Geodetic Kinematic Terrestrial Navigation using a MMS – Multi-constellation and multi-frequency Galileo/GPS/GLONASS performance comparisons

R. Cefalo[1]*, P. Snider[1], T. Sluga[1], F. Viler[2], P. Pavlovčič-Prešeren[2]

[1] GeoSNav Lab, Department of Engineering and Architecture, University of Trieste, Via Valerio 6/2, 34127 Trieste, Italy – (raffaela.cefalo, tatiana.sluga)@dia.units.it; snider.paolo@gmail.com

[2] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova cesta 2, SI-1000 Ljubljana, Slovenia – (polona.pavlovcic-preseren, filip.viler)@fgg.uni-lj.si

KEY WORDS: Galileo, GNSS (Global Navigation Satellite System), MMS (Mobile Mapping System), INS (Inertial System), GPS (Global Positioning System), GLONASS (GLObal NAvigation Satellite System).

ABSTRACT:

This paper presents a part of the research activities performed from 2019 to 2022 in the framework of WP 5.3 “Field campaign” and in particular, the activities “Land urban and extra-urban data measurement campaigns” of the European GRC-MS (Galileo Reference Center – Member States) Project - GSA/GRANT/04/2016.
The dynamic data-collection campaigns were conducted by three participating member states (Portugal, Italy, and Romania), in three different environments: aerial, terrestrial, and maritime, respectively.
This article presents a comparison of the results obtained for the terrestrial environment, considering the performance of Galileo used in conjunction with other GNSS systems, such as GPS, using different geodetic and navigational multi-constellation and multi-frequency receivers/devices experimental dynamic activities. Starting from the user’s needs and requirements, the experimental setup and the methodology for the estimation of the reference («actual») trajectory are provided. These are complemented by numerical results and reasons for possible performance degradations analyses.
The processed rover trajectories and the produced outputs were compared to the reference trajectory obtained from GNSS/INS (INertial System) integrated high-performance solution.
Galileo-only and GPS-only solutions, so as multi-system solutions (GPS+Galileo, GPS+GLONASS and GPS+GLONASS+Galileo) were analysed. PVT (Position Velocity Time) solutions were computed using post-processing geodetic interferential techniques.
From the performed analyses, some preliminary conclusions relative to the Galileo performances applied to terrestrial urban and extra-urban navigation were derived.
These activities need to be continued in the near future, taking into consideration the Galileo constellation improvements and the ITS (Intelligent Transport Systems) applications in order to improve the offered services and the road safety.

1. INTRODUCTION

The Galileo program is a European initiative to create a technologically advanced, highly accurate and guaranteed global satellite navigation positioning system under civilian control. The Galileo satellite system is able to provide autonomous navigation and positioning services interoperable with other GNSS systems such as GPS, GLONASS and BeiDou. Once completed, the system will consist of 30 satellites and their control segment.
The Galileo Reference Center, one of the service facilities that complement Galileo's main infrastructure, managed by EUSPA (EU Agency for the Space Programme), is located in Noordwijk, the Netherlands, and manages data and integrated products provided by research partner centers from European Union countries, including Norway and Switzerland (MS), to perform independent monitoring of the OS (Galileo Open Service) and CS (Commercial Services) data dissemination performance and report it to the relevant stakeholders (EUSPA, 2022).
The countries that signed in September 2017 a FPA (Framework Partnership Agreement) in support to GRC are: Austria, France, Germany, Italy, Norway, Poland, Portugal, United Kingdom, Czech Republic, Romania, Spain and Sweden.
An important part of Galileo’s performance assessment is the evaluation of the performance experienced by a generic user in different propagation environments: thus, in support of GRC, in the frame of the GRC-MS project, periodic kinematic campaigns using multi-constellation satellite receivers were performed. The dynamic data-collection campaigns were conducted from 2019 to 2022 by three participating member states (Portugal, Italy, and Romania) in three different environments: aerial, terrestrial, and maritime, in the framework of WP 5.3 “Field campaign”.
The European GRC-MS (Galileo Reference Center – Member States) Project - GSA/GRANT/04/2016, was co-funded by EUSPA, European Union and by each participating research partner: among them, the GeoSNav Lab, Department of Engineering and Architecture, University of Trieste, Italy.
This article presents some results of the terrestrial campaigns performed starting from 2019 using the GeoSNav Lab MMS (Mobile Mapping System), a Septentrio® AsterX-U geodetic GNSS multi-constellation/multi-frequency receiver and a multi-constellation/double frequencies smartphone with the principal aim of evaluating the Galileo performances.
These performances were evaluated comparing the Galileo PVT (Positioning, Velocity, Time) parameters (Leick et al., 2003; Subirana et al, 2013; Hofmann-Wellenhof et al., 2015; Cefalo et al., 2018) obtained using GPS, GLONASS, GPS+GLONASS, GPS+Galileo and GPS+GLONASS+Galileo, both in urban and extra-urban areas (Bastos et al., 2022; Tarantino et al, 2018).
The processed rover trajectories and the produced outputs were compared with integrated high-performance trajectory obtained from GNSS/INS (INertial System), giving a “reference”, stable and highly accured trajectory.
Some “ad hoc” optimized hardware/software configurations were set up in order to achieve the best acquisition performances

