A MOBILE MULTI-SENSOR SYSTEM FOR GIS APPLICATIONS IN URBAN CENTERS

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ABSTRACT :

A mobile highway mapping system has been jointly developed by The University of Calgary and GEOFIT Inc., a high-tech company in Laval, Quebec. The system named VISAT, stands for Video-Inertial-SATellite and integrates inertial and GPS technology with a cluster of CCD cameras. The overall objective was the development of precise multi-sensor mobile survey system that could be operated at a speed of 60 km per hour and achieve an accuracy of 0.3 m (RMS) with respect to given control and a relative accuracy of 0.1 m (RMS) for points within a 35 m radius from the van. This accuracy is required in rural as well as in urban areas, including city centers. The updated GPS/INS information is used to georeference the images collected by the CCD cameras which record all details along the highway within a corridor of about 35 m. The shutters of the cameras and the output of the INS system are synchronized by the clock of the GPS receiver.
A number of projects recently finished in Montreal and Quebec city provided the opportunity to test the system under different field conditions. Results of these tests are reported in this paper. A brief overview of system integration will be given followed by a detailed discussion of the system calibration. The analysis of recent field test will concentrate on the calibration results and the relative and absolute accuracy of the system. Overall, the results indicate that the required accuracies have been reached or surpassed by the current system.

1. INTRODUCTION

The dynamics of urban and rural development, the changes of land use and the increasing demand for precise Geographic Information Systems (GIS) in planning, make GIS information updating a permanent task. Keeping maps or GIS systems up to date is only possible to a limited extent. Even if the concept of the classical map is changed to that of a digital map as a consequence of technology available today, the core of the problem remains: ideally, data collection and storage has to be continuous and the identification of changes must be reliable. Classical methods of acquiring GIS data are no longer adequate because they are too slow and personnel-intensive. Satellite remote sensing and aerial photogrammetry can provide a variety of GIS information at very high data rates and at reasonable cost. However, the accuracy of satellite imagery is not sufficient for many GIS applications and the near vertical field of view of photogrammetric images provides only part of the information needed in urban centers.

To address this problem, a mobile data acquisition system has been developed which generates georeferenced video images at a rapid rate. The system which was jointly developed by The University of Calgary and Geofit Inc., Laval, Quebec, is a Multi-sensor system, called **VISAT**, which integrates a cluster of digital cameras with an Inertial Navigation System (INS) and a pair of GPS receivers (Figure 1). It automatically collects georeferenced digital images along both sides of the road while moving at velocities of 50-60 km/h. Features of interest in these images can be selected in the office and positioned with an absolute accuracy of better than 0.3m if the distance to the van is 35m or less. A workstation (GEOSTATION) facilitates the quick selection and efficient storage of such features in a GIS system.

The system integrate a strap-down INS system, two L1/L2 GPS receiver, eight CCD cameras, Anti-Braking-System (ABS), image control unit, and SVHS cameras. In the vehicle, all the sensors are interfaced to a Pentium PC, which control different data streams through programmed hardware interrupt process software. For more details on the design of the VISAT system see Schwarz e. al (1993a) and El-Sheimy et al (1995); for the workstation design, see Li et al (1994).

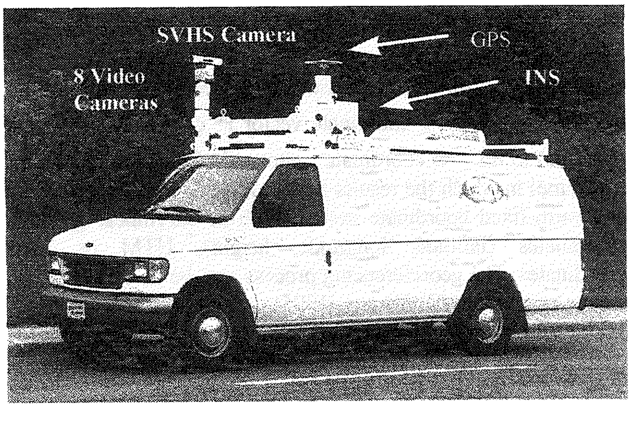

Figure 1 : The VISAT system.

