LOW-COST MULTI-FREQUENCY GNSS RECEIVERS: PERFORMANCE EVALUATION FOR POSITIONING AND NAVIGATION

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ABSTRACT:

In recent years, the possibility of using interoperable global constellations, the growing number of Continuously Operating Reference Stations (CORS) and the technological progress of instrumentation, computing algorithms and GNSS products are significantly marking the evolution of the various satellite survey techniques and the diffusion of mass-market technologies contributing to innovation transfers in different sectors including smart cities, smart mobility, connected automated driving, precision farming and others (Egea-Roca et al., 2022).

Currently, the study of low-cost GNSS systems for navigation and precision positioning especially utilised in monitoring applications is the focus of numerous research activities (Joubert et al., 2020; Raza et al., 2022; Bellone et al., 2016; Hamza et al., 2020).

The aim of this work is to test the performance of some of the latest generation multi-constellation and multi-frequency GNSS medium and low-cost sensors, evaluating their possible application in the mentioned fields.

Differential and undifferential techniques were compared (Dardanelli et al., 2021; Ocalan et al.,2016); Precise Point Positioning (PPP) has become a valid alternative to differential methods allowing to obtain comparable accuracy offering greater flexibility (Lin, 2021). The multi-constellation permanent stations network GPS-Umbria was utilised for differential mode tests (Radicioni and Stoppini, 2019).

The tests were carried out in different modes (static and kinematic) and operating conditions; various intermediate and low-cost sensors were employed, while the data of a high precision geodetic receiver were used as reference for the comparison of the different solutions.

1. INTRODUCTION

The technological progress that is constantly revolutionising the field of satellite positioning, taking into account the evolution of the space infrastructure, the new constellations (in particular the advent of the Galileo system) (Steigenberger and Montenbruck, 2017; Yalvac, 2021), the development of ground positioning services and the improvement of GNSS products, has led to having on the market a wide selection of receivers characterised by reduced costs and dimensions with different features and performances(Dabove and Manzino, 2014; Poluzzi et al., 2020; Jackson, 2018; Dabove, 2019).

As the European Union Agency for the Space Program report attests (EUSPA, 2022), the use of GNSS technology will continue to grow in the next decade and the vast majority of current receivers is multi-constellation and features multi-frequency support thanks to the greater number of open signals with benefits including increased availability, increased accuracy (better geometry, and more signals) and improved robustness. This, in addition to the growing demand for localization and navigation services for numerous types of applications with different levels of accuracy, significantly marks the evolution of the various satellite positioning techniques, with specific reference to the use of low-cost systems.

Thanks to the ever-increasing development of GNSS Continuously Operating Reference Stations (CORS) networks and the possibility of using both real-time and post-processing services, the limits of distances between stations have been overcome with the use of the NRTK technique which enables to achieve high levels of accuracy with reduced time sessions and costs (Dardanelli and Pipitone, 2021; Gümüş and Selbesoğlu, 2019; Janos and Kuras, 2021).

Regarding undifferencial approach, although limited by the use of specific software and the availability of precise GNSS products until recently, today the PPP technique (Zumberge et al., 1997; Kouba and Héroux, 2001) (thanks to the availability of multi-frequency sensors) is considered a valid solution to differentiated methods, demonstrating precisions potentially comparable to them for many applications (in particular for those cases where precision positioning and navigation in remote locations are required and where infrastructures based on local or regional permanent stations networks are not available), (Gomaa et al., 2022; Wang, 2013).

In recent years, a lot of research has developed in this methodology to verify the possibilities of both static and kinematic multi-constellation measurements and to improve the convergence of PPP solutions. (Bulbul et al., 2021; Ogutcu, 2020; Angrisano et al., 2020; Li et al., 2015; Anquela et al., 2013). GNSS technology is therefore a useful and fundamental

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tool in various fields, including precision positioning and navigation, continually presenting new challenges to both researchers and device manufacturers and suppliers (Huang et al., 2023; Gonzalez and Dabove, 2019).

The present research is part of this context and involved tests with a differentiated and undifferentiated approach, in real-time and post-processing mode with two intermediate receivers (by Topcon Positioning Systems company) and two low-cost ones (by u-blox company). The data of a high precision geodetic receiver were used as reference for the comparison of the different solutions. The work is divided into two parts: the first relating to tests in static and "almost-static" mode (with imposed slow movements through the use of a micrometric sled); the second one deals with kinematic tests in order to track a vehicle in different urban contexts with numerous obstructions (in particular, the behaviour of one among the sensors characterized by an integrated inertial measurement unit was evaluated). The results obtained were compared to evaluate their consistency as well as to assess their accuracy and reliability for possible technical application.

