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GPS and Inertial Systems for High Precision Positioning on Motorways

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The accurate location of a vehicle in the road is one of the most important challenges in the automotive field. The need for accurate positioning affects several in-vehicle systems like navigators, lane departure warning systems, collision warning and other related sectors such as digital cartography suppliers. The aim of this paper is to evaluate high precision positioning systems that are able to supply an on-the-centimetre accuracy source to develop on-the-lane positioning systems and to be used in future applications as an information source for autonomous vehicles that circulate at high speeds on public roads. In this paper we have performed some on-road experiments, testing several GPS-based systems: Autonomous GPS; RTK Differential GPS with a proprietary GPS base station; RTK Differential GPS connected to the public GPS base station network of the National Geographic Institute of Spain via vehicle-to-infrastructure GPRS communications; and GPS combination with inertial measurement systems (INS) for position accuracy maintenance in degraded satellite signal reception areas. In these tests we show the validity and the comparison of these positioning systems, allowing us to navigate, in some cases, on public roads at speeds near 120 km/h and up to 100 km from the start position without any significant accuracy reduction.

KEY WORDS

1. DGPS. 2. Inertial Systems. 3. RTCM DGPS Correction Message.

1. INTRODUCTION. The fully autonomous vehicle with the capacity to navigate a route automatically without human intervention has not been possible until some kind of Global Navigation Satellite System (GNSS) such as GPS has been installed in order to position the vehicle with digital cartography that defines the target route to be completed. In recent years, some research projects and publications referring to autonomous vehicles have obtained proven results.

The first autonomous vehicle prototypes only had the capacity to keep to the circulation lane of a private circuit [1] or to keep to the circulation lane, automatically managing the steering wheel, when travelling along a public highway [2]. In the same way, the first autonomous vehicle prototypes of Carnegie Mellon University's Navigation Laboratory (NavLab) were able to manage the steering and the speed of the cars using neural network algorithms but without the capacity of a high level plan layer that indicated a complete route to be achieved [3].

Turning off the Selective Availability (SA) in the GPS signal meant an improvement in GPS positioning accuracy, reducing the error from 100 m to 15–10 m when working in autonomous mode [4]. Until SA was turned off GPS devices were not massively used in the autonomous vehicle field as reference sensors.

Differential correction techniques allow the improvement in GPS accuracy from 15–10 metres of error to an error of 1 cm. Differential correction consists of adding a second GPS unit in the position calculus. This second GPS, named base station, is geo-referenced and installed in a static infrastructure. The mechanism used to improve the precision is simple but effective. The base station calculates its position using the GPS satellite constellation, taking into account the error. Once its position has been calculated, the base station compares it with the geo-referenced one, obtaining the offset of the positioning error. This offset is sent via state-of-the-art wireless communications to all the connected autonomous GPS devices that work in an operative range (around 30 km), so that their position may be corrected using the offset received from the base station. If this differential correction is obtained using only GPS pseudo-range code, it is named Differential GPS (DGPS) and can achieve accuracies of around 1 to 5 metres. If it is obtained using the GPS carrier phase information, it is named Real Time Kinematics (RTK) DGPS and its accuracy is around 1 to 10 cm. This is the method used, for example in the AUTOPIA autonomous vehicle program, where a set of cars has been automated using RTKDGPS as the main sensorial input in order to perform the autonomous routes [5]. However, this system for positioning has a clear limitation. These cars can only travel a short distance around the base station because of the 30 km accuracy limitation and the shorter distance of the WiFi communications used for transmitting the differential correction.

A solution to overcome this distance limitation is the use of differential correction transmitted via the OMNISTAR satellite constellation. This system transmits the information using geostationary satellites and is received by compatible receivers with a previous subscription. This kind of correction allows GPS receivers to obtain accuracies between 4 m and 10 cm. These types of systems are used in new generation autonomous vehicles like DARPA Grand Challenge's KAT-5 [6]. Other solutions for via-satellite differential correction are the SBAS (Satellite Based Augmentation Systems) such as the one used by the SciAutonics Team [7]. Unfortunately these satellite based systems have an important drawback: when they are used in urban environments, the tunnel effect caused by buildings can cause an important reduction in precision.

