

# A GPS/INS/Imaging System for Kinematic Mapping in Fully Digital Mode

**Mohamed M.R. Mostafa and Klaus-Peter Schwarz**

Department of Geomatics Engineering, The University of Calgary, 2500 University Drive N.W., Calgary, Alberta, Canada T2N 1N4, Tel: (403) 220-8794, Fax : (403) 284-1980, e-mail: mrashad@ensu.ucalgary.ca

**Abstract** This paper describes the development and testing of a multi-sensor system for kinematic mapping in fully digital mode. The system consists of a navigation-grade strapdown Inertial Navigation System, two GPS receivers, and two high resolution digital cameras. The two digital cameras capture strips of overlapping nadir and oblique images. The INS/GPS-derived trajectory describes the full translational and rotational motion of the carrier aircraft. During postprocessing, image exterior orientation information is extracted from the trajectory. This approach eliminates the need for ground control to provide 3D position of objects that appear in the field of view of the system imaging component. Test flights were conducted over the campus of The University of Calgary. In this paper, the multi-sensor system configuration and calibration is briefly reviewed and results of the test flights are discussed in some detail. First results indicate that major applications of such a system in the future are the mapping of utility lines, roads, pipelines (at mapping scales of 1:1000 and smaller), and the generation of digital elevation models for engineering applications.

**Keywords.** GPS/INS, georeferencing, digital mapping, multi-sensor systems

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## 1 Mapping The Earth's Surface - A Kinematic Approach

Helmert (1880) defined geodesy as the science of measuring and mapping the Earth's surface. Interpretations of this definition cover the whole spectrum of geomatics. The geodetic positioning specialist considers the measurement of the Earth's surface as a point positioning problem with reference frame implications. The accurate determination and monumentation of points on the surface of the Earth is therefore seen as the major task. In order to express these points in a consistent coordinate system over larger parts of the Earth's surface, networks are established and the datum problem must be solved. Once this has been done, the network points are used for point densification in local areas. The concept implied by this approach is that the higher the point

accuracy, the better the mapping. This is true for pointwise mapping, but obviously not for surface mapping. Simple interpolation between network points will, for instance, create large errors in a topographic map. Thus, the accuracy of the surface representation will not be uniform. In addition, although networks may stretch over a large part of the Earth's surface, they are globally disconnected when established by conventional procedures. This means that the datum problem cannot be solved without extraterrestrial measurements.

The photogrammetrist, on the other hand, considers the measurement of the Earth's surface as an imaging problem. It is solved by deriving a model of the surface from digital or photographic images. In this case, patches of the Earth's surface are actually measured and mapped in accordance with Helmert's definition. The concept behind this method is that the surface of the Earth can be presented by pixels measured in projected images. The smaller the pixel size and the better the geometry, the better the mapping. In this case, the accuracy is more or less uniform across the image and interpolation of specific image features is possible with high accuracy, once the image has been properly georeferenced. This is done by solving the datum problem using geodetic ground control in the survey area. Comparing the view of the positioning specialist with that of the photogrammetrist shows that they are essentially complementary. One provides highly accurate point positions in an adopted reference system which can be used by the other to georeference measurements and solve the datum problem for the precise local maps derived from images.

Because of this complementarity, the problem of measuring and mapping the surface of the Earth can be solved by combining geodetic point positioning with digital imaging. To do this efficiently, mobile mapping methods should be employed and the use of ground control should be avoided. This is possible by using differential GPS together with an inertial measuring unit (IMU). Currently, GPS is widely seen as a highly accurate relative positioning method. Interstation vectors are the output of differential GPS methods and, in this sense, GPS is viewed as a sophisticated tool for

network densification. What is lost in this view of GPS positioning is the fact that the receiver output is directly connected to the global reference frame by way of satellites. Thus, ground control can be replaced by sky control. This means that it is possible to determine globally referenced positions without direct access to networks or dense ground control. Instead of tying into monumented control points one links into satellites which, in their orbital positions, carry accurate reference system information with them.