2. INSTRUMENTS, SOFTWARES AND METODOLOGY

Two intermediate Topcon receivers (MR-2 and B-125 board) and two low cost u-blox application boards (C099-F9P and C102-F9R boards with a cost of a few hundred euros) were employed for the tests. The ZED-F9R module is equipped with an inertial platform (IMU) and it is based on HPS technologies (High Precision Sensor Fusion). The data of a high precision geodetic receiver (Hiper HR Topcon) were used as reference for the comparison of the different solutions. Different types of multiconstellation and multiband antennas (Legant antennas produced by Topcon Positioning System company and ANN-MB-00 by u-blox company) were also used.
Various software for data acquisition and processing were employed: U-center that allowed communication with receivers using u-blox positioning technology, Topcon Magnet Tools used for the GNSS data post-processing and adjustment, CSRS-PPP online service (Canadian Spatial Reference System Precise Point Positioning) to obtain PPP evaluation and the open source application QGIS for data visualization. In addition, the Ferens+ software, developed by the Geomatic Laboratory of Perugia University for the Umbria Regional Council, was used to compute the necessary coordinate and datum transformations by means of the IGM parameters, while the Euref online coordinate converter ECTT (ETRF/ITRF Coordinate Transformation Tool) (Bruyninx, 2023) allowed converting between coordinates expressed in ITRF14 realisation and those in ETRF00.

The experimentation consists of two parts: the first one involves static or "almost-static" tests with slow movements imposed through the use of a micrometric sled both in post-processing (with PPP algorithms) and in real time (NRTK technique), which were carried out at the Engineering Department of the University of Perugia. The second one concerns kinematic positioning conducted by installing on a vehicle the low-cost sensors and the high-precision geodetic receiver for collecting data as a reference.

3. STATIC AND "ALMOST" STATIC TESTS

3.1 Test 1

The first activity involved a 24-hour static survey; the four receivers (MR-2, B125, C099-F9P, C102-F9R) (Figure 1) were connected to four antennas attached to tribrach attachment plate while the Hiper HR was put on station through a magnetic plate. An initial data quality analysis confirmed a high number of tracked satellites (maximum number of 40), good GDOP values (ranging from a minimum of 0.8 to a maximum of 1.4), low multipath errors, and a good signal-to-noise ratio (SNR) with comparable values for all tested receivers.

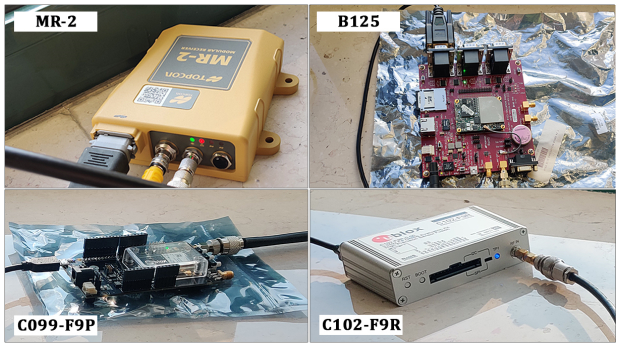

Figure 1. Intermediate and low-cost receivers used for the tests.

The data post-processing was performed both with a differenced approach by double difference (DD) algorithms, and with an undifferenced one using PPP estimates (both in static and kinematic mode).
In the first case, the UNPG permanent station that is part of the GPSUmbria network was used as reference point with known coordinates, resulting in small baselines (about 70 meters each), while PPP processing shows high percentages of fixed ambiguity (between 96% and 98%) for all receivers.
The differences between the solutions and the planimetric and altimetric component errors of PPP estimates were evaluated (Figure 2).

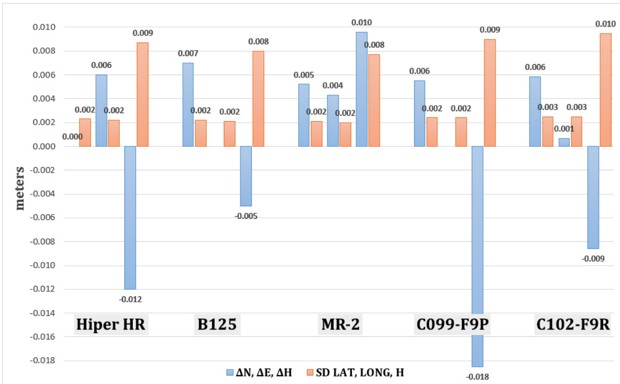

Figure 2. Differences between DD and PPP static solutions and standard deviations of PPP estimates.