and test different satellite/signal combinations and processing options (Viler et al, 2023; Snider, 2023).
Starting from 2019 till 2022, in the framework of the GRC-MS Project, 11 campaigns were performed; here the scheme of the campaigns will be described, including: campaign planning, survey description, performed data processing, comparisons with the reference GPS/INS MMS trajectory, all the performed analyses and the obtained results particularly focused on the Septentrio's performances.
The comparisons were performed in terms of:

- the mean planimetric and altimetric difference values calculated epoch by epoch (GNSS acquisition rate: 1 Hz; MMS acquisition rate: 200 Hz) comparing the Septentrio AsteRx-U and the contemporaneous MMS values;
- the standard deviations;
- the total obtained solutions;
- the mean satellites number used in the different surveying sessions and
- the mean PDOP (Position Dilution Of Precision) values.

For each campaign both the urban and extra-urban trajectories were computed and separately analysed (Figure 1).

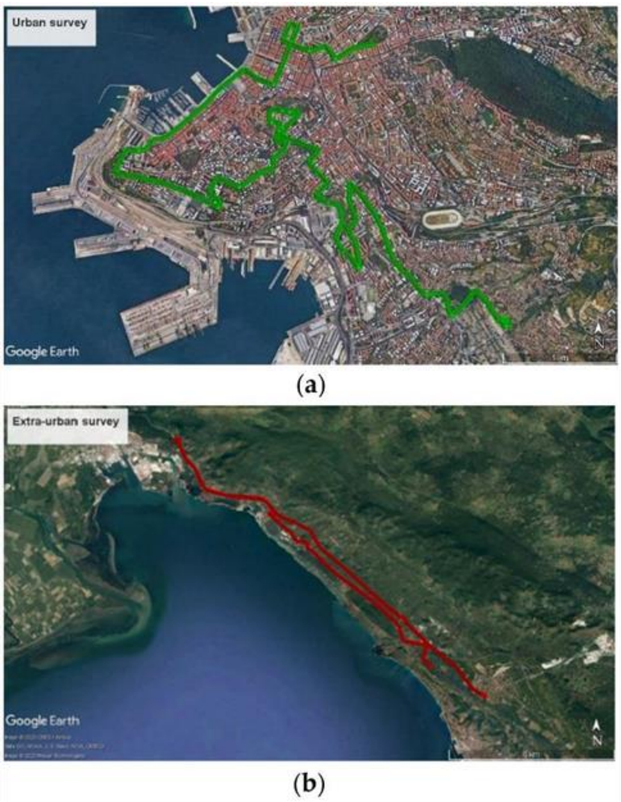

Figure 1. The surveyed area for a campaign performed in March 2022: (a) in green, the reference trajectory produced by the MMS in the urban environment; (b) in red, the extra-urban survey.

2. MATERIALS AND METHODS

2.1 Survey Design

In Table 1 the high priority requirements for the road transportation domain are reported: the key GNSS requirements are in the range of decimetric-level accuracies and authentication availability > 99.5%.

Then, the experimental setup and methodology for the estimation of the reference («actual») trajectory are provided.

Applications	Safety Related Automatic Actions in V2X, Autonomous Driving, eCall, Tracking and Tracing of Dangerous Goods	Liability: RUC, Pay-as-you-Drive, Taxi Meter, Smart Tachograph	Smart Mobility: Road Navigation Automated Parking Dynamic Ride Sharing
Key GNSS requirements	Accuracy (decimeter-level) Authentication Availability (>99.5%) Integrity Robustness TTFF	Accuracy (decimeter-level) Authentication Availability (>99.5%) Integrity Robustness TTFF	Authentication Integrity
Other requirements	Connectivity (mainly short range) Interoperability	Connectivity (short range and long range)	Connectivity (long range)

Table 1. High priority requirements for the road transportation domain.