In order to solve the limitations of the two previous systems, a new technology solution has recently appeared. The geographical institutions of Europe presently offer a solution of differential correction via the Internet that can be accessed via Vehicle-to-Infrastructure communications through GPRS cellular telephony. The main novelty of this system is that, in order to generate the optimum differential correction, it creates a virtual reference station, always near the mobile GPS. Then, the correction information always has the best features to make an accurate position. This virtual station is created through a cluster of GPS reference station European networks, which means this method works within an accuracy of centimetres in any location in Europe [8].

However, there are situations where the reception of a GPS satellite signal is impossible and consequently, the GPS receivers do not run. These situations are tunnels, crossing under bridges, circulating under a tree canopy or in a built-up area. In this case, it is necessary to add new dead reckoning sensors that maintain the positioning with a high accuracy during the time the GPS receiver is out of service [9]. This way, Nebot et al. [10] describe the models and sensors to de-correlate GPS errors in navigation tasks. Studies of combinations of these systems for intelligent vehicle applications currently exist, but are focused on high signal integrity, low precision and low cost [11].

Nowadays there is a big demand for high precision and high reliability positioning systems to use as reference sensors in vehicle safety operations. Several European Projects like NextMAP or PREVENT-MAPS&ADAS are focused on analyzing the new generation of GPS related systems, accurate digital maps and the applications for vehicular safety systems and Advanced Driver Assistance Systems (ADAS) [12] [13]. Because of the importance of this area of research, the European Union established a Digital Maps Working Group inside the eSafety Initiative in order to act as a framework to address all the European and worldwide initiatives related to the presence of digital maps and their future applications [14]. Among these safety systems there are some results in the application of GPS-based technologies to develop Collision Driving Systems [15] [16].

In this paper we present the comparison of results of different RTK DGPSs that use the differential correction provided by the virtual base station service of the National Geographical Institute of Spain, RTK DGPS with proprietary base station, and GPS autonomous positioning. In order to obtain the highest level of quality, we have improved the positioning accuracy with a gyroscopic platform and a non-contact speed sensor, used to maintain the highest positioning accuracy in degraded satellite signal reception situations. This maintains the positioning accuracy in situations of satellite signal loss such as, for example, in tunnels or the tunnel effect of buildings in cities. With these systems, some real road experiments have been performed on highways around Madrid, running more than 500 km of tests. This newly developed technology has a wide range of future applications, like autonomous driving on public roads, safe intersection management systems, adaptive cruise control, lane departure warning systems or high precision digital cartography development.

2. TESTBED VEHICLES ONBOARD EQUIPMENT.

In order to carry out the comparative analysis between different types of GPS receivers, a passenger car with an onboard defined reference instrumentation configuration was used. The configuration was maintained for every test and comprised:

- Inertial measurement system:
    - Correvit L-CE- non-contact speed sensor to measure speed and the distance travelled
    - RMS FES 33 gyroscopic platform to provide measurement of the angles drawn about three axes

The X axis was aligned along the longitudinal axis of the vehicle, the Z is the vertical and Y forms a right-handed system with the other two. Thus, the angle around Z and the speed signal will allow the path to be obtained, while angles around X and Y will give the banking and the slope respectively, information that is not available from other measuring equipment.

- Autonomous GPS positioning system:
  - Astech G12 GPS autonomous receiver with an update frequency of 10 Hz.

Furthermore, the following DGPS devices were used in order to compare their behaviour with the reference configuration:

- Equipments with JAVAD MAXOR virtual reference station:
  - RTK-DGPS1: RTK DGPS of an update frequency of 5 Hz with the differential correction obtained from the National Geographic Institute of Spain, using GPRS to connect the Server via Internet
  - RTK-DGPS2: RTK DGPS with the same characteristics, but with an update frequency of 1 Hz.
  - RTK-DGPS3: RTK DGPS with an update frequency of 10 Hz and the possibility of using GPS and GLONASS

The Virtual GPS base station was supplied by the National Geographic Institute of Spain through the European EUREF-IP Service. This service is based on a number of permanent GPS stations that are able to create a virtual base in the position where each connected client is placed. The system uses the RTCM Recommended Standards for Networked Transport of RTCM via Internet Protocol (NTRIP) to transmit through the Internet the necessary differential corrections that the mobile GPS connected to the client can work in RTK DGPS mode.

