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Impact of Galileo Observations on the Position and Ambiguities Estimation of GNSS Reference Stations

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***Abstract*—Development of Galileo navigation system has caused that it is increasingly used in various areas. One of the most important of them is precise positioning of the reference networks. In this paper we present the impact of Galileo observations on the differential precise positioning as well as ambiguities resolution of selected GNSS stations. We tested five different solutions: GPS-only, Galileo-only, GPS/Galileo, GPS/GLONASS and GPS/GLONASS/Galileo. Calculations were performed using Bernese 5.2 software. Results indicate that the best positioning results are possible when the GPS and Galileo observations are used together, excluding GLONASS. We obtained standard deviation below 2 mm for North and East coordinates and below 6 mm in Up direction. Moreover, when GPS/Galileo observation were performed, we reached wide-lane and narrow-lane mean ambiguities resolution more than 90 % and 85 % for Galileo and 80 % and 75 % for GPS. Furthermore, we discussed impact of the IGS14 antenna calibrations on Galileo positioning results.**

Keywords—Satellite navigation systems; Global Navigation Satellite System; Global Positioning System.

I. Introduction

In the frame of the European Union, the Galileo civil navigation system has been developed since 1999. The main goal of this system is to obtain independence from the US monopoly in the field of satellite navigation. The unit responsible for the construction and implementation of Galileo is the European Space Agency (ESA), which is supported by the Council of the European Union and many of the scientific and business consortia. Despite the fact that Galileo satellite constellation still does not have a nominal number of satellites in space (14 satellites as of January 2017), in December 2016 the European Commission inaugurated the launch of the system, whereas the missing satellites are supposed to supplement the constellation until 2020. Some receivers in the reference networks, e.g. EUREF Permanent Network (EPN), are already equipped with modules that allow to track Galileo satellites and perform position estimation using their signals. Usage of Galileo observations in combination with observations from other satellite navigation systems can result in increased reliability and accuracy of the station positioning and consequently, the stability of the whole network. On the other hand, addition of another satellite system to the calculation process may cause numerical problems and may not result in accuracy increase, as expected by many users.

From the beginning of Galileo program many researches were conducted on the use of its signals. However, until the number of the satellites enabled to determine position solely using Galileo system, researchers could only use simulated signals or observations together with other navigation systems. During that time many papers in this topic were published. They focused on e.g. bias estimation between GPS and Galileo [1] or using Galileo triple frequency to ionospheric delay estimation [2]. However, the biggest emphasis is being put on the precise positioning. Paziewski and Wielgosz [3] used simulated Galileo signals to demonstrate positioning accuracy as well as ambiguity resolution for both separate and combined GPS and Galileo method. They concluded that tightly combined GPS and Galileo positioning provides accurate and reliable solution even when processing observations from just a single observational epoch. Li et al. [4] focused on the multi-GNSS precise point positioning (PPP). They used Galileo observations together with GPS, GLONASS and BeiDou to improve accuracy and convergence time of PPP method. Similar works were conducted by e.g. Tegedor et al. [5] or Afifi and El-Rabbany [6]. In both cases they showed similar results that using Galileo observations together with another system improves positioning results. However, there are not many papers dedicated exclusively to Galileo positioning, especially basing on the real observation data and differential mode.

In this paper we present positioning results obtained using strategies employing different combinations of GNSS systems: GPS-only, Galileo-only, GPS/Galileo, GPS/GLONASS and GPS/GLONASS/Galileo. We show that, despite the early stage of Galileo system, using Galileo signals together with GPS improve position determination, and the obtained results are on the same level as in GPS/GLONASS solution. Besides the positioning results we also show the impact of the Galileo signals on the ambiguities resolution.

II. DATA AND METHODOLOGY

A. GNSS Data

In presented studies we performed analysis of the position and ambiguities resolution for the selected stations in Europe, which are equipped with the GNSS receiver enabling to track and collect observations from the GPS, GLONASS and Galileo satellites. We analyzed data from 26 stations for the period covering several weeks before and after the Galileo EOC (Early Operational Capability), namely from 1883 to 1934 GPS week (from 7th February 2016 to 29th January 2017). Spatial distribution of used station is presented in Fig. 1. For these stations observational data stored in RINEX 3 files from MGEX project [7] (http://www.igs.org/mgex) were used.