The GPS is capable of providing very accurate position and velocity under ideal conditions. However, such conditions do not often exist. Independent GPS navigation requires at least four satellites. The major drawback GPS is the accuracy degradation due to poor satellite geometry, cycle slips, satellite outages, and dynamic lag during maneuvers.

The INS measures linear acceleration and angular rates very accurately and with minimum time delay. For short time intervals, the integration of acceleration and angular rate results in extremely accurate velocity, position, and attitude with almost no noise or time lags. However, because the INS outputs are obtained by integration, they drift at low frequencies. To obtain very accurate outputs at all frequencies, the INS should be updated periodically using external measurements

The function of each component of the VISAT system can be divided into primary and secondary function. In terms of primary functions, the camera cluster provides three-dimensional positioning with respect to the VISAT reference which in most cases is the perspective center of one of the cameras. The position of this reference with respect to the existing control is determined by differential GPS, while the camera orientation in three-dimensional space is given by the INS. The ABS system will trigger the cameras at constant distance using the VISAT controller trigger channel. In terms of secondary functions, the camera cluster provides redundancy (i.e., more than two images of the same object), the GPS controls the INS error propagation, and the INS, when used in positioning mode, bridges GPS outages, corrects GPS cycle slips, and gives precise interpolation between GPS fixes. The ABS data can be used to update the INS data if the GPS signal is blocked for periods more than the INS bridging level required to fix the GPS ambiguities (half a cycle).

The prerequisite for precise 3-D positioning from the VISAT video images is the systems calibration. System calibration includes the determination of the cameras inner orientation parameters, the relative location and orientation of the cameras, the relative location and orientation between the cameras and the navigation sensors. Surveying by VISAT, therefore, consists essentially of three parts: system calibration, position and orientation of the moving VISAT reference using GPS and INS data, positioning of objects in the road corridor with respect to the VISAT reference using two or more georeferenced camera images.

2. GEOREFERENCING OFVIDEO IMAGES

Georeferencing video images can be defined as the problem of transforming the 3-D coordinate vector $\mathbf{r}^c$ of the camera frame (c-frame) to the 3-D coordinate vector $\mathbf{r}^m$ of the mapping frame (m-frame) in which the results are required. The m-frame can be any earth-fixed coordinate system such as curvilinear geodetic coordinates (latitude, longitude, height), UTM or 3TM coordinates. The georeferencing process can be described by the following formula (El-Sheimy, 1995) :

$$\mathbf{r}_i^m = \mathbf{r}_{INS}^m(t) + S^i \cdot \mathbf{R}_b^m(t)\,(\mathbf{R}_c^b \cdot \mathbf{r}^c + \mathbf{a}^b) \qquad (1)$$

Figure 2 shows the elements of the georeferencing formula, where :

$\mathbf{r}_i^m$ is the coordinate vector of point (i) in the mapping frame (m-frame),

$\mathbf{r}_{INS}^m(t)$ is the vector of interpolated coordinates of the INS in the m-frame,

(t) is the time of exposure, i.e. the time of capturing the images.

$\mathbf{R}_b^m(t)$ is the interpolated rotation matrix between the INS body frame (b-frame) and the m-frame, as measured by the INS gyros.

$\mathbf{R}_c^b$ is the differential rotation between the camera coordinate frame (c-frame) and the INS b-frame