- Equipment with our own proprietary reference station:
  - DGPS base station with an RTCM update frequency of 10 Hz and the possibility of using GPS and GLONASS

The GPS receivers were placed near to each other in order to reduce the effect of the gap in final comparison results. This distance was taken into account in data post-processing. GPS positioning and inertial measurement system analogue data were recorded by a laptop and a DAQCard-6062E acquisition card. Figure 1 shows where the sensors were placed on the vehicle.

3. EXPERIMENTS.

We performed two types of tests in order to test the performance of the positioning equipment when used in real world situations. First, we performed a set of repetitive tests around the South Campus of the Polytechnic University of Madrid in order to check the repetitiveness of the positioning system and to compare it with an extensively tested driving area used for other research projects [17] [18]. In this paper we present the second set of experiments that involves travel along some public highways around the region of Madrid as well as on some single carriageway roads. This allowed us to test the positioning systems in real traffic situations that should be useful in developing autonomous vehicle systems as well as a new generation of in-vehicle safety systems.

The quality of positioning was measured in these tests, as a factor of the signal GPS quality following the standard GPS NMEA convention: type 4 or fixed for

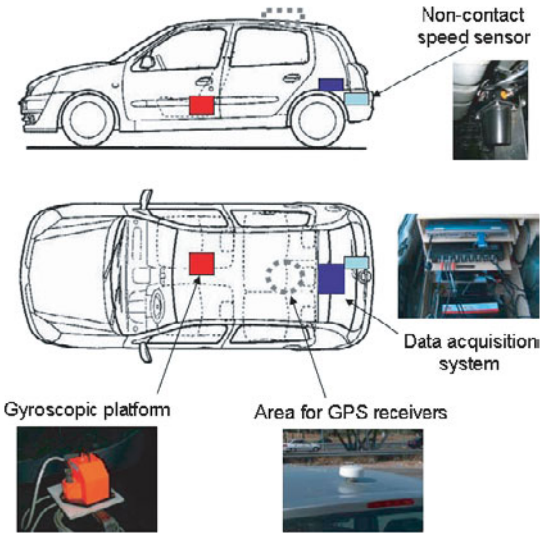

Figure 1. Sensor placement on the vehicle.

centimetric accuracy, type 5 or floating for sub-metric accuracy and type 1 or autonomous (the device is positioning without differential correction) for decimetric accuracy (error of 10–15 m as maximum). A factor to test the correct performance of the systems is the amount of time the receivers work in fixed or float positioning mode, the amount of time they work in autonomous mode and the time they are out of service during the journey.

3.1. *RTK-DGPS1* (*M607 Motorway route*). The first highway journey was along the M-607 motorway. The main feature of this road is that it routes through open field, without buildings, mountains, tree canopies or any other element that could obstruct the GPS satellite signal reception. The maximum circulation speed was 100 km/h and average speed was 94·5 km/h. The distance travelled was 30 km on the outward journey and 30 km on the return. After the motorway the route followed a single carriageway road (M-104), from Colmenar Viejo to San Agustín de Guadalix. This road is located in a valley between mountains, with several zones of canopies. This section of the route has a length of 13·5 km, the maximum speed was 90 km/h with an average speed of 79·5 km/h. In this case, the RTK DGPS device supplied information at 5 Hz and its differential correction was obtained from a virtual base using the data from the National Geographic Institute of Spain through I2V communications using GPRS to connect with the server via the Internet.