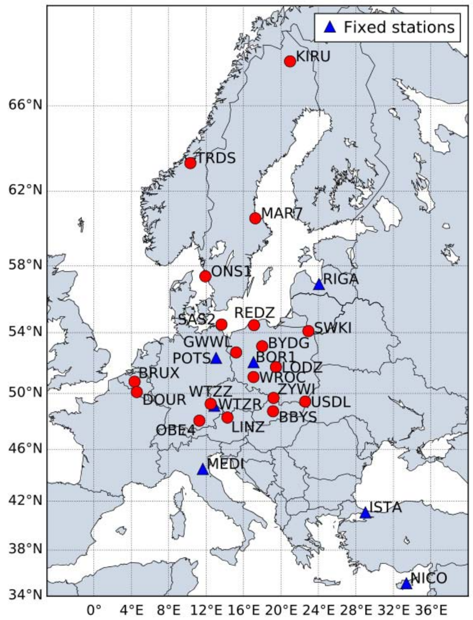

Fig. 1. Distribution of stations included in the analysis.

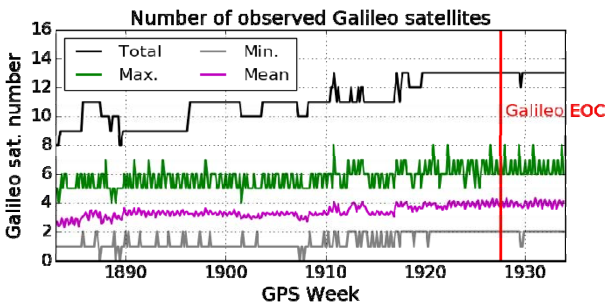

Fig. 2. Number of observed Galileo satellites at BBYS station. Black line – total number of satellite observed during whole day; Maximum, minimum and mean number of satellite observed in one time during the whole day are marked by the green, grey and magenta line respectively.

The number of Galileo satellites observed by the receiver at the BBYS station during the analyzed period is presented in Fig. 2. It is seen that from week 1920 the total number of Galileo satellite was 13. At the same time the mean value of observed satellites was about 4. This means that it is possible to perform single point positioning based only on Galileo observations for almost a whole day. It is worth to notice, that if we sum the number of GPS, GLONASS and Galileo satellites, the total number of observed satellites during the day will amount to about 70. Such a big number of observations during a day should give a precision increase, but also causes prolongation of the calculations.

B. Processing Strategies

Five processing strategies employing different combinations of GNSS systems were tested, namely GPS, Galileo (GAL), GPS/Galileo (GPS_GAL), GPS/GLONASS (GPS_GLO) and GPS/GLONASS/Galileo (GPS_GLO_GAL). Numerical tests were conducted using Bernese 5.2 software [8]. Due to the fact that the Bernese software supports only observations in RINEX 2 format, we converted all files using RNXSMT tool. For Galileo satellites E1 and E5 code and phase observations were used. Also some modifications of input files were necessary by adding information related to Galileo system. Based on the information from the MGEX project and the European GNSS Service Center (http://www.gsc-europa.eu/), we modified files containing information about GNSS receivers (receiver.gal) and satellites (sat_gal.i08). Moreover, antenna phase center file has been prepared in accordance with IGS08. For this purpose, we used IGS (IGS08.ATX) and EPN (EPNC.ATX) antex files, which include absolute and average calibration for antennas of GNSS satellites and receivers. Precise ephemeris distributed by CODE center, as an input to MGEX project, were used. The processing parameters for all strategies were the same and consistent with the official processing options of the EPN guidelines for the Analysis Centre [9]. Detailed parameters, which were used in our studies, are presented in Table I.

