Performance of Galileo for geodetic positioning under challenging signal reception conditions

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1. Abstract

The modern design of Galileo is promising enhanced performance compared to other Global Navigation Satellite Systems (GNSS). Several studies have already demonstrated the good performance of Galileo, which for certain positioning techniques proved to be superior compared to that of other GNSSs. Most of these studies evaluate the performance of Galileo under good observation conditions. In this study we assess Galileo's performance in challenging environments. For this purpose, we analyze data collected with geodetic receivers under tree canopies and in the presence of electromagnetic interferences (EMI). At a first level, the raw data are analyzed to infer the impact of these error sources on the tracking quality of the Galileo signals with respect to the signals of other GNSSs. At a second level, the observations are processed using relative carrier-phase positioning to assess the performance of each GNSS under unfavorable tracking conditions. According to the results, Galileo performs well in the tested environments. Moreover, according to several benchmarks concerning the signal tracking quality, Galileo showed a superior behavior compared to other GNSSs. To reach more generalized conclusions we analyze also data from the EUREF Permanent Network (EPN) collected with receivers of different architectures. The results of the analysis of these data are presented indicating that the tracking performance depends also on the processing techniques used in the receiver.

Keywords: GNSS, Galileo, Canopies, Electromagnetic interferences, EPN.

2. Introduction

In recent years, the number of launched Galileo satellites has increased significantly and the system is approaching its completion. As the number of operational Galileo satellites growths, an increasing number of users are exploiting the system in different environments. At the same time GPS, GLONASS and BeiDou are fully operational. This allows to make a comparison of the performance of the four Global Navigation Satellite Systems under both favorable and challenging tracking conditions. The performance of a GNSS depends mainly on the satellites' geometry and the characteristics of its signals, i.e. chipping rate, signal power and modulation method. These parameters are given for each GNSS in the following.

3. Characteristics of GNSS signals

3.1 Carrier frequencies

One of the fundamental characteristics of a GNSS are the carrier frequencies used to transfer the information required for positioning. GPS and GLONASS started their operation using two frequencies (L1/L2 and G1/G2). After their modernization, both systems are emitting also in a third frequency (L5, G3). Moreover, for the sake of interoperability, different GNNSs are sharing the same frequencies. For example, the primary frequencies of GPS (L1), Galileo (E1) and BeiDou

(B1) are all centered at 1575.42 MHz. Similarly, L5 (GPS), E5a (Galileo) and B2a (BeiDou) are centered at 1176.45 MHz. These details are shown in Figure 1.

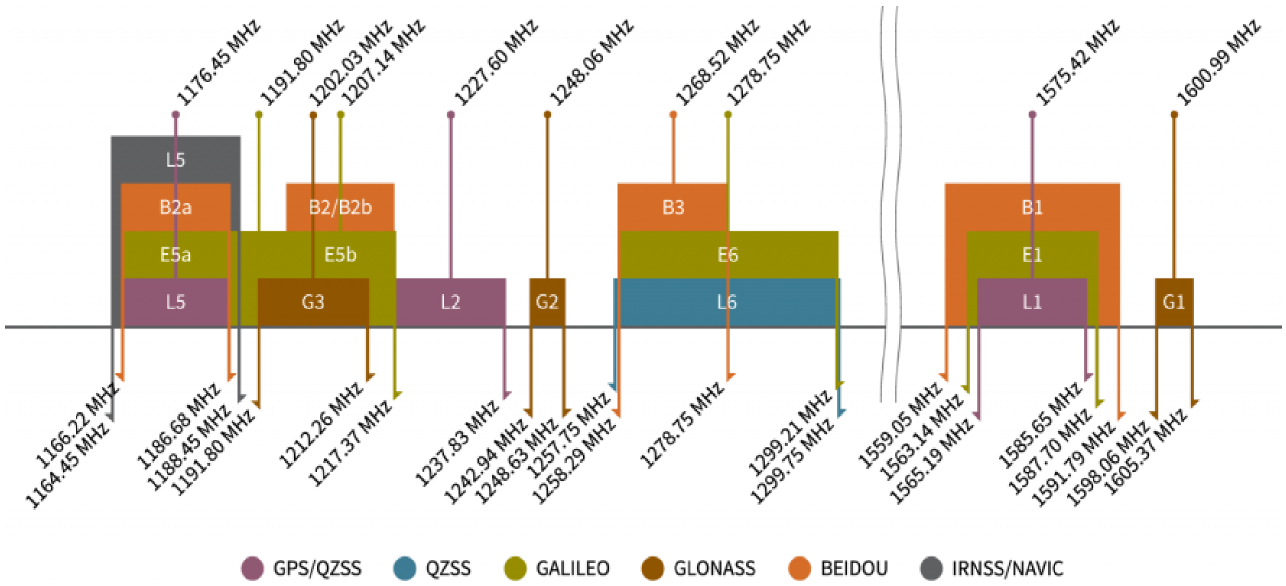

Fig. 1 Frequencies used by the main global and regional navigation satellite systems (source *www.tallysman.com*).

3.2 Signals and modulation methods

Two of the most important parameters affecting the performance of a GNNS are the characteristics of the ranging codes and the modulation schemes used for modulating the ranging and data codes onto the carriers.

The first important characteristic of a ranging code is its type. There are several types of codes used in GNSSs. For example, GPS uses m-sequences for the P(Y) code, while C/A is a Gold code. Each type of code has different autocorrelation and cross-correlation properties, that directly affect the tracking performance. The second crucial characteristic of a ranging code is its chipping rate, i.e. the number of transmitted chips per second. For example, the GPS C/A code is transmitted at a rate of 1.023 Mcps (Mega chips per second), whereas the P(Y) code is transmitted at a ten-times higher rate (10.23 Mcps), which corresponds to ten-times higher ranging precision. Modern GNSS signals often use high rates, for example L5 (the new civil signal of GPS), which is transmitted at a rate of 10.23 Mcps. The signals of the four GNSSs are listed in Table 1. Signals of particular interest in our study (modernized GPS signals and Galileo E5a+b) are marked bold.

Apart from the type and the rate of a certain ranging code, its performance depends also on the method used for its modulation. The most common modulation scheme among the GNSSs is Binary Phase Shift Keying (BPSK). Legacy GPS and GLONASS signals, as well as BeiDou-2 signals are modulated using exclusively BPSK. The modernized GPS and GLONASS signals and the signals of BeiDou-3 and Galileo are using also a more advanced modulation scheme called BOC (Binary Offset Carrier) or its variants TM BOC (Time Multiplexed BOC), CBOC (Composite BOC), AltBOC (Alternative BOC; Shivaramaiah et al. 2009) and TD-AltBOC: (Time Division AltBOC). In particular, Alt-BOC is offering exceptional performance (Simsky et al. 2006; Silva et al. 2012; Colomina et al. 2011; Luo et al. 2017). The modulation methods used in each GNSS are listed in Table 1, where BOC-based schemes are marked bold.

Table 1. GNSS signals (*based on: Montenbruck et al. 2017, Hegarty. 2017, Revnivykh et al. 2017*)

GNSS	Block	Signals	Modulations used *
GPS **	IIR IIR-M IIF III	L1 C/A, L1/L2 P(Y) L1 C/A, L1/L2 P(Y), **L2C** L1 C/A, L1/L2 P(Y), L2C, **L5** L1 C/A, L1/L2 P(Y), L2C, L5, **L1C**	BPSK, BPSK mux, TM**BOC**
GLN ***	M K1 K2	L1OF, L1SF, L2OF, L2SF L1OF, L1SF, L2OF, L2SF, L3OC L1OF, L1SF, L2OF, L2SF, L1OC, L1SC, L2OC, L2SC, L3OC	BPSK, **BOC**
BDS-2		B1-2, B2b, B3	BPSK
BDS-3		B1-2, B1, B2a, B2b, B3	BPSK, BOC, TM**BOC**, TD-**AltBOC**
GAL		E1, E6, E5a, E5b, **E5a+b**	CBOC, BPSK-BOC, **AltBOC**

(*) BPSK: Binary Phase Shift Keying, mux: multiplexed, TM: time multiplexed, BOC: Binary Offset Carrier, CBOC: Composite BOC, AltBOC: Alternative BOC, TD-AltBOC: Time Division AltBOC.
(**) GPS Military Codes are not listed
(***) GLONASS signals are identified by the frequency band (first two characters), the service type (O: open, S: authorized special) and the modulation type (F: FDMA, C: CDMA).

3.3 Signals' strength

Apart from the type of a ranging code, its transmission rate and modulation method, another critical parameter that influences its tracking performance is the power at which the satellite signal is received. The received signal strength depends mainly on the power at which the signal is transmitted from the satellite and the (free) space loss. The specified minimum received power levels of the main GNSS signals are given in Table 2. As we can see, the received power varies considerably among the different signals. For example, the received strength of the Galileo E1 signal is approximately two times higher than that of GPS L2C.

As known, the received signal strength directly affects the measurement precision. The stronger the signal, the higher the Signal-to-Noise Ratio (SNR); and the higher the SNR, the smaller the variance in the tracking lock loops (Gianniou and Groten, 1996). In our study, the SNR is widely used to assess the performance of the different GNSS signals.