In Figure 2, the route followed by the car during the experiment is shown, repesenting on the X axis the GPS UTM West coordinates of the route and on the Y axis, the GPS UTM North coordinates. The graph represents in grey the route data of the autonomous GPS and in black the data supplied by the RTK DGPS. The north/south part of the route follows the M607 and the east/west section is the single carriageway road. The evolution of accuracy on both roads is the same; this demonstrates that the performance of the RTK GPS positioning is the same regardless of the kind of road, to the contrary of other systems whose performance depends

Table 1. Error comparison between RTK DGOS and Autonomous GPS during the M607 route.

	DGPS Precision	Average Difference (m)	Standard Deviation (m)	Samples	%
Outward	4	1·32	0·36	5036	29·58
	5	1·41	0·88	3232	18·98
	1	1·51	1·21	6484	38·09
	No signal	—	—	2272	13·35
Return	4	1·45	0·32	10869	53·64
	5	2·36	1·27	3292	16·24
	1	6·34	5·2	3037	14·98
	No signal	—	—	3067	15·14

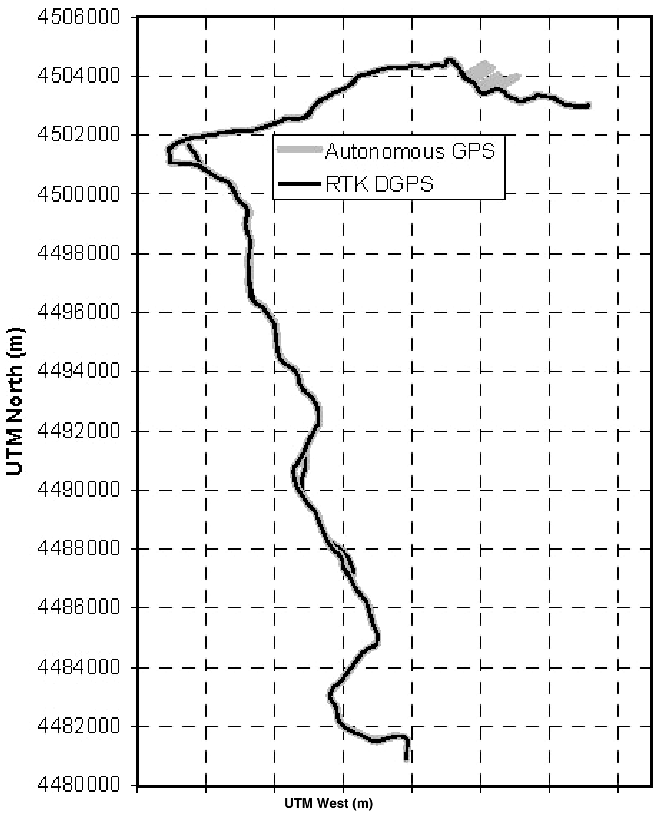

Figure 2. Graphical representation of the route along the M607 motorway joined to the M104 single carriageway road.

on the infrastructure equipment, for example in the California PATH Program [19] which uses beacons placed on the road for vehicle location.

After completing the route, we compared the results of both GPS devices, obtaining the results that are shown in Table 1. From these results we can see that on the outward journey, the average error is very similar whatever the DGPS precision.

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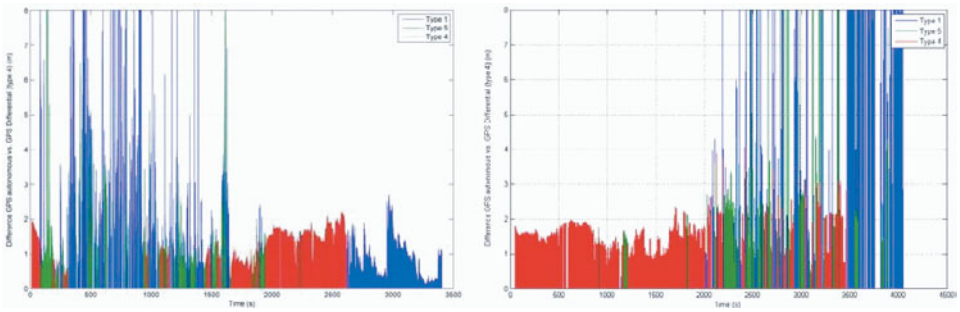

Figure 3. Comparison of the evolution of GPS precision during the two routes along the M607.

