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ORIGINAL ARTICLE

Evaluating Repeatability of RTK (GPS and Galileo/GPS) performance in the analysis of points located in areas with and without obstructions

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Abstract

Galileo is Europe's Global Navigation Satellite System (GNSS), which provides improved positioning and timing data with significant benefits for many European services and users. Galileo enables users to know their exact location with greater precision than other available systems. Access to the Galileo signal in the obstructed and unobstructed environment provides benefits and opportunities for work, thanks to the improved performance and accuracy. The use of a Galileo-enabled receiver increases the number of satellites in view significantly. When compared to the performance of single-constellation receivers, this significantly reduces the time required to obtain a position with centimetre-level accuracy. The results indicate the current Galileo constellation's suitability for high-precision RTK applications, as well as improved availability, accuracy, reliability, and time-to-fix in the obstructed and unobstructed environments. The results of RTK GPS and RTK GPS/Galileo obtained at different times of the same day by using two reference points were compared. The results of this study illustrate that integrating RTK GPS system with Galileo is favorable for surveying applications (cm accuracy). This study shows that in surveying applications requiring centimetre accuracy, the RTK GPS/Galileo method can replace other survey methods (Total Station).

Key words: RTK GPS/Galileo, RTK GPS, Woodland, Accuracy, Total station

1 Introduction

Galileo is a Global Navigation Satellite System (GNSS) that the European Union launched in 2016 by the European Space Agency (ESA). The European Union Agency for Space Programme (EUSPA) is in charge of it, and it has two ground operations centers in Facino, Italy, and Oberpfaffenhofen, Germany. One of Galileo's objectives is to create an independent high-precision positioning system so that European nations are not dependent on the US GPS or the Russian GLONASS systems, both of which can be disabled or worsened at any time by their operators. By July 2018, 26 of the planned 30 active satellites (including spares) were in orbit. Galileo began providing Early Operational Capability (EOC) services with a signal on December 15, 2016, with the aim of reaching Full Operational Capability (FOC) in 2020. To achieve proper interoperability with other GNSS constellations, all Galileo signals in the E1 and E5 frequencies, i.e. E1, E5a, E5b, and AltBOC (Alternative Binary Offset Carrier), are used for positioning in the firmware and receivers. The development of FOC satellites is being accelerated by Galileo. There are many previous articles on this topic: Angrisano et al. (2013); Borio et al. (2020); Cai et al. (2014, 2016); Carlin et al. (2021); Diessongo et al. (2014); Elmezayen and El-Rabbany (2019); ESA (2017, 2021); Feng and Moody (2006); Feng and Rizos (2005); Gaglione et al. (2015); Hatch (2006); Li et al. (2015); Lu and Lian (2016); Luo et al. (2017); Montenbruck et al. (2017); Odijk et al. (2012, 2014); Odolinski et al. (2015); O'Donnell et al. (2003); Pan et al. (2017); Simsky et al. (2006); Steigenberger and Montenbruck (2017); Steigenberger et al. (2015);