Table 2. Received power of the main GNSS signals
(*after: Montenbruck et al. 2017, China Satellite Navigation Office. 2018*)

GNSS	Band	Signal	Power (dBW)
GPS	L1	C/A P(Y) L1C-P	-158.5 -161.5 -158.25
	L2	P(Y) L2C	-161.5[a] -163.0[b]
	L5	L5 I, Q	-157.9[c]

GLN	G1	C/A	-161.0
	G2	C/A	-161.0
GAL	E1	D(B) P(C)	-160.0
	E5	E5a E5b	-158.0
	E6	D(B) P(C)	-158.0
BDS	B1-2	OS	-163.0
	B2b	OS	-163.0
	B3I	OS	-163.0
(a) -164.5 for Block IIA/IIR, (b) -161.5 for Block III, (c) -157.0 for Block III			

4. Analysis strategy

In the present study the performance of Galileo in challenging environments is assessed relative to that of other GNSSs. In order to make a fair evaluation, certain comparison rules have been set. These rules are described in the following.

4.1 Comparison of SNR among GNSS

As mentioned in section 3.3 the SNR is a crucial parameter that influences the measurement quality of the satellite signals. However, when comparing the SNR of signals from different satellites, one should keep in mind that SNR depends on the elevation angle, particularly for elevations below 30^{o}. Moreover, under certain conditions, SNR can also vary with the azimuth of the satellite (e.g. due to different slant TEC values). Especially for measurements under tree canopies or close to sources of E/M interference, the azimuthal dependence of SNR can be very strong. For these reasons, in our study we compared SNR values solely from satellites having very similar elevation and azimuth angles. An example is shown in Figure 2, where comparable satellites are marked with red circles.

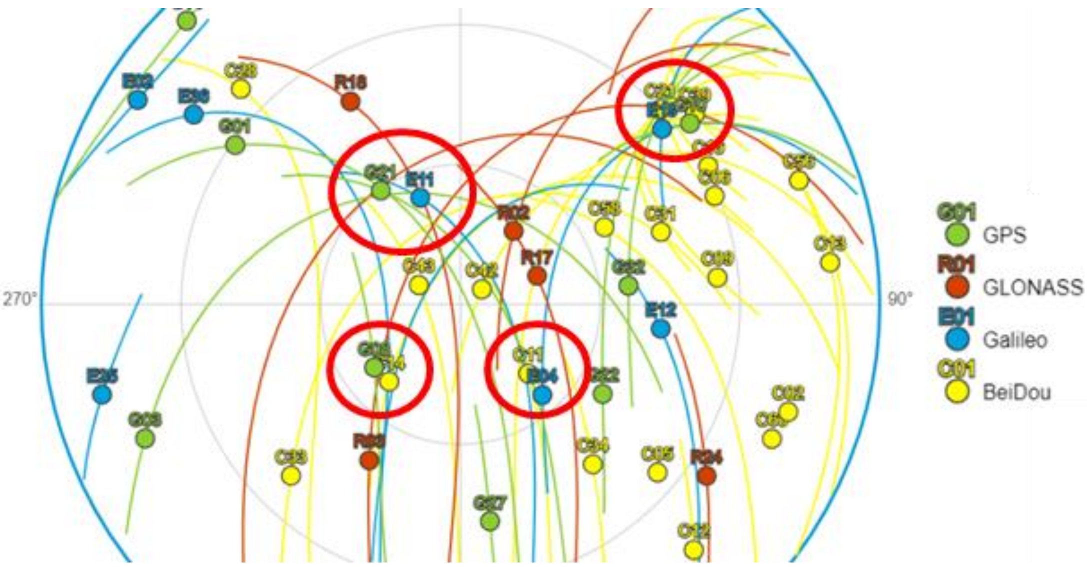

Fig. 2 Detail from a sky plot showing satellites that can be compared (marked with red circles).

4.2 Comparison of signals among GNSS

At the time when each GNSS was transmitting ranging codes at only two frequencies, the comparison of signals among different GNSSs was straightforward. For example, in the case of GPS and GLONASS, the GPS L1 frequency was compared to GLONASS G1 and the GPS L2 frequency was compared to GLONASS G2. Nowadays, each GNSS is using three frequencies and the comparison of the secondary frequencies is somewhat ambiguous. For instance, the E5 signals of Galileo should be compared to the L2 or to the L5 signals of GPS? From a theoretical point of view, comparing E5 to L5 is more correct as these two carriers are centered at the same frequency (see Fig. 1). However, from a practical perspective, it seems more appropriate to compare E5 with L2. This is because of two (coupled) reasons: First, not all GPS satellites are transmitting L5 and second, the majority of the algorithms used for processing GPS carrier phase measurements are primarily using L1 and L2 observations, not L1 and L5. In our study we made both comparisons:

- E5 with L2 (which represents better the current status w.r.t. the existing processing algorithms)
- E5 with L5 (which represents better the future status w.r.t. the upcoming processing algorithms).

4.3 Comparison of coordinate errors among GNSS

In challenging environments, provided that a position estimate is available, the most important aspect from a practical point of view is the accuracy of the obtained coordinates. Considering that the number of usable satellites strongly differs among the GNSSs (e.g. 31 for GPS vs. 24 for Galileo) a question arising is how to make a fair comparison between solutions obtained from different GNSSs. From the users' perspective, the results can be directly compared to each other, without considering the different number of satellites used in each system. However, from a scientific point of view, if we want to assess the potential of advanced technologies used in modern (or modernized) GNSSs, comparisons between different GNSS should be made under comparable conditions. In our study we compared both:

- solutions obtained using all available satellites of each GNSS
- solutions obtained using the same number of satellites for each GNSS (selecting satellites that lead to comparable configuration and PDOP values).

5. Case studies

In order to assess the performance of Galileo in challenging environments, several test measurements have been conducted under tree canopies and close to sources of E/M interference. In the next sessions, the results from four representative cases are demonstrated: two cases under trees and two cases in the presence of E/M interferences. The measurements were conducted using Trimble R8s GNSS receivers and the baseline processing was done using Spectra Precision Survey Office ver. 5.50.

5.1 Measurements under tree canopies

The field measurements under tree canopies were conducted in Athens, Greece in December 2020. The first case is illustrated in Fig. 3. The reference receiver (base) was located in open sky and the rover receiver was located at a short distance from the base under a high pine tree. The satellites G16 and E31 were selected for the comparison as they had very similar elevation and azimuth angles throughout the measurement session, as shown in the sky plot of Fig. 3.

Fig. 3 Case 1a: Base in open sky (left), rover under canopy (middle) and paths of the satellites under comparison (right).

The SNR values of the satellites G16 and E31 are shown in Fig. 4. The upper part of the figure shows the SNR of the base receiver observing in the open sky. As can be seen, the SNR values of the primary frequencies (L1 and E1, in blue) are comparable, with E1 being slightly better. In contrast, E5 performs dramatically better than L2. The big difference in the SNR of E5 and L2 (almost 30 dB-Hz) can be explained by two main reasons:

- G16 at the time of the test was a Block IIR satellite, and, according to Table 2, the specified minimum received strength for the P(Y) on L2 is -164.5 dBW, i.e. more than 4 times weaker than the specified minimum strength of E5 (-158 dBW).
- P(Y) is encrypted and the tracking of L2 is being made using special techniques (e.g. Z-tracking and cross-correlation) which further reduce the SNR in the tracking loops.

