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Analysis of the Impact of Galileo Observations on the Tropospheric Delays Estimation

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***Abstract*—In this study we present analysis of the impact of Galileo observations on the ZTD and tropospheric gradients estimation. The tropospheric parameters were obtained in various scenarios, which differ from each other only in used satellite systems: Galileo-only, GPS-only, GPS/Galileo, GPS/GLONASS and GPS/GLONASS/Galileo. Then, comparative analysis between Galileo-only solution and the other ones, was carried out. As a reference, the combined EPN solution was adopted. Analysed period covers two time spans: one year (02.2016 – 01.2017) and nearly EOC (10.2016-01.2017). Results shows standard deviation of Galileo solution at the level of 6 mm (w.r.t. reference solution), which is higher than the other ones. However, adding a Galileo observations can cause decreasing of solution standard deviations, which lead to the higher quality. A positive impact of new standard of antennas calibrations (IGS14) on Galileo ZTD bias standard deviation was also noticed. At the end some discussion about gradients estimation are presented.**

Keywords—Global Navigation Satellite System; satellite constellations; atmospheric modelling; atmospheric measurements.

I. Introduction

GNSS (Global Navigation Satellite System) signal propagation through neutral part of the atmosphere is delayed by the physical properties of the troposphere. It was agreed to express the size of this delay in the zenith direction and called it ZTD (Zenith Tropospheric Delay). From the one hand, precise estimation of tropospheric delay is extremely important factor on the way of obtaining high accuracy coordinates. This result from the fact, that ZTD is estimated together with the coordinates, in one process. In consequence, its accuracy affects the accuracy of obtained coordinates, especially the vertical one [18]. Effects of this relation between vertical component and troposphere delay parameters are still investigated [20, 13]. From the other hand, thanks to the correlation of the ZTD value with such meteorological parameters like air pressure, temperature and humidity, it allows for estimation the amount of the water vapour content in the atmosphere [4]. Consequently it can be used for the purpose of climate monitoring [19, 2, 3] or in assimilation process in Numerical Weather Models [11, 12]. Therefore, the reliable values of tropospheric parameters are crucial from both geodetic and climatological point of view.

In Europe, GPS (Global Positioning System) has been playing a key role in the process of coordinates and ZTD precise estimation, since 1996, which is the beginning of the existence of EPN (EUREF Permanent Network) [6]. Nowadays, also GLONASS (GLObalnaya NAvigatsionnaya Sputnikovaya Sistema) is used by selected EPN Analysis Centre (EPN AC) in routine service and in reprocessings of EPN. However, both mentioned above satellite systems were designated for the military purpose. In 1999, in order to become independent from the USA's (GPS) and Russian (GLONASS) navigation systems, the European Union have started to develop the new global and civilian navigation system, called Galileo. Its satellite constellation still does not provide full global coverage (14 satellites in January 2017). However, on 15th December 2016, the European Commission announced the Early Operational Capability (EOC) of the system, what allowed users to start using Galileo for the positioning.

In this paper the impact of Galileo observations on the process of tropospheric parameters estimation, was investigated. In order to verify obtained results, five different combination of used satellite constellations were carried out: Galileo-only, GPS-only, GPS/Galileo, GPS/GLONASS and GPS/GLONASS/Galileo. ZTD obtained on the basis of them were compared to the combined EPN solution [16]. From the one hand, such approach allowed for verification of the size of differences between Galileo and official EPN solution. From the other hand, it gave opportunity to verify how these differences between Galileo solution and the official EPN products look like in relation to the commonly used observation processing strategy (in term of used satellite constellations), and how Galileo observations affect them.