$\mathbf{r}^c$ is the image coordinate of the object in the c-frame

$\mathbf{a}^b$ is the offset between the INS center and the cameras

S^i is a scale factor specific to a one point/one camera combination

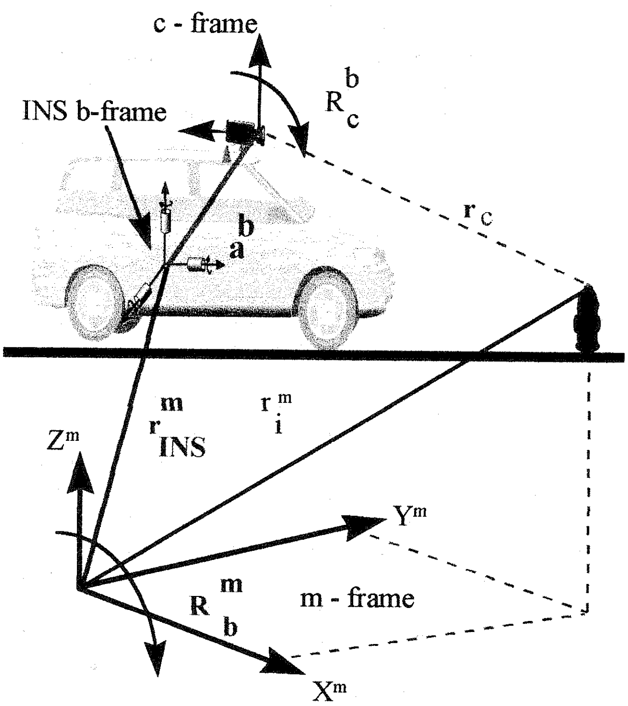

Figure 2 : The Georeferencing Concept

The INS position $\mathbf{r}_{INS}^m$ is the position resulting from the INS/GPS integration. In the event of a continuous loss of the GPS signal, the INS will be used in stand alone-mode to extend the mission. The high data rate of the INS, 50 Hz, facilitates the interpolation of the camera coordinates. $\mathbf{R}_c^b$ transforms the vector $\mathbf{r}^c$ from the c-frame to the b-frame. $\mathbf{R}_b^m(t)$ transforms the vector $(\mathbf{R}_c^b \cdot \mathbf{r}^c + \mathbf{a}^b)$ from the b-frame to the m-frame. $\mathbf{R}_c^b$ and $\mathbf{a}^b$ are determined through calibration procedures before the survey. Table 3. outlines how different quantities are obtained and their expected accuracy. For more details on the georeferencing process see Schwarz et. al. (1993b) and El-Sheimy and Schwarz (1994).

The georeferencing equation (1) contains four unknowns (3 coordinates and one scale factor) in three equations. Having a N images of the same scene will add Nx3 extra equations and N unknowns (scale factors) for the same point (i). A least squares solution of the space intersection between the N rays is computed with (3xN - 3 - N) degree of freedom.

Variable	Obtained from	Expected accuracy
r_i^m	**Unknown** (3)	30 cm (Req.)
$r_{INS}^m(t)$	Interpolated from the GPS/INS positions at the time of exposure(t)	10-15 cm
S^i	**Unknown** (1)	scale factor
$R_b^m(t)$	Interpolated from INS gyros output at the time of exposure(t)	1-5 arcmin
R_c^b	Calibration	1-5 arcmin
r^c	Measured image coordinates	0.5 pixel
a^b	Calibration	2 - 5 mm

Table 3. Elements of the Georeferencing Formula

3. SYSTEM CALIBRATION

Highly accurate calibration of all sensors of the integrated system is an essential requirement to ensure accurate 3-D positions. System calibration includes the determination of camera parameters which define the internal geometry of the camera. They are termed the inner orientation parameters. The relative location and orientation between the camera cluster and the navigation sensors (GPS and INS) are defined by the relative orientation parameters. The relative orientation parameters will be used in the transformation of the 2-D image coordinates into the 3-D world coordinates in the georeference process.

The calibration requires a number of Ground-Control-Points (GCP). A test-field of circular reflective targets of 5 inch diameter were used. An automatic detection method was implemented for measurement of the target centers (Cosandier and Chapman, 1992). In order to determine the relative position and orientation between the cameras and the GPS/INS, the coordinates of the target points were determined in the m-frame using a total station on the end points of a baseline which had been measured previously using GPS receivers. In the remainder of this chapter, the mathematical model for each set of parameters will be discussed.