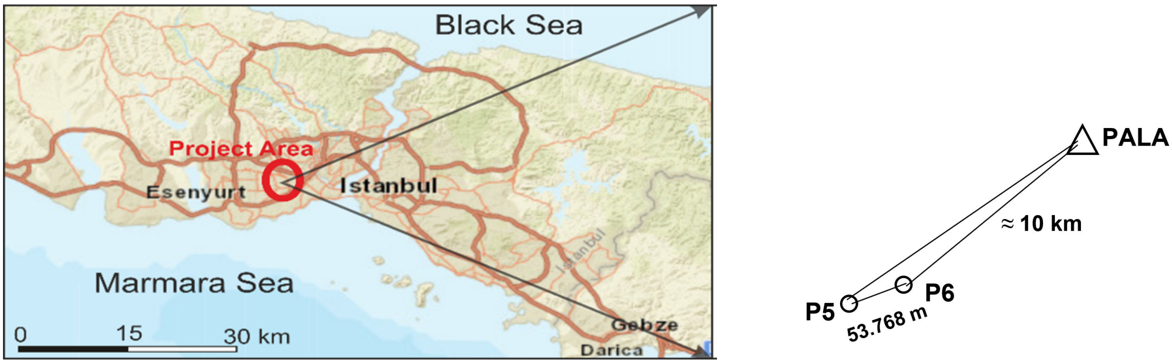


Figure 1. The study area (Davutpaşa) and GNSS network

Wu et al. (2020); Zaminpardaz and Teunissen (2017). In these articles in the applications made with RTK GPS/Galileo, the accuracy was obtained at the cm level. However, in these articles, it seems that the repetition test and the effect of Galileo satellites on multipath regions have not been examined in a field study. The aim of this study is to evaluate RTK (GPS and GPS/Galileo positioning accuracy and performance) and to evaluate the repeatability of the results under different satellite constellations by using two reference points (P5 and P6). For this purpose, an experimental survey was conducted in the unobstructed and obstructed areas (woodland area). The RTK GPS and RTK GPS/Galileo results were also compared to total station measurements in the final step.

2 Testing RTK GPS and RTK GPS/Galileo Techniques

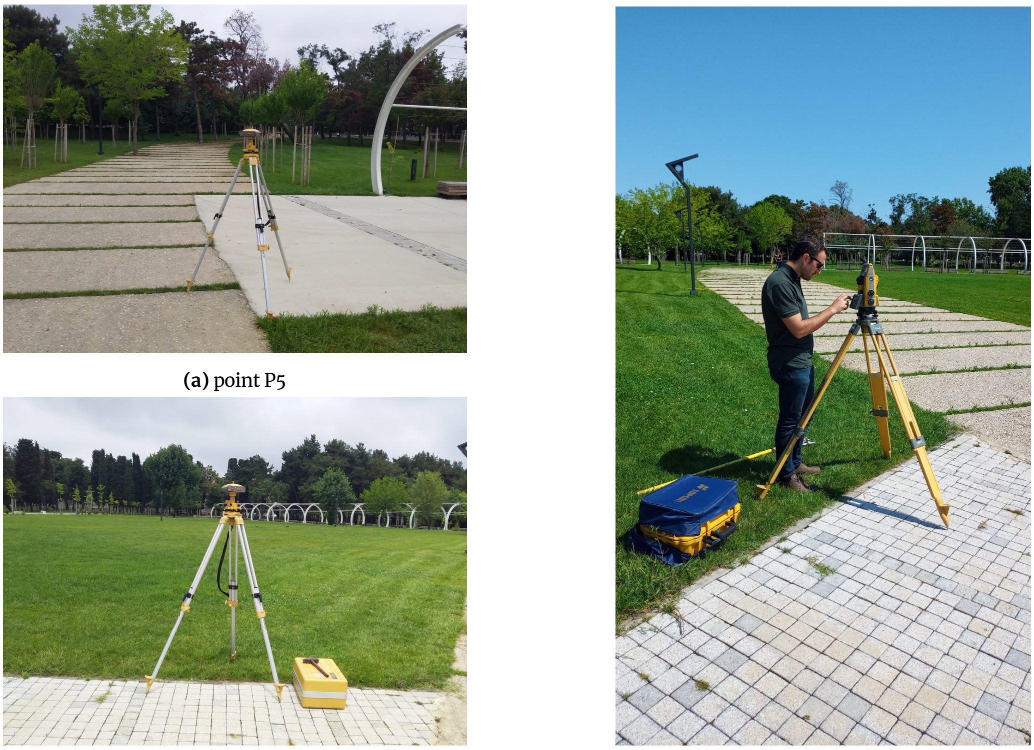
When GPS and Galileo are used together, the receiver adds one more satellite to the solution to account for the two systems' different reference times (Galileo time). Thus, a combined GPS/Galileo RTK system is extremely useful, especially for ambiguity resolution in the obstructed and unobstructed environment. This test assessed the accuracy and repeatability of RTK GPS and RTK GPS/Galileo by comparing the coordinates of a group of test points (68 points) determined from RTK GPS and RTK GPS/Galileo and using by total station (Pirti et al., 2013).