II. Analysed Data

ZTD is a parameter which reflect the troposphere influence on GNSS radio signal propagation. The value of this delay is divided into delay caused by the hydrostatic (ZHD, Zenith Hydrostatic Delay) and wet (ZWD, Zenith Wet Delay) part of the troposphere. ZHD accounts for about 90% of total amount of ZTD and is relatively easy to model due to the small variation in time and space. ZWD accounts for the rest 10 %, but its modelling is much more sophisticated due to the high temporal and spatial variability of water vapour content in the troposphere. In GNSS processing the a priori value of ZTD is assumed (e.g. from tropospheric models or NWP models) and then correction to its value is calculated. Because most of satellites tracked by receiver are observed not in zenith, but in slant direction, the value of delay is originally expressed as STD (Slant Tropospheric Delay) and can expressed by:

$$STD = ZHD \cdot mf(e)_{hyd} + ZWD \cdot mf(e)_{wet} + \\ + mf(e)_G [G_n \cos(\alpha) + G_e \sin(\alpha)] \quad (1)$$

where $mf(e)_{hyd}$ is a mapping function for hydrostatic delay, $mf(e)_{wet}$ is a mapping function for wet delay, $mf(e)_G$ is gradient mapping functions, G_n and G_e are north and east components of tropospheric gradients [15, 14, 7], and α is the azimuth.

We tested five processing strategies employing different combinations of GNSS systems, namely GPS, Galileo (GAL), GPS/Galileo (GPS_GAL), GPS/GLONASS (GPS_GLO) and GPS/GLONASS/Galileo (GPS_GLO_GAL). The processing parameters for all strategies were the same and consistent with the official processing options of the EPN guidelines for the Analysis Centre [10]. Detailed processing parameters, which were used in our studies, are presented in Table I. Whole calculations were performed using Bernese 5.2 software [8]. For the numerical tests, GNSS observations in RINEX3 format were used. Due to the fact, that Bernese 5.2 Software allows for simultaneously processing of only two frequencies (RINEX2 format is accepted), for Galileo system code and phase observations on E1 and E5 frequencies, were used. Input files have been modified by adding information about Galileo system. Files which contain information about GNSS receivers (receiver.gal) and satellites (sat_gal.i08) have been supplemented by data sourced from MGEX project (http://www.igs.org/mgex) and European GNSS Service Centre (http://www.gsc-europa.eu/). File which contains information about antenna phase centre models were prepared according to the IGS08 standards. The IGS type mean (IGS08.ATX) and individual (EPNC.ATX) calibration models were used. All observations in RINEX3 format were converted to the RINEX2 format by using RNXSMT software.

From each of these solution (GPS, GAL, GPS_GAL, GPS_GLO, GPS_GLO_GAL) the reference one was subtracted and the ZTD bias time series were obtained. The reference solution was taken from EPN ftp (ftp://igs.bgk.bund.de). This solution is a combined official troposphere EPN product, which was created based on solutions delivered from several EPN AC (ftp://igs.bkg.bund.de/EUREF/products).

III. RESULTS

As it can be seen in Fig. 1. ZTD bias time series from Galileo had various quality during all analysed period of time. The biggest discrepancies between this solution and the reference one occurred at the beginning of analysed period of time and constantly decreasing until the mid-October 2016. This is a directly consequence of the number of available Galileo satellites, on the basis of which the tropospheric delay was estimated. At the beginning of 2016 there were less Galileo satellites in space, than at the beginning of 2017. As it can been easily noticed, the time for which Galileo solutions have achieved stable quality (2016.10) does not covered with EOC announcement. This results from the fact that 15 December 2016 is the official confirmation of Galileo capability to provide stable solutions, which was preceded by several weeks of testing. These tests were conducted on the same number of satellites (14) which are now available.

As a consequence of these two periods of Galileo solutions stability, results of comparative analysis between various constellation scenarios are given in two subsection. In the first one, data from one year time span (02.2016-02.2017), in order to provide maximum number of available solutions, are investigated. In second one data from nearly EOC (2016.10 – 2017.01) time span are analysed, in order to compare current Galileo quality to the other combinations.