The IGb08 reference frame has been moved to newly defined points using 6 IGS reference stations whose coordinates and speeds are determined in this frame. After the geocentric coordinates in IGb08 reference frame were estimated, transformation to the topocentric coordinates was performed. For each day we adopted the reference values based on the official station coordinates and velocities published by the EUREF. Such approach allows to avoid the linear trend in the data which could cause interpretation problems. We decided to analyze results in IGb08 instead of ETRF to avoid the errors caused by the transformation between the frames.

TABLE I. PARAMETERS OF USED SOLUTIONS

Solution name	GPS	GAL	GPS_GAL	GPS_GLO	GPS_GLO _GAL
Satellite systems	GPS	Galileo	GPS Galileo	GPS GLONASS	GPS GLONASS Galileo
Method	Differential				
Obs. window	24 hours				
Cut-off angle	3°				
Orbits, clocks, EOP	Precise satellite clock, orbits and EOP from CODE MGEX				
Iono. handling	Global model (CODE) for HOI L3				
Tropo. handling	A priori model: GMF; Mapping function: WET GMF; CHENHER Gradients model				
Amb. est.	Melbourne-Wübbena combination (Wide-lane and Narrow-lane linear combinations)				
Antenna models	IGS08 + EPNC				

III. RESULTS

In this section we present results of differential precise positioning as well as ambiguities resolution. In the first case we focused on the Galileo only positioning and impact of Galileo signals on multi-GNSS positioning. All presented results are expressed in topocentric coordinates. In the second case, the ambiguities resolution results are shown. We analyzed percentage of properly estimated ambiguities for phase Wide-lane (WL) and Narrow-lane (NL) linear combinations. We present impact of GNSS systems on Galileo ambiguities resolution as well as impact of Galileo observations on percentage of GPS ambiguities estimation.

A. Position

Fig. 3 shows the estimated topocentric coordinates of DOUR stations for GAL solution (blue line). In addition, two other solutions (GPS_GAL and GPS_GLO_GAL) were placed as a comparison. Based on Fig. 3 it is seen that GAL solution are correlated with the amount of Galileo satellites (Fig. 2). Before the week 1920, where the total number of satellite amounted 13, the results obtained using GAL solution are of low precision, standard deviation was: 4.39, 4.35 and 10.36 mm for North, East and Up coordinates respectively. After the week 1920, position has stabilized and standard deviation decreased almost twice (σ_N = 2.73 mm, σ_E = 2.15 mm, σ_U = 6.17 mm). In Fig. 3 it is also seen that GPS_GAL and GPS_GLO_GAL results are very similar regardless of whether before or after the week 1920.

In Fig. 4 histograms of the residuals for all stations are presented. It is noteworthy that the presented results refer to the period after 1920 week. We decided to choose this week as an epoch after which the GAL solution are stable. Such approach allowed reliable comparison of the results obtained from different solutions. Based on Fig. 4, it is seen that the GAL solution is characterized by the lowest precision (highest value of the standard deviation – σ), which amounted 3.56, 2.70 and 8.55 mm for North, East, Up coordinates respectively. Such bad results are not surprising because the Galileo system is still under development and there are slightly more than half the number of the nominal satellite constellation in space. However, it can already be stated that nowadays the precise positioning using only Galileo satellites can be performed with the horizontal and vertical precision below 1 cm.