To perform the terrestrial urban and extra-urban campaigns, a MMS equipped with a POS/LV (Position and Orientation System/Land Vehicles) from Applanix Corporation was used (Figure 2).
The core of the Applanix system is the PCS (POS Computer System), which collects and processes data from integrated sensors (Applanix Corporation, 2016); in the present case:

- a Litton LN-200 Inertial Measurements Unit (IMU) with three accelerometers and three solid-state fibre-optic gyros ;
- A Trimble Zephyr GPS L1/L2 antenna used for positioning (Rear antenna);
- A Trimble Zephyr GPS L1 antenna used for attitude determination (Front antenna).

Each Zephyr antenna is connected to its BD950 GPS card, parts of the PCS.

Figure 2. GNSS/INS GeoSNav Lab MMS surveying in urban environment in the city centre of Trieste, Italy.

During the survey performed in March 2022, the GPS receivers acquired data at the rate of 1 Hz, while IMU data at a 200 Hz rate. The integrated measurements from each sensor were processed using Kalman filtering techniques.
For the purposes of these surveys, the vehicle was additionally equipped with a GNSS multi-constellation Septentrio AsteRx-U geodetic receiver and a PolaNt-x MF antenna; in one of the campaigns an Xiaomi Mi8 smartphone was also used (Figure 3).

Figure 3. Rear and Front POS/LV antennas, Septentrio® PolaNt-x MF antenna and the box containing the Xiaomi Mi8 smartphone mounted on the roof of the MMS.

All the receivers' antennas are mounted on a metal bar on the roof of the vehicle; the position of each antenna and the other system components, included the smartphone contained in a plastic box, was surveyed using a high accuracy total station and referred in a local reference frame integral with the vehicle (Figure 4).

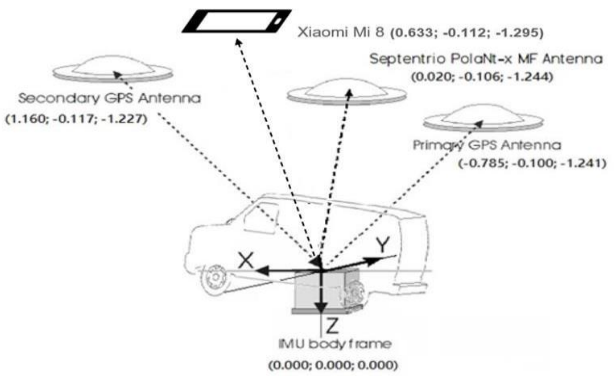

Figure 4. Component's lever arms.

To evaluate the Galileo navigation performances, the positions calculated using the different GNSS devices were compared epoch by epoch with the reference GPS/INS "true trajectory".
The ellipsoidal GNSS positions were transformed to East, North UTM - ITRF2014 (International Terrestrial Reference Frame) and ITRF2014 Heights.
In order to directly compare the coordinates, PVT (Position Velocity Time) solutions computed by Applanix POS/LV were referred to the Septentrio PolaNt-x MF Antenna Reference Point (ARP). Instead, as far as regard the Xiaomi Mi8 smartphone (Viler et al., 2023), the PVT GPS/INS solutions were referred to the geometrical smartphone centre, being its ARP position known only approximately.

