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Precise positioning in Europe using the Galileo and GPS combination

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Abstract. For many years American GPS and Russian GLONNAS were the leading navigation systems widely used for navigation purposes. In recent years two new navigational systems have been developed. These systems are the European Galileo system and the Chinese BeiDou System. The full operability of both systems is foreseen for 2020. The full Galileo constellation will consist of 30 Medium Earth Orbit (MEO) satellites. In this paper the GPS and Galileo combination is used to obtain precise positions using the MAFA method. Results from GPS only and GPS+Galileo positioning are presented. In the test 11 Galileo satellites were used. The number of visible GPS satellites during the test was between 8 and 12. For Galileo the number of visible satellites was between 2 to 4, with 4 satellites visible for most of the day. Adding Galileo satellites to GPS reduces the PDOP factor value and improves the DGNSS and RTK results.

Keywords: GPS, Galileo, MAFA method, RTK.

Conference topic: Technologies of geodesy and cadastre.

Introduction

For many years GPS and GLONNAS were leading navigation systems. However, recent years two new navigational systems have appeared. These systems are the European Galileo system and the Chinese BeiDou System. The full operability of both systems is foreseen for 2020. The full Galileo constellation will consist of 30 Medium Earth Orbit (MEO) satellites (Li 2015). This system is still under construction, so the number of available satellite during the performed test was only 11 Galileo satellites. However, even though the Galileo system is still not in full operability it is widely used in many tests (Chu, Yang 2013; Paziewski, Wielgosz 2013), not only in combination with GPS but also with other systems (Li *et al.* 2015; Tegedor *et al.* 2014). The method mainly used is the LAMBDA method. For this test the MAFA method was used (Cellmer *et al.* 2010; Cellmer 2011a, 2011b, 2012a, 2013). The test presented in this paper was performed on data obtained from one IGS and one MGEX station in the RTK mode.

GPS and Galileo

Galileo is a European navigation system whose full operability is foreseen for 2020. With 30 satellites (Li *et al.* 2015) – 24 operational satellites plus six in-orbit spares Galileo is one of four Global Navigation Satellite Systems. Galileo satellites are placed on three circular planes with an inclination of 56°, while the GPS satellites are placed on six planes with an inclination of 55° (Verhagen *et al.* 2007). Galileo's satellites are placed at an altitude of about 23 222 km, while the GPS satellites are placed at an altitude of about 20 200 km (O'Keefe *et al.* 2005). Galileo uses its own reference time system, called Galileo System Time (GST). The GST start epoch is 00:00:00, 22 August 1999, and just like in GPS leap seconds are not taken into account. The reference frame for Galileo is the Galileo Terrestrial Reference Frame (GTRF), while the reference frame for GPS is WGS-84. The frequencies of both GPS and Galileo are presented in Table 1 (Chu, Yang 2013; Paziewski, Wielgosz 2013).

GPS and Galileo share two frequencies, L1 and E1 with a frequency of 1575.42 MHz, and L5 and E5a, with a frequency of 1176.45 MHz. These common signals allow the combination of both systems and use that combination for positioning purposes. However, for this solution the time and coordinate system differences must be taken into account, and also the difference between the receiver hardware delays affecting the signals from different systems (Montenbruck *et al.* 2011; Odijk *et al.* 2013). This bias is termed inter-system bias (ISB). The ISB is caused by the correlation process within the GNSS receiver, and thus it is present in both the carrier phase and code data (Hegarty *et al.* 2004). The ISB can be estimated, which has been widely described in many articles (Paziewski, Wielgosz 2013, 2014, 2016; Odijk *et al.* 2016). However, for the purposes of this test no ISB was estimated, and the results presented in (Paziewski, Wielgosz 2016) showed that precise positioning without taking ISB into account allows for obtaining correct solutions for the GPS and Galileo combination.