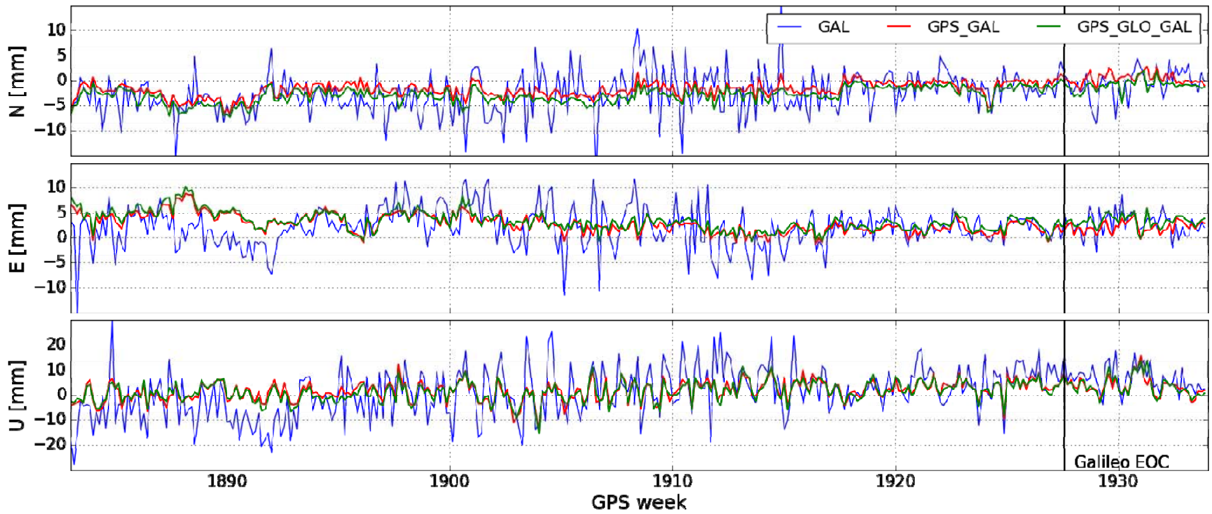

Fig. 3. Positioning results for DOUR station for three solutions: GAL (blue line), GPS_GAL (red line) and GPS_GLO_GAL (green line).

Very interesting results can be seen in case of multi-GNSS positioning, because the highest precision for the horizontal coordinates was obtained for GPS_GAL solution, 1.95 and 1.96 mm respectively for North and East. Presented results are even better than the GPS_GLO solution (N: 2.13 mm, E: 2.08 mm), which is used and recommended by the EUREF community. Moreover, using only GPS and Galileo satellites gave better results than using three satellite systems. Thus, it can be concluded that the use of GLONASS satellites causes loss of the positioning precision. The GPS_GLO solution allowed to obtain a better precision in case of Up coordinate, which amounted 5.35 mm (GPS_GLO_GAL: 5.44 mm, GPS_GAL: 5.96 mm). This results are probably caused by the larger number of GLONASS satellites than Galileo, which translates to better geometry of the satellites. However, in near future, with increasing number of Galileo satellites, it should be expected that the precession of the Up coordinate will be better.

In presented results some biases are seen for all components of topocentric coordinates. They can arise from the fact that we estimated the coordinates for different network than it is in case of reference EUREF solution. We chose only several stations from the whole network in Europe, so both the spatial distribution of the stations, baselines lengths and the references stations are different. However, if we compare the biases between obtained solutions, it is seen that for each coordinate they have the same sign and the differences between solutions do not exceeded 0.5 mm for East coordinate and 2.0 mm for both North and Up. However, the highest bias was obtained for Galileo solution. It can be explained, as in case of position standard deviation, by the low number of the satellites and early stage of the system operation. The lowest bias was obtained for the raw GPS solution and amount -2.31, 1.74 and 0.48 mm for North, East, Up respectively. In case of multi-GNSS solutions, the lowest value of the bias was obtained for the GPS_GAL solution. For all coordinates the results were better than in case of GPS_GLO and GPS_GLO_GAL.

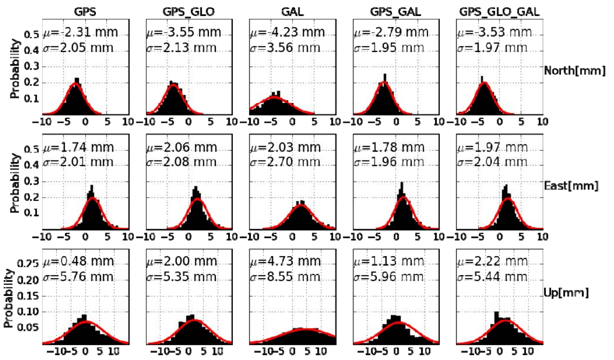

Fig. 4. Histograms of the residuals for all analyzed solutions after week 1920. From the top: North, East and Up coordinates.

