PERFORMACE ANALYSIS OF AN INS/GPS INTEGRATED SYSTEM AUGMENTED WITH EGNOS

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Abstract

Continuous, accurate and reliable position are important requirements for many positioning and navigation applications. In the last years, accurate results had been accomplished using Global Positioning System (GPS) and Inertial Navigation System (INS) in conjunction, taking advantage of the complementary nature of both systems. However, these integrated positioning systems have not still the integrity required for some applications, for example land navigation in the urban canyon where is difficult to have line-of-sight GPS signal visibility, neccesary to bound the inertial sensor errors. A loosely coupled integration approach using a GPS receiver and a low-cost INS strapdown system to land navigation is presented. This combination is augmented by the Signal in Space through Internet (SISNET) technology which provides access to the EGNOS System Test Bed (ESTB) to enhance the integrity, reliability and availability of the system in problematic environments.

1 Introduction

Land navigation applications require accuracy, integrity and continuity of service. The most navigation systems had exploited the advantages of the GPS and INS systems taking the best features of both: the high rate and continuous data of the INS and the long-term accuracy of GPS are combined to compensate the inertial sensor errors and the GPS signal gaps caused by signal blockage [1], [2].

The accuracy of the GPS solution will define the absolute accuracy of the integrated system, but the main disadvantage is that GPS signal propagates in straight line, and in many situations there are outages or poor satellite geometry and we can't get a suitable positioning. With the objective to increase the performance of the satellite navigation systems, research have been done for years, augmenting the satellite geometry with additional satellite constellations like GLONASS or EGNOS, or improving the quality of the measurements (differential navigation) or both. However the new satellite geometry is likely to still be too poor for vehicle navigation in urban areas, first because GLONASS system actually has an unstable service and EGNOS satellites have also the disadvantage of the shading effect. In this context, the European Space Agency (ESA) has developed the SISNET technology that broadcast the EGNOS information by Internet, and with this is only neccesary to have an internet access to benefit from EGNOS signal. Therefore, the accuracy of the combined INS/GPS system will be improved, increasing the availability, accuracy and integrity of the navigation system.

This work has the premise to implement an algorithm using a simple INS/GPS architecture aided with EGNOS signal trying to get a system more accurate and available overall in the urban areas.

*Work supported by the Mexican and Spanish Governments under grants CONACYT-132227 and TIC2001-2356-C02-01

2 General Model

Several architectures are possible for an integrated INS/GPS system. The first classification relates to which information is shared between the GPS and INS components: tight versus loose integration. In the first approach, a centralized filtering strategy is utilized to process GPS and INS data. The raw GPS measurements are directly used as the update measurements in the single filter for the INS instrument calibration and navigation. Whereas in the loosely coupled integration mode, a descentralized filtering strategy is used, where the GPS raw measurements are preanalysed via a local Kalman filter to produce the navigation solution which is then used to update the master filter and calibrate the INS errors and generate position, velocity and attitude information to users. It has been recognized the higher performance of the tightly-coupled because it is more accurate, robust and jamming-resistant, but tend to be complex, requiring precise, high-rate exchange data and exacting synchronization in that exchange [3]. These difficulties have provoked a widespread use of loosely coupled technique for its modularity and simplicity. For these reasons, and because it is necessary to analyse and correct the GPS pseudoranges with the EGNOS information, we choice the loosely coupled integration technique for this work.

In the configuration choiced, the INS will be the primary navigation system which calculates the navigation state at a high rate, and the GPS aiding information will be used when it is available and satisfies the conditions designed to verify proper operation. When GPS information is not available or judged inaccurate, the INS will continue its normal operation. As is normal, the technique implemented is the feedback configuration, to correct the INS errors with the Kalman filter error estimates after each GPS update.

2.1 Inertial Model

The navigation algorithm is designed in the geographic frame n, with axes North, East, Down (NED). The derivations and the notation are based on [4], thus the inertial measurement unit (IMU) outputs are processed by the INS according to

$$\begin{bmatrix} \dot{\hat{n}} \\ \dot{\hat{e}} \\ \dot{\hat{h}} \\ \dot{\hat{v}}_N \\ \dot{\hat{v}}_E \\ \dot{\hat{v}}_D \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \\ 0 & -2\omega_{ie} sin(\hat{\lambda}) & 0 \\ 2\omega_{ie} sin(\hat{\lambda}) & 0 & 2\omega_{ie} cos(\hat{\lambda}) \\ 0 & -2\omega_{ie} cos(\hat{\lambda}) & 0 \end{bmatrix} \begin{bmatrix} \hat{v}_N \\ \hat{v}_E \\ \hat{v}_D \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \hat{f}_N \\ \hat{f}_E \\ \hat{f}_D \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \hat{g} \end{bmatrix} \tag{1}$$