This was caused because the satellite conditions were very stable and in optimum conditions an autonomous GPS can generate positions with a near-to-the-metre accuracy. However, as is shown on the return route when the satellite configuration was worse, the difference of the two GPS increases dramatically up to 6 metres in type 1. In this case, we cannot say which part of this error is caused by the RTK or the autonomous device but it is clear that this error is not valid for lane positioning.

Figure 3, shows the results of the GPS precision evolution during the two journeys. As we can see, at the beginning of the outward journey and the end of the return routes, there is an important GPS reduction in precision. This loss of precision is caused because on this part of the motorway near Madrid, where there are a lot of buildings, tunnels and bridges, the GPS satellite signal is not correctly received. This is a clear example of the need to combine the GPS with a secondary system that allows the maintainance of position even when the GPS does not work properly or it totally loses its reference.

It is important to take into account that thanks to the virtual base station, it is possible to maintain the highest positioning accuracy, moreover when the distance from the starting point is further than the maximum distance ($\sim$30 km) specified for a classical base station.

3.2. *RTK-DGPS2* (*A1 Highway route*). The second experiment consisted of a route along the A1 highway. In this case, the RTK DGPS equipment consisted of a receiver that works at 1 Hz using the differential corrections supplied by the National Geographic Institute. Basically it is the same receiver but with a lower refresh rate. This highway is characterized by a lot of buildings along its sides, mainly near Madrid, followed by a zone without obstacles and finishing in a mountain area with some obstacles for the GPS signal reception. With this test we tried to show the evolution of GPS high accuracy positioning in a more hostile environment than in the previous case. In this case, the distance travelled was about 90 km in each direction, with a maximum speed of 120 km/h and an average speed of 80·45 km/h. The statistics of the route are shown in Table 2.

In this case, the number of samples is lower than in the previous experiment because this GPS refresh rate is a fifth of the previous GPS one. Another important factor is that due to a bad signal reception environment on some parts of the route the GPS did not receive satellite signal (55·85% of samples), reducing the number of positions tracked.

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Table 2. Error comparison between RTK DGPS and Autonomous GPS during the A1 route.

DGPS Precision	Average Difference (m)	Standard Deviation (m)	Samples	%
4	1·29	0·37	868	11·41
5	2·45	1·64	1943	25·54
1	1·79	1·76	548	7·20
No Signal	—	—	4248	55·85

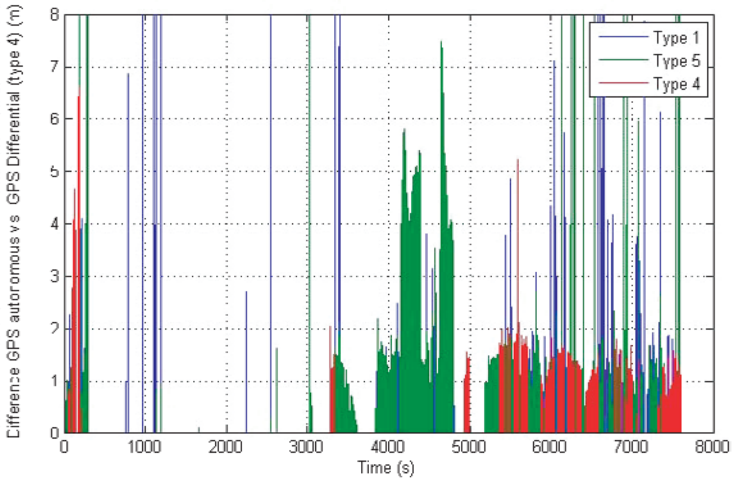

Figure 4. Comparison of the evolution of GPS precision during the route along the A1.