3.1 Inner Orientation

Inner orientation is a standard problem which has to be performed before using any uncalibrated metric or digital camera. It determines the interior geometry of the cameras. A self-calibration bundle adjustment is used for this purpose. It solves for the basic position (X_o, Y_o, Z_o) and the orientation (ω, Φ, κ) parameters for each camera. These parameters will be used to relate the cameras to the navigation sensors. In addition, the nine elements which define the inner geometry of the camera are solved for, namely principal point coordinates (x_p, y_p), lens focal length (f), y-axis scale factor (k_y- used when pixels are not square) , three radial lens distortion coefficients (k1, k2, and k3), and two tangential distortion coefficients (p1 and p2) .

The mathematical model of the bundle adjustment with self-calibration is based on the collinearity conditions. They are formulated as follows:

$$Fx = (x - x_p) = - f\frac{U}{W} + \Delta x$$

$$Fy = (y - y_p) = - f\frac{V}{W} \cdot k_y + \Delta y \qquad (2)$$

Using the auxiliary parameters,

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = R_m^c \begin{bmatrix} X-X_o \\ Y-Y_o \\ Z-Z_o \end{bmatrix} \qquad (3)$$

where,

x, y	Image coordinates,
R_m^c	Orthogonal matrix defining the rotation between the m-frame and the camera coordinate system (c-frame)
X,Y,Z	Object coordinates in the m-frame (WGS 84),
Δx, Δy	Correction terms of additional parameters, mainly the lens distortion parameters.
ky	y axis scale factor.

3.2 Relative Orientation

The imaging component of the VISAT system consists of 8 video cameras with a resolution 640 x 480 pixels. The cameras are housed in a pressurized-case and mounted inside a two fixed-base towers on top of the VISAT-Van (Figure 4), thus eliminating any chance for the cameras to move during the survey.

The relative orientation parameters can be divided into two groups. The first group contains the parameters which define the relative position and orientation between different stereo-pairs. The second group consists of the parameters that define the relative position and orientation between the cameras and the navigation sensors. The latter are essential for the georefencing process. To estimate the two group of parameters, some constraints , are added to the bundle adjustment program (El-Sheimy and Schwarz 1994). The constraint equations make use of the fact that both the cameras and the INS are fixed during the mission. This is achieved by acquiring a number of images at different positions and distances from a test field of ground control points .

These constraints can be written for two van positions (i) and (j) and two cameras (c1) and (c2) as follows:

- $B^i = B^j$
- $R_b^{c1}(i) = R_b^{c1}(j)$, $R_b^{c2}(i) = R_b^{c2}(j)$
- $R_{c1}^{c2}(i) = R_{c1}^{c2}(j)$ (4)

For the stereo-pair (i),

- $B^i = \sqrt{(X^{c1} - X^{c2})^2 + (Y^{c1} - Y^{c2})^2 + (Z^{c1} - Z^{c2})^2}$
- $R_b^c(i) = R_m^c(i) \cdot R_b^m(i)$
- $R_{c1}^{c2}(i) = R_{c1}^{m}(i) \cdot R_m^{c2}(i)$ (5)

Where,

B	is the base vector between each stereo-pair
R_c^m	is the rotation matrix between the camera coordinate frame (c-frame) and the mapping frame (m-frame)(c)
R_c^b	is the rotation matrix between the camera coordinate frame (c-frame) and the INS b-frame
R_{c1}^{c2}	is the rotation matrix between camera (1) and camera (2)