B. Ambiguities

An inherent element of position determination using phase observation is also estimation of the ambiguities. Their incorrect determination significantly affects the position accuracy. In our studies, due to the long baselines between stations, we used Melbourne-Wübbena combination, which consists of two linear combinations: wide-lane (WL) and narrow-lane (NL). In this section results of ambiguities resolution of these two linear combination are presented. Fig. 5 shows the percentage (the average value for all analyzed stations) of ambiguities resolution for Galileo satellites for each processing day. It can be seen that in the early epochs the percentage of properly estimated ambiguities was significantly lower, especially for NL. Until the week 1920 the mean value of the ambiguities resolutions amounted to 69.45±9.46 % and 55.20±10.74 %, for WL and NL method respectively. After the EOC and the few weeks before that date, these values significantly raised and amounted to 80.85±4.31 % and 70.97±5.68 %. It is worth to notice that the standard deviation for both solutions decreased twice after the EOC.

In Fig. 6 we present the results which show impact of satellites of others systems on Galileo WL ambiguities resolution. In this figure the comparison between three solutions: GAL, GPS_GAL, and GPS_GLO_GAL are presented. Based on these results, it is clearly seen that combined solutions significantly increased the number of properly solved ambiguities. For the entire time, the mean percentages for the GPS_GAL and GPS_GLO_GAL solutions were more than 90 %. What is important, it did not matter whether it was before or after the Galileo EOC. It is worth to notice, that a little bit better percentage was obtained for GPS_GAL (93.14 %) than GPS_GAL_GLO (92.83 %). Also the lowest standard deviation was obtained when GPS and Galileo are calculated together. Thus, we can conclude that adding GLONASS observation adversely affects the ambiguities estimation process. This happens despite the fact that number of total processed satellites was significantly higher.

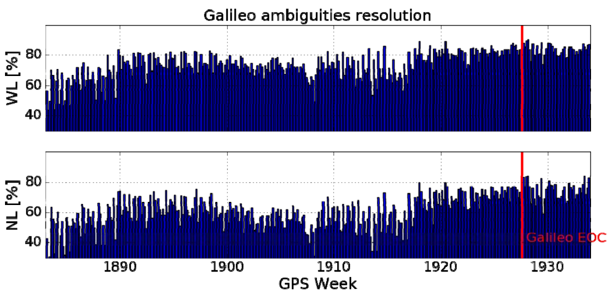

Fig. 5. Mean ambiguities resolution for Galileo satellites, method WL (top) and NL (bottom).

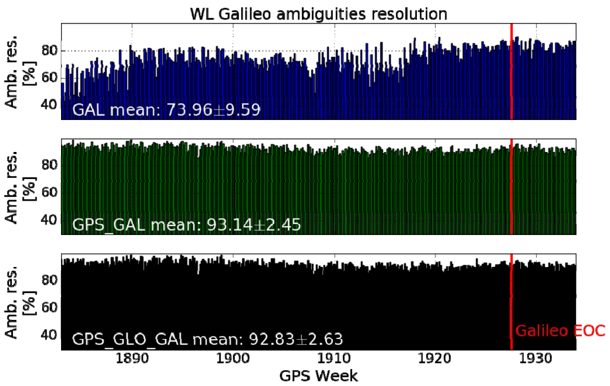

Fig. 6. Comparison of mean Galileo ambiguities resolution obtained from different combination of used satellites systems. From the top: Galileo only, GPS/Galileo, and GPS/GLONASS/Galileo.

In our analysis we also checked how the application of Galileo satellites impacts ambiguities resolution of other systems. We analyzed GPS WL and NL ambiguities. Fig. 7 shows the mean percentages of GPS WL ambiguities resolution for four solutions: GPS, GPS_GAL, GPS_GLO, GPS_GLO_GAL. If we analyze the entire presented period, it will be seen that the best results were obtained when GPS and Galileo observations were calculated together. In that case the mean value of the ambiguities resolutions was 79.15±3.45 %. In the other cases we obtained: GPS 72.03±3.99 %, GPS_GLO 74.11±5.10 %, GPS_GLO_GAL 75.36±4.49 %. We can conclude that by adding additional system to the GPS processing we obtained better performance of ambiguities estimation. The greater gain was obtained by adding Galileo satellites than GLONASS. However, when we added these two systems at once to GPS processing, the results were worse than in case where only GPS and Galileo were used.