The daily results obtained for the five receivers are extremely comparable (with the exception of a singular case for the C099-F9P altimetric component): the latitude and longitude standard deviations are 0.002 m for all devices, except for the C102-F9R whose value is 0.003 m for both components. For height, the deviation ranges between 0.008m and 0.010m. Regarding planimetric components, the displacement differences show an average planimetric value of approximately 0.006 m.

For the 24-hour session, the PPP estimate was repeated with the same initial configurations, obtaining a different position for each epoch. The solutions were averaged and compared with the coordinates obtained previously in the static case. The differences for the planimetric component (Hz) and the altimetric component (H) are in the range of a millimetre in almost all cases (Table 1). The graphs (Figure 3) show planimetric errors (referred to as DRMS, Distance Root Mean Square) of the order of a centimetre and RMS for the altimetric component between 0.020m and 0.030m for all receivers.

Δ PPP Static/ Kin	Δ Hz (m)	Δ H (m)	DRMS (m)	RMS H (m)
HR	0.0008	0.0036	0.013	0.034
B125	0.0003	0.0007	0.011	0.028
MR-2	0.0014	0.0006	0.011	0.023
C099-F9P	0.0016	0.0011	0.012	0.020
C102-F9R	0.0014	0.0000	0.012	0.022

Table 1. Differences between static and kinematic PPP solutions.

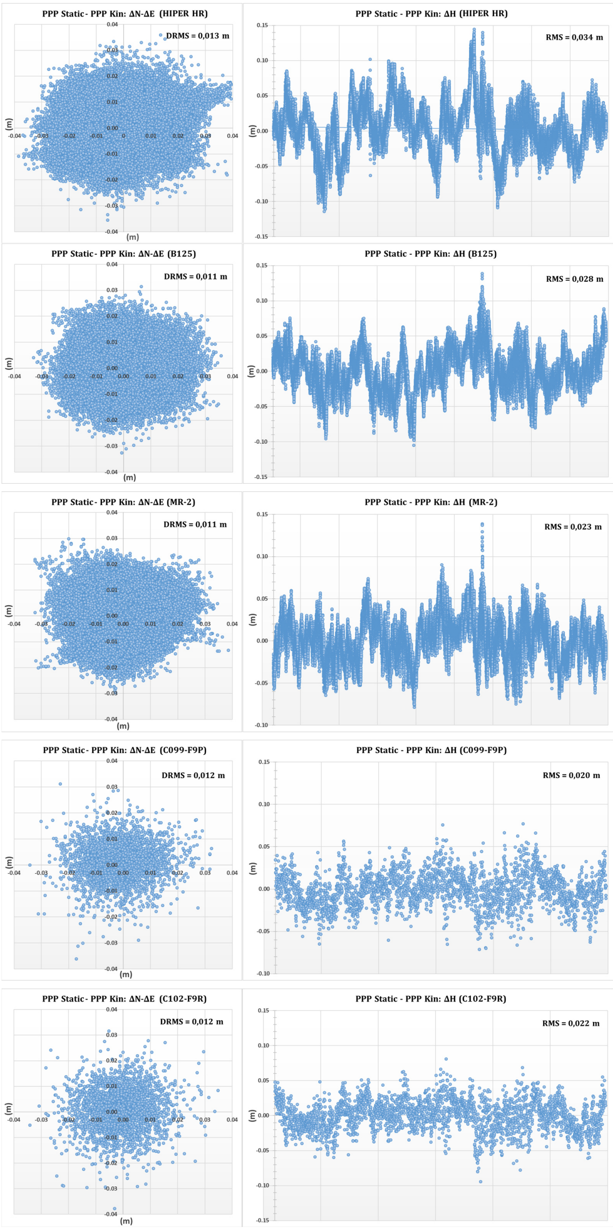

Figure 3. Differences between static and kinematic PPP solutions (Hiper HR, B125, MR-2, C099-F9P, C102-F9R).

The variation of the standard deviations for each epoch was analysed: Table 2 shows the mean values and deviations obtained for latitude, longitude and height, displaying comparable values for all receivers.

Sd PPP Kin	Mean Sd ϕ	Mean Sd ω	Mean Sd H	Sd ϕ	Sd ω	Sd H
HR	0.023	0.020	0.050	0.003	0.002	0.009
B125	0.023	0.020	0.049	0.003	0.002	0.008
MR-2	0.023	0.019	0.048	0.003	0.002	0.008
C099-F9P	0.026	0.023	0.059	0.004	0.003	0.012
C102-F9R	0.026	0.023	0.060	0.004	0.003	0.013

Table 2. PPP kinematic standard deviations.