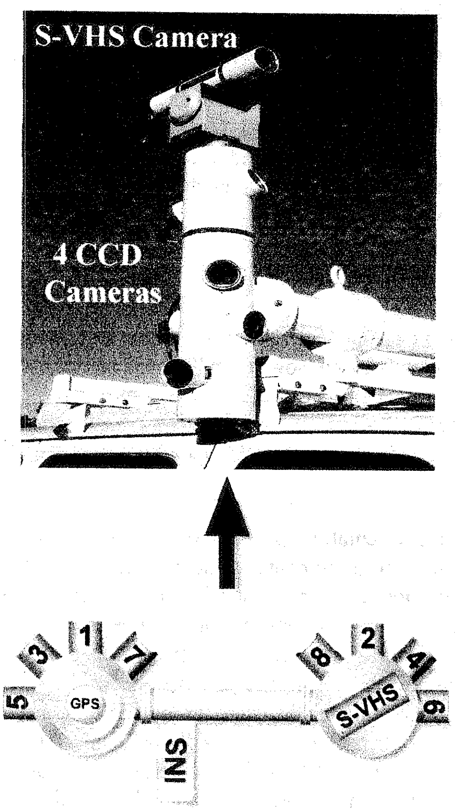

Figure 4. The VISAT System Roof Mount

3.3 System calibration Results

A test field of ninety evenly distributed circular targets was established for calibrating the system. The coordinates of these targets were determined using a network of six points, determined by GPS, as base stations for a total station survey. A baseline of 1.3 km was used to estimate the azimuth of the network using GPS static survey.

System calibration was performed three times at one month intervals. In each calibration test, eight images were grabbed from at least five different van positions. For each calibration test, the adjustment was calculated twice; with and without the relative orientation constraints. Table 5 lists the second calibration results for cameras (1) and (2) without the relative orientation constraints, where ($\Delta\omega$, $\Delta\Phi$, $\Delta\kappa$) are the relative orientation angles between the cameras and the INS system b-frame. Similar results were obtained for calibration (1) and (2). The results indicate that the relative orientation parameters are different and have an accuracy of ± 1 cm for the base vector and ± 5 arminutes for the relative orientation angles. The reason for having large corrections for the relative orientation angles is the fact that the accuracy of aligning the INS is about 3-5 arcminutes. This adds more distortion to the bundle adjustment, which is then reflected in the large corrections to the relative orientation parameters. Table 6 summarizes the final results of the three different calibrations for camera (1) and camera (2) after applying the relative orientation constraints. It is obvious that even with one month difference between the three calibrations, the changes in the base vector and the relative orientation angles are about ± 2 mm. and ± 2 arcminutes respectively. The probable error due to system calibration on a distance of 35 m is about 3 cm (35 m x tan 2 arcminutes = 3 cm) for the relative orientation angles. On the other hands, a constant bias of 2 mm in the base between the cameras, especially the front ones, can introduce an error of 7 cm, mainly along track, for an object 35 m away from the cameras. For more details about the contribution of calibration error to the error budget see El-Sheimy et. al. (995).

4. SYSTEM TESTING

The system was tested in Montreal and Quebec City in September 1995. The test areas included open areas, urban centers with narrow roads, and minor and major highways with a number of overpasses. Some of the Montreal City test results will be presented in this paper. They are in six sectors, about 180 km, surveyed in five days. They were surveyed such that the results in all sectors can be used to evaluate the system repeatability in forward and backward runs on the same day as well as on different days.

4.1 Relative Accuracy

The system's relative accuracy can be estimated by the system's repeatability and the accuracy of measuring distances. In order to test the system repeatability, some well-defined landmarks along the test course were used for comparison. Figure 7 shows results of a comparison of different runs in both forward and backward directions in the same day, taking the forward runs as the reference. Figure 8 shows the relative accuracy of the same landmarks for day-to-day repeatability, by taking the results of one day as a reference.

Table 5. The relative orientation parameters of calibration (2) without applying the relative orientation constraints
(Results of Camera (1) and Camera (2))

Calibration No. 2	B (cm)	Δω (deg.) cam (1)	Δω (deg.) cam (2)	ΔΦ (deg.) cam (1)	ΔΦ (deg.) cam (2)	Δκ (deg.) cam (1)	Δκ (deg.) cam (2)
Van set-up 1	182.71	80.4003	81.3991	0.1379	0.7130	-7.8114	9.2847
Van set-up 2	183.21	80.3921	81.4491	0.1535	0.7021	-7.8303	9.2422
Van set-up 3	182.44	80.4064	81.3714	0.1464	0.6200	-7.8164	8.9672
Van set-up 4	183.98	80.4453	81.3655	0.1849	0.7349	-7.6452	9.2266
Van set-up 5	182.91	80.4495	81.4095	0.1478	0.6639	-7.7682	9.1123