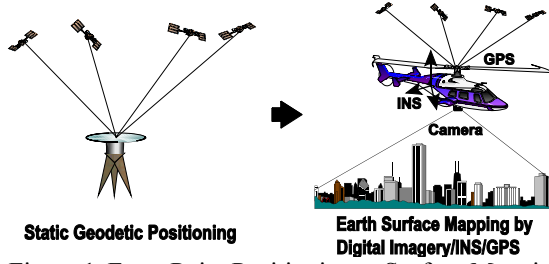


Figure 1. From Point Positioning to Surface Mapping

By making use of this aspect of GPS, it is possible to design kinematic systems that integrate the georeferencing and imaging aspects of the problem discussed here. Such systems will provide a consistent and uniform representation of the Earth's surface worldwide. This is possible because a highly accurate global reference frame now exists which can be accessed everywhere by using GPS receivers as measurement tools. Since GPS receivers work in kinematic mode, there is no reason to separate the positioning process from the imaging process. By determining the perspective centre of the imaging sensor lens by DGPS at the moment of exposure, the first three parameters of exterior orientation are obtained in an accurate global reference frame, such as the WGS84. The other three parameters describing the orientation of the camera at the moment of exposure can be obtained by integrating an IMU with DGPS and the camera. This has the advantage that each individual image will now get its full set of exterior orientation parameters. Thus, any two images with overlapping image content can be directly used for mapping part of the Earth's surface in a consistent global coordinate frame, see Figure 1. The implementation of such a system and its current accuracy will be described in the following sections.

## 2 Kinematic Motion Determination by Geodetic Tools

The 3D motion of a rigid body can be described by the sum of two vectors. One models the position vector to

a reference point (o) of the rigid body with respect to an Earth-fixed coordinate system (e-frame), while the other accounts for the orientation of the rigid body in 3D space. This can be written as:

$$\mathbf{r}_i^e(t) = \mathbf{r}_o^e(t) + \mathbf{R}_b^e(t) \Delta \mathbf{r}^b \quad (1)$$

where,

$\mathbf{r}_i^e(t)$  is the position vector of an arbitrary point i of the rigid body in the e-frame at time t;

$\mathbf{r}_o^e(t)$  is the position vector of point o of the rigid body in the e-frame at time t;

$\Delta \mathbf{r}^b$  is a constant offset vector between point i and o in the rigid body b-frame; and

$\mathbf{R}_b^e(t)$  is the rotation matrix between the b-frame and the e-frame at time t.

If an IMU is located at point o and a GPS antenna at point i, then their common carrier platform motion can be fully described by Equation 1 and estimated from inertial and satellite measurements. For a detailed discussion on GPS/INS integration modelling estimation, and applications, see Schwarz (1998).

## 3 Photogrammetric Reconstruction of a 3D Point Position

Although mapping patches of the Earth's surface is the final product of imaging applications, the basic analytical form, needed to relate an image frame (c) and a mapping frame (M), is still expressed pointwise. Therefore, the process of reconstructing a 3D object position from 2D image data follows the collinearity concept. As shown in Figure 2, the object point, its image on the acquired photo, and the perspective centre of the lens in use have to be collinear. This can be expressed as:

$$\mathbf{r}_G^M = \mathbf{r}_E^M(t) + s_g \mathbf{R}_c^M(t) \mathbf{r}_g^c(t) \quad (2)$$

where,

$\mathbf{r}_G^M$  are the 3D object point coordinates of point G in the M-frame;

$\mathbf{r}_E^M(t)$  are the 3D coordinates of the exposure station E at the instant of exposure t, in the M-frame;

$\mathbf{r}_g^c(t)$  are the 3D coordinates of the image point g in the c-frame at the instant of exposure t (2D image coordinates plus lens focal length);

$s_g$  is an image point scale factor implicitly derived during the 3D reconstruction of objects using image stereopairs; and

$\mathbf{R}_c^M(t)$  is a rotation matrix rotating the c-frame into the M-frame at time t, utilizing the three c-frame orientation angles  $\omega(t)$ ,  $\phi(t)$ , and  $\kappa(t)$ , and the primary, secondary, and tertiary elementary rotation matrices  $\mathbf{R}_1$ ,  $\mathbf{R}_2$ , and  $\mathbf{R}_3$ , respectively.

This rotation matrix can therefore be expressed by:

$$\mathbf{R}_c^M(t) = \mathbf{R}_3(\kappa(t)) \mathbf{R}_2(\varphi(t)) \mathbf{R}_1(\omega(t)) \quad (3)$$

In other words, once a coordinate system has been attached to the imaging sensor, the mapping coordinates of any point that appears in an image stereopair can be determined using Equation 2, if the position and orientation parameters of the image at the instant of exposure are known.