3 Test Description

The study was performed on the Davutpaşa campus of Yildiz Technical University in Esenler, Istanbul, Turkey (Figure 1). The performance of RTK GPS and RTK GPS/Galileo was evaluated in the unobstructed and obstructed (woodland) environments. Two reference points (P5 and P6) were chosen for this investigation in the project area. The reference stations (P5 and P6, see Figure 2) were located in the center of the survey area. A static GNSS survey was carried out to determine the coordinates of these two reference points. The static survey was conducted at this network with at least 1.5 hours of observation time. The sample rate and minimum elevation cut-off angle were 30 seconds and 10 degrees, respectively. Two Topcon Hiper Pro GNSS receivers were used in all static and RTK surveys. The Topcon HiPeR Pro's performance standards for static and kinematic positions are 3 mm + 0.5 ppm for horizontal and 5 mm + 0.5 ppm for vertical positioning, and 10 mm + 1 ppm for horizontal and 15 mm + 1 ppm for vertical positioning, respectively. Topcon Magnet Tools Version 7.1.0 Software was used to process and adjust these data. In addition, total station survey was performed to compute the coordinates of 68 test points (calculate the coordinates by using P5-P6 reference points, ITRF 2014 coordinates of the ISKI-CORS (PALA) point that was held fixed, see Table 1). The stations of ISKI-CORS (Istanbul Water and Sewerage Administration Continuously Operating Reference Stations) are employed only in Istanbul. These permanent stations create a precise geodetic network by continuously tracking the visible GNSS satellites. ISKI-CORS (PALA and other stations) satellite system is not compatible with GALILEO. ISKI-CORS reference station PALA is about 10 km away from the study area (see Figure 1 and Table 1).

The number of satellites is an important parameter for determining positions and other calculations. Figures 3 and 4 illustrate test results (skyplot and charts of number of satellites and Dilution of Precision (DoP) values) in which green circles available GPS satellites, however both GPS (green) and Galileo satellites (blue) in the study area. The number of GPS satellites was 8–10 and the number of GPS/Galileo satellites was 13–17 in the study region (for the unobstructed area). The recorded Position Dilution of Precision (PDOP) values on 9 July 2021 for RTK GPS were 1.40–2.25 and the recorded PDOP values on 9 July 2021 for RTK GPS/Galileo were 1.1–1.7. In woodland area, the PDOP value of RTK GPS and PDOP value of RTK GPS/Galileo were not the same. When the Galileo satellite was added, lower PDOP values were only observed in open and woodland areas. On 9 July 2021, the satellite visibility in the woodland area was 6–8 for RTK GPS and 7–10 for RTK GPS/Galileo, with recorded PDOP values were 2.80–3.40 and 2.00–2.40, respectively (Figures 3b and 4b). The achievable accuracy from RTK GPS and RTK GPS/GALILEO techniques were evaluated on the same day (9 July 2021) in the clear sky and the woodland (trees) areas (see Figure 5) by using the Topcon HiPeR Pro field unit. GPS/Galileo tracking is available on the Topcon Hiper Pro, providing more satellite coverage than GPS alone.

While the measurement points were determined in the study area, especially open area and obstructed areas were selected. In this study, the RTK GPS and RTK GPS/Galileo surveys were carried out in the points' sequence (1 through 68). Figure 5 illustrates the distribution of the test points, with the maximum distance between points in both the North-South and East-West directions being about 75 m and 150 m, respectively. The RTK surveys were performed on the same day with the different satellite configurations (RTK GPS [I], 9 July 2021, 7:45:13 – 9:26:43 h local time (LT)); (RTK GPS [II], 9 July 2021, 11:54:57 – 12:53:03 h local time (LT)) and (RTK GPS/Galileo [I], 9 July 2021, 9:55:00 – 10:25:41 h local time (LT)); RTK GPS/Galileo [II], 9 July 2021, 11:16:36 – 11:51:54 h local time (LT)). With a cut-off elevation mask angle of 10 degrees, the data acquisition and processing rate was set to one second. Ten epochs (1 epoch = 1 second) of coordinates were recorded using the RTK GPS and RTK GPS/Galileo by two base stations (P5 and P6 points). In addition, the accuracy and repeatability of RTK GPS and RTK GPS/Galileo were evaluated by comparing the coordinates of the sixty-eight points surveyed with RTK GPS-only and RTK GPS/Galileo using the two, P5 and P6, stations.