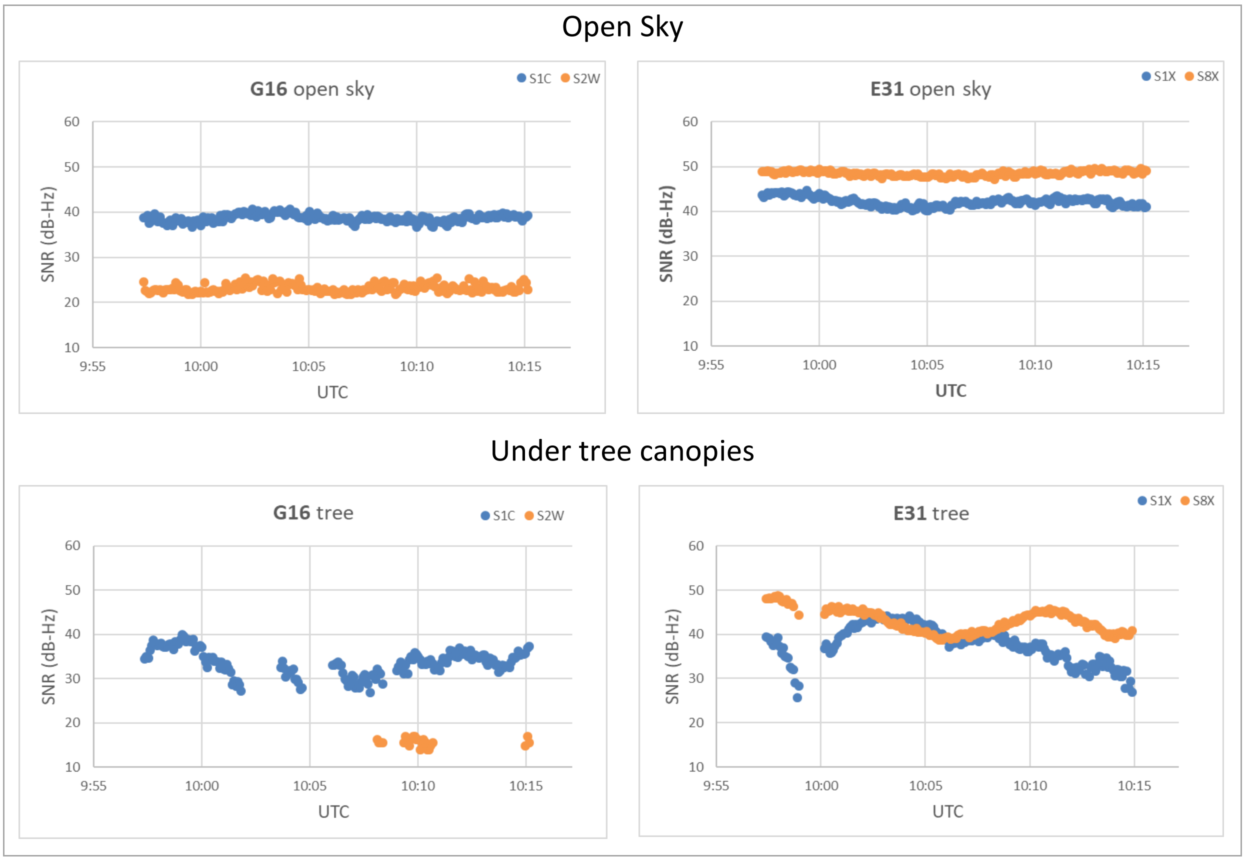

Fig. 4 Case 1a: SNR comparison between GPS and GAL in open sky and under tree canopy. Primary frequencies (L1, E1) are marked blue; Secondary frequencies (L2, E5) are marked orange.

In the upper part of Fig. 4 we also notice that, the secondary frequency of Galileo (E5) is stronger than the primary one (E1), in contrast with GPS, where L1 is stronger than L2. This finding is consistent with the values presented in Table 2.

The lower part of Fig. 4 shows the SNR of the rover receiver observing under the pine tree. It is obvious that under the tree, the L1 SNR is considerably reduced (up to 10 dB-Hz) w.r.t. the open sky, whereas the L2 SNR GPS dropped down below the tracking threshold. As a result, the tracking on L1 was significantly degraded while the tracking on L2 was not possible most of the time. In contrast, the Galileo signals were much less affected and could be tracked almost continuously.

In addition to evaluating the tracking performance of Galileo signals, we also investigated the quality of Galileo positioning performance. For this purpose, we processed the baseline from the base (open sky) to the rover (under canopy) five times: one time using all GNSSs and four times using each time only one GNSS. The first solution (all GNSSs) was used as reference solution for computing the coordinate errors. Fig. 5 shows the ΔE, ΔN and ΔH values (left) and the 3D coordinate errors (right). Regarding the horizontal coordinates, GLN performs best, followed by GAL, BDS and GPS. Regarding the 3D coordinate error GAL performs best, followed by BDS, GLN and GPS.

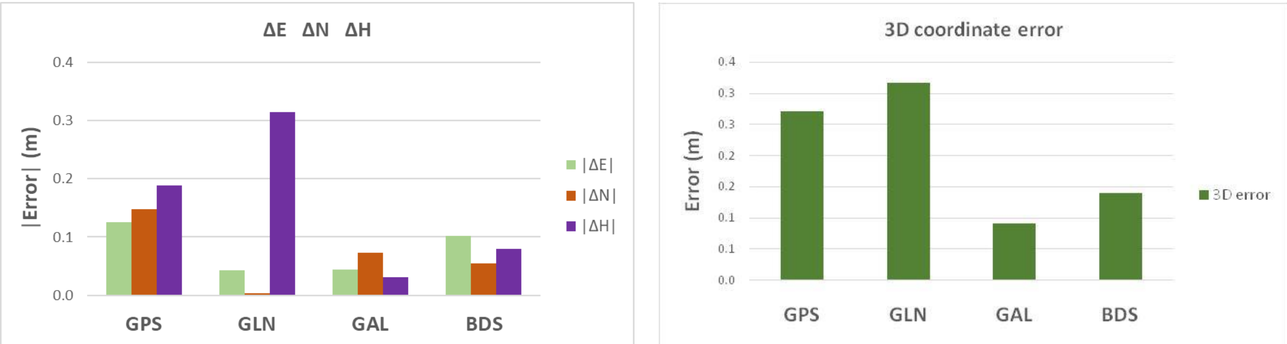

Fig. 5 Case 1a: Comparison of coordinate errors among GPS, GLN, GAL and BDS: ΔE-ΔN-ΔH (left) and 3D error (right).

The second case of measurements under trees is illustrated in Fig. 6. The reference receiver (base) was located in open sky and the rover receiver was located at a short distance from the base under a high brachychiton tree. The satellites G09 and E05 were selected for the comparison as they had very similar elevation and azimuth angles throughout the measurement session.

Fig. 6 Case 2a: Base in open sky (left), rover under canopy (middle) and paths of the satellites under comparison (right).

The SNR values for the satellites G09 and E05 are shown in Fig. 7. The upper part of the figure shows the SNR of the base receiver observing in the open sky. As can be seen, the SNR values of the primary frequencies (L1 and E1 in blue) are comparable, with E1 being again slightly better. In contrast to case 1a, here we consider L5 as the secondary frequency for GPS, and we compare E5 to L5 (rather than L2). It becomes very clear that E5 and L5 perform practically equally. The lower part of the Fig. 7 shows the SNR of the rover receiver observing under the tree. At first glance, the tree canopy does not degrade dramatically the depicted SNR values of the GPS satellite, as was the case in Fig. 4. This outcome confirms the better tracking performance of the L5X (i.e. L5 I+Q) signal compared to L2W (i.e. L2 P tracking under AS). In order to make a detailed comparison among all tracked GNSS signals, we computed the mean SNR value of comparable satellites for each signal observed: a) in the open sky and b) under the tree. The obtained results are summarized in Fig. 8. In terms of the primary frequencies (left part of Fig. 8) it comes out that E1 performs best (remains practically unaffected by the tree canopy) followed by L1 (which shows a small degradation of about 1 dB-Hz), B1 (which is considerably affected) and G1 which is extremely degraded. Regarding the secondary frequencies (right part of Fig. 8) the ranking (best to worst) is as follows: E5, L5, L2C, B2, L2, G2(P), G2(C/A).

Apart from the tracking performance evaluation, we investigated the Galileo positioning performance following the same scheme as in case 1a. Fig. 9 shows the ΔE, ΔN and ΔH values (left) and the 3D coordinate errors (right). GAL performs best in terms of both horizontal and 3D errors, followed by GPS, GLN, and BDS. Noting that the scale of Y-axes in Fig. 9 is logarithmic, the large differences in the coordinate errors among the four GNSSs become obvious. Some details that are worthy to mention are: a) The default GPS solution was a float one; one satellite had to be excluded to get a fixed solution b) Due to the bad reception of the GLN signals, only few satellites were available and for less time than the required duration for a fast-static session; This explains