To assess the PPP algorithms, shorter duration sessions (12h, 6h, 3h, 2h, 1h, average of 12-hour solutions) were also considered and each estimated coordinate was compared with the PPP solution derived from 24-hour session data.

The results are comparable also in this case (Figure 4): the differences from the 24-hour solution tend to increase with the reduction of the measurement session (as was to be expected), varying from even submillimetre values (in the case of the 12-hour session) to values (for the one-hour session) in most cases lower than 0.005 m (or in any case less than a centimetre) as regards the north and east coordinates and of the order of a centimetre as for the height component. The standard deviations range in planimetry from 0.002 m for the 24-hour sessions to values of the order of a centimetre for the hourly solution, while they reach maximum values of 0.050 m (for the one-hour session) in altimetry.

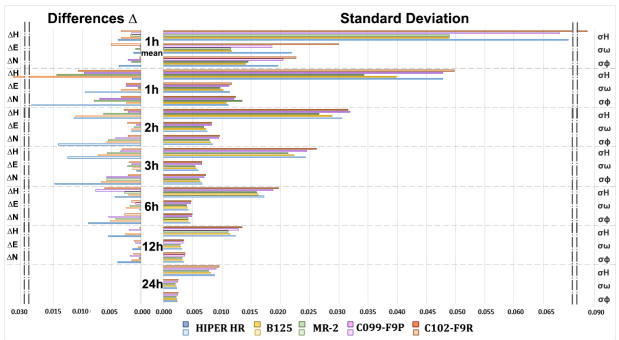

Figure 4. PPP solutions for the different sessions: differences (N, E, H) from 24-hour session estimate (on the left) and standard deviations (on the right).

3.2 Test 2

The aim of the second part of the work was to acquire positions moving with orthogonal translations an antenna (Topcon Legant) connected to a micrometric sled. The tests were repeated connecting alternately three different receivers: the Topcon MR2 and the u-blox boards (Figure 5).
A sampling interval of 1 second was set for each receiver and the antenna was kept stationary on the same vertex for approximately two hours; the same processing (with double difference algorithms or PPP ones) as in the previous tests was carried out (Figure 5).

The coordinates obtained from the measurements were compared with each other and with those deduced from the knowledge of the imposed path. The standard deviations for the DD solutions of each vertex were comparable and ranged between 0.001m and 0.002m in almost all cases, apart from a few exceptions (with regard to C102-F9R board). As concerns PPP solutions, the standard deviations (averages of the four vertices) for the planimetric coordinates are comparable and range between 0.007m and 0.010m, while the behaviour of the MR-2 appears to be slightly better in terms of height component, not exceeding 0.030m (Table 3).

All the solutions obtained from both the DD and PPP evaluations were correlated with the MR-2 coordinates obtained with the relative positioning technique, since they reconstruct the imposed path with submillimetric errors or at most of millimetric order.

The differences from the reference solution show values (in terms of planimetric distances) ranging between 0.001m and 0.007m (being generally lower if the coordinates from the double differences estimate are considered); only in two cases (relating to PPP estimates) the deviations are in the range of a centimetre. The largest differences generally relate to the altimetric component referring to the two u-blox sensors.

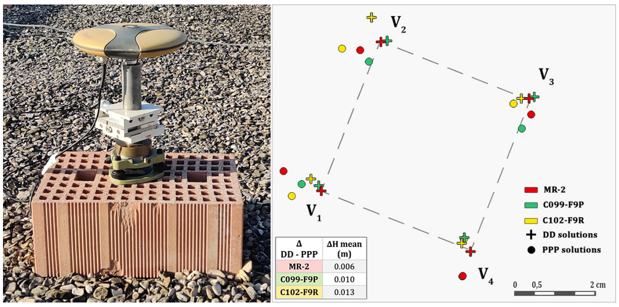

Figure 5. Micrometric sled used in the test (on the left); DD and PPP solutions (on the right).

The same elaborations were repeated in order to obtain a position for each epoch of the session (Figure 6).
As for the previous cases, the kinematic solutions deviations (Sd Kin) and the differences between the static solutions and the averages of the kinematic estimates were evaluated.

Regarding the PPP evaluations, the average of the deviations of the planimetric components of the four vertices relative to MR-2 and C099-F9P are substantially coincident (with values of 0.008m and 0.006m for the north and east coordinates respectively) and approximately 0.002m lower than those obtained with C102-F9R. In terms of altimetric component, however, the MR-2 device's response with a mean deviation for the four vertices of 0.017m is better than both other sensors by approximately 0.003m (Table 4).