The average positioning difference of both GPS units when the RTK unit is in type 4 positioning is very low. The cause of this low error is due to the very good satellite configuration and the good quality of the autonomous receiver. However, on some parts of the route, the autonomous GPS loses the signal, obtaining an error of 10 to 20 m which, because of the high number of points considered in the average, has no consequences on its calculus. In this case, when the positioning of the differential GPS is in type 5 the error increases to 2·45 m. This means that in these parts of the route, the conditions are much degraded for both GPSs and the differential system maintains the sub-metrical precision thanks to the differential correction but the autonomous system cannot maintain the maximum precision and fluctuates a lot. Finally, when the differential GPS is in type 1, both receivers work in a similar way and their behaviour is very close.

Figure 4 shows the variation of this error vs. time during the experiment. We can see that at the beginning of the test on some parts of the route the satellite signal was lost, consequent to the small number of samples obtained on this route. It is also shown that some important parts of the type 5 positioning have an error from the autonomous GPS of more than four metres, which explains the high average value of this kind of positioning. It is mainly caused by the existence of buildings and other obstacles besides the road. In the last one third of the

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Table 3. Error comparison between RTK DGPS and Autonomous GPS during the A1 second route.

	DGPS Precision	Average Difference (m)	Standard Deviation (m)	Samples	%
Going	4	0·59	0·28	6958	22·99
	5	0·8	0·5	9369	30·95
	1	2·18	1·37	4145	13·69
	No signal	—	—	9796	32·27
Return	4	0·92	0·29	1720	7·70
	5	1·28	0·49	10832	48·50
	1	1·88	1·03	5573	24·05
	No signal	—	—	4411	19·75

experiment the position of the differential GPS remains fine, even if the highway is located in a zone with some mountains and valleys. In this experiment we demonstrated the need for another type of GPS receiver with a higher speed to recover the positioning and for a redundant system that maintains the position when the GPS fails.

3.3. *RTK-DGPS3* (*Second A1 Highway route*). In order to solve some of the previous limitations, we repeated the test on highway A1 using a different model of GPS differential receiver. This new model is able to use American GPS and Russian GLONASS satellites while at the same time, increasing the possibility of receiving the minimum number of satellites for positioning as well as the speed of recovering the position when it is lost. The position refresh rate of this device is 10 Hz. This feature also influences the recovery speed when the position disappears due to a satellite becoming lost because the speed of the control loop also increases and it finds new satellites faster.

In this case, the number of samples increases dramatically because the GPS loses its signal less frequently (32·27% in outward, 19·75% in return). It also fits with an exceptional behaviour of the autonomous GPS. Even if it loses its position more frequently than the differential, the positioning provided is very accurate due to the good satellite configuration, as described in Table 3. The evolution of the satellite signal quality is also shown in Figure 5, where the type 1 positioning quality only appears sporadically.

With this kind of GPS receiver, we have demonstrated that a high refresh rate and the inclusion of a second constellation in order to increase the number of visible satellites is an important improvement when we want to have maximum precision most of the running time. However, this system loses type 4 signals frequently. The reason for this loss is that the virtual base station used is based on the visible satellites of the National Geographic Institute base station network, which only uses the GPS satellite constellation. This means that our receiver only uses GLONASS in type 1 positioning to recover the position faster but not to calculate the position solution in differential positioning.

3.4. *RTK-DGPS3+proprietary base station* (*combined highway-city route*). In order to solve this drawback, we performed a final test. In this case we installed our own base station that was able to calculate differential correction using GPS+ GLONASS satellites allowing, in this way, remote GPS positioning in differential

Table 4. Error comparison between RTK DGPS and Autonomous GPS during highway-city route, near the Campus.

DGPS Precision	Average Difference (m)	Standard Deviation (m)	Samples	%
4	1·48	0·50	6899	60·25
5	2·83	2·13	3085	26·94
1	1·60	1·39	1088	9·50
No signal	—	—	377	3·29