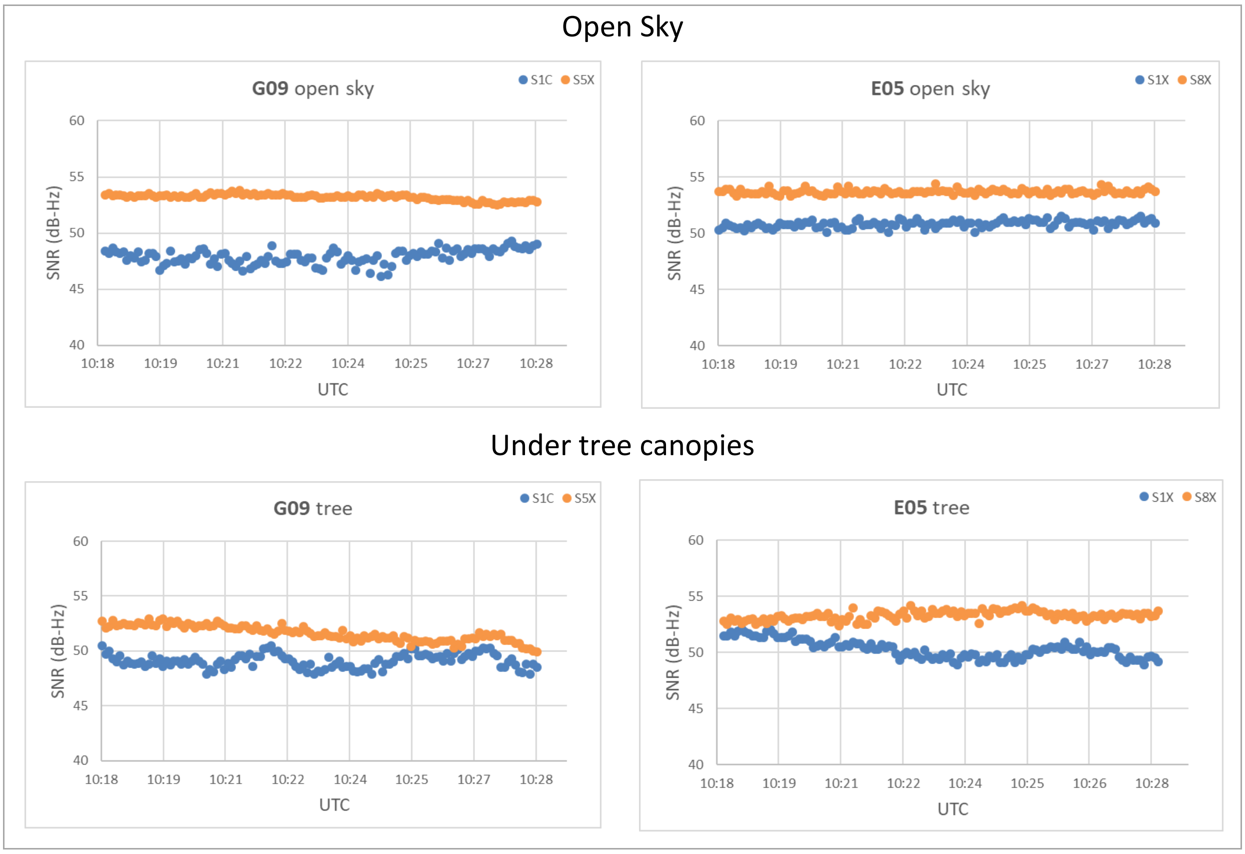

Fig. 7 Case 2a: SNR comparison between GPS and GAL in open sky and under tree canopy. Primary frequencies (L1, E1) are marked blue; Secondary frequencies (L5, E5) are marked orange.

why the obtained solution had a high RMS and is not reliable (~6 m 3D error) c) Only three BDS satellites were tracked on both frequencies (B1 and B2); another pair of satellites were tracked only in B1 for a limited amount of time; This explains why the obtained solution was a float one. Of course, the results of this experiment should not be generalized.

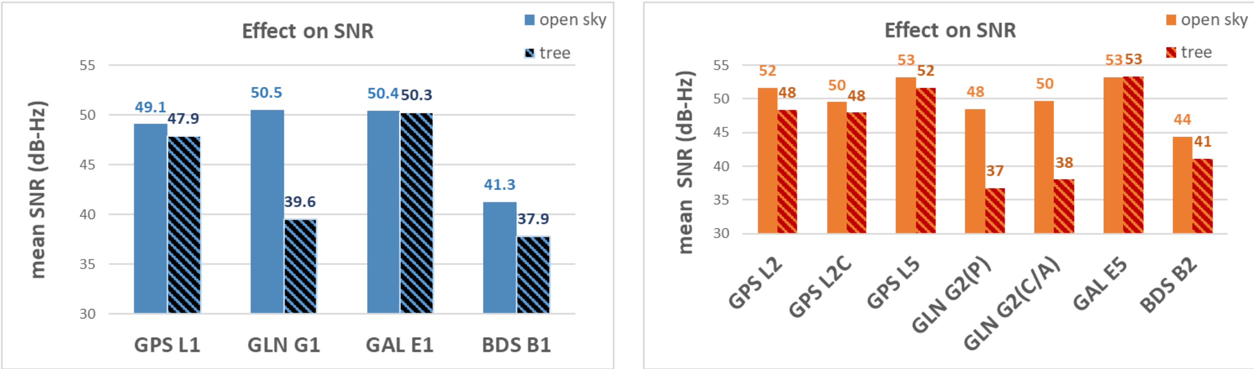

Fig. 8 Case 2a: SNR comparison between GPS, GLN, GAL and BDS in open sky and under tree canopies for the primary frequencies (left, in blue) and the secondary frequencies (right, in orange).

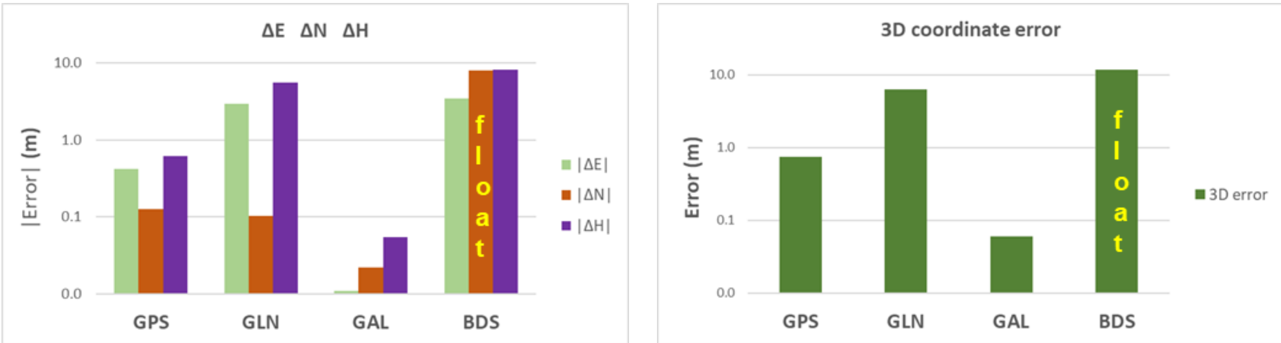

Fig. 9 Case 2a: Comparison of coordinate errors among GPS, GLN, GAL and BDS: ΔE-ΔN-ΔH (left) and 3D error (right).

5.2 Measurements in the presence of E/M interferences

The field measurements close to sources of E/M interferences (EMI) were conducted in Athens, Greece in May 2022. In this section, two representative cases are analyzed. In both cases, a permanent reference station (HEPOS station 098A equipped with a Trimble Alloy receiver) was used as base for solving the baselines. This reference station was located at a distance of 4 km from the rover receiver. This short distance ensures that the atmospheric conditions at the base and rover were similar. In addition, the base station was unaffected from E/M interferences. The first case is illustrated in Fig. 10. The rover receiver was placed under an electricity pylon. The following pairs of satellites (having very similar elevation and azimuth angles throughout the measurement session) were used for the comparison among the GNSSs: G21-R02 (GPS vs. GLN), G21-E11 (GPS L1/L2 vs. GAL), G10-E19 (GPS L1/L5 vs. GAL) and G21-C11 (GPS vs. BDS).

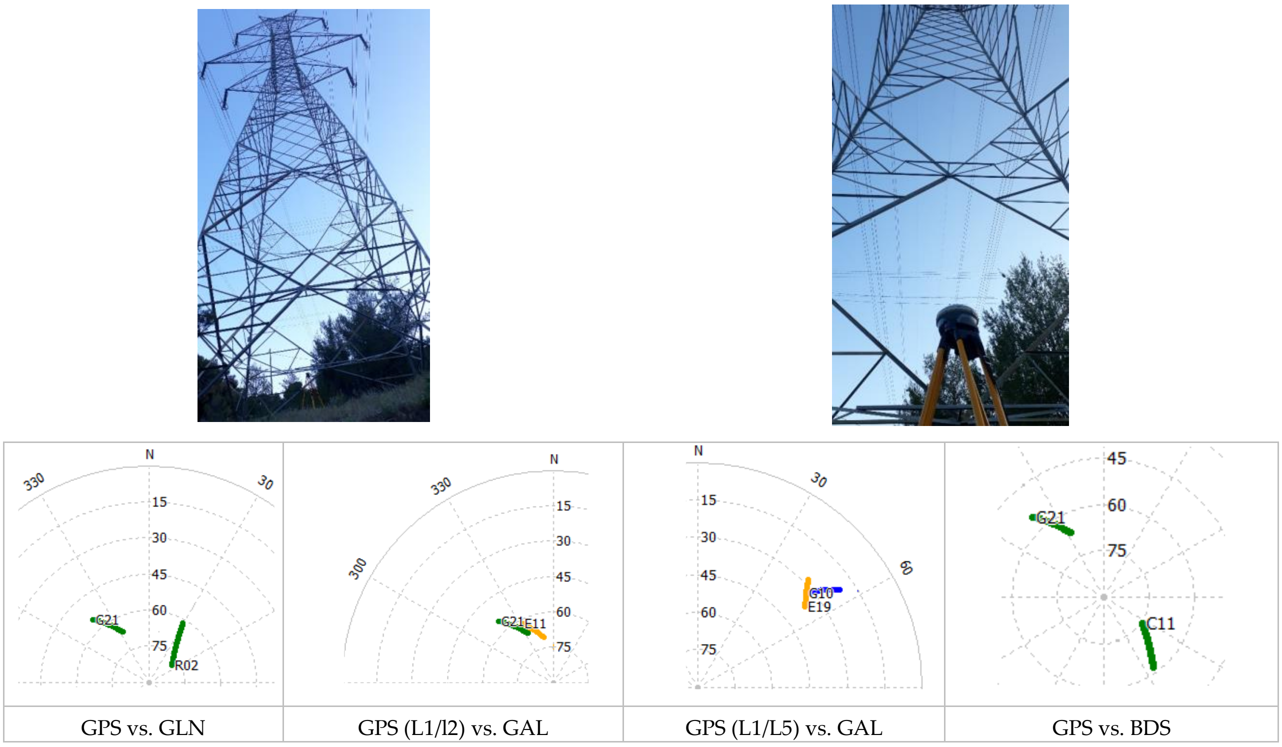

Fig. 10 Case 1b: Location of the rover under a power line pylon and paths of the satellites under comparison.