In addition, the influence of used antennas calibrations was investigated. These analysis was conducted on the example of three stations: BRUX, OBE4 and DOUR, which are equipped with antenna with individual calibration for GPS, GLONASS and Galileo signals.

TABLE I. DETAILED PROCESSING PARAMETERS

Solution name	GPS, GLO, GPS_GAL, GPS_GLO, GPS_GLO_GAL
Method	Differential
Observation window	24 hours
Cut-off angle	3°
Sampling interval	180s
Orbits, clocks, EOP	Precise satellite clock, orbits and EOP from CODE MGEX
Ionosphere handling	Global model (CODE) for HOI L3
Troposphere handling	A priori model: GMF [5]; Mapping function: WET GMF; CHENHER Gradients model
Ocean Loadings	FES2004
Tidal Atmospheric Loadings	Sourced from ECMWF
Ambiguities estimation	Melbourne-Wübbena combination
Antenna models	IGS08

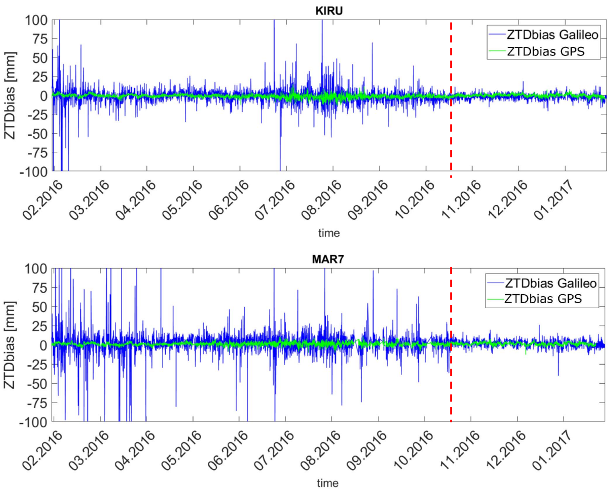

Fig. 1. ZTD bias time series of Galileo solutions for KIRU (top) and MAR7 (bottom) stations (01.2016-01.2017 period of time).

A. One Year Time Span

For all stations included into analysis, mean value of ZTD bias (w.r.t. to the reference solution) and their standard deviations, were calculated and presented in Fig. 2. As it can be seen, for most of stations ZTD bias reached up to 1 mm. Only in three cases (BBYS, KIRU and MAR7) they exceed 1 mm, but still were smaller than 2 mm. The lowest ones were noticed for ONS1 station (all bellows 0.3 mm). Although these values of Galileo solutions look promising in term of their similarity to the other satellite constellations, the number of available Galileo satellites significantly influenced its quality. This can be seen on Fig. 3, on which values of ZTD bias standard deviations are presented. Between results obtained based on only Galileo satellites and the other combinations, is distinct discrepancy. For every station, solutions: GPS, GPS_GAL, GPS_GLO and GPS_GLO_GAL, have mean value of standard deviation at the level of 2 mm. Only WTZR station is characterized by higher STD value (3 mm), but this is for solution which also include Galileo observations (GPS_GAL).

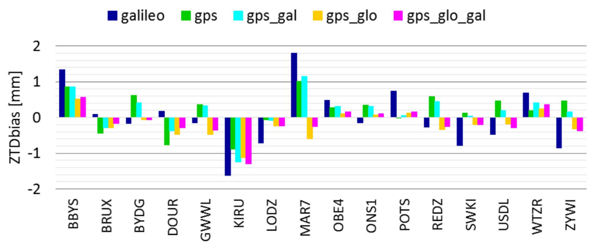

Fig. 2. Mean ZTD bias (w.r.t. to the reference solution) for analysed EPN stations and various constellations (01.2016-01.2017 period of time).