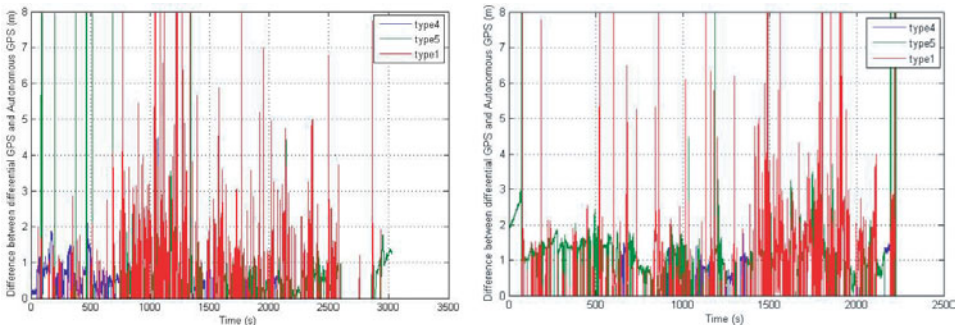

Figure 5. Comparison of the evolution of the GPS precision during the second route along the A1.

mode with both constellations too. This base station has the ability to generate differential corrections at 10 Hz, faster than standard base stations that generate it at 1 Hz. Although this feature does not influence the mobile behaviour in RTK positioning, it may be useful when we require synchronized operations in real time without low latency differential correction refresh.

In this case, the differential correction transmission method used point to point radio-modems with a power of 5 Watts. Unfortunately, there is only a range of 10 km around the base station with this equipment. This means that only local tests were possible on the UPM campus zone as well as on the A3 highway near the Campus.

In this experiment, the driving area includes clear satellite visibility zones, tall building zones, canopies, and bridges. However, the results were better than in any other case, as is shown in Table 4. The number of samples in type 4 positioning is more than double that for the other types. This means that it is very easy for the GPS receiver to calculate the position with this precision because it can use the satellites of both constellations to obtain a fixed solution. In this case, the average number of available satellites to calculate the position in type 4 was eight. This is a real improvement for on-the-lane level positioning.

We show the positioning error evolution in Figure 6. As we have pointed out, most of the time the differential GPS is running in type 4 (fixed) positioning, being occasionally of type 5 (float) and only a few times of type 1 (autonomous). This equipment provides the best results but, on the other hand, we can only use it in small zones around the Campus.

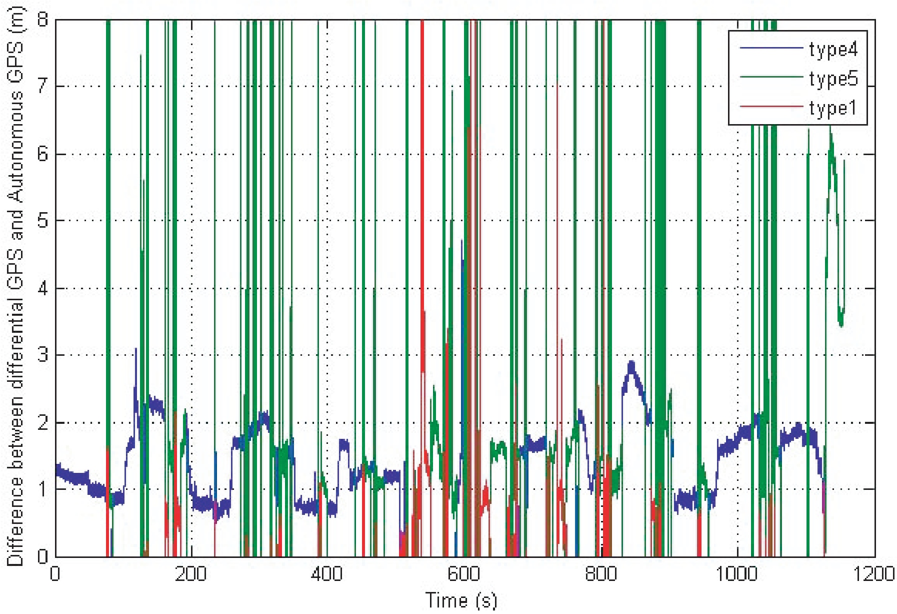

Figure 6. Comparison of the evolution of GPS precision during the second route around the UPM South Campus.

3.5. *INS Results.* The inertial measurement system can be used under two main circumstances: when GPS accuracy is degraded (type 5 or type 1) or when the GPS signal is lost. The main problem with this method is that the error is cumulative. Obviously, long distances lead to large errors between GPS positioning and inertial system positioning, but these signals can be used for short periods of time until good GPS accuracy is recovered. Then the position is updated.