(a) point P5

(b) point P6

(c) Total station surveys

Figure 2. Reference points P5 (a) and P6 (b) in the study area for the RTK GPS and RTK GPS/Galileo and Total station surveys (c)

Table 1. Standard deviation and coordinate values of the two reference points (P5 and P6) by using static surveys ($\approx$ 1.5 h) in the study area

			Static				
Point	**Easting [m]**	**Northing [m]**	**Elevation [m]**	**Std (E) [mm]**	**Std (N) [mm]**	**Std (H) [mm]**	**Explanation**
PALA	412882.267	4550678.133	170.543	0	0	0	
P5	406720.778	4543860.778	113.953	1	1	1	Reference point
P6	406724.335	4543807.128	112.328	1	1	1	Reference point

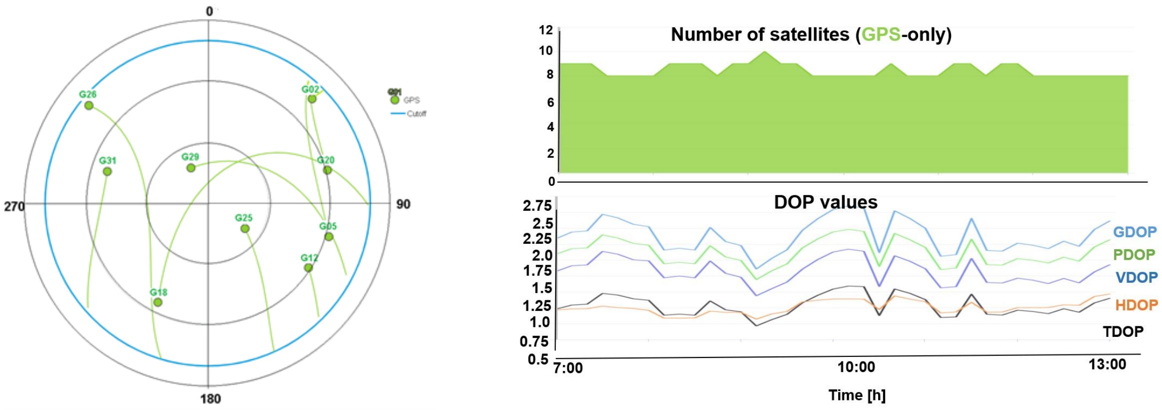
4 Results

4.1 Horizontal and vertical repeatability of RTK GPS

The first test objective was to check the RTK GPS and evaluate its performance in the study environment. To ensure the independence of the results, the RTK GPS surveys were conducted at different times of the day (9 July 2021) by using P5 and P6, with different satellite constellations. A total of 136 point observations for the 68 test points were obtained. The differences of the coordinates of the 136 test points were obtained by using the RTK GPS surveys (P5 and P6 stations), such as P5 – P6. Figure 6 illustrates the test points' coordinate differences and their mean values (2.4 – 3.1 cm); standard deviation values (3.2 – 5.8 cm). The analysis of the test for the RTK GPS results revealed that the horizontal coordinate discrepancies ranged from a few millimeters to about 15 centimeters and the height coordinate discrepancies ranged from a few centimetres to about 35 cm (see Figure 6). Because of the tree covers in a certain part of the study area, some points have poor lines of sight to the satellites (see Figure 5). The results of these points given in Figure 6 showed that the trees degraded the RTK GPS positioning because they frequently blocked the signals of the low-medium satellites and affected the signals. The differences in horizontal coordinates of these points between RTK GPS surveys were greater than 10 cm, as shown in Figure 6. These surveys, taken at the reference point P6, resulted in the largest coordinate differences of the day, as shown in Figure 6. The RTK GPS [II] measurements were taken at noon on July 9th, 2021 (11:54:57 – 12:53:03 h local time (LT)), when the satellite configuration was not suitable, resulting in poor accuracy of these points in the obstructed area. As a result of all of this information, it is clear that if satellite signals are distorted by trees, the accuracy of RTK GPS surveys degraded significantly (Pirti et al., 2013).

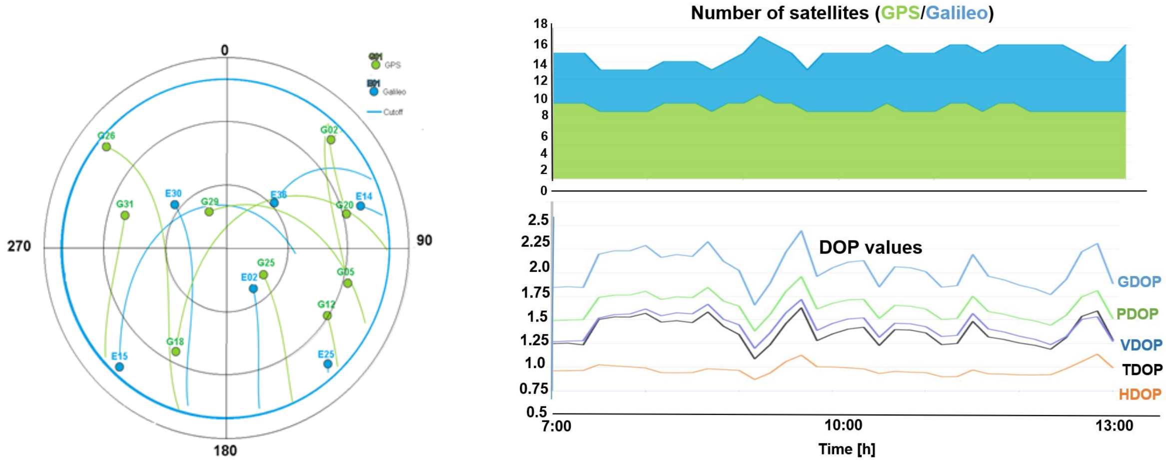
4.2 Horizontal and vertical repeatability of RTK GPS/Galileo