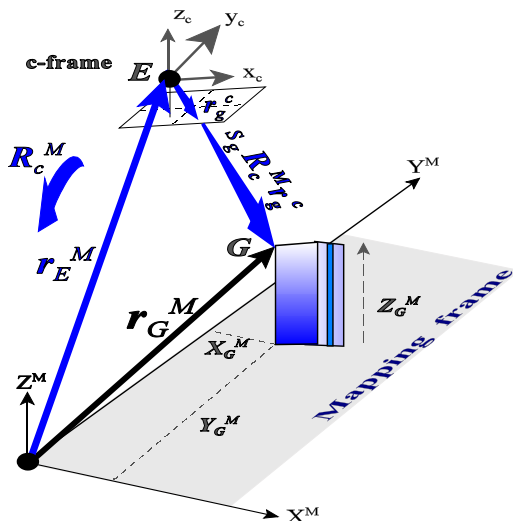


Figure 2. Image-to-Object Space Relationship

#### 4 Integration of Kinematic Geodesy and Aerial Imaging for Surface Mapping

The measurable quantities in Equation 2 vary according to the sensors available onboard. In standard aerial photography applications, known ground control points are used to relate the camera frame to the mapping frame. In this case,  $\mathbf{r}_G^M$  and  $\mathbf{r}_g^c(t)$  are the observables used to recover  $\mathbf{r}_E^M(t)$  and  $\mathbf{R}_c^M(t)$  of each image. They are then subsequently (or simultaneously) used to determine  $\mathbf{r}_G^M$  of other points of interest. This process is indirect from the standpoint that camera position and orientation, needed to determine positions of points on the ground, are determined using other ground points with known coordinates. This process is called aerotriangulation.

With the development of GPS kinematic techniques, the combination of kinematic positioning with aerial triangulation was proposed in Schwarz et al (1984). First test results were published in the late 1980s and since then, GPS-assisted photogrammetry has become an operational procedure. Yet, GPS only provides the position component of the exterior orientation parameters, and thus, blocks of images are always

needed to recover the orientation matrix for each image. To orient individual images which are not part of a block structure, an IMU is needed in the data acquisition system to fully describe the platform motion, as briefly discussed in section 2. GPS/INS integration in support of photogrammetric mapping has, therefore, been an active area of research over the past decade. The mathematical model and proposed applications were demonstrated by Schwarz et al (1993). Lechner and Lahmann (1995) and Škaloud et al (1996) showed the success of this method to georeference aerial photos by GPS/INS. On the other hand, Mostafa et al (1997), Cramer et al (1997), and Toth and Grejner-Brzezinska (1998) reported on systems that integrated GPS/INS with digital cameras. Economically, such systems have a great potential to replace the currently used aerial mapping systems due to their lower cost, shorter turn-around-time, and the rapid development in the digital camera industry. Figures 3 and 4 show a comparison between current aerial mapping systems and the integrated navigation/imaging systems discussed here. For details, see Lyon et al (1995) and Congalton et al (1998).

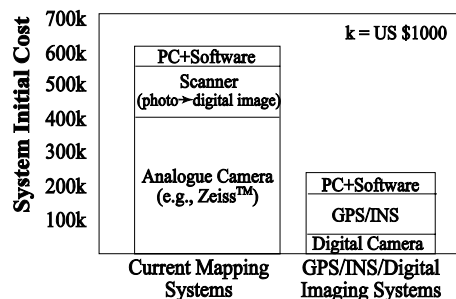


Figure 3. Economics of Mapping Systems

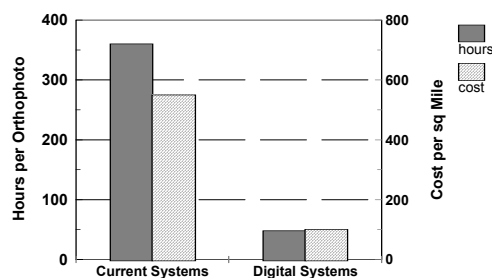


Figure 4. Operating Cost of Mapping Systems

#### 5 System Configuration

The two major components of such a system are the navigation component and the imaging component. The navigation component comprises two GPS receivers to allow for ground-to-aircraft DGPS positioning, and a navigation-grade inertial navigation system. The imaging component includes two digital cameras. One

is mounted vertically, while the other is oblique. They were configured in such a way as to reduce the geometric limitations that arise when using a single camera; for details, see Mostafa et al (1998b). Accommodated onboard a CESSNA 310 twin engine aeroplane, two dual-frequency GPS receivers, two Kodak DCS 420 digital cameras, and a Honeywell LRFIII INS, were used for the test. The GPS receivers, the INS, and the digital cameras were interfaced to three laptops, which control the different tasks required for data acquisition, as shown in Figure 5.