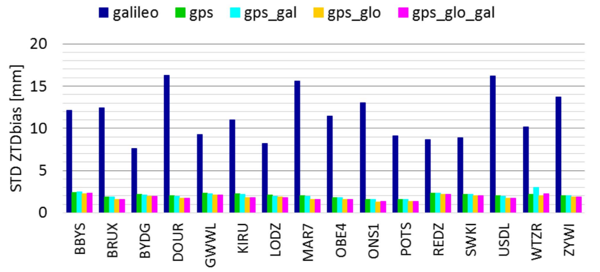

Fig. 3. Standard deviation of ZTD bias for analysed EPN stations and various constellations (01.2016-01.2017 period of time).

In comparison to these results, results which are based on Galileo only constellation are burdened with much greater uncertainty. For 9 from 16 analysed EPN stations, values of ZTD bias standard deviations exceed 10 mm. The highest one was noticed for DOUR station (16.3 mm) and the lowest one for BYDG station (7.6 mm). Detailed differences between ZTD bias from Galileo and GPS solution, is also presented in Fig. 1. In this case, GPS solution can represent all others combinations (with exception of GAL), due to the fact that their ZTD bias standard deviations are similar.

B. Nearly EOC Time Span

Analysed data covered 15 weeks of observations (1919-1933 GPS week). Similar as in case of one year period of time, the mean values of ZTD bias did not differ significantly from each other. However, they were slightly higher than in case of one year period of time (e.g. OBE4, ONS1 and POTS stations). As it can be seen in Fig. 4, for most of stations they varied in the range of -1.5 mm to 1.0 mm. Exceptions of this were KIRU, and MAR7 stations. The highest discrepancies were noticed for MAR7 station and they were in the range from -0.4 mm (GPS_GLO solution) to 1.5 mm (GAL) solution. The lowest one were noticed for BRUX station, which were practically equal to zero and vary from -0.4 mm (GAL) to 0.01 mm (GPS_GLO and GPS_GLO_GAL solutions). Although the mean ZTD biases from Galileo solution were significantly differ between both time spans, their standard deviations have been clearly improved (Fig. 5).

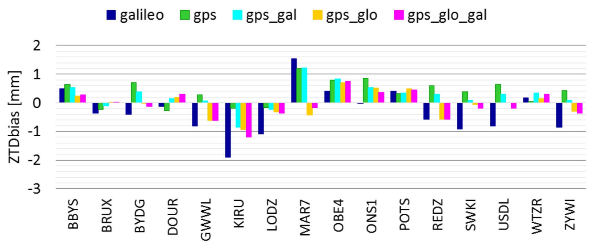

Fig. 4. Mean ZTD bias (w.r.t. to the reference solution) for analysed EPN stations and various constellations (10.2016-01.2017 period of time).

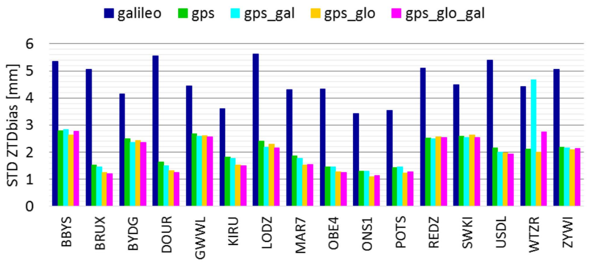

Fig. 5. Standard deviation of ZTD bias for analysed EPN stations and various constellations (10.2016-01.2017 period of time).

For nearly EOC time span, most of stations were characterized by standard deviation value below 5 mm (the average value was 4.6 mm). In comparison to the longer time span (which was 11.5 mm), it proves an achievement of higher quality of solution obtained based on only Galileo observations. However, these results still do not have such high quality as e.g. GPS (STD: 2.1 mm) or GPS_GLO (STD: 1.9 mm). However, generally GPS_GAL solutions presents higher quality than GPS and similar as GPS_GLO or GPS_GLO_GAL (with exception of WTZR station).