The surveys for RTK GPS/Galileo were conducted at different times of the day by using P5 (9th July 2021, 9:55:00 – 10:25:41 h local time (LT)), and P6 (9th July 2021, 11:16:36 – 11:51:54 h) points with different satellite configurations to ensure the independence of the results. A total of 136 point observations for the 68 test points were collected. In the analysis step, the differences in coordinates of the 68 test points obtained from P5 and P6 surveys. The coordinate differences between the test points and their mean values (1.4 – 1.6 cm) and standard deviation values (1.7 – 2.1 cm) are shown in Figure 7. Horizontal coordinate differences for RTK GPS/Galileo range from a few millimeters to seven centimeters, according to test results. The differences in height coordinates ranged from a few millimeters to 8 centimeters (Figure 7). As previously stated, some points in the study area have poor lines of sight to the GPS/Galileo



(a) (b)

Figure 3. The sky plot (GPS-only) on 9 July 2021 (a) and charts of number of GPS satellites and Dilution of Precision (DoP) values on 9 July 2021 in the study site (b)



(a) (b)

Figure 4. The sky plot (GPS/Galileo) on 9 July 2021 (a) and charts of number of GPS/GALILEO satellites and Dilution of Precision (DoP) values on 9 July 2021 in the study site (b)

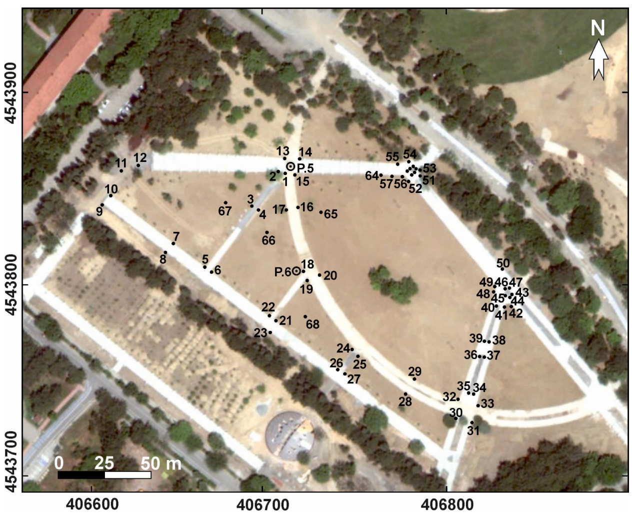


Figure 5. The distribution of the study points

satellites due to tree cover, as shown in Figure 5. However, the results of these points in the project area by using RTK GPS/Galileo were not affected by the tree canopies as well as RTK GPS. During this time of day, seven to ten (GPS/Galileo) satellites were visible for this location. The PDOP values of RTK GPS/Galileo ranged between 2.0 and 2.4. (Figure 4b). The ambiguity resolution time for these points was about 5 minutes.