The comparison between the GPS and GLN satellites is illustrated in Fig. 11, which depicts the SNR values of the satellites G21 and R02. The upper part of the figure shows the SNR of the base receiver observing in an open sky environment free from EMI. As can be seen, the SNR values of the GLONASS satellite are higher than those of the GPS satellite. Moreover, the SNR of the secondary frequency of GLONASS (G2) is only 2-3 dBW lower that the SNR of the primary frequency (G1). In contrast, the secondary frequency of GPS (L2) is much weaker (6-7 dBW) than the primary one (L1). The bigger difference between the SNR of primary and secondary frequencies of G21 and R02 can be explained by two main reasons:

- G21 at the time of the test was a Block IIR satellite, and, according to Table 2, the specified minimum received strength for the C/A in L1 is -158.5 dBW, whereas the corresponding value for the P(Y) on L2 is 6 dBW lower. In contrast, the nominal signal strengths of G1 and G2 are equal.
- P(Y) is encrypted and the tracking of L2 is being made using special techniques (e.g. Z-tracking and cross-correlation) which further reduce the SNR in the tracking loops.

The lower part of Fig. 11 shows the SNR of the rover receiver observing under the electricity pylon. The impact of the E/M noise is clearly reflected in the variations of the SNR of all signals. The tracking of the GLONASS satellite is less affected compared to the GPS satellite, whereas the mostly affected signal is L2 P(Y) which can be attributed to the aforementioned reasons. It is also noteworthy that the fluctuations of the L2-SNR are quite strong exceeding 10 dBW.

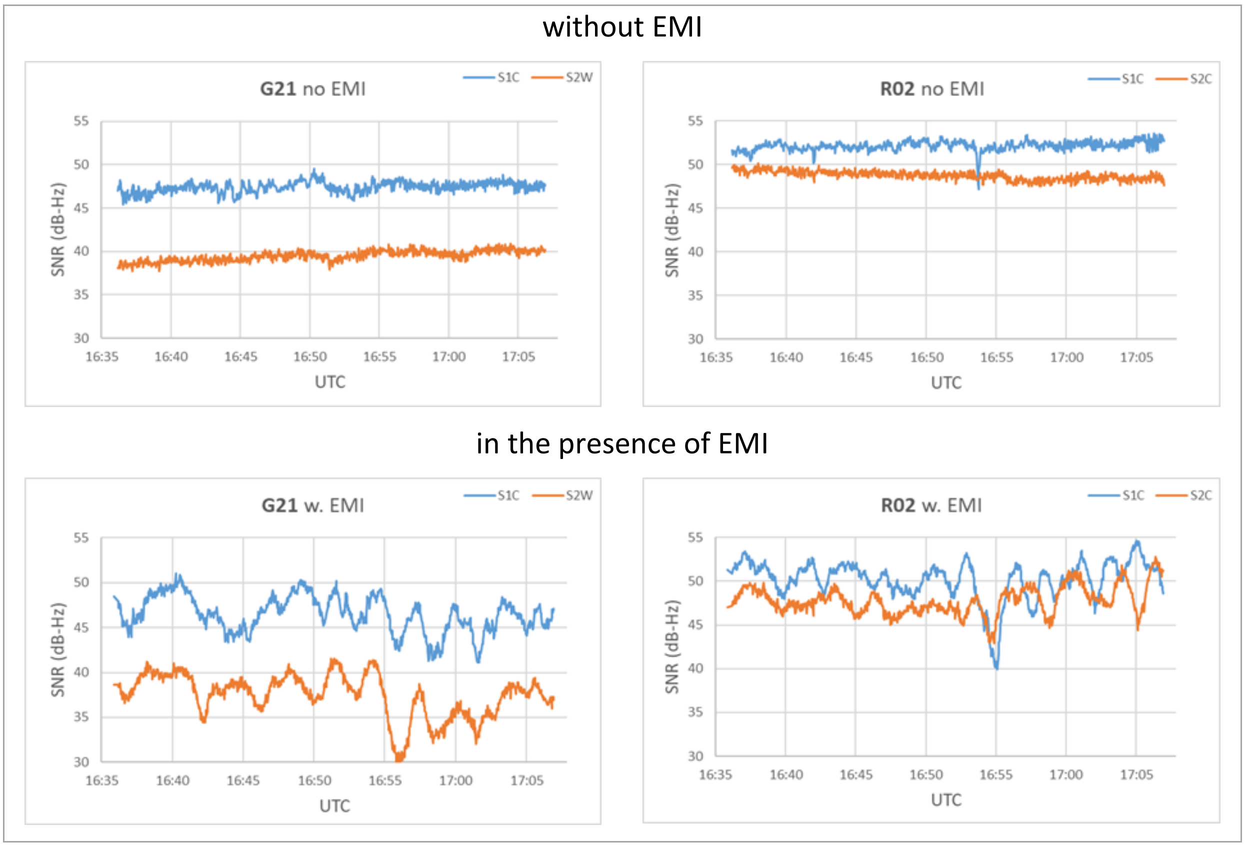

Fig. 11 Case 1b: SNR comparison between GPS and GLN with and without EMI. Primary frequencies (L1, G1) are marked blue; Secondary frequencies (L2, G2) are marked orange.

A comparison between GPS and GAL satellites is shown in Fig. 12-13. Fig. 12 compares the satellite G21 (which does not emit L5) with the satellite E11, i.e. E5 is compared to L2. Fig. 13 compares the satellite G10 (which emits L5) with the satellite E19, i.e. E5 is compared to L5. In the upper part of Fig. 12, we can see that the main difference between G21 and E11 in the absence of EMI is that E5 is stronger than E1, and approximately 10 dB-Hz stronger than L2. This behaviour has been already observed and explained in Fig. 4. In the lower part of Fig. 12 we can see that the GPS signals (and mainly L2) are more affected by the EMI compared to the GAL signals. The situation is quite different in Fig. 13, in which the L5 is considered instead of L2. Both in the absence of EMI (upper part of Fig. 13) and in the presence of EMI (lower part of Fig. 13), L1 and L5 perform more or less equally and comparably to E1 and E5. Comparing the lower parts of Fig. 12 and Fig. 13 it comes out that that L5 performs significantly better than L2.

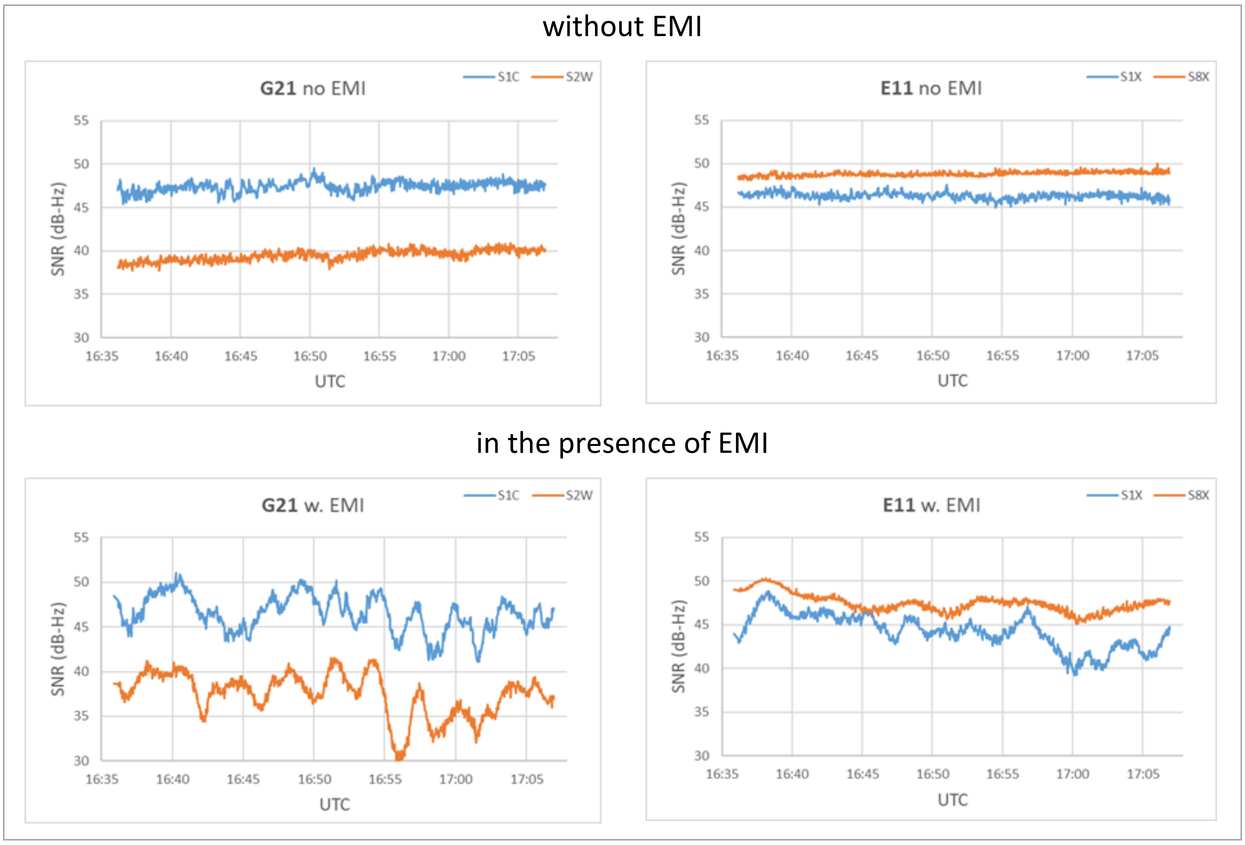

Fig. 12 Case 1b: SNR comparison between GPS and GAL with and without EMI. Primary frequencies (L1, E1) are marked blue; Secondary frequencies (L2, E5) are marked orange.