2.2 MMS Reference Trajectory

The three-dimensional trajectory to be used as a reference for comparisons was obtained post-processing the MMS data using POSPac™ MMS™ (Position and Orientation System Post-Processing Package - Mobile Mapping Suite).
The POS/LV system is capable to provide more than fifty data fields as output including: position data (latitude, longitude and ellipsoidal height), vehicle attitude (roll, pitch and heading angles), speed with respect to the North, East and Z axes, accelerations, angular velocities, standard deviations.
POSPac™ MMS with IN-Fusion™ technology uses a Kalman filteing tecnique to combine IMU data with phase and pseudo-range measurements recorded by the GPS receivers. Applanix IN-Fusion technology continuously accesses the entire GPS constellation, and is able to record and use GPS data even when receiving less than four satellites.
The used MMS uses only GPS technology in order to compute the reference trajectory, but the accuracy of the combined GPS/INS solution was higher than any multi-constellation GNSS-only solution, so to justify its use as "true" trajectory.
The reference station used in the post-processed solution was "TRSE", part of the "Antonio Marussi" GNSS network managed by Friuli Venezia Giulia Region (Regione Autonoma Friuli-Venezia Giulia-Rete GNSS FVG — A. Marussi, 2022), located about 3.5 Km from the starting point of the survey; the farther point was distant about 16 Km, so a "network solution" was not needed.
The obtained accuracies were in the range of a few centimeters for the extra-urban trajectories (Figure 5); with a maximum peak of 0.5 m in the North component for the urban survey (Figure 6), where it is possible to identify short static tracts mainly due to the stops at traffic lights, characterized by low rms.

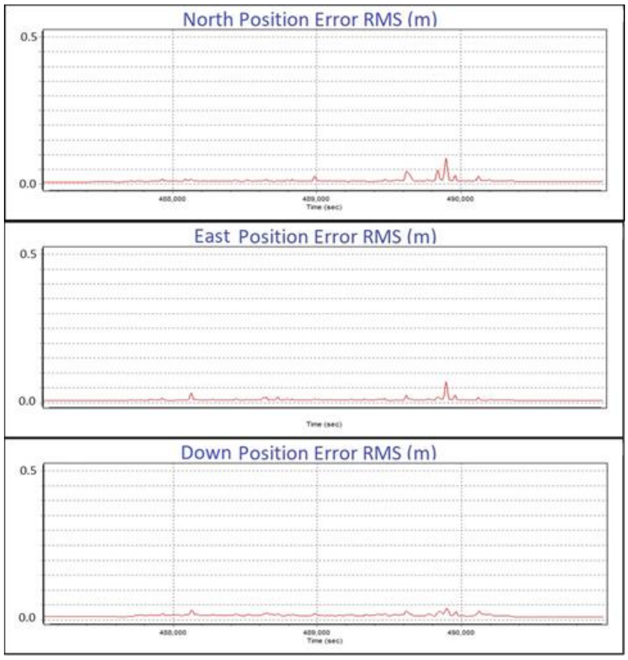

Figure 5. Positioning accuracies of the MMS reference trajectory in extra-urban environment.

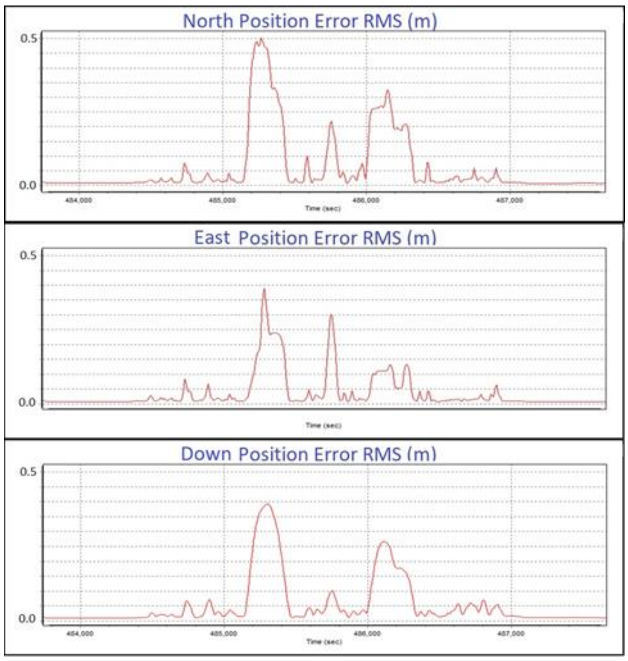

Figure 6. Positioning accuracies of the MMS reference trajectory in urban environment.

2.3 Survey Planning

Each survey was carefully planned to identify time slots when a sufficient number of Galileo satellites (Figure 7) were visible to provide a suitable PDOP value (Figure 8); Trimble® GNSS Planning Online software and Septentrio® RxPlanner tool were

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used. Plannig was necessary especially for urban surveys where buildings mask the satellites' signals.