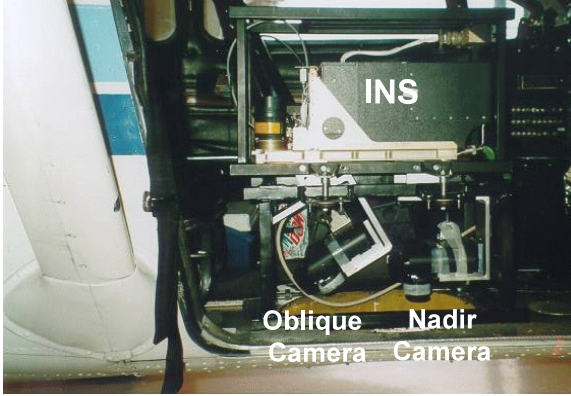


Figure 5. The Multi-Sensor System Installed

## 6 System Calibration

An overall system calibration is required to relate GPS-derived positions, INS-derived attitude parameters, and image-derived object point coordinates. In addition, the digital cameras have to be calibrated to establish their interior geometry and to determine their lens distortion.

Both digital cameras were calibrated at the University of Calgary using a self-calibrating software (Lichti and Chapman, 1997). The precision of calibration of each camera was at the level of 5-7 cm on the ground, for a flight altitude of 450 m. For details, see Mostafa and Schwarz (1999). Sensor position offsets were precisely surveyed to mm accuracy. A critical part of the calibration process is the computation of the rotation offset between the INS and each of the two camera coordinate systems. Since both have invisible coordinate system axes, their orientation offset has to be computed indirectly. To do this, either in-flight calibration or static calibration can be used. In in-flight calibration, known ground control is used to determine the camera orientation angles. They are then compared to the INS-derived ones to determine the orientation offset

$$\mathbf{R}_{c_i}^M(t) = \mathbf{R}_{INS}^M(t) \mathbf{R}_{c_i}^{INS} \quad (4)$$

where,  $\mathbf{R}_{c_i}^{INS}$  is a rotation matrix rotating the c-frame of each camera  $i$  into the INS-frame. The second approach is similar to the former one, except that it is implemented in static mode on the ground using a close range target field. Both approaches have their inherent advantages and drawbacks because they differ in geometry, resolution and motion. For details, see Mostafa and Schwarz (1999). Substituting Equation 4 into Equation 2 and accounting for a 3D position offset vector from the INS to each camera's coordinate system origin  $\mathbf{a}_i^{INS}$ , the model represented by Equation 2 can be written as:

$$\mathbf{r}_G^M + \mathbf{r}_{E_i}^M(t) \% \mathbf{R}_{INS}^M(t) \left( \mathbf{a}_i^{INS} \%_{S_{g_i}} \mathbf{R}_{c_i}^{INS} \mathbf{r}_g^{c_i}(t) \right) \quad (5)$$

The right-hand side of Equation 5 contains all the measurable/processed quantities except for  $\mathbf{R}_{c_i}^{INS}$  and  $\mathbf{a}_i^{INS}$ , which are determined by calibration. The data flow of the entire georeferencing process is briefly shown in Figure 6; for details, see Mostafa et al (1998a).

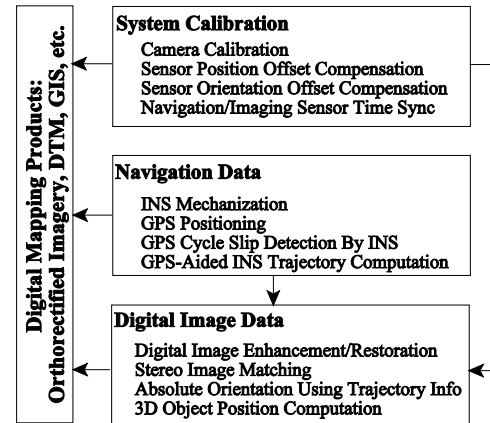


Figure 6. Multi-Sensor System Data Flow

## 7 In-Flight System Testing

A test flight was conducted over the campus of the University of Calgary. The university campus was chosen because of its detailed urban character as well as the ease with which ground control points could be placed on roads, in parking lots, and on building rooftops. Almost a hundred ground control points were established by GPS all over the campus. They were distributed in such a way that an optimal geometry for in-flight calibration of the digital cameras and the entire system could be achieved, see Figure 8.

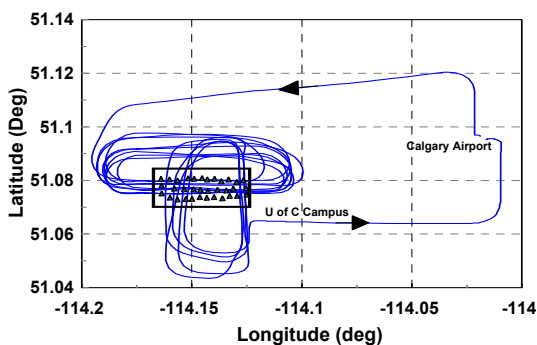


Figure 7. GPS/INS-derived Trajectory

Using the characteristics of the digital cameras (9mm x 13mm image size and  $f = 28$  and 52mm, respectively, and their data rate, typically, 4 seconds per image, the flight pattern was designed to cover the entire campus by a block of standard 60% endlap and 40% sidelap, using repeated flight lines. The flight pattern is shown in Figure 7. Figure 8 shows a nadir image over the Calgary campus.