where λ is the geodetic latitude, ω_{ie} is the Earth rotation rate, (f_N, f_E, f_D) and (v_N, v_E, v_D) represent the specific force and the velocity in navigation frame, and g is the gravitacional acceleration at the Earth surface. Along the document, the quantities with hat $(\hat{f})$ and tilde $(\tilde{f})$, represent computed and measured data respectively.

For obtain the specific force in navigation frame and use it in the above equation, we have

$$\begin{bmatrix} \hat{f}_N \\ \hat{f}_E \\ \hat{f}_D \end{bmatrix} = \hat{C}_p^n \left(\begin{bmatrix} \tilde{f}_u \\ \tilde{f}_v \\ \tilde{f}_w \end{bmatrix} - \begin{bmatrix} \hat{b}_u \\ \hat{b}_v \\ \hat{b}_w \end{bmatrix} \right) \tag{2}$$

were $(\tilde{f}_u, \tilde{f}_v, \tilde{f}_w)$ are the platform specific forces measured by the acceleromters and $(\hat{b}_u, \hat{b}_v, \hat{b}_w)$ represent estimated accelerometers error compensation terms (e.g. bias estimates). $\hat{C}_p^n$ is the platform to navigation frame transformation matrix which is calculated based on the Euler angles. These angles are obtained by solving

$$\begin{bmatrix} \dot{\hat{\phi}} \\ \dot{\hat{\theta}} \\ \dot{\hat{\psi}} \end{bmatrix} = \begin{bmatrix} 1 & sin(\hat{\phi})tan(\hat{\theta}) & cos(\hat{\phi})tan(\hat{\theta}) \\ 0 & cos(\hat{\phi}) & -sin(\hat{\phi}) \\ 0 & \frac{sin(\hat{\phi})}{cos(\hat{\theta})} & \frac{cos(\hat{\phi})}{cos(\hat{\theta})} \end{bmatrix} \begin{bmatrix} \hat{p} \\ \hat{q} \\ \hat{r} \end{bmatrix} \tag{3}$$

where the inputs are the gyro attitude rate measurements (p, q, r). These are processed as follows

$$\begin{bmatrix} \hat{p} \\ \hat{q} \\ \hat{r} \end{bmatrix} = \left(\begin{bmatrix} \tilde{p} \\ \tilde{q} \\ \tilde{r} \end{bmatrix} - \begin{bmatrix} \hat{b}_p \\ \hat{b}_q \\ \hat{b}_r \end{bmatrix} \right) - \hat{C}_n^p \left(\omega_{ie} \begin{bmatrix} cos(\hat{\lambda}) \\ 0 \\ -sin(\hat{\lambda}) \end{bmatrix} + \frac{1}{R+\hat{h}} \begin{bmatrix} \hat{v}_E \\ -\hat{v}_N \\ -\hat{v}_E tan(\hat{\lambda}) \end{bmatrix} \right) \tag{4}$$

again, $(\hat{b}_p, \hat{b}_q, \hat{b}_r)$ are the gyro bias in platform frame, and R is the Earth's radius.

The dynamic equations for the linearized INS error are

$$\delta\dot{x}(t) = F(t)\delta x(t) + \epsilon(t) + \omega(t) \tag{5}$$

considering $\delta x(t) = [\delta p, \delta v, \delta\rho]^T = [\delta n, \delta e, \delta h, \delta v_N, \delta v_E, \delta v_D, \delta\epsilon_N, \delta\epsilon_E, \delta\epsilon_D]^T$ the state vector and $\epsilon(t)$ represents the instrument and gravity modeling errors, we have

$$F = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ \frac{-2\omega_N v_E}{R} & 0 & 0 & 0 & 2\omega_D & 0 & 0 & f_D & -f_E \\ \frac{2}{R}(v_N\omega_N + v_D\omega_D) & 0 & 0 & -2\omega_D & 0 & 2\omega_N & -f_D & 0 & f_N \\ \frac{-2v_E\omega_D}{R} & 0 & \frac{-2\mu}{R^3} & 0 & -2\omega_N & 0 & f_E & -f_N & 0 \\ \frac{\omega_D}{R} & 0 & 0 & 0 & 0 & 0 & 0 & \omega_D & -\omega_E \\ 0 & 0 & 0 & 0 & 0 & 0 & -\omega_D & 0 & \omega_N \\ \frac{-\omega_N}{R} & 0 & 0 & 0 & 0 & 0 & \omega_E & -\omega_N & 0 \end{bmatrix} \tag{6}$$