Table 6. The relative orientation parameters of three different calibrations after applying the relative orientation constraints
(Results of Camera (1) and Camera (2))

Calibration	B (cm)	Δω (deg.) cam (1)	Δω (deg.) cam (2)	ΔΦ (deg.) cam (1)	ΔΦ (deg.) cam (2)	Δκ (deg.) cam (1)	Δκ (deg.) cam (2)
No. 1	183.47	80.4691	81.4191	0.1691	0.6313	-7.8631	9.1923
No. 2	183.12	80.4325	81.3991	0.1603	0.6778	-7.8484	9.2010
No. 3	183.33	80.4495	81.3723	0.1642	0.6538	-7.8521	9.1892

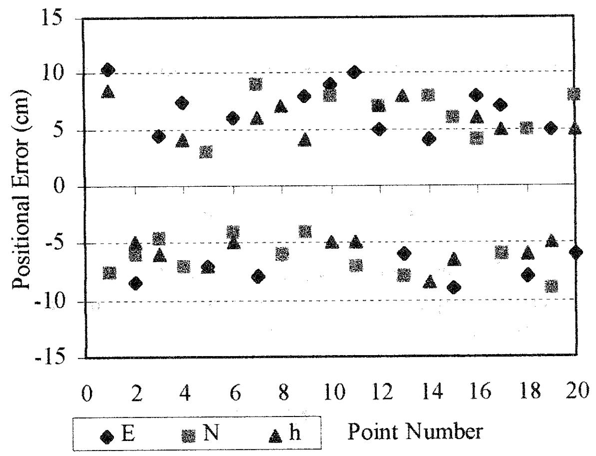

Figure 7. Repeatability of Forward-Backward Runs on the Same Day

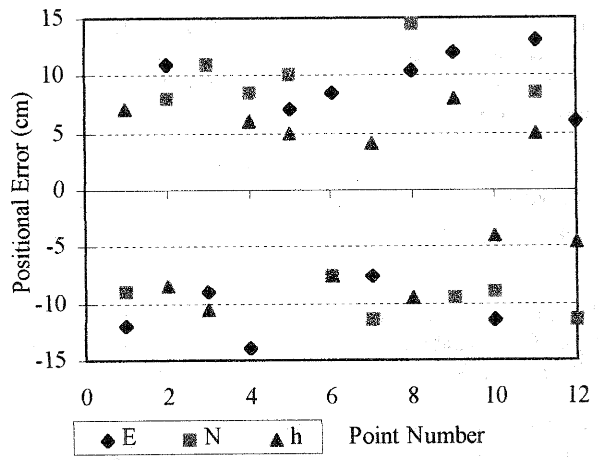

Figure 8. Repeatability of Forward-Backward Runs on Different Days

Table 9 summarizes the system repeatability as obtained from the tests described above. The RMS(x,y) is the composite horizontal error, computed from:

$$RMS(E,N) = \sqrt{(\delta E)^2 + (\delta N)^2}$$

, where δE and δN are the errors in E and N coordinates.

Repeatability	RMS (E, N) (cm)	RMS (h) (cm)
Forward-backward, same day	± 8	± 5
Same Direction, different days	± 6	± 4
Forward-backward, different days	± 10	± 7

Table 9: Statistical summary of the system repeatability

The results in height indicate that the GPS/INS positioning component is working at the centimeter level. Since the height component in GPS is the weakest, it can be expected that the X and Y components are at least of the same accuracy. The increase in errors for the horizontal components must therefore be due to the camera array. The most likely explanation is that the increase in RMS(x,y) as compared to RMS(h) is due to the along track error caused by the errors in determining the base between the cameras. The across-track error should be small and comparable in size to the height error. Another explanation would be a poor synchronization between the GPS/INS component and the camera component. This would result again in an along-track error. Repeatability in the same direction, even on different days, seems to be consistently better than the repeatability between forward and backward runs. But the RMS of 10 cm in horizontal and 7 cm vertical are still reasonable considering the fact that the errors in forward-backward direction should be $\sqrt{2}$ times the same direction errors.