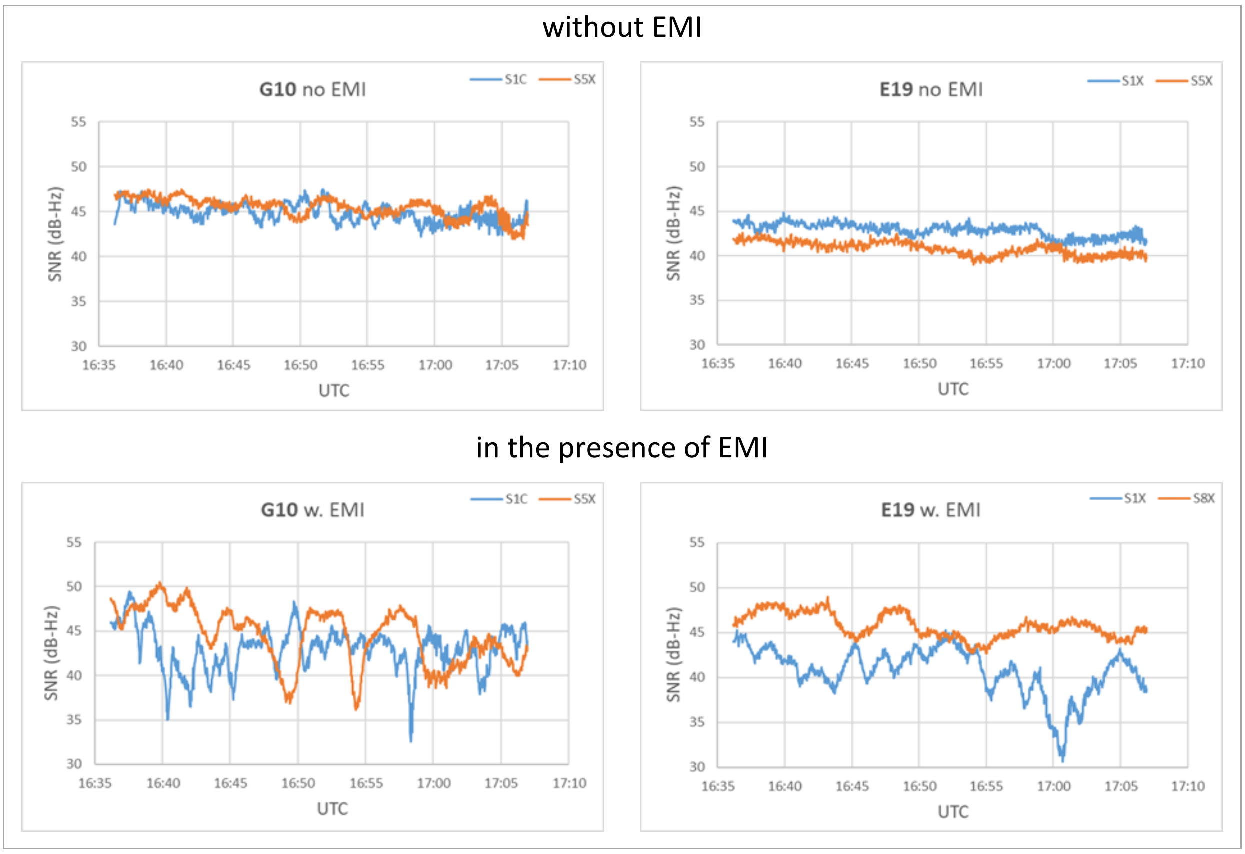

Fig. 13 Case 1b: SNR comparison between GPS and GAL with and without EMI. Primary frequencies (L1, E1) are marked blue; Secondary frequencies (L5, E5) are marked orange.

The comparison between GPS and BDS satellites is given in Fig. 14, which compares the satellite G21 with the satellite C11. The upper part of Fig. 14 shows that the main difference between G21 and C11 in the absence of EMI is that B2 is stronger than B1, and approximately 10 dB-Hz stronger than L2. It is noteworthy that a similar behaviour was detected for Galileo E5 and E1 and L2 (upper part of Fig. 12). In the lower part of Fig. 14 we can see that L1 and B1 are similarly affected by the EMI, whereas L2 seems more vulnerable to EMI compared to B2, a result that can partly be attributed to the encryption of P(Y) and higher signal strength of B2 compared to L2 (-163 dBW vs. -164.5 dBW).

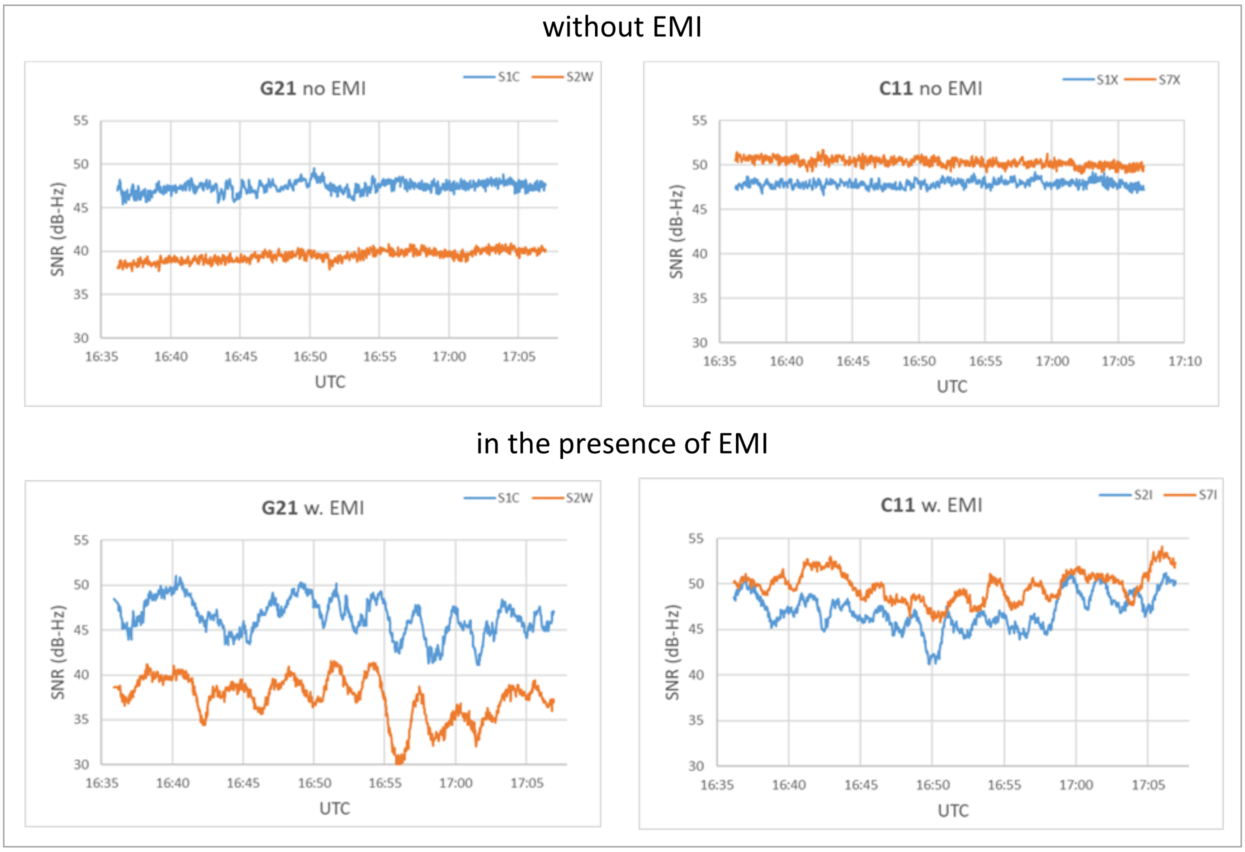

Fig. 14 Case 1b: SNR comparison between GPS and BDS with and without EMI. Primary frequencies (L1, B1) are marked blue; Secondary frequencies (L2, B2) are marked orange.

In order to facilitate the comparison among all GNSSs, Fig. 15 illustrates the impact of the EMI on each GNSS. Since the impact of EMI on our data is characterized by the fluctuation of the SNR, we used the standard deviation of SNR (σSNR) to quantify the impact of EMI's on each GNSS signal. The left part of Fig. 15 refers to the primary frequencies (L1, G1, E1, B1), while the right one refers to the secondary frequencies (L2-L5, G2, E5, B2). It can be seen that the primary frequencies are more or less equally affected, whereas the secondary frequencies of GLN, GAL and BDS are considerably less affected (in an absolute manner) compared to GPS. Having a more detailed look at Fig. 15 we see that the smallest SNR-variations are those of E5. Moreover, Galileo shows the smallest SNR variations (both in E1 and E5) compare to GPS, GLN and BDS also in the absence of EMI.