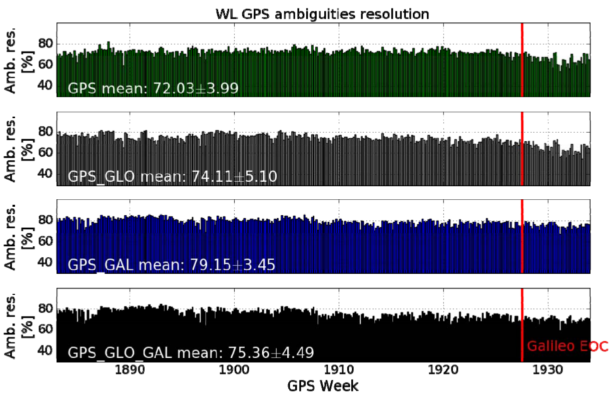

Fig. 7. Comparison of mean GPS ambiguities resolution obtained from different combination of used satellites systems. From the top: GPS only, GPS/GLONASS, GPS/Galileo, and GPS/GLONASS/Galileo.

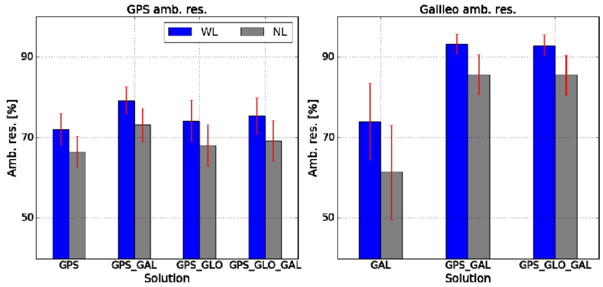

Fig. 8. Mean percentage of GPS (left) and Galileo (right) WL (blue) and NL (grey) ambiguities resolutions for tested solutions.

Thus, we can state that in both presented cases the best results were obtained for GPS_GAL solution. However, the profit of usage second satellite system was bigger in case of Galileo, apparently due to greater number of GPS satellites. By using GPS observations the mean percentage of Galileo ambiguities estimation increased by more than 12 % (after Galileo EOC). In case of GPS ambiguities, usage of Galileo observations allows to improve the results by about 6% before EOC and 10 % after EOC. Also, in case of Galileo ambiguities, obtained values of standard deviations are lower than in case of GPS. For the same solution GPS_GAL, the mean percentage for GPS ambiguities was 79.15±3.45 % while for Galileo it was 93.14±2.45 %.

Detailed statistics of Galileo and GPS ambiguities resolution are presented in Fig. 8. It is seen that for NL the results are very similar. The best results for both GPS and Galileo NL ambiguities were obtained for GPS_GAL solution. However, the NL percentage values are generally smaller than for WL regardless of used solution.

C. *Impact of New Antenna Models – IGS14*

On 29 January 2017 IGS recently adopted IGS14 as a new reference frame. At the same time, an updated set of satellite and ground antennas calibrations was implemented – igs14.atx file [10]. One of the most important changes in igs14.atx is the addition of calibration for frequencies of new satellite systems such as Galileo or BeiDou. Unfortunately, new models are not available for all ground antennas. The problem is particularly visible when multi-GNSS positioning is performed. In such case, when station has antenna without model for a particular frequency, model for different one is often used. As an example, the frequencies of the Galileo system can be specified. Because E1 in Galileo and L1 in GPS use the same frequency (1575.42 MHz) the calibration models can be used interchangeably. However, in case of Galileo E5 signal the problem is more complicated. Difference in frequency between Galileo E5 (1191.795 MHz) and GPS L2 (1227.60 MHz) is only 35.805 MHz. It might seem that such a small difference should not affect the reception capacity of the antenna and consequently its calibration. Thus, antenna models for GPS L2 frequency are often used as a substitute for model of Galileo E5. In this section we present that such approach has some disadvantages, because differences between calibrations for these frequencies are visible and can affect the position estimation. The impact of antenna calibration on position determination is still being analyzed. Araszkiewicz and Völksen [11] show the impact of the antenna models on the coordinates in the EPN network. They prove that differences between type's mean and individual calibration may cause discrepancy in the final position of 10 mm for horizontal and vertical components. Thus, it can be expected that applying GPS L2 antenna calibration for Galileo E5 can also cause some divergence.