Ric	Vertex	DD			PPP		
		Sd N (m)	Sd E (m)	Sd H (m)	Sd ϕ (m)	Sd ω (m)	Sd H (m)
MR-2	V_1	0.001	0.001	0.001	0.009	0.007	0.028
	V_2	0.001	0.001	0.001	0.008	0.007	0.029
	V_3	0.001	0.001	0.001	0.008	0.007	0.026
	V_4	0.001	0.001	0.001	0.008	0.007	0.029
C099-F9P	V_1	0.001	0.001	0.002	0.010	0.008	0.035
	V_2	0.001	0.001	0.002	0.010	0.008	0.031
	V_3	0.001	0.001	0.002	0.008	0.008	0.037
	V_4	0.001	0.001	0.002	0.010	0.009	0.033
C102-F9R	V_1	0.002	0.002	0.004	0.007	0.006	0.023
	V_2	0.003	0.002	0.007	0.008	0.007	0.028
	V_3	0.013	0.007	0.013	0.009	0.008	0.037
	V_4	0.001	0.001	0.002	0.010	0.007	0.037

Table 3. Standard deviation of static DD and PPP solutions.

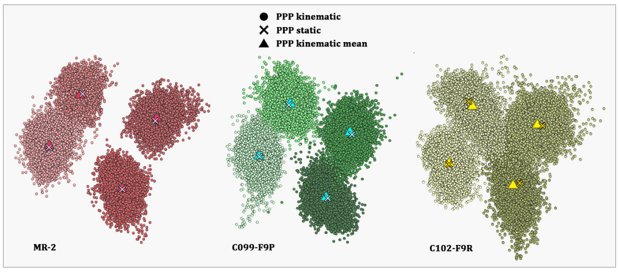

Figure 6. Kinematic PPP solutions of MR-2, C099-F9P, C102-F9R.

Sd mean (m)	DD			PPP		
	Sd N	Sd E	Sd H	Sd ϕ	Sd ω	Sd H
MR-2	0.003	0.002	0.009	0.008	0.006	0.017
C099	0.002	0.002	0.006	0.008	0.006	0.020
C102	0.002	0.002	0.006	0.010	0.007	0.021

Table 4. Avarage of standard deviations of kinematic DD and PPP solutions relative to each vertex.

To assess the impact of using a different type of antenna, the same test was repeated by mounting a Topcon PG-S1 on the sled; the solutions were found to be perfectly comparable with no particular variations attributable to the use of a different type of antenna.

3.3 Test 3

The tests with the micrometric sled were repeated using real-time acquisitions (NRTK) (Figure 7) with the u-blox boards and the Topcon geodetic receiver (Hiper HR). Multi-constellation NRTK differential corrections (VRS mountpoints) were provided by the GPSUMBRIA network with RTCM messages via the internet (Ntrip protocol).

At each displacement of 1 cm, the antenna was left stationary in acquisition for approximately three minutes, until the path corresponding to the sides of the square was completed. All the receivers recorded HDOP values between 0.5 and 0.7.

The ublox boards demonstrated good solutions: 98.1% and 80.9% ambiguity-fixed solutions for the C099-F9P and C102-F9R cards respectively (compared to 92.3% obtained by the Hiper HR), (Figure 8). The presence of failed solutions for the real-time test was attributed to a momentary disconnection of the sending corrections service.

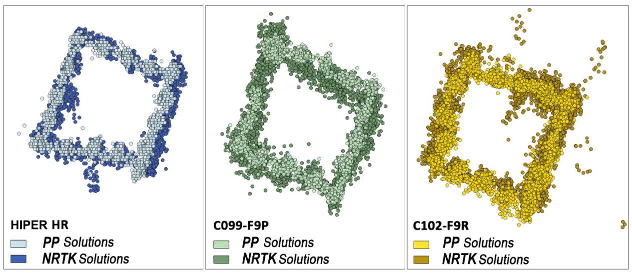

Figure 7. Graph of post-processed (PP) and NRTK solutions.

The differences with respect to the four sides (S_1, S_2, S_3, S_4) were determined for the estimates obtained from both differentiated and undifferentiated approaches. The positions of the four reference sides were defined by evaluating the vertex coordinates obtained from the post-processing of the geodetic receiver data.