Due to the reasons stated above, it is necessary to evaluate the magnitude of the cumulative error. This verification was carried out computing the path using the inertial system between points where the GPS signal is lost. Considering that the first point of this segment is taken as the origin, the final point is compared with the positioning when the GPS signal was recovered. The differences for one of the tests along the A1 road are shown in Figure 7. As can be seen, there is a fairly linear relationship between the error and the distance travelled between both points.

Considering the previous results, this accurate inertial system can improve the accuracy of GPS positioning when the signal is lost or signal degradation does not take too much distance (situation presented in Section 3.4). The problem arises when type 4 accuracy level is quite infrequent (Section 3.2 and 3.3). In these cases, the error committed with the inertial system can become inadmissible for certain purposes.

4. CONCLUSIONS.

In this paper, we have presented a set of real road tests to evaluate the performance of different high precision GPS systems that involve

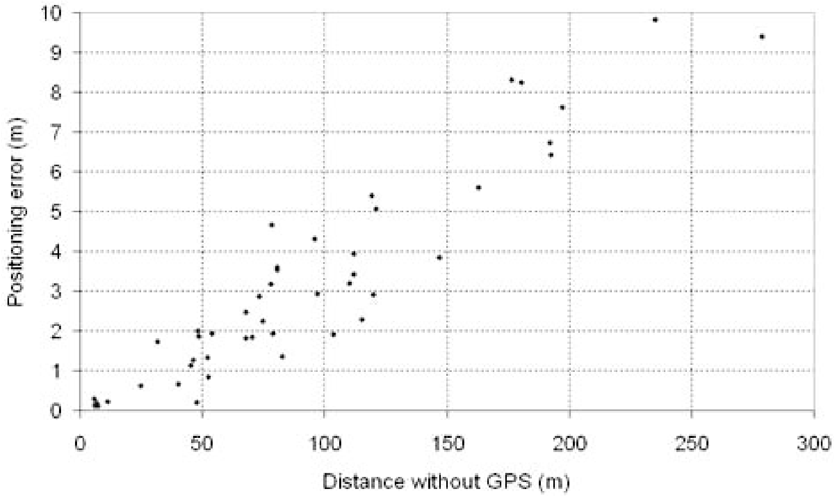

Figure 7. Positioning error using the inertial measurement system.

I2V communications and whose results can be applied to designing new generations of in-vehicle safety systems that require on-the-lane location of the vehicles.

In these experiments some high speed routes have been covered, using RTK differential GPS at several position refresh rates, GPRS and UMTS communications, and two different sources to obtain differential correction to improve positioning accuracy: a proprietary infrastructure base station and the virtual base system provided by the National Geographic Institute of Spain. Finally we have tested the combination of GPS American satellite constellation with GLONASS Russian satellite constellation, obtaining a wide set of available satellites, a very useful feature in urban environments. The system with its proprietary base station provides us better results than systems based on virtual stations, and deviations larger than 1 metre are very infrequent, so it can be used in applications that require on-the-lane positioning. The main drawback is its small range, so accurate results can only be obtained near the station and corrections are not possible too far away from it.

In order to improve the quality of positioning when GPS signals are lost, for example in tunnels, canopies or occlusions caused by tall buildings, we have complemented the GPS devices with a combination of a gyroscopic platform and a non-contact speed sensor that allows maintaining the precision in situations when there was no satellite information reception or when GPS accuracy was degraded for short periods of time.

There is a wide range of applications of this kind of systems such as, for example, collision avoidance, high precision digital cartography development (mainly on secondary roads), traffic management, lane-keeping warnings, cooperative driving or, of course, autonomous vehicle development for public road circulation. However some of them need high accuracy (on-the-lane) positioning to work properly. This requirement implies deep knowledge of those several GPS positioning technologies that can provide these accuracy levels.

For future work we plan to join the two innovative solutions: V2I communications through GPRS and double satellite constellation GPS + GLONASS.

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