C. *Gradients*

Tropospheric delays obtained on the basis of observations from selected station returns information about troposphere influence on GNSS radio signal propagation. However, this is only influence from one direction and does not provide information about horizontal distribution of atmospheric refractivity. This kind of information are described by tropospheric gradients, which reflect tropospheric asymmetry [9]. Most commonly, their heterogeneity occurs in case of passing atmospheric fronts near the station [16]. Therefore, their estimation together with the tropospheric delay, complementing information about troposphere inhomogeneity and in consequence leads to the increase of the positioning precision [10]. Thus, we also consider impact of Galileo observations on obtained gradients. Their values, from GPS, GPS_GAL, GPS_GLO, GPS_GLO_GAL solutions were similar to each other and for most of the time they overlapped each other. Slightly different situation occurred for Galileo solution.

Fig. 6. presents Galileo gradients in comparison to the GPS one. As it can be seen, for most of the time they were differences both in term of North and East component. In both these cases, Galileo were characterized by higher values of gradients. The biggest discrepancies occurred during summer months, especially in the East component. However, after EOC these differences decreased and have remained at a constant level. Detailed illustration of various size and character of gradients between GAL and the other solutions is given in Fig. 7. In this figure Galileo is compared to the commonly used GPS and GPS_GLO combination, as well as to the GPS_GAL and GPS_GLO_GAL solutions. It can be seen, that in presented here 8 days (23.11.2016 – 30.11.2016), the direction of horizontal maximum atmospheric refractivity can be differ depending on using satellites constellation. It is especially easy to seen at the 29th November (Fig. 8, bottom). During analysed period of time we investigated that results obtained using GAL solution differ most in terms of both directions and values, as well. It can be seen that in most cases the lengths of the vectors (created from estimated gradients component in north and east direction) are clearly higher. This is probably a consequence of insufficient number of satellite. However, is worth to noticed here, that addition of Galileo observations to the GPS ones resulted in higher consistency of gradients value (w.r.t. to GPS) than adding a GLONASS observations.

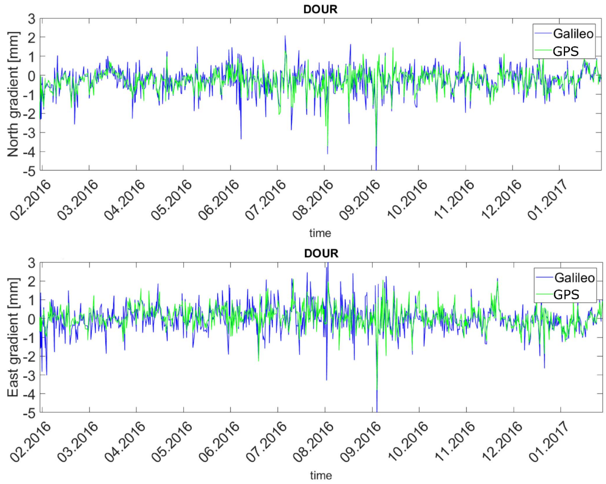

Fig. 6. North (top) and East (bottom) gradients for Galileo (blue) and GPS (green) solutions.

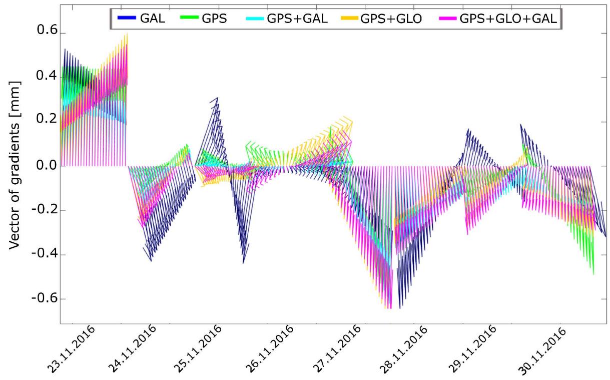

Fig. 7. Vector composed of North and East gradients for Galileo, GPS, GPA_GAL, GPS_GLO and GPS_GLO_GAL solutions and 23-30.11.2016 period of time.