4.3 Comparison of RTK GPS and RTK GPS/Galileo Measurements

In this study, we compared the results of the RTK GPS with the results of RTK GPS/Galileo. Figures 8, 9, 10 and 11 illustrate the differences in the horizontal and vertical coordinates of the test points between RTK GPS and RTK GPS/Galileo surveys. Figure 8 shows the discrepancies of the test points by using two reference points (P5 and P6), together with their mean and standard deviation values (compare the RTK GPS results with the RTK GPS/Galileo results on 9 July 2021). As explained above, RTK GPS positioning was affected by the tree canopies, which regularly blocked and affected the signals of the low-medium satellites. The test point's discrepancies and their mean values (1.4 – 2.4 cm) and standard deviation values (1.8 – 3.4 cm) are shown in Figure 8. The horizontal coordinate differencess between RTK GPS/Galileo and RTK GPS ranged from a few millimeters to 15 centimeters. The height coordinate discrepancies

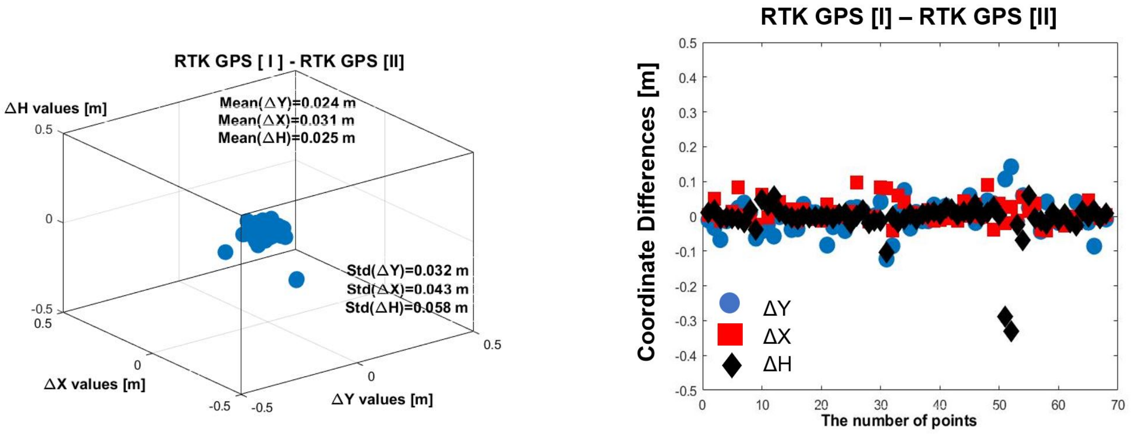


Figure 6. Comparison of the coordinates derived from Point P5 on 9 July 2021 (7:45:13 – 9:26:43 h) with the coordinates derived from Point P6 on 9 July 2021(11:54:57 –– 12:53:03 h), (using RTK GPS)

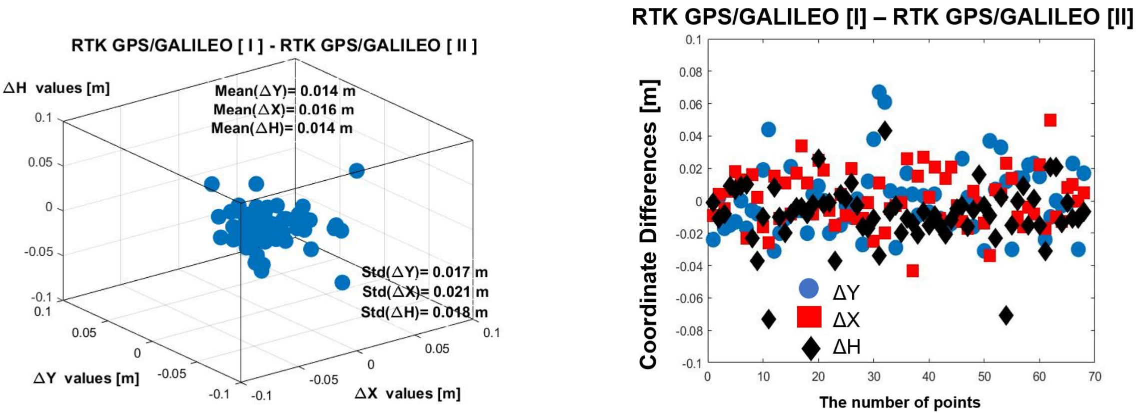


Figure 7. Comparison of the coordinates derived from Point P5 on 9 July 2021 (9:55:00 – 10:25:41) with the coordinates derived from Point P6 on 9 July 2021 (11:16:36 –– 11:51:54), (using RTK GPS/Galileo)