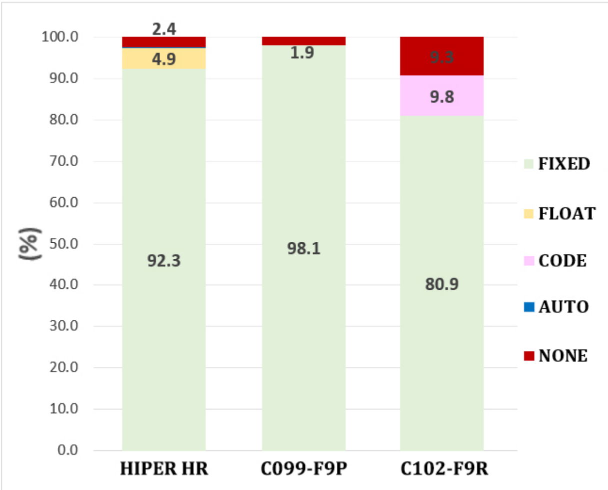

Figure 8. Relative frequency of NRTK solutions type.

The deviations related to the NRTK solutions are characterised by comparable values for the three sensors and range between 0.001m (value for Hiper HR) and 0.004m (value for the two u-blox sensors), (Table5). With regard to the differences from the four sides, the averages show comparable absolute values with differences of the order of millimetres (C102-F9R board has the highest values).
The relative frequency of differences for the three receivers is shown in histograms referring to interval classes of 0.001m (-0.015m to +0.015m), (Figure 9).

	Side	S_1	S_2	S_3	S_4
HR	Mean (m)	-0.002	0.000	-0.001	-0.002
	Sd (m)	0.001	0.002	0.001	0.003
C099	Mean (m)	0.002	0.001	0.001	0.000
	Sd (m)	0.002	0.004	0.002	0.003
C102	Mean (m)	0.004	-0.001	0.003	-0.003
	Sd (m)	0.003	0.004	0.002	0.002

Table 5. Mean and standard deviation of the differences of NRTK solutions from the imposed path.

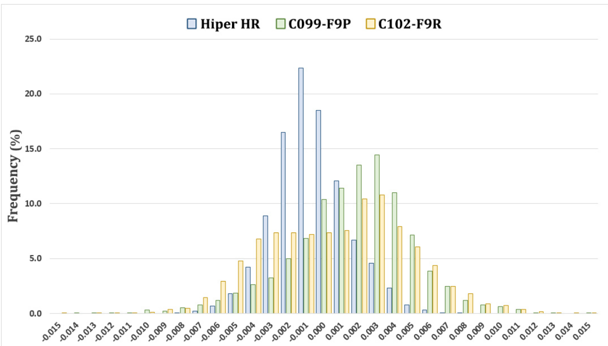

Figure 9. Relative frequency of deviations of NRTK solutions.

4. KINEMATIC TESTS

The last phase of the activity concerned the kinematic tracking of the trajectory of a vehicle. The u-blox devices were connected to u-blox multiconstellation antennas (ANN-MB-00) which were positioned on the vehicle in longitudinal alignment with respect to the Topcon Hiper HR (Figure 10). The kinematic tracks of low-cost sensors were compared with those obtained from the geodetic receiver.

The tests were carried out on different routes characterized by obstructions such as vegetation and tunnels but they were also repeated following the same roads to assess the repeatability of the solutions quality. Given the highly comparable results of the different tests conducted, the data for three tests are shown: two characterised by the same route (test1, test2) while the third (test3) relating by a longer route with different features (presence of several consecutive tunnels) (Figure 10, Figure 11).

The images show the positions obtained in test1 and test3: in green the fixed ambiguity solutions, in yellow the float solutions, in pink the DGNSS solutions (which correspond to densely built-up areas and/or areas characterised by the presence of dense vegetation), and in purple the Dead Reckoning (DR) solutions (which coincide with the route of the various tunnels).

Figure 10. Instruments for the kinematic tests, on the left; Real-time track of the u-blox application boards (test1), on the right.

As for C102-F9R board, it requires an initialization phase during which no INS/GNSS fusion can be achieved (cyan points in Figure 11); when the vehicle is subject to sufficient dynamics, the automatic IMU-mount alignment engine can estimate the IMU-mount misalignment angles.
In all the tests carried out, the C102-F9R sensor, thanks to the integration of the IMU data, was able to guarantee the continuity of positions without obvious drift event, retrieving the INS/GNSS solution immediately at each tunnel exit, even in the case of the test3 track characterised by several close tunnels (varying in length from 500m up to 1000m).

The graphs (Figure 12) show the percentages of the different solutions obtained, while Table 6 shows the mean value and standard deviations of the differences between the positions for the fixed solutions only (the post-processed -PP- Hiper HR track and the real-time one -NRTK- were taken as reference). In the case of test1, only data relating to the post-processed track were acquired for the geodetic receiver, while the real-time one is absent.