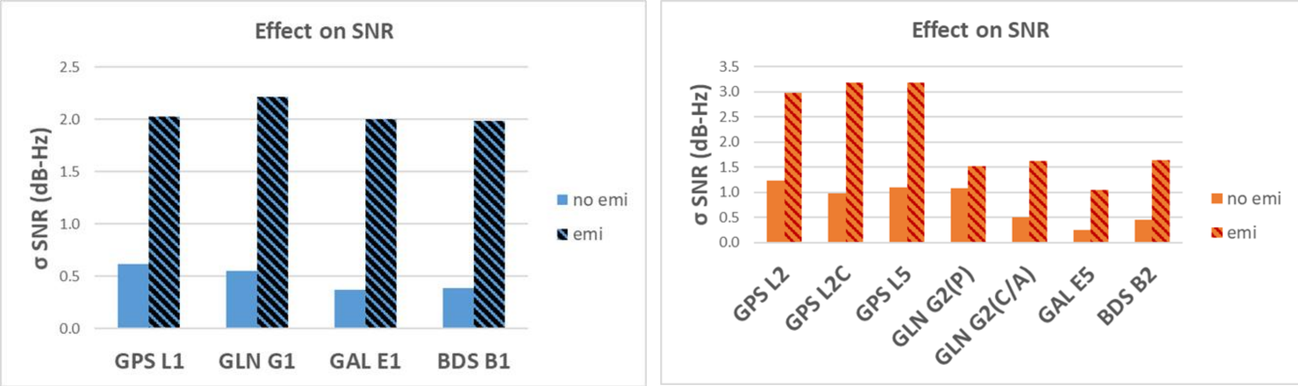

Fig. 15 Case 1b: SNR comparison between GPS, GLN, GAL and BDS with and without EMI for the primary frequencies (left, in blue) and the secondary frequencies (right, in orange).

The measurements below the electricity pylon have demonstrated the impact of the EMI on the reception of the satellite signals. However, the steel elements of the pylon may have an additional effect on the received signal quality than that of the EM field. For this purpose, we conducted another test measurement below the power lines but at a distance of 100m from the closest pylon. The location of this test measurements is shown in Fig. 16. Following the processing scheme described in section 5.1, we processed the baseline from the reference station (open sky) to the rover (under the power lines) five times: one time using all GNSSs and four times using each time only one GNSS. The first solution (all GNSSs) was used as reference solution for computing the coordinate errors. Moreover, for the reasons explained in section 4.3, the processing was made following two scenarios: a) using all available satellites of each GNSS and b) using the same number of satellites for each GNSS having similar PDOP values. Fig. 17 shows the obtained ΔE, ΔN and ΔH values (left) and the 3D coordinate errors (right) for the scenario a) (upper part of Fig.) and the scenario b) (lower part of Fig.). It can easily be seen that in both scenarios Galileo performs better than any other GNSSs. Its superiority is even better in the second scenario, i.e. when the same number of satellites is used for each GNSS. It is worthy to mention that the statistics of GAL are the same in both scenarios. This is because Galileo was the system with the lowest number of observed satellites (i.e. 6, which was used as the common number of satellites among the different GNSSs in the second scenario). Thus, the Galileo baseline solution is the same in both scenarios.

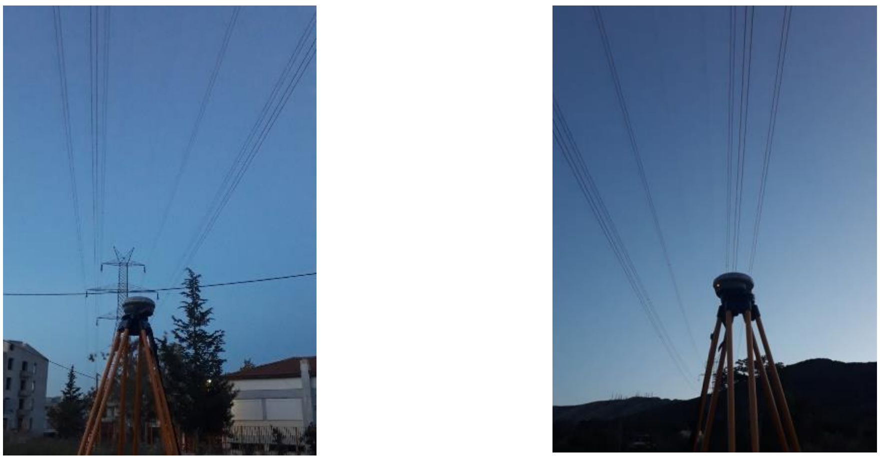

Fig. 16 Case 2b: Location of the rover under the power lines.

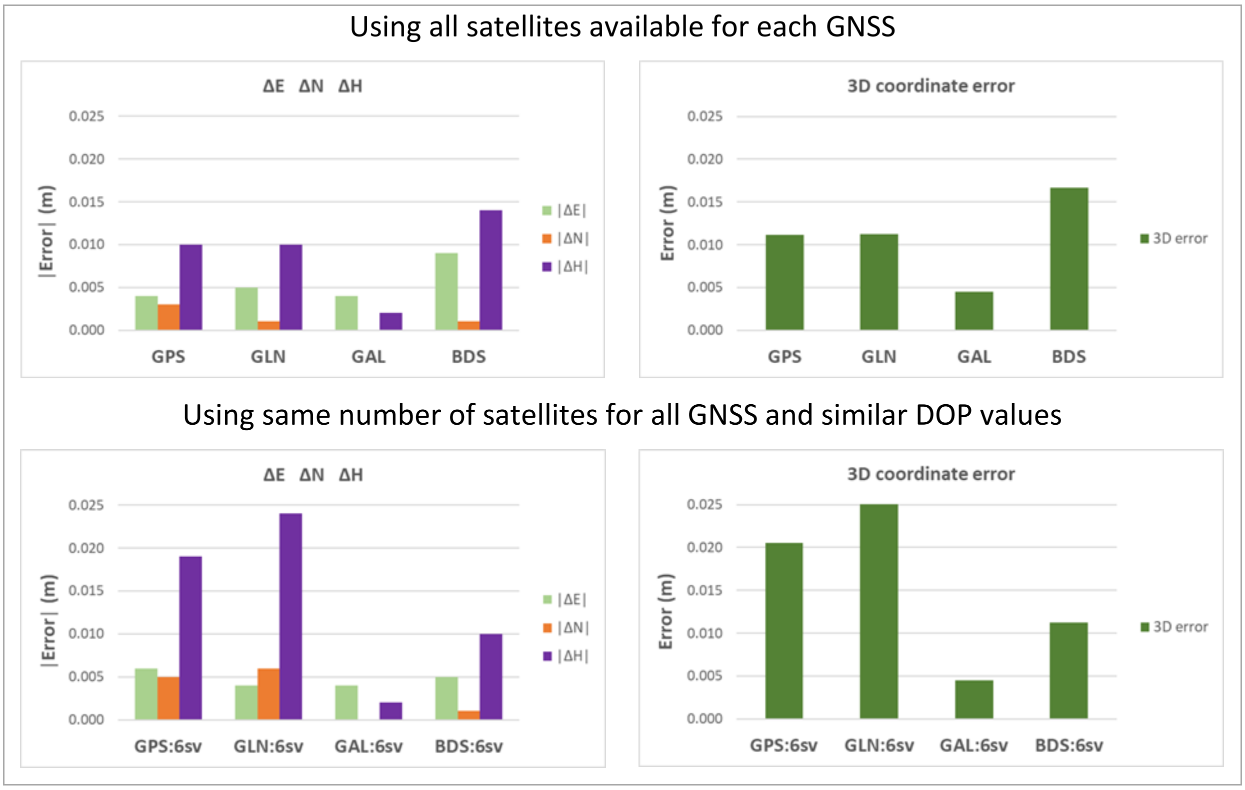

Fig. 17 Case 2b: Comparison of coordinate errors among GPS, GLN, GAL and BDS: ΔE, ΔN and ΔH (left) and 3D error (right).

5.3 Evaluation based on EPN data

As it is known, the quality of the GNSS observations depends not only on the characteristics of the tracked signal, but also on the receiver's architecture (hardware, signal processing methods etc.). In order to reach more generalized conclusions on the quality of the Galileo observations, we analyzed data collected with receivers of different architectures. For this purpose, we examined a significant amount of data from the EUREF Permanent Network (EPN; Bruyninx et al., 2019). In the following, some characteristic examples are presented. Among the various quality indicators (maximum number of observations, number of missing epochs, observed/expected observations percentage) we decided to use the number of cycle slips (CS) for assessing the tracking performance. In our analysis we distinguished between two cases: a) stations showing a stable performance within the examined time period and b) stations exhibiting significant performance variations due to equipment changes.