Table 1. GPS and Galileo signals and frequencies

GPS		Galileo	
Signal	Frequency	Signal	Frequency
L1	1575.42 MHz	E1	1575.42 MHz
L2	1227.60 MHz		
L5	1176.45 MHz	E5a	1176.45 MHz
		E5b	1207.14 MHz
		E5	1191.795 MHz
		E6	1278.75 MHz

The MAFA method

The Modified Ambiguity Function Approach (MAFA) is a method of processing GNSS carrier phase observations. The integer nature of the ambiguities is taken into account in this method. The MAFA method has been widely described in many articles (Cellmer *et al*. 2010, 2013; Cellmer 2011a, 2011b, 2012a, 2013). The MAFA method can be easily used for one epoch positioning (Kwaśniak *et al.* 2016; Cellmer 2012b). The following model for a double differenced (DD) carrier phase observable is assumed (Cellmer 2013):

$$\Phi + v = \frac{1}{\lambda}\rho\left(X_c\right) + a, \tag{1}$$

where: Φ – DD carrier phase observable (in cycles), λ – signal wavelength, v – residual (measurement noise), X_c – receiver geocentric radius vector, $\rho\left(X_c\right)$ – DD geometrical range, a – integer number of cycles (DD initial ambiguity).

Taking into account the integer nature of the ambiguity parameter a and assuming that the residual values are much lower than half a cycle, the linearized general formula of the residual equations can then be shown in the following form:

$$v = \frac{1}{\lambda}Ax + \delta \tag{2}$$

with:

$$\delta = round\left(\Phi - \frac{1}{\lambda}\rho_0\right) - \left(\Phi - \frac{1}{\lambda}\rho_0\right), \tag{3}$$

where: v – residual vector (n×1), x – parameter vector (increments to a priori coordinates vector $x0$), A – design matrix (n×3), d – vector of misclosures(n×1), ρ_0 – DD geometric distance vector computed using a priori position and satellite coordinates.

Test description

Tests were performed on a baseline about 70 m-long located in southern Germany. The location of the baseline is presented in Figure 1. For test purposes the IGS station – WTZR and MGEX station – WTZ2 were used. The WTZR station was used as a reference station and the WTZ2 station was used as Rover. 24h long data from these stations were obtained with 30 second intervals from 19 November 2016. In the first part of the test Differential GPS (DGPS) and Differential GPS+Galileo (further called DGNSS) were performed. This part was also used to find a period of time when the number of Galileo satellites is the highest. In the second part of the test precise positioning using the MAFA method was performed in the RTK mode. In that mode, after every three epochs a result is given. For test purposes the GPS L1 and Galileo E1 frequency was used. To compute coordinates from the first and second parts of the test a special program was created that used the MAFA method. The difference between the obtained coordinates and the actual coordinates were transformed to the topocentric coordinates system dN, dE and dU and presented in figures. To check if the obtained solution was correct, ambiguities computed using real coordinates and obtained coordinates were compared. If the ambiguity values were the same, the solution was accepted as correct.

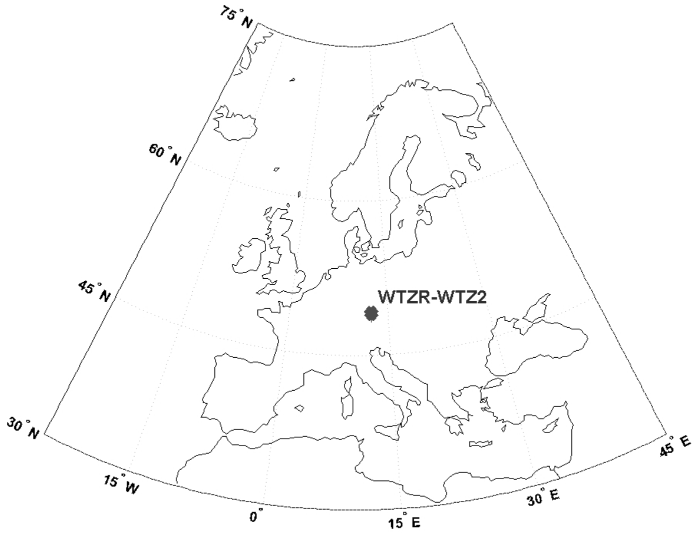

Fig. 1. Location of the WTZR-WTZ2 baseline used in tests

Analysis and results

First the PDOP factor and number of satellites will be analysed. Figure 2 shows the number of GPS, Galileo and GPS+Galileo satellites. The number of visible GPS satellites during test was between 8 and 12. For Galileo the number of visible satellites was between 2 and 4, with 4 satellites visible for most of the day. On November 19, 11 Galileo satellites were available: E01, E02, E08, E09, E11, E12, E19, E22, E24, E26 and E30. The total number of GPS and Galileo satellites was from 11 to 16. Analysing the number of available Galileo satellites for the second part of the test time, between 03:00 UTC to 15:30 UTC was chosen. Figure 3 shows the value of PDOP factors for GPS and GPS+Galileo. The maximum value of PDOP for GPS only was 2.40, the minimum value was 1.12, while for GPS+ Galileo the maximum PDOP value was 1.91 and the minimum was 1.01. Figure 3 shows that adding Galileo satellites decreases the value of the PDOP factor.