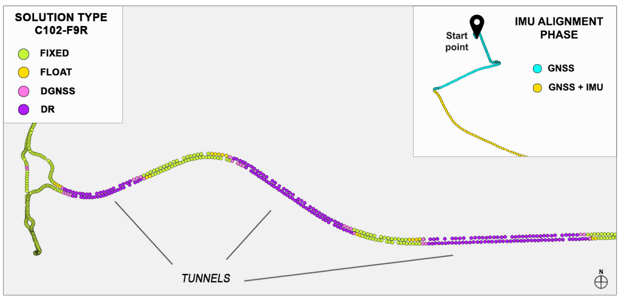

Figure 11. Real-time track of the C102-F9R application board (test3); initialization IMU phase (on the right).

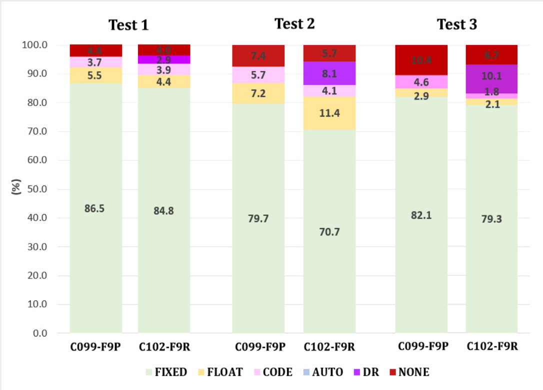

Figure 12. Relative frequency of the type of NRTK solutions obtained (test1, test2, test3).

Test	Δ (m)	PP HR - NRTK F9P	PP HR - NRTK F9R	NRTK HR - NRTK F9P	NRTK HR - NRTK F9R
1	Mean (m)	0.003	0.008	-	-
	Sd (m)	0.066	0.065	-	-
2	Mean (m)	-0.012	0.000	-0.021	-0.018
	Sd (m)	0.054	0.054	0.021	0.016
3	Mean (m)	0.025	0.015	0.008	0.002
	Sd (m)	0.068	0.066	0.013	0.011

Table 6. Mean and standard deviation of the solutions differences compared to the post-processed (PP) and real time (NRTK) Hiper HR track.

With the exception of singular areas in which the differences between the positions clearly deviate from the general trend of the solutions with values far above the average (Figure 13), the data show a rather homogeneous behaviour with deviations ranging between 0.050 m and 0.070 m in the case of the post-processed Hiper HR trajectory, while lower values are obtained when referring to the evaluations of real-time Hiper HR positions (standard deviations between 0.015m and 0.020m).

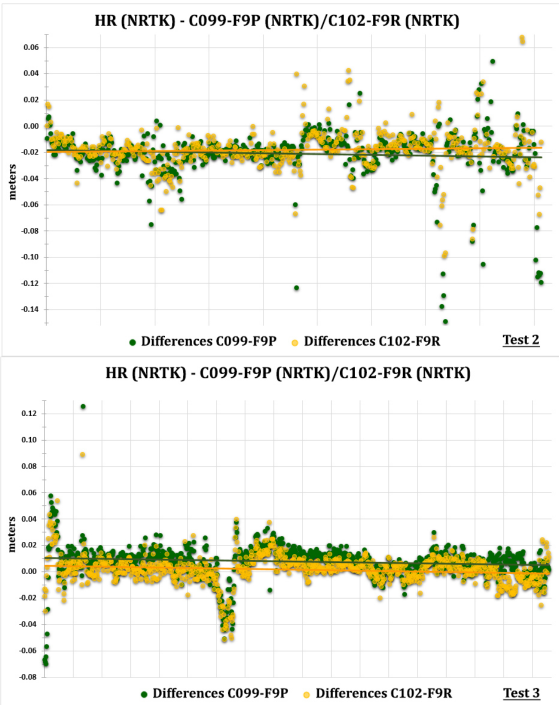

Figure 13. Displacement differences from real-time Hiper HR track (test2 and test3).

The relative frequencies of deviations for the different receivers with interval classes of 0.010m (-0.010m to 0.010m) were evaluated (Figure 14, Figure 15). The distributions are comparable both between receivers and among the different tests performed. The solutions obtained by tracking the vehicle over the longest route therefore confirmed the repetitiveness and consistency of the measurements obtained in the tests performed on the same track.