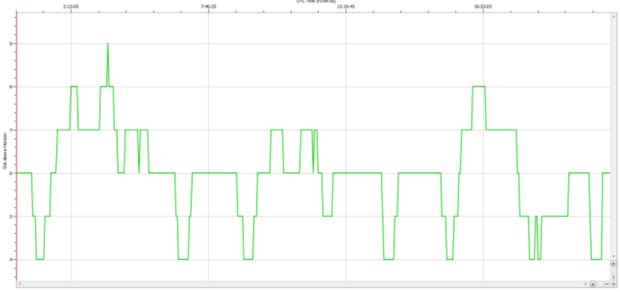

Figure 7. Number of the visible Galileo satellites (cut-off 15°).

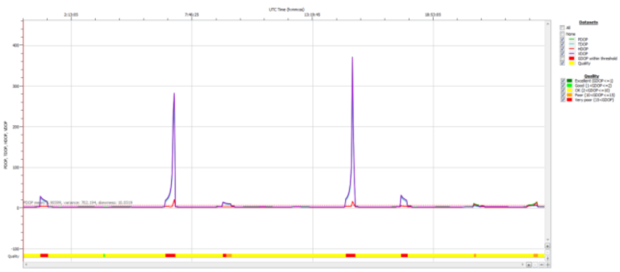

Figure 8. DOP parameters related to the Galileo satellites (cut-off 15°).

2.4 Data processing results

Both data recorded by the Septentrio® receiver and by the Xiaomi® smartphone, were post-processed to obtain PVT solutions (combining "forward" and "backward" techniques) by using the Novatel GrafNav® v.8.90.2428 software.
For each environment, different solutions were computed:

- GPS (L1/L2);
- Galileo (E1/E5b);
- GPS+Galileo (L1/L2, E1/E5b);
- GPS+GLONASS (L1/L2, G1/G2);
- GPS+GLONASS+Galileo (L1/L2, G1/G2, E1/E5b).

Several analyses were carried out comparing the mentioned solutions and observing the behavior of the computed solution using the different constellations and their combinations.
Particularly in urban environment, due to buildings' mask, it was not possible to obtain the PVT solutions for each epoch.
In this contest, analyzing the Septentrio's solutions, it was evidenced that much more PVT data were obtained from Galileo than from GPS. In extra-urban environment, Galileo data permitted to calculate the PVT solutions in a shorter time than GPS in correspondence of a under bridge passage.
The performed analysis revealed similar performances for the Galileo-only and GPS-only solutions, respectively, with better results for the Galileo-only solution in the more recent road campaigns (Figure 8 and Figure 9), (Table 2 and Table 3).

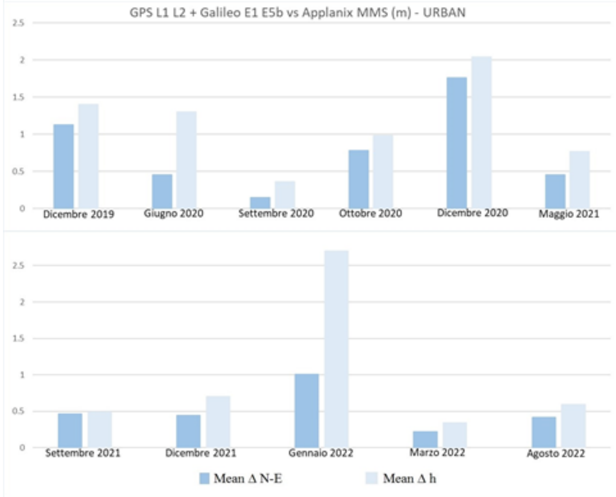

Figure 9. Mean values of the planimetric and altimetric differences (m) between the Septentrio® and MMS trajectories for GPS + Galileo data in the urban environment (2019-2022).

		GPS															
		Fixed				Float				Code				No data			
		Δ N-E (m)		Δ h ass (m)		Δ N-E (m)		Δ h ass (m)		Δ N-E (m)		Δ h ass (m)		Δ N-E (m)		Δ h ass (m)	
		GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal
Galileo	Fixed	0.042	0.033	0.080	0.073	0.599	0.208	0.230	0.173	0.322	0.233	0.136	0.164	-	0.121	-	0.175
	Float	0.053	0.385	0.138	0.670	0.409	0.366	0.389	0.599	2.556	0.904	2.041	1.151	-	0.653	-	0.888
	Code	0.042	1.021	0.203	2.165	0.294	1.142	0.364	1.413	0.658	1.066	0.427	3.825	-	2.241	-	3.246
	No data	0.056	-	0.128	-	0.411	-	0.417	-	0.983	-	0.441	-	-	-	-	-

Table 2. Comparison matrix relating the average planimetric and altimetric differences obtained with the GPS and Galileo systems for the March 2022 campaign in the urban survey (Septentrio® AsteRx-U receiver with PolaNt-x antenna).