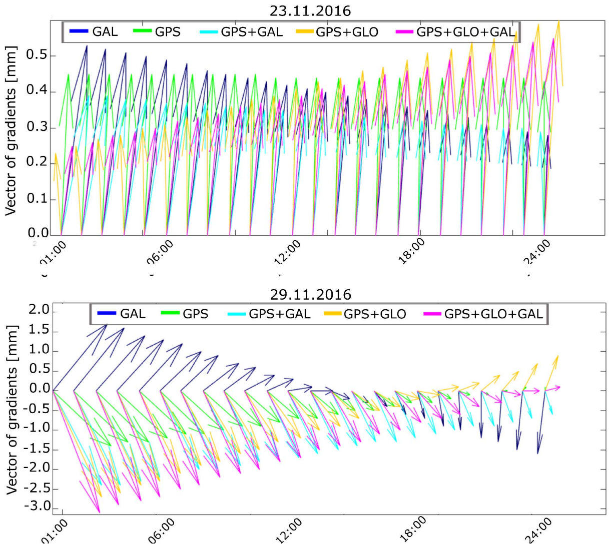

Fig. 8. Vector composed of North and East gradients for Galileo, GPS, GPA_GAL, GPS_GLO and GPS_GLO_GAL solutions for DOUR station and 23.11.2016 (top) and 29.11.2016 (bottom).

This can be seen on Fig. 8 (top), where solutions which included GLONASS data (GPS_GLO and GPS_GLO_GAL) are less similar to the GPS, than GPS_GAL solution (visible also in most of days in Fig. 7). Even when vectors of gradients between GPS and Galileo were opposite, combination of their observations gave consistent to the GPS values of a vectors (Fig 8, bottom). This confirms the fact, that directions of vectors are depending on the satellites constellations and number of the satellites in each constellation.

D. Antenna Calibration

Together with introduction of new reference frame (ITRF2014), an updated standard of satellite and ground antennas calibrations was implemented – IGS14 [17]. One of the novelties in this standard is placing calibrations of ground antennas for Galileo signals. Before IGS14 standard were introduced, users usually used GPS antennas calibrations for Galileo signals. The assumption that these calibrations were very similar was accepted. This is true for Galileo E1 and GPS L1 signals, because they are on the same frequency. In case of e.g. Galileo E5 signal, this case looks more complicated, because this signal has no equivalent in GPS. However, because frequency of E5 signals is very close to GPS L2, users just used calibrations for this frequency. Despite the fact that Galileo signals frequencies are very close to those from GPS, differences in calibrations can be seen (does not apply for Galileo E1 signal, which has the same frequency as GPS L1). As is well known, usage of antenna calibration has impact on station coordinates [1]. Thus, it can also has impact on tropospheric parameters estimation. In IGS14 standard, antennas with calibration for GPS, GLONASS and Galileo signals are available for only several EPN stations.

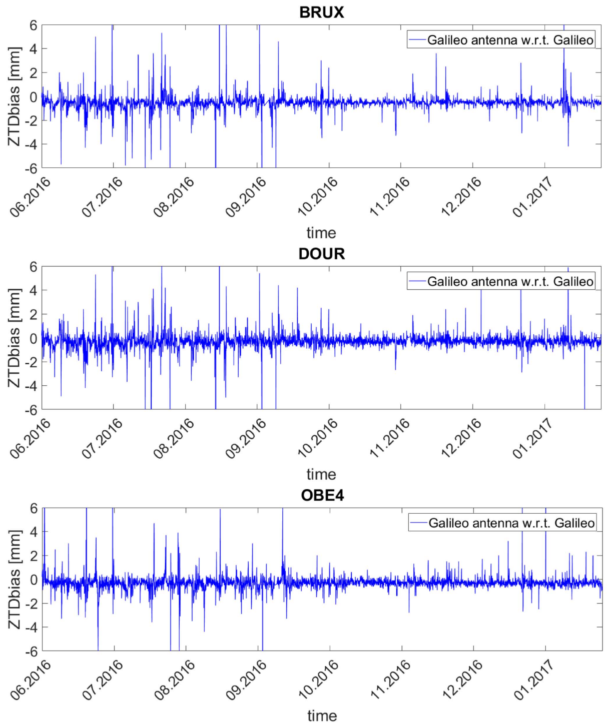

Fig. 9. ZTD bias time series of Galileo_antenna solution w.r.t. to the Galileo only solution, for BRUX, DOUR and OBE4 stations (06.2016-01.2017 period of time).