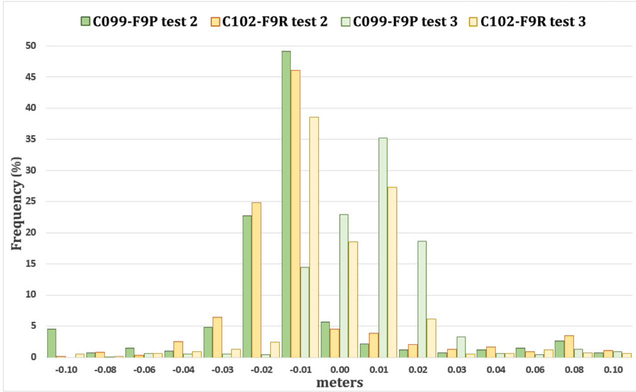

Figure 14. Relative frequency of differences between the post-processed Hiper HR track and the u-blox boards ones (test2, test3).

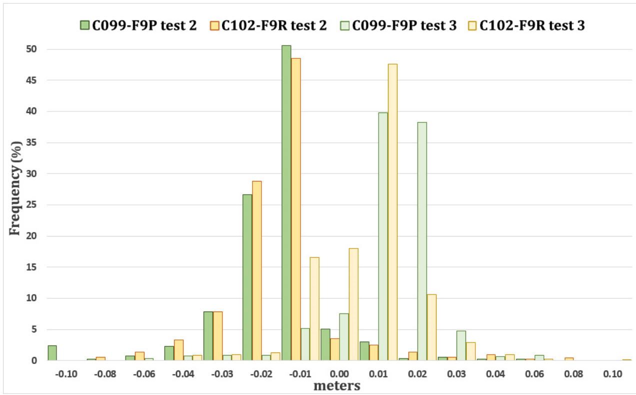

Figure 15. Relative frequency of differences between the real-time Hiper HR track and the u-blox boards ones (test2, test3).

5. CONCLUSIONS

The aim of this research activity was to test the performance of intermediate and low cost GNSS sensors in order to assess their possible application for precision positioning and navigation. Undifferentiated (PPP) and differentiated techniques were evaluated and compared; the results obtained independently in the different processes were compared in order to assess their congruence and verify their accuracy and reliability.

Considering the good quality of the GNSS multifrequency signals acquired from all the constellations, the tests conducted have generally shown repeatability and consistency of the measurements with homogeneous behavior and comparable values for the different sensors employed both with respect to displacement differences and standard deviations.
They have proved good sensitivity and reliability with performances comparable to geodetic class receivers in most cases. The data quality analysis confirmed the advantage of using multi-constellation: high number of tracked satellites, good DOP values, low multipath errors and a good signal-to-

noise ratio (SNR) with comparable values for all tested receivers.

As regards the PPP approach, it has provided solutions in a short time and satisfactory results when compared with the differentiated techniques; evaluations show high fixed ambiguity rates for all receivers. The standard deviations increase in the case of shorter measurement sessions (as is to be expected) but still provide good estimeates even in the most unfavourable cases, showing comparable values; it has emerged that longer occupation times affect the accuracy of the altimetric component more significantly than the planimetric one.

On the other hand, the application of NRTK techniques based on multi-constellation corrections from the GPSUmbria network ensured the stability of the solutions by providing satisfactory responses with homogeneous and comparable frequency distributions in the various cases (take into consideration the fact that low-cost multi-constellation antennas were used for the kinematic tracks with the vehicle). The Umbria GPS network has proved to be an essential geodetic infrastructure to support technical activities on the regional territory (Radicioni et al., 2022); more generally the use of NRTK methods, with network software that allows increasingly reliable phase ambiguity estimates in real time, enables the field of application of GNSS techniques to be extended to low-cost systems with significant benefits both in terms of economy (time and instrumentation) and accuracy. This makes it possible to expand the application field of GNSS techniques with particular reference to the possibility of adopting low-cost systems.
Regarding the C102-F9R sensor, it showed good performance in static and especially in kinematic tests; thanks to the integrated IMU, it manages to guarantee continuity in solutions even in areas where GNSS data is not available. In all tests, the evaluations obtained in these situations succeed in reconstructing the track without obvious drift event by garanting the INS/GNSS solution immediately at the exit of each tunnel travelled by the vehicle. In general, the solutions obtained by tracking the vehicle on routes with different lengths and types of obstructions demonstrated the repetitiveness and consistency of the measurements obtained in the tests performed on the same route.

The collected results are not to be considered definitive: further tests and analyses will have to be carried out in critical situations and different conditions in order to expand the amount of data available for a more complete evaluation and consideration of the use of low-cost sensors in technical fields. Future developments in this research activity include the study of the advantages to be gained from the hybridisation of PPP and RTK survey modes in mass-market devices (Wübbena et al., 2005; Robustelli et al., 2022; Hou et al., 2023).

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