conclusion, for this set of optics and cameras a single polynomial can be used independently of the camera and lens to model lens radial distortion. However, the calibration parameters are not interchangeable because focal length and principal point parameters are significantly different between each camera.

3.2 Camera boresight calibration

In order to be able to compute the absolute position of any photograph in the object space, it is mandatory to compute accurately the relative position and attitude of each camera to the inertial reference frame defined by the GEOMÒBIL orientation subsystem.

The calibration site is in the neighborhood of the ICC and consists of two cylindrical walls in an open environment (with excellent GPS visibility). On these walls, about 60 points are surveyed with an accuracy of 1-2 cm. A GPS Ground Reference Station is set close to the calibration site.

In the procedure, the wall is imaged by the GEOMÒBIL system from different positions, azimuths and distances. A few stereopairs are selected from this set of images. The selection criterion is to obtain some stereopairs at different distances, azimuths and positions of the GEOMÒBIL with respect to the calibration site. The acquisitions are performed in static and dynamic mode (van in movement). Dynamic acquisitions demonstrate that the synchronization subsystems work as expected.

Wall control points are identified in the selected images and a Bundle Block Adjustment is performed. In the adjustment, the adjusted camera calibration parameters are taken into account (focal length, principal point and lens distortion). The goal of the Bundle Block Adjustment is to determine a set of boresight parameters per camera (eccentricity vectors and misalignment matrix between the image reference frame and the inertial reference frame) and a set of relative orientation parameters (camera relative orientation).

Adjusted relative orientation obtained accuracies of 1 cm for position and 60-80 arc seconds for attitude. Adjusted boresight parameters obtained accuracies of 1-2 cm for the eccentricity vector and 120-150 arc seconds for the misalignment matrices.

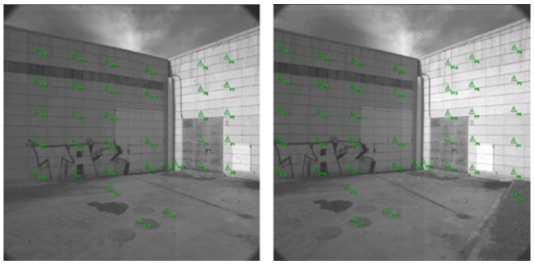


Figure 7: A stereopair of a calibration data set with some control points identified and marked on the images.

No significant residuals in the position and attitude parameters (orientation) of the dynamic acquisitions were found. Thus, it may be concluded that the synchronization subsystem has neither drift nor biases that affect image timetagging.

Once the boresight parameters are computed, the GPS/IMU subsystem orientation parameters may be transferred to the images. Preliminary results on the empirical accuracy of the system using direct orientation are summarized in table 2. Up to 39 objects in the calibration test field were identified in photogrammetric models when the van was moving (at 16-18 meters distance of the wall) and its coordinates computed using direct orientation techniques. The coordinates were compared to the coordinates computed using surveying methods. As the azimuth during acquisition was nearly zero degrees, northing is approximately along-track and easting and H are across-track. Note that these empirical accuracies are coherent with the theoretic accuracies shown in figure 3.

	σ
Easting (across-track)	0.05 m
Northing (along-track)	0.13 m
H (across-track)	0.03 m

Table 2: Empirical accuracies

4. PRACTICAL RESULTS

Some missions have been carried out under different environmental conditions. In this article, we focus on the results obtained by one of them. The mission under discussion is an urban case.

4.1 Mission results

The acquisition took place in Sitges, a tourist resort town near Barcelona, on 5th November 2003. The acquisition was performed with the GEOMÒBIL image subsystem and the recently integrated terrestrial LiDAR. A GPS reference station was set within a 5-10 Km distance from the mission site.

In Sitges there is 1:1000 3D digital cartography, which was used to check the GEOMÒBIL accuracy and precision. Map accuracy is 20 cm (1.64 σ) per component.

From the whole GPS/IMU trajectory, only two pieces with excellent GPS visibility have been taken into account. These pieces are referenced as zone 1 and zone 2 in the following lines. As some discrepancies between terrain and trajectory had been detected in the original GPS/IMU trajectory, a new one has been computed and considered in both zones. Although the new trajectory has discrepancies too, these are smaller.

In some stereopairs of the selected pieces of the trajectory, some well-defined objects are identified using GEOMÒBIL extraction software. The identified objects are corners of street flowerbeds, pavements and water outlets. There are 5 objects in zone 1 and 5 in zone 2. Once the coordinates have been computed, they are compared against the 1:1000 cartography of Sitges. Results of this comparison are summarized in table 3.

	Zone 1			Zone 2		
	RMS	Mean	σ	RMS	Mean	σ
Easting	0.22	-0.11	0.21	0.50	0.38	0.36
Northing	0.13	0.09	0.10	0.39	0.34	0.20
H	0.26	0.26	0.04	0.48	0.47	0.07

Table 3: Empirical accuracies in urban environment (units are in meters).

Notice the difference in precision and accuracy in height. Precision in height is directly correlated to the precision in height of the computed van trajectory. Indeed Easting and Northing coordinates are also affected by trajectory errors. Differences in mean suggest different discrepancies between trajectory and map depending on the piece of trajectory. In summary, the photogrammetric quality of the image subsystem is good. However, to make the most of it, GPS/IMU trajectory determination must be improved.

5. LASER SCANNER INTEGRATION

Recently, ICC has acquired a terrestrial LiDAR system. The system has been successfully integrated in the GEOMÒBIL system.

5.1 Boresight calibration

Laser scanner is set in a configuration according to the goals of each mission. In particular, the laser can be set in two main configurations scanning direction upside-down or scanning direction right-to-left. Each configuration requires its own calibration.

It is used the same calibration scenario that the used for the CCD camera boresight calibration. On the CCD camera calibration wall 15 of the 60 measured points (see section 3.2) were signalized with reflecting targets. The laser from different positions and azimuths scans the calibration wall. Targeted points are identified automatically on each scan of the wall. A Bundle Block Adjustment is performed taken into account the laser observations of targeted points at each laser location, the coordinates measured of the 15 targeted points and the positions and attitudes computed by the orientation subsystem. In the adjustment there are determined the eccentricity vector and misalignment matrix (boresight parameters, an amount of 6 parameters), which defines de relationship between the inertial reference frame (the one of the orientation subsystem) and the laser scanner reference frame.

Some pilot missions have been carried out. Calibration and mission results are discussed deeply in Talaya et al, 2004b.

6. FUTURE DEVELOPMENTS

Further developments focus on two issues. The first one is the integration of new digital color cameras pointing forward and backwards. The second is to improve trajectory determination. In general, this improvement may be achieved by integrating new sensors (as barometers), which can help in the computation of trajectory. In urban environments with existing maps and/or aerial photography, some objects may be extracted and used as "ground control". These points will be used to improve trajectory computation.

7. CONCLUSIONS

Since the development of the GEOMÒBIL system started, the ICC has successfully integrated and operated simultaneously two digital CCD cameras and a terrestrial laser range system. The ICC development consists of sensor integration, calibration and data extraction software. Current experiences prove that the GEOMÒBIL system exhibits an excellent photogrammetric behavior. In fact, experiences confirm theoretical accuracies of the image subsystem (plotted in figure 3). It has also been proved that the calibration protocol obtains expected accuracy so that obtain the best performance of the image subsystem can be achieved.

Despite the excellent results concerning photogrammetric capabilities and laser data orientation (Talaya et al. 2004b), in urban environments and projects demanding a high accuracy the GEOMÒBIL system and LBMM systems require a more reliable direct orientation subsystem than the current one.

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