The accuracy of measuring distances with the VISAT system is another way for testing the system's relative accuracy. For this purpose a special test was done by measuring the length of some well defined features along the test course and taking some images for these features in kinematic mode. Figure (10) shows the difference between the VISAT computed distances and the known distances. The figure shows that these errors are distance dependent, as expected, and reach a magnitude of 10-14 cm for objects 30 m away from the van.

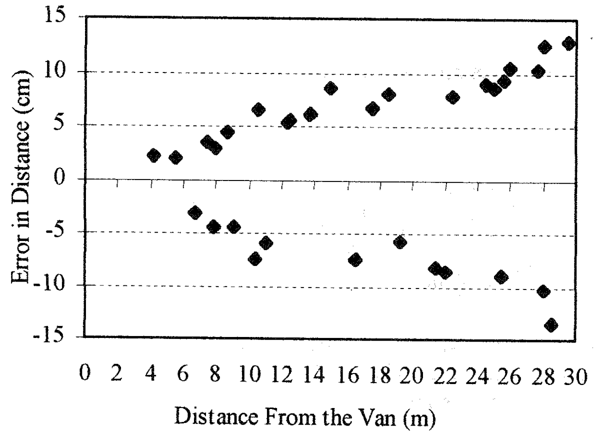

Figure 10 . The Accuracy of Measuring Distances With The VISAT System

4.2 Absolute Accuracy

The main objective of the VISAT system is the determination of the 3-D coordinates for all objects within the video cameras' field of view. The final accuracy of the 3-D coordinates is a function of the complete processing chain which involves GPS positions, INS position/attitude, target localization in the images, and system calibration. Figure 11 shows the errors in the computed 3-D coordinates of 14 control points located along one of the test sectors. The 3-D coordinates are computed from 2-images using the georeferencing formula described in Section 2. The distance between the control points and the cameras was approximately 10-30 m. The figure shows clearly that an RMS of 16 cm in the horizontal coordinates and 7 cm in height are achievable for distances up to 30 m away from the van.

CONCLUSION

The VISAT system presented in this paper is a mobile multi-sensor system which can be operated continuously under many operational conditions. In particular, the complementing features of the integrated INS/GPS positioning and orientation subsystem permit the resolution of cycle slips and outages as well as INS drift control. System calibration results indicate that accuracies of 7 cm (RMS) can be obtained. System testing indicate that highway velocities of 60 km/h can be maintained with adequate data transfer and target positioning in a post-processing mode at a workstation. Run-to-run and day-to-day repeatability achieved in the first system testing is about 8 cm (RMS) in horizontal and about 6 cm (RMS) in height. There is no significant difference between run-to-run and day-to-day results. This indicates that the system positioning component, GPS/INS, works at a consistent level from day to day. In general, the results of system testing show that the absolute accuracy surpasses the development objectives for the system..

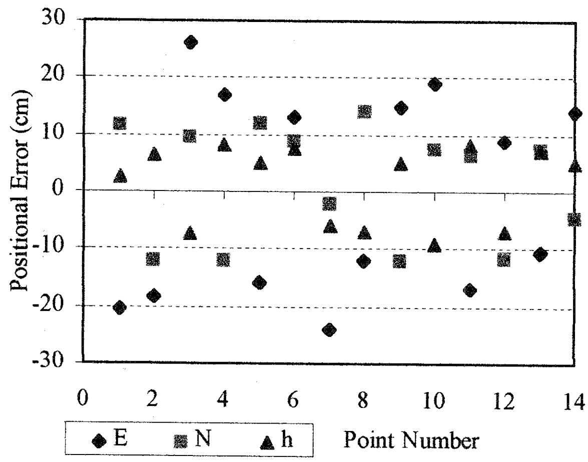

Figure 11. The VISAT System Absolute Accuracy

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