Fig. 18 shows the number of cycle slips for each GNSS from January 2021 to April 2022 for four stations belonging to the first group (AQUI, AGRI, ARJ6 and CEBR). During this time-period, no equipment changes took place at these stations (with the exception of a firmware change at CEBR). Comparing the plots of the four stations, it can be clearly seen that there are significant differences in the tracking performance of each GNSS among the four stations: At station AQUI the best-performing GNSS is BDS followed by GLN, GPS and GAL. At stations ARGI and ARJ6 the best-performing GNSS is GAL followed by GPS, BDS and GLN. At station CEBR the best-performing GNSSs are BDS and GAL, followed by GPS and GLN. The details of the equipment used on each station as well as the ranking of the GNSSs with respect to the number of cycle slips are summarized in Table 3.

Fig. 18 Number of cycle slips for GPS, GLN, GAL and BDS at EPN stations AGRI, AQUI, ARJ6 and CEBR.

Table 3. EPN stations of Fig. 18: Receiver model, firmware version and GNSS ranking w.r.t. the number of cycle slips.

Station	Receiver	Firmware	GNSS ranking
AQUI	LEICA GR30	4.20/7.30	BDS-GLN-GPS-GAL
ARGI	Trimble Net R9	5.22	GAL-GPS-BDS-GLN
ARJ6	Trimble Net R9	5.45	GAL-GPS-BDS-GLN
CEBR	Septentrio Polarx5TR Septentrio Polarx5TR	5.3.2 5.4.0	BDS-GAL-GPS-GLN

Six representative cases of EPN stations at which equipment changes took place within the time period under investigation are given in Fig. 19. The stations' codes, the receiver model and firmware (FW) are given in the first three columns of Table 4, respectively. In Fig. 19 the green vertical lines denote receiver changes and blue vertical lines denote changes in the receiver configuration (including firmware). Combining the information in Fig. 19 and in Table 4 it comes out that:

- The change of FW at station ACOR reduces the number of CS in BDS but it increases the number of CS in GAL.
- The change of FW at station ALBA reduces the number of CS in GLN but it increases the number of CS in GPS and GAL.
- The (second) change of receiver at station AXPV decreases the number of CS in GLN but it increases the number of CS in GPS and GAL.
- The change of FW at station BACA reduces the number of CS in BDS and GAL but it increases the number of CS in GPS.
- The change of receiver at station BRMF decreases dramatically the number of CS in BDS but it increases the number of CS in GLN and GAL.
- The change of FW at station HOFN reduces the number of CS in GAL and BDS without altering the performance for GPS and GLN.

The ranking of the GNSSs w.r.t. the number of cycle slips is given in last column of Table 4.

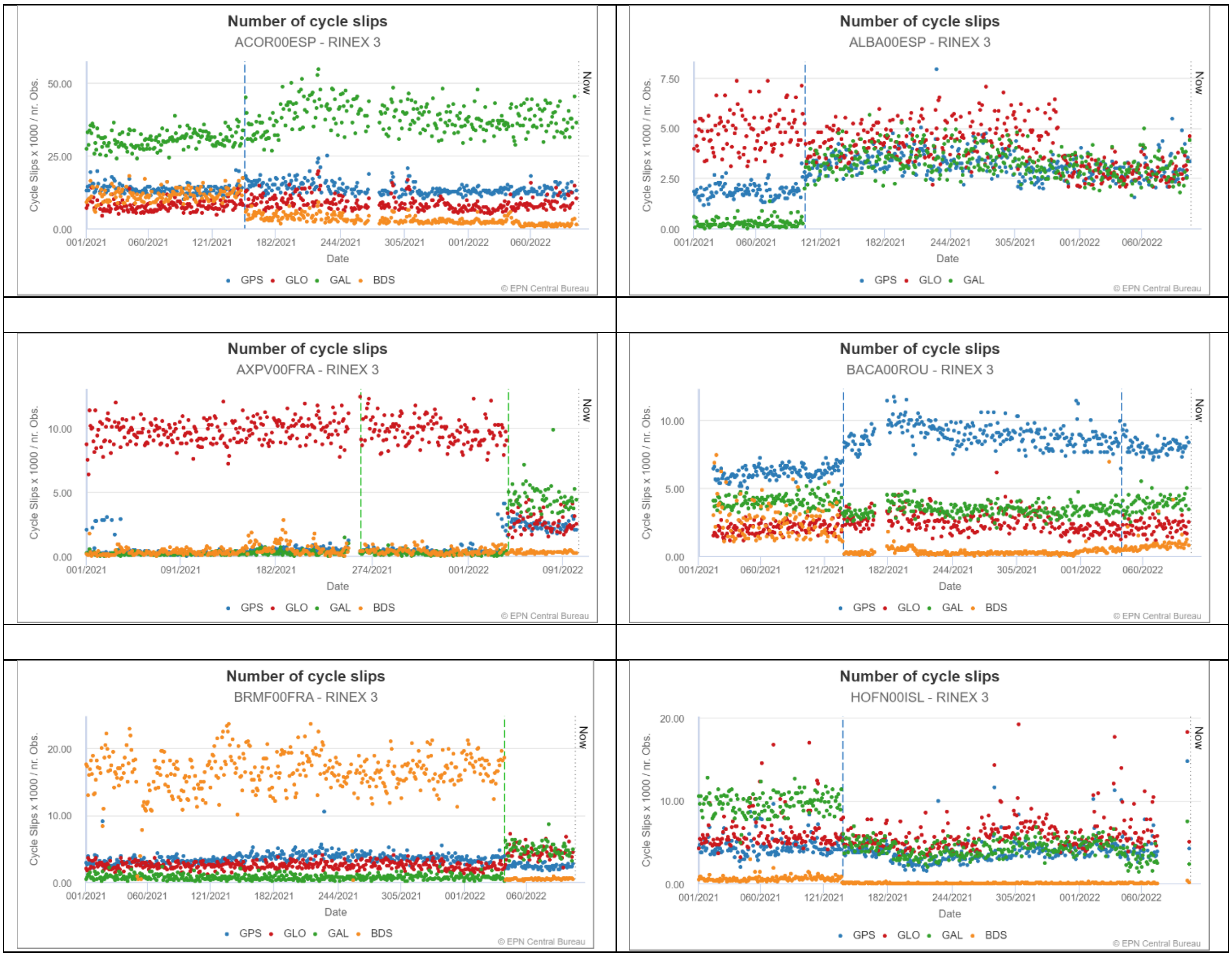

Fig. 19 Number of cycle slips for GPS, GLN, GAL and BDS at EPN stations ACOR, ALBA, AXPV, BACA, BRMF and HOFN.

Table 4. EPN stations of Fig. 19: Receiver model, firmware version and GNSS ranking w.r.t. the number of cycle slips.

Station	Receiver	Firmware	GNSS ranking
ACOR	Leica GR50	4.31/7.403	GLN-BDS-GPS-GAL
	Leica GR50	4.50/7.710	BDS-GLN-GPS-GAL
ALBA	LEICA GR10	3.11/6.524	GAL-GPS-GLN
	LEICA GR10	3.11/6.713	GPS-GAL-GLN
AXPV	Trimble Net R9	5.37	GAL-BDS-GPS-GLN
	Trimble Net R9	5.37*	GAL-BDS-GPS-GLN
	Leica GR50	4.51	BDS-GPS-GLN-GAL
BACA	Leica GR50	4.31/7.403	GLN-BDS-GAL-GPS
	Leica GR50	4.50/7.710	BDS-GLN-GAL-GPS
	Leica GR50	4.52/7.711	BDS-GLN-GAL-GPS
BRMF	Leica GR25	4.31	GAL-GLN-GPS-BDS
	Leica GR50	4.51	BDS-GPS-GLN-GAL
HOFN	Leica GR50	4.31/7.403	BDS-GPS-GLN-GAL
	Leica GR50	4.50/7.710	BDS-GPS-GAL-GLN

(*) replacement with same receiver & firmware

6. Conclusions

The main results of the analysis of the test measurements under the tree canopies are summarized as follows. Regarding the primary frequencies, E1 and L1 performed best (E1 slightly better) remaining almost unaffected by the canopies; B1 was considerably more affected and G1 was mostly affected. Regarding the secondary frequencies, E5 performed dramatically better than L2, but only slightly better than L5, which demonstrates the importance of the GPS modernization. B2 was slightly more affected, whereas G2 was the most affected.

The main results of the analysis of the test measurements in the presence of electromagnetic interferences can be outlined as follows. The primary frequencies E1, L1, G1 and B1 performed more or less similar. Regarding the secondary frequencies E5 performed considerably better than L2, L5, G2 and B2.

Regarding the positioning performance, the Galileo solution always showed the best performance in all cases (tree canopies, EMI), exhibiting a considerably smaller 3D coordinate error than any other GNSS.

The comparative analysis of data from several EPN stations showed that the tracking performance of each GNSS depends also on the receiver architecture, even on the version of the firmware running on the receiver. Based on the examined stations, GAL and BDS show usually the best tracking performance with respect to the number of cycle slips. Of course, one should keep in mind that EPN stations are using an elevation cut-off mask of 0 degrees, which considerably increases the number of cycle slips. Rover receivers are using elevation masks of ~13 degrees, which strongly reduces the appearance of cycle slips.

To conclude, our research indicated the good performance of Galileo under challenging signal reception conditions. In many cases Galileo's performance was superior to that of the other GNSSs. To draw more generalized conclusions, more measurements are planned under different conditions (different kinds of tree canopies and electromagnetic interferences) using a wide range of receivers of different architectures.

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