where $\omega_N = \omega_e cos(\lambda)$ and $\omega_D = -\omega_e sin(\lambda)$ are the north and vertical components of Earth rotation rate in the navigation frame. The equation (5) can be written as

$$\begin{bmatrix} \delta\dot{p} \\ \delta\dot{v} \\ \delta\dot{\rho} \end{bmatrix} = \begin{bmatrix} F_{pp} & F_{pv} & F_{p\rho} \\ F_{vp} & F_{vv} & F_{v\rho} \\ F_{\rho p} & F_{\rho v} & F_{\rho\rho} \end{bmatrix} \begin{bmatrix} \delta p \\ \delta v \\ \delta\rho \end{bmatrix} + \begin{bmatrix} e_p \\ e_v \\ e_\rho \end{bmatrix} + \begin{bmatrix} \omega_p \\ \omega_v \\ \omega_\rho \end{bmatrix} \tag{7}$$

Equation (7) shows that the velocity error is driven by accelerometer and gravitational model errors denoted by e_v, so, x_a will denote the state to be augmented to account for these errors. Equation (7) shows also that the attitude error is driven by gyro errors denoted by e_ρ. Let x_g denote the state to be augmented to account for these gyro errors. Linear error models can be defined with matrices F_{vx_a} and $F_{\rho x_g}$ such that

$$e_v = F_{vx_a} x_a + \nu_a \tag{8}$$

$$e_\rho = F_{\rho x_g} x_g + \nu_g \tag{9}$$

With these definitions, equation (7) can be expanded as

$$\begin{bmatrix} \delta\dot{p} \\ \delta\dot{v} \\ \delta\dot{\rho} \end{bmatrix} = \begin{bmatrix} F_{pp} & F_{pv} & F_{p\rho} \\ F_{vp} & F_{vv} & F_{v\rho} \\ F_{\rho p} & F_{\rho v} & F_{\rho\rho} \end{bmatrix} \begin{bmatrix} \delta p \\ \delta v \\ \delta\rho \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ F_{vx_a} & 0 \\ 0 & F_{\rho x_g} \end{bmatrix} \begin{bmatrix} x_a \\ x_g \end{bmatrix} + \begin{bmatrix} \omega_p \\ \omega_v + \nu_a \\ \omega_\rho + \nu_g \end{bmatrix} \tag{10}$$

$$
\begin{bmatrix} \delta\dot{p} \\ \delta\dot{v} \\ \delta\dot{\rho} \\ \dot{x}_a \\ \dot{x}_g \end{bmatrix} = \begin{bmatrix} F_{pp} & F_{pv} & F_{p\rho} & 0 & 0 \\ F_{vp} & F_{vv} & F_{v\rho} & F_{vx_a} & 0 \\ F_{\rho p} & F_{\rho v} & F_{\rho\rho} & 0 & F_{\rho x_g} \\ 0 & 0 & 0 & F_{x_a x_a} & 0 \\ 0 & 0 & 0 & 0 & F_{x_g x_g} \end{bmatrix} \begin{bmatrix} \delta p \\ \delta v \\ \delta\rho \\ x_a \\ x_g \end{bmatrix} + \begin{bmatrix} \omega_p \\ \omega_v + \nu_a \\ \omega_\rho + \nu_g \\ \omega_a \\ \omega_g \end{bmatrix} \tag{11}
$$

For the moment we are only estimating the accelerometer and gyro biases, so modeling these biases as random walk processes, $F_{x_a x_a}$ and $F_{x_g x_g}$ are identically zero, and by the chain rule

$$
F_{vx_a} = \frac{\partial v}{\partial f^p}\frac{\partial f^p}{\partial x_a} = C_p^n \frac{\partial f^p}{\partial x_a} \tag{12}
$$

$$
F_{\rho xg} = \frac{\partial \rho}{\partial \omega_{ip}^p}\frac{\partial \omega_{ip}^p}{\partial x_g} = C_p^n \frac{\partial \omega_{ip}^p}{\partial x_g} \tag{13}
$$

2.2 Signal in Space through Internet (SISNET)

Another augmentation technique is to improve the quality of the measurements, where the most used procedure is the differential GPS that permits to get better accuracy of the positioning by canceling the common mode errors that affect to GPS receivers in a geographic region (atmospheric delays, satellite clock bias and ephemeris errors). The basic idea is that the availability of four pseudoranges allows the base station receiver estimates its position and the offset required to synchronize its clock with GPS time. The discrepancy between the base station receiver's computed position and its known position is due to errors and biases on each pseudorange. The base station receiver sums these errors and biases for each pseudorange, and then broadcast these corrections to the rover receivers, which apply the corrections to their own measurements.