Differences of antenna phase center corrections (PCC) between GPS L2 and Galileo E5 frequencies are presented in Fig. 9. As an example we chose JAVRINGANT_DM antenna which is mounted at BRUX (Brussels) station. The PCC values are calculated both on phase center offset (PCO) and phase center variations (PCV) and reflects total correction values which should be included in observational equations. Based on Fig. 9. it is seen that significant differences occur, which range is almost 14 mm. On the surface presented in the figure it can be seen some kind of "hollow" which is caused by the difference location of the PCO for each frequency. Indeed, for presented antenna, GPS L2 frequency PCO value amount: (-0.94, 0.37, 124.97) mm for North, East and Up component respectively. For Galileo E5 frequency these values are (-0.19, 0.52, 131.37) mm. For PCV values the differences between frequencies amount almost to 2 mm. This all causes such big differences of PCC. Considering presented results, we can conclude that presented differences can affect the position determination when E5 frequency is used. Moreover, this problem not only concerns antenna calibration of this frequency but also all new models which are included in new igs14.atx file and which were previously copied from the GPS system.

As we mentioned before, in presented studies four station support antenna individual calibration for Galileo E5 frequency which is included in new IGS14 set: BRUX, DOUR, ISTA, and OBE4. In Fig. 10 Galileo only positioning results for BRUX station are presented. Two solutions are shown: GAL_14, marked with red line, where individual calibrations were used; and GAL, grey line, where calibration for Galileo E5 were copied from GPS L2. Based on the presented results some bias between solutions is seen, especially in Up coordinate and reached 8.58 mm (bias for GAL_14: 4.54 mm, GAL:-4.04 mm). Smaller bias, which is about 1 mm, can be seen in North and East direction. It is worth to notice, that use of individual calibration caused only bias change without changing the standard deviations. For both presented results their values were the same. For other three stations we obtained similar results.

We can conclude that use of individual calibration antenna for E5 Galileo frequency impacts on positioning results, especially the altitude of the station. However, it is worth to notice, that in network which was tested in this study only four station have such calibration. For all others, as an antenna calibration for E5 frequency, we used this for GPS L2. Such approach and differential method can cause error propagation, which caused biases in presented solutions. Thus, usage of antenna individual calibration models for Galileo frequencies seems to make sense only when all station in network have antennas with such calibration or use a non-differential positioning method such as PPP. In the future we will try to perform additional calculations in order to evaluate impact of new antenna calibrations on the multi-GNSS positioning results.

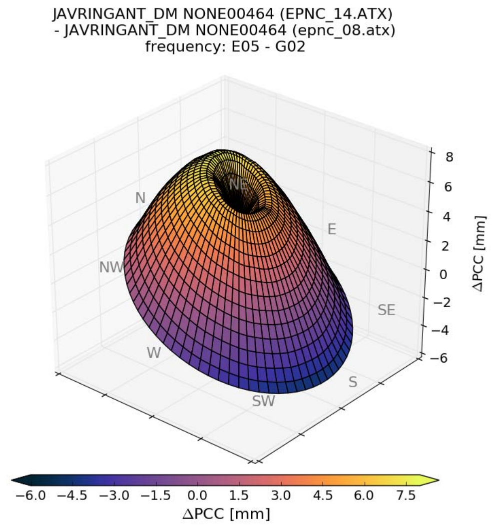

Fig. 9. Difference of antenna Phase Center Correction (PCC) between Galileo E5 and GPS L2 frequencies. Example for JAVRINGANT_DM NONE antenna which is mounted at BRUX station.