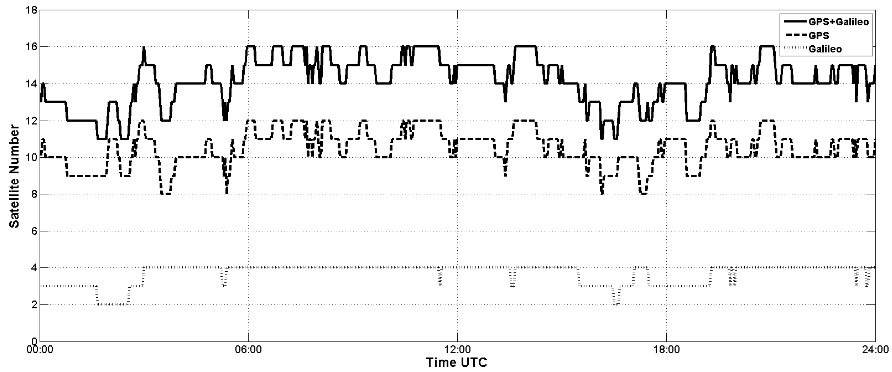

Fig. 2. Satellite number on 19 November 2016 for the WTZR-WTZ2 baseline

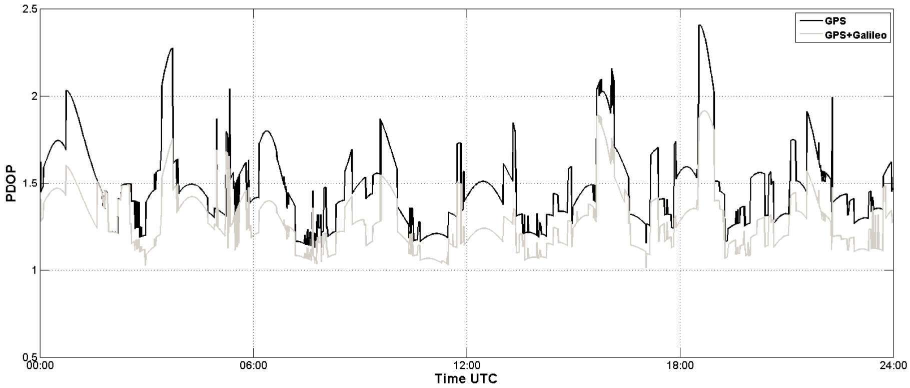

Fig. 3. PDOP factor values on 19 November 2016 for the WTZR-WTZ2 baseline

The last stage of the first part was computing Rover coordinates using DGPS and DGNSS. That part was important for further computing because coordinates from this stage were used while computing the precise position using the MAFA method. Table 2 shows the results of differential positioning. As can be seen in this table, the mean for coordinates does not change too much between DGPS and DGNSS. However, the standard deviation (STD) value for dN, dE and dU for DGNSS is lower than for DGPS, especially for dU, where the STD value is about 10 cm lower.

Table 2. DGPS and DGNSS results

	DGPS		DGNSS	
	Mean [m]	STD [m]	Mean [m]	STD [m]
dN	0.005	0.365	0.002	0.320
dE	–0.042	0.279	–0.042	0.251
dU	–0.027	0.636	–0.032	0.545

The second part of the test was performed using coordinates from the first part of the test. The elevation mask was set to 15 degrees, and the confidence level was set to 0.95. As previous analyses showed the time between 03:00 UTC to 15:30 UTC was the time when the number of Galileo satellites was highest, that time was chosen for the second part of the test. Figure 4 shows the results of precise positioning with the MAFA method in North-South and East-West directions. As can be seen, the precision of both solutions, GPS and GPS+Galileo, are with high accuracy. However, the GPS only solution provides two incorrect solutions, while the GPS+Galileo combination provides only one incorrect solution. As can be seen in Figure 5, the precision of both solutions in the vertical direction is high.