Taking the pseudorange equation

$$
\begin{aligned}
\rho^i &= \sqrt{(X^{(i)} - x)^2 + (Y^{(i)} - y)^2 + (Z^{(i)} - z)^2} + c\Delta t_r \\
&\quad + MP^{(i)} + \eta^{(i)} + c\Delta t_{sv}^{(i)} + c\Delta t_a^{(i)} + E^{(i)}
\end{aligned} \tag{14}
$$

where $(X^{(i)}, Y^{(i)}, Z^{(i)})$ are the ECEF coordinates of the ith satellite; (x, y, z) are the user's ECEF coordinates; Δt_r is the receiver clock bias; $MP^{(i)}$ is the multipath error; $\eta^{(i)}$ is the receiver tracking error noise; $\Delta t_{sv}^{(i)}$ is the satellite clock bias; $\Delta t_a^{(i)}$ is the atmospheric delay (ionospheric and tropospheric), $E^{(i)}$ represents error in the broadcast ephemeris data, and c is the speed of light. The common errors are

$$
\Delta_{DGPS}(t) = -c[\Delta t_{sv}(t) + \Delta t_a(t)] + E(t) \tag{15}
$$

broadcasting this correction, the GPS accuracy could be substantially improved. But this procedure is valid for baseline less than 50 Km.

With the objective to improve the accuracy, integrity and availability of the basic GPS and GLONASS signals in wide areas, developments of Satellite–Based Augmentation System (SBAS) are done, where the accuracy is enhanced through the use of wide area corrections for satellite orbits and atmospheric errors. Integrity is enhanced by the SBAS network quickly detecting satellite signal errors and sending alerts to receivers to not use the failed satellite. Availability is improved by providing an additional ranging signal to each SBAS geostationary satellite.

EGNOS is a SBAS system, but its service may be not available in areas where exist low visibility of GEO satellites (urban canyon). For this reason, ESA has developed a technology to provide access to the EGNOS System Test Bed (ESTB) messages through Internet, and be able to compute the corrections using the wide area coverage data contained in the GEO message plus a spatial interpolation at the user location. This project is the Signal in Space through the Internet (SISNET).

In a general outline, the Data Server to Data Client (DS2DC) software implements the DS2DC protocol (based on TCP/IP) to connect to the Data Server (DS) and obtain the EGNOS messages in real time (one message per second) [5]. We process these messages and obtain the pseudorange corrections and the integrity information, which are used to correct the GPS receiver's pseudoranges obtaining an improve GPS information, but it still have a small error. On the other hand, the INS output is processed to provide an estimate of the GPS measurement. The differences between the estimates GPS and the EGNOS corrected GPS measurements are the input to the Kalman filter which implements an error state estimator based on the linearized error dynamic equations. This is summarized in figure 1. At the moment, our DS2DC software (figure 2) saves the data in files that are used in post-processing together with the GPS information, but our principal goal is to work in real-time.