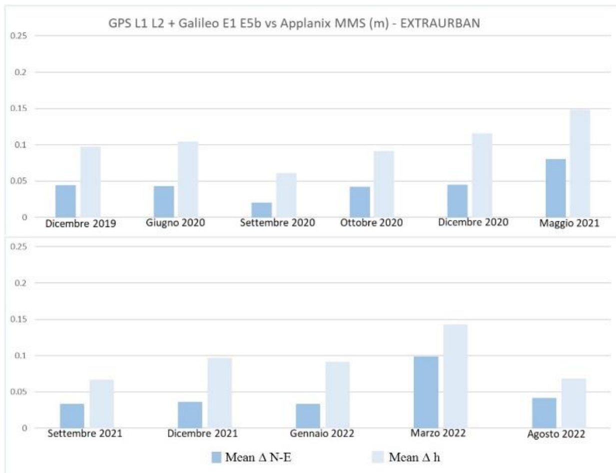

Figure 9 Mean values of the planimetric and altimetric differences (m) between the Septentrio® and MMS trajectories for GPS + Galileo data for the extra-urban environment (2019-2022).

		GPS															
		Fixed				Float				Code				No data			
		Δ N-E (m)		Δ h ass (m)		Δ N-E (m)		Δ h ass (m)		Δ N-E (m)		Δ h ass (m)		Δ N-E (m)		Δ h ass (m)	
		GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal	GPS	Gal
Galileo	Fixed	0.095	0.096	0.128	0.124	0.165	0.132	0.243	0.213	1.018	0.060	1.273	0.105	-	0.207	-	0.298
	Float	0.059	0.209	0.137	0.714	0.137	0.091	0.221	0.226	0.950	0.947	0.747	0.718	-	0.206	-	0.412
	Code	0.068	0.860	0.135	3.042	0.084	0.254	0.209	0.107	-	-	-	-	-	0.576	-	0.312
	No data	0.053	-	0.080	-	0.402	-	0.242	-	-	-	-	-	-	-	-	-

Table 3. Comparison matrix relating the average planimetric and altimetric differences obtained with the GPS and Galileo systems for the March 2022 campaign in the extra-urban survey (Septentrio® AsteRx-U receiver with PolaNt-x antenna).

The results obtained with the Xiaomi® smartphone show poor stability in the reception of GNSS signals, especially in urban areas and subsequent difficulty in calculating the PVT solutions. In this case the time series comparisons were not possible, as the smartphone was used only in the March 2022 campaign.

From the performed analyses, some preliminary observations relative to the Galileo performances applied to terrestrial urban and extra-urban navigation were derived:

- The mean number of Galileo satellites visible in urban areas was almost always lower than the GPS ones. Despite this, in several campaigns the Galileo PDOP values were lower than GPS and the total Galileo solutions were higher than GPS.
- In urban areas the Galileo system, compared with the GPS satellite system, showed comparable performances.
- As observed for the GPS and Galileo satellite system, for all the analysed combinations between the various GNSS systems (GPS+GLONASS, GPS+Galileo, GPS+GLONASS+Galileo), the average altimetric and planimetric differences between the calculated trajectories and the reference ones show a variable trend over time. In particular, it can be seen that this trend is similar to that obtained using GPS only.
- For three of the carried-out campaigns, the number of the Galileo only solutions was higher than the GPS+GLONASS combination ones.

3. CONCLUSIONS

During the time of the carried-out surveys, the number of Galileo satellites, due to some system maintenances, remained more or less the same, so the expected improvements were not evident.
From the presented experimental activities it can be noticed that Galileo clearly shows high accuracy performances even if reduced conditions respect the other GNSS systems are actually present, in particular as far as regards the Galileo constellation implementation phase.
The research activities herein presented need to be continued in the near future, taking into consideration the Galileo constellation improvements (in terms of satellites number and considering the advent of the new Galileo satellite generation – Galileo System Test Bed – Version 2/B).
Furthermore, these research activities and applications will become more and more relevant in view of ITS (Intelligent Transport Systems) and M2M (Machine to Machine) applications to vehicle road navigation in order to improve the offered services and the road safety.

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