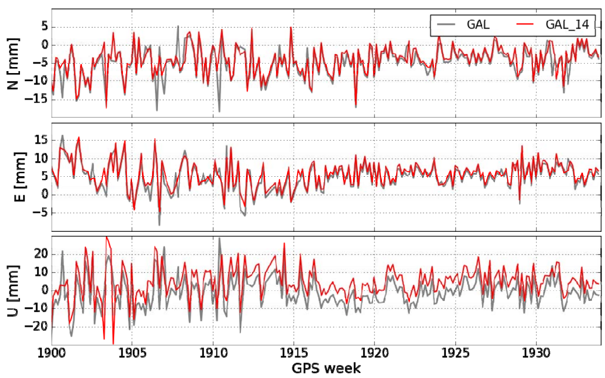

Fig. 10. Galileo only positioning results for BRUX station for two solutions: with IGS14 antenna model - GAL_14 (red line); GAL (grey line).

IV. Summary and Discussion

In this study we presented positioning results obtained with five different combinations of GNSS systems: GPS, Galileo, GPS/Galileo, GPS/GLONASS and GPS/GLONASS/Galileo. In first place we focused on the precision of the position determination. Based on the presented results, we can conclude, that results obtained using Galileo only observation are characterized by the highest standard deviation of the analyzed solutions. This is due to the low number of the Galileo satellite. However, even when the constellation is not completed, the differential precise positioning using only Galileo observations can be performed with the horizontal and vertical precision below 1 cm.

The Galileo observations have significant impact on the multi-GNSS positioning results. Among the analyzed solutions, the highest horizontal coordinates precision was obtained when GPS and Galileo observations were performed together. We received the results amounting to 1.95 and 1.96 mm respectively for North and East coordinates. Presented results are even better than the GPS/GLONASS solution. However, this solution gave us better precision in case of Up coordinate, which amounted 5.35 mm (for comparison, GPS_GAL: 5.96 mm). This result is probably caused by the larger number of GLONASS satellites than Galileo, which translates to better geometry of the satellites. However, the GPS_GAL solution enabled us to obtain the lowest bias values for all coordinates.

Besides the positioning results, we also analyzed the ambiguities resolution for wide-lane and narrow-lane linear combination. After the EOC and the few weeks before that date, the mean ambiguities resolution for the Galileo satellites amounted to 80.85±4.31 % and 70.97±5.68 %, for WL and NL respectively. In case of multi-GNSS positioning, the best results of ambiguities resolution for GPS and Galileo satellites were obtained for GPS_GAL solution. In that case the mean value of the WL ambiguities resolutions was 79.15±3.45 % for GPS and 93.14±2.45 % for Galileo. The obtained results of ambiguities resolutions are consistent with the results presented by Paziewski and Wielgosz [3], who obtained, based on simulated signals, similar results.

Based on presented studies we conclude that the best results, both in case of position determination and ambiguities resolution, were obtained for GPS/Galileo solution. Presented results are better than the GPS/GLONASS solution (which is used and recommended by the EUREF) and even when all satellites systems were used (GPS/GLONASS/Galileo). In near future the increasing number of Galileo satellites should be expected. Thus, the positioning precision should be even better especially in case of the Up coordinate. In this case, it seems that position determination using GPS/Galileo will be more efficient than GPS/GLONASS or even GPS/GLONASS/Galileo. Especially, if we take into account the computation time of multi-GNSS observations.

We also presented differences of antenna Phase Center Corrections (PCC) between antenna individual calibration for Galileo E5 frequency and for GPS L2 frequency. We obtained results between -6 and 8 mm. Such big differences show that copying calibration from L2 to E5, as was often done before, can cause significant errors. We also showed preliminary Galileo-only positioning results with E5 frequency antenna calibration. For four tested stations we obtained bias (especially in Up direction) between Galileo solution with individual calibration and with copied from GPS L2. These biases can be caused by the network error propagation, because for other stations of our tested network, as a Galileo E5 calibration we used data from GPS L2. Thus, usage of antenna models for Galileo frequencies seems to make sense only when all station in the network support such calibration.

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