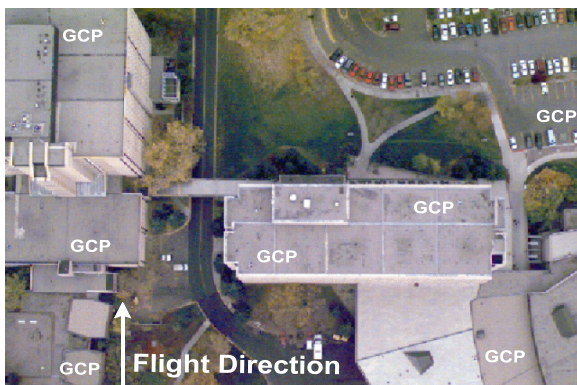


Figure 8. A Digital Image Over U of C Campus

## 8 System Performance

The GPS/INS raw data were processed using the KINGSPAD software. Figure 9 shows the Kalman filter-derived estimates of the positioning accuracy for the three components as well as the Position Dilution of Precision (PDOP) during the entire test flight.

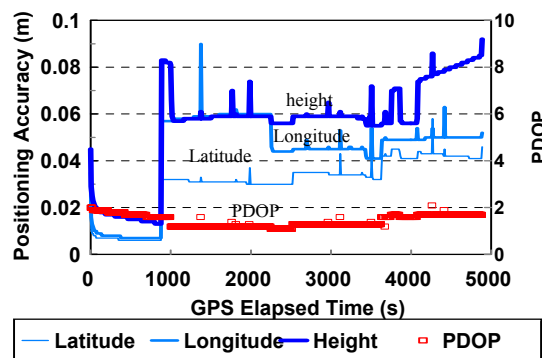


Figure 9. GPS/INS Positioning Accuracy

The attitude at the interpolated camera exposures was accurate to about twenty arcseconds in roll and pitch and about one arcminute in azimuth. Using those parameters, together with the digital imagery which was processed in stereopairs, strips, and blocks, using the PCI OrthoEngine software, the ground control point coordinate values were independently computed and compared with their reference values obtained from the GPS ground survey. The statistics of the differences are shown in Table 1. These accuracies are consistent with those achieved by simulations. The composition of the total error budget is given in Figure 10, for details see Mostafa et al (1998b).

Table 1. Accuracy of Georeferencing by GPS/INS

Processing Mode	East (m)	North (m)	Height (m)
Stereo*	0.45	0.51	0.75
Strip # 1*	0.34	0.42	0.65
Strip # 2*	0.39	0.47	0.59
Strip # 3*	0.37	0.46	0.57
3 x 3 Block**	0.22	0.24	0.34

\*using nadir and oblique images

\*\*using nadir and oblique images and cross strips in two directions

## 9 Conclusions and Future Work

Results achieved with a prototype system show that the concept of using georeferenced digital images to map patches of the Earth's surface in kinematic mode is sound and that accurate 3D positions can be obtained without the use of ground control. It thus reduces turn-around-time for airborne mapping very considerably. Accuracies achieved are at the level 20 cm in horizontal and 30 cm in height. Higher accuracy is possible if larger format digital cameras are used. For highest accuracy, especially in the height component, it is recommended that a laser scanner be added to the system.

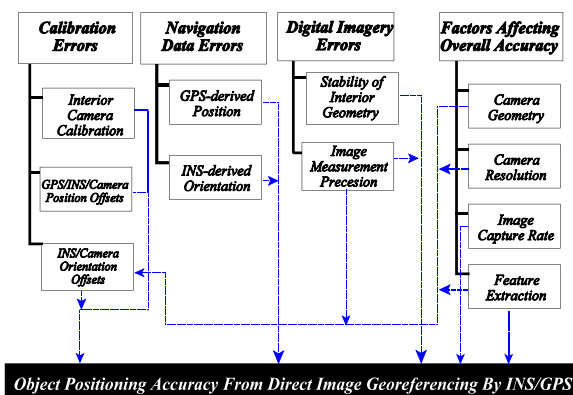


Figure 10. Factors Affecting System Accuracy

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