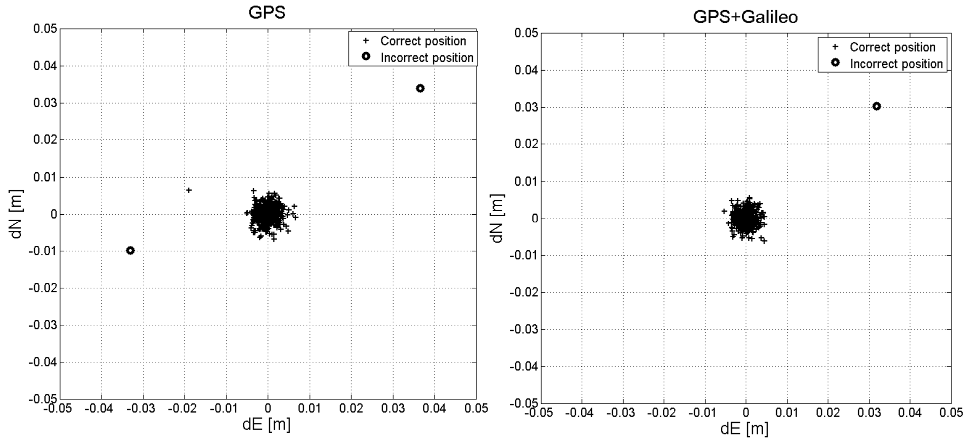

Fig. 4. dN, dE results for GPS and GPS+Galileo

As can be seen in table 3, in case of the GPS+Galileo combination the obtained results are with higher accuracy, and the STD values for this combination are lower than in the case of the GPS only solution. As mentioned earlier, in the case of GPS only two incorrect solutions occurred, while for the GPS+Galileo combination only one incorrect solution appears.

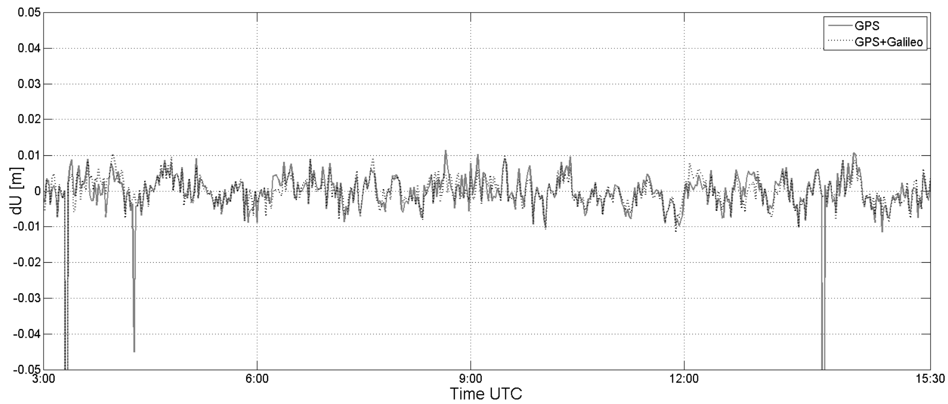

Fig. 5. dU results for GPS and GPS+Galileo

Table 3. Precise positioning results for correct positions for GPS and GPS+Galileo

	GPS		GPS+Galileo	
	Mean [m]	STD [m]	Mean [m]	STD [m]
dN	0.000	0.003	0,000	0,002
dE	0.000	0.003	0,000	0,002
dU	–0.002	0.020	0,001	0,017
Number of correct solutions	99.6% 496/498		99.8% 497/498	

Summary and conclusions

Tests showed that the combination of GPS and Galileo reduces the value of the PDOP factor and improves the precision and accuracy of results obtained in DGNSS. Also, in precise positioning, using the MAFA method, the GPS+Galileo solution increases the accuracy and precision of the obtained coordinates compared to the GPS only solution. Also, for the GPS+Galileo solution the number of incorrect solutions is lower, only one incorrect, while for the GPS only solution two incorrect solutions occurred. Also, one point with lower precision and accuracy appeared for the GPS only solution even if it is known as the correct solution. The still increasing number of Galileo satellites will soon allow the use of the Galileo only solution or the use of satellites of this system to increase the precision and accuracy of positioning. Even now Galileo satellites can increase the precision and accuracy of positioning in the RTK mode. The test also showed that the MAFA method can be easily used for one system positioning, but also for multisystem combination positioning.

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