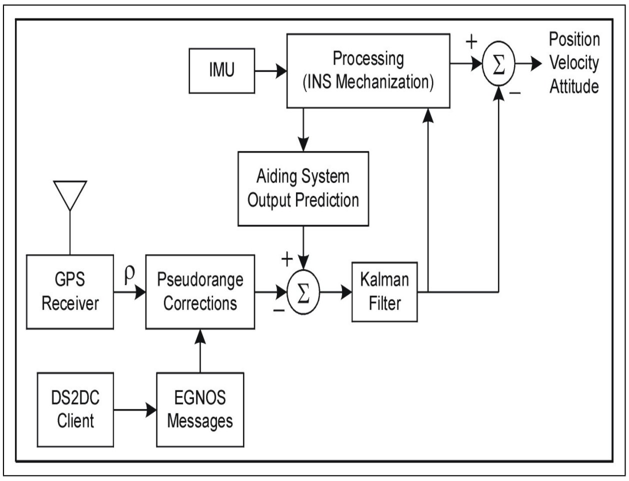

Figure 1: *General Integrated Model*

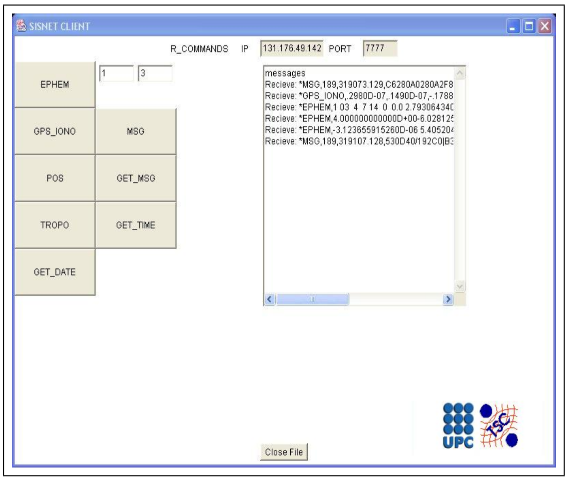

Figure 2: *DS2DC Interface*

3 Experiment Description

To verify the performance of the algorithm developed, we realize some experiments along the Ronda de Dalt avenue and in a mountainous environment. We choice this environments because there are many unevenness, tunnels and we can analyse the behaviour of the system in areas with high density of trees. In figure 3, we can see part of the distance travelled.

The system is composed of a laptop to record and analyze the data, and a Novatel OEM4 GPS receiver and a MicroStrain 3DM-G were used (figure 4). This INS uses Micro-Electro-Mechanical Systems (MEMS) technology and it includes three orthogonal accelerometers, three angular rate gyros, and three orthogonal magnetometers. The sensors' characteristics are shown in table 1. The measurement cycle by the GPS receiver is 1 Hz because we have the EGNOS messages at this rate too. The rate of the INS in this case es 76 Hz, because we obtain the gyro-stabilized instantaneous vectors. The system allows us to estimate the vehicle position, attitude and the sensor errors (bias).

Device	Range	Measurement Precision	Rate
Novatel OEM4		6 cm (RMS), 0.03 m/s (RMS)	1-20 Hz
Gyroscope	+/- 300 deg/sec FS	0.1 deg	
Accelerometer	+/- 2 G's FS	Not available	50-150 Hz
Magnetometer	+/- 1 Gauss FS	Not available	

Table 1: *Sensors' characteristics*

Figure 3: *Distance travelled*

Figure 4: *INS and GPS antenna*

4 Results

In this section we present some results based on the post-processing data. In figure 5 we can see two GPS signal gaps. The first one, enclosed in a circle, is a simulated loss of GPS signal, with the intention to calibrate the inertial sensors and to verify the right acquisition of the EGNOS information during the experiment. We choice this area of the route because is near to the department and we have done many adquisition in this zone and we have the necessary elements to know the integrity of the data captured by our DS2DC software. The second gap is provoked by a loss of the necessary signals for positioning (we detect two or three satellites). The same problem is found in other zone of the route (figure 6).

As we can see in figures 7 and 8, during the loss of satellite signals, the inertial navigation accuracy is degraded considerably (labeled lines with 'A' in the figures). In the post-processing procedure, we take advantage of availability information of the EGNOS data to benefit from the additional ranging signal and have the satellite signal necessary to obtain positioning. Furthermore, we use also the wide area correction information of EGNOS to improve the pseudorange data and get a better position. That is fundamental for the Kalman filter to compute the sensor errors and improve the final position. With the Kalman filter output and the continuous INS data, we get an enhanced positioning, as we can see in figures 7 and 8 (labeled lines with 'B'). We observed a better performance of the algorithm in figure 7 than figure 8, and we suppose that is result of detect only two GPS satellites in the second region. In spite of that inconvenient, the general results observed are suitable.

5 Conclusions

In this study has been developed and tested a system which estimates the position, velocity and attitude of a land vehicle in post-processing using a loosely coupled technique with a Novatel OEM4 GPS receiver and a low cost INS. We concentrate in minimize the effects of the loss of line-of-sight of the GPS signal in urban areas using the SISNET technology which provides access to the EGNOS signal through net. The results show that integrated system can contribute to high–precision positioning in terms of performance and reliability enhancement in problematic environments.