In order to verify impact of such calibration on the obtained value of tropospheric delays parameters, ZTDs for three stations (BRUX, DOUR and OBE4) were computed another time. For Galileo solution we performed new calculation with adopting new antennas calibrations which conform to IGS14 standard (solution called here Galileo_antenna). Fig. 9 presents ZTD bias between Galileo_antenna and Galileo solutions obtained for BRUX, OBE and DOUR stations. The mean values of differences amounted -0.5 mm for BRUX, -0.3 mm for DOUR and -0.3 mm for OBE4 stations. In case of standard deviation values, they were at the level of 0.9 mm, 0.9 mm and 0.7 mm for BRUX, DOUR and OBE4 stations, respectively.

These results shows, that applying antennas with absolute calibrations for Galileo signals caused only slight changes in the obtained value of ZTD differences. However, these results do not give information which of these solutions is better. Thus, similarly as previous, we performed comparison to the combined solution derived from EPN. Based on our analysis we can stated that the values of mean ZTD bias and standard deviation for BRUX station, have increased (Fig. 10 and Fig. 11). In case of Galileo_antenna solution it was -1.1 ± 13.2 mm, whereas for Galileo it was 0.1 ± 12.4 mm. As it can be seen, the differences between solutions are below 1 mm for both ZTD bias and standard deviations. Taking into account total number of Galileo satellites and formal error of

ZTD estimation, these differences can be neglected. The situation is different for DOUR and OBE4 stations. In Fig. 11 it is seen, that usage of antennas calibrations for Galileo signals decreased standard deviations by 3.7 mm and 5.1 mm for DOUR and OBE4 stations respectively. Thus, we stated that positive impact of IGS14 standard can be seen. However, to better check this impact, the additional calculation should be performed for more stations which have calibrations for Galileo signals. It is worth to notice, that we performed estimations using differential mode. Thus, only for these four stations we can used calibrations for Galileo signals. For rest of stations, the calibrations for GPS frequencies were used. Such approach cause error propagation, which can caused biases in presented solutions. Thus, additional studies based on PPP method should be performed to evaluate and extension of presented results.

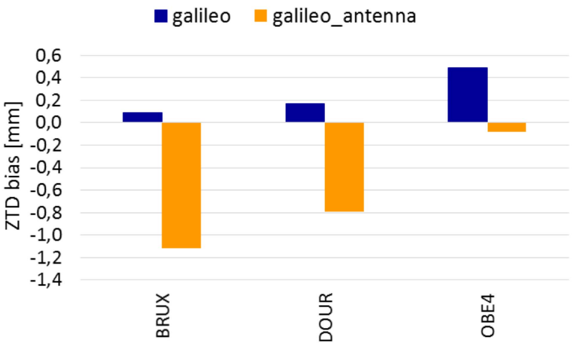

Fig. 10. Mean ZTD bias of Galileo and Galileo_antenna solutions (w.r.t. EPN combined solution), for BRUX, DOUR and OBE4 stations (06.2016-02.2017 period of time).

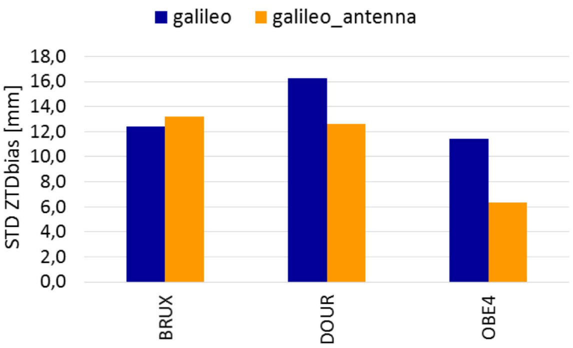

Fig. 11. Standard deviation of ZTD bias of Galileo and Galileo_antenna solutions (w.r.t. EPN combined solution), for BRUX, DOUR and OBE4 stations (06.2016-02.2017 period of time).

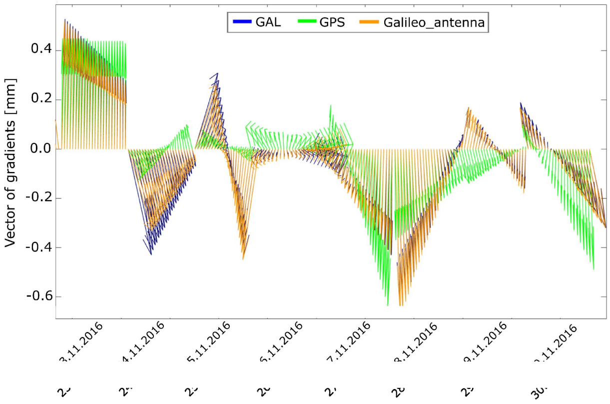

Fig. 12. Vector composed of North and East gradients for Galileo, GPS, Galileo_antenna solutions for DOUR station and 23-30.11.2016.

We also investigated impact of antenna calibration on tropospheric gradients. Fig. 12 contains their distribution for selected before period of time (23-30.11.2016). As it can be seen, new antenna calibration introduced only slight corrections to the Galileo only solutions. On the example of these days it can be seen that the use of new antennas calibrations in the GNSS observations processing, caused small decrease of the North and East gradients vector, which resulted in higher consistency with the GPS vectors. However, for most of the time, direction and value of these vectors are practically identical, still deviates from GPS solutions.

IV. Summary

In our study we investigated impact of Galileo observations on tropospheric parameters. Obtained results showed, that usage of only Galileo-only solution does not provide as precise solutions as in case of e.g. GPS. However, the addition of its observations to observations from the other satellite systems, positively affect final solutions. We analysed five different satellite combinations: GPS-only, Galileo-only, GPS/Galileo, GPS/GLONASS, and GPS/GLONASS/Galileo, for the two periods of time, which covered one year (02.2016 – 02.2017) and nearly EOC (10.2016 – 02.2017) time span. Obtained results were compared to the combined, official EPN product. As we expected, not sufficient number of satellites at the beginning of the analysed period, resulted in much higher standard deviation of Galileo results, compared to the other ones (more than 10 mm for most of stations in case of Galileo, and less than 2 mm in case of other combinations). The results quality has improved in nearly EOC period of time (reduction of standard deviation to about 6 mm), however it is still not as high as in case of rest of considered here solutions. It is worth to noticed, that after EOC, addition of Galileo observations to the e.g. GPS caused slightly improvements in obtained ZTD values, which were on the similar level as in case when GLONASS observations were added. Multi GNSS solution is characterized by the highest quality (in term of standard deviation).

Besides the ZTD, we also analysed the results of tropospheric gradients. In case of only Galileo observations their values, both in case of North and East components, were significantly higher than e.g. GPS gradients, especially before the EOC. However, after EOC, it seems that addition of a Galileo observations to the GPS ones resulted in higher consistency of gradients value (w.r.t. to GPS) than adding a GLONASS observations. Next to the increase of the number of Galileo satellites, improvement of the Galileo only solutions can be achieved thanks to the new standard of antennas calibrations (IGS14). ZTD bias time series obtained without and with calibrations for Galileo signals, showed a decrease of ZTD bias standard deviation. New antenna calibration have also small, but positive, impact on Galileo gradients.

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