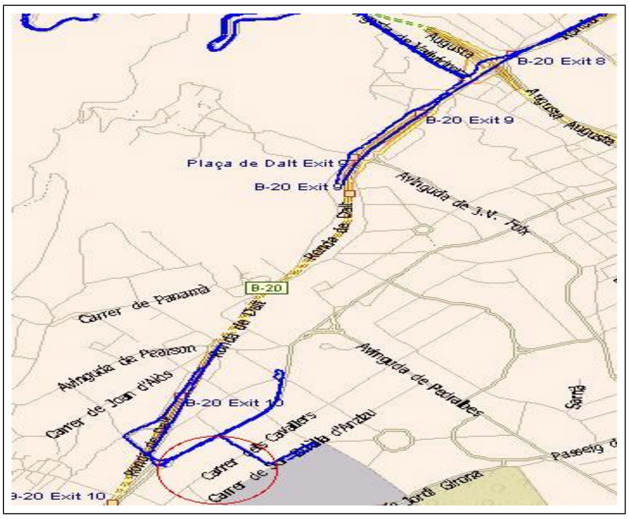

Figure 5: *GPS signal gaps*

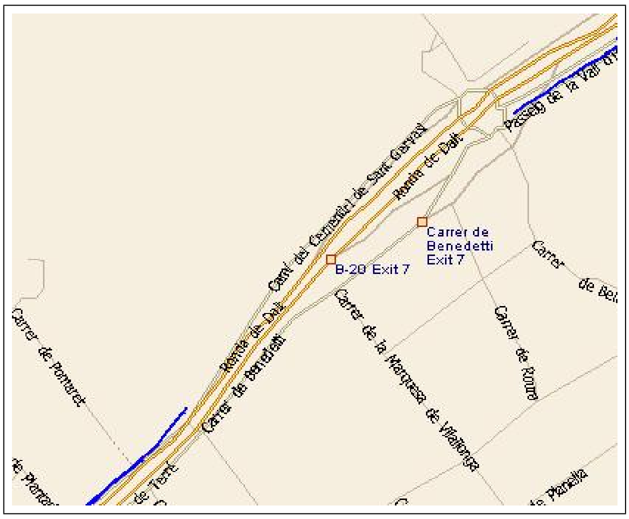

Figure 6: *GPS signal gap*

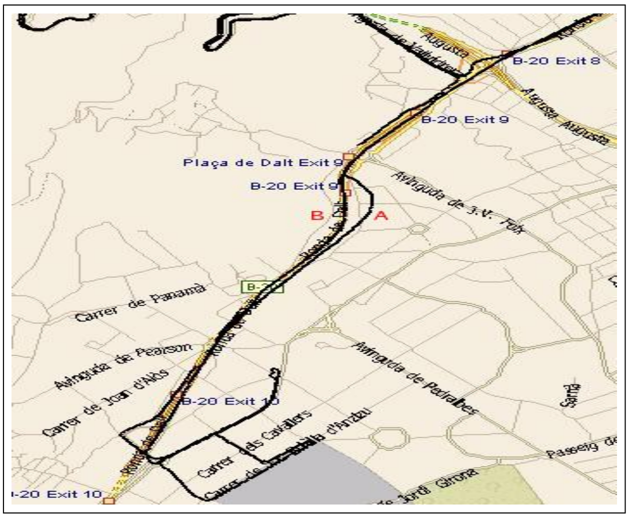

Figure 7: *Comparison between INS and integrated system positioning*

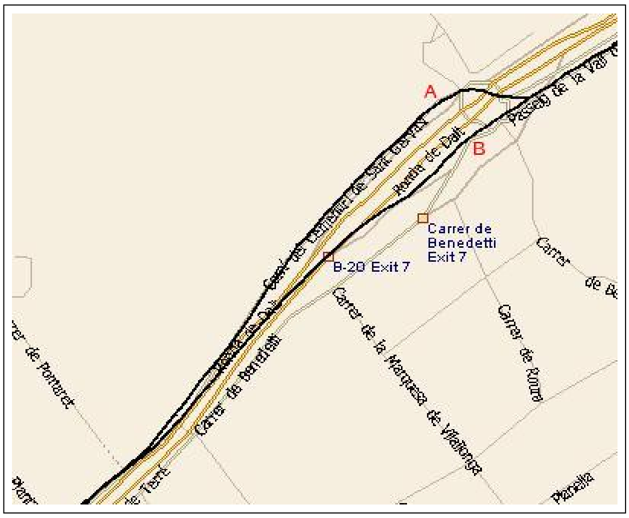

Figure 8: *Comparison between INS and integrated system positioning*

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