ranged from a few millimeters to roughly 7 centimeters. As previously noted, due to the presence of trees, some points in the study region have poor lines of sight to GPS and GPS/Galileo satellites, as illustrated in Figure 5. The RTK GPS/Galileo results of these points in the study region, however, were not affected by the tree canopies as well as RTK GPS. Figures 9, 10 and 11 show the differences between the test points and their average values (1.4 – 2.5 cm) and standard deviation values (1.9 – 5.8 cm). The horizontal coordinate differences of the RTK GPS results range from a few millimeters to 15 centimeters. The differences in height coordinates ranged from a few millimetres to roughly 35 cm. Some points in the research region have limited lines of sight to the satellites due to the tree covers. The results of these points in Figures 9 and 11 show that trees hindered RTK GPS positioning by often blocking and affecting the signals of the low-medium satellites. The differences in horizontal coordinates of these points between the RTK GPS surveys were larger than 10 cm. As seen in Figures 9 and 11, these obtained observations by using the reference point P6 resulted in the biggest coordinate differences of the day. As explained before, the measurements were collected at noon on July 9, 2021 (11:54:57 – 12:53:03 h LT) when the satellite configuration was not favorable, resulting in poor precision and accuracy of these points in the obstructed areas.

4.4 Total station measurement results and comparisons

A calibrated total station was used to determine the 68 point coordinates in the second step of the test. For the total station surveys, the two, P5 and P6, points were used as control points. The Topcon GT1201 instrument (Angle Accuracy = 1'', Distance Accuracy = 1 mm + 2ppm) was used for total station survey. As previously stated, the coordinates of P5 and P6 were computed by using the static GNSS method (about 90 minutes of survey time) by fixing ISKI-CORS point PALA. The total station surveys gone the same way as the RTK surveys. The horizontal direction, zenith angle, and slope distance were recorded in order to compute the coordinates of the 68 test points. Sight distances should be kept to less than 250 meters in order to reduce errors caused by curvature and refraction. Depending on their visibility in total station survey, the sixty-eight test points were observed from P5 and/or P6 points. The test points' coordinates were averaged. The survey of the test points by using the P5 and P6 stations took roughly 60 minutes. The accuracy and repeatability between the total station survey and RTK surveys (RTK GPS and RTK GPS/Galileo) for the sixty-eight points were evaluated in this study.

4.5 Comparison of RTK GPS and RTK GPS/Galileo Survey Results with Total Station Survey Results

The test points' coordinates by using RTK-GPS were compared with the coordinates obtained by using total station. The purpose of the comparison was to evaluate the performance and accuracy of the RTK GPS and RTK GPS/Galileo systems. Figure 12 illustrates the coordinate discrepancies between the RTK GPS/Galileo [I] and total station surveys. The coordinate differences were bigger in horizontal coordinates (particularly for X coordinates due to obstructed region) and smaller in height coordinates, according to the results

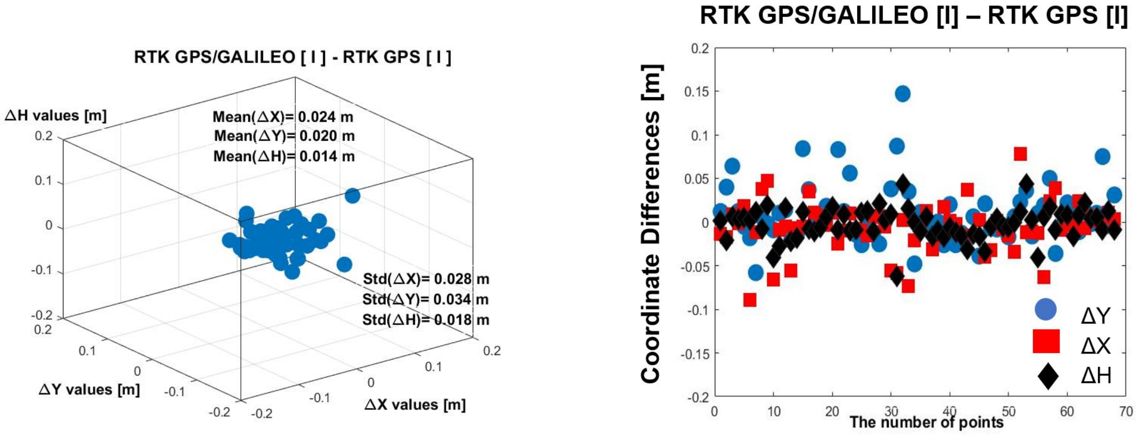


Figure 8. Comparison of the coordinates derived from Point P5 on 9 July 2021 (using RTK GPS) with the coordinates derived from Point P6 on 9 July 2021, (using RTK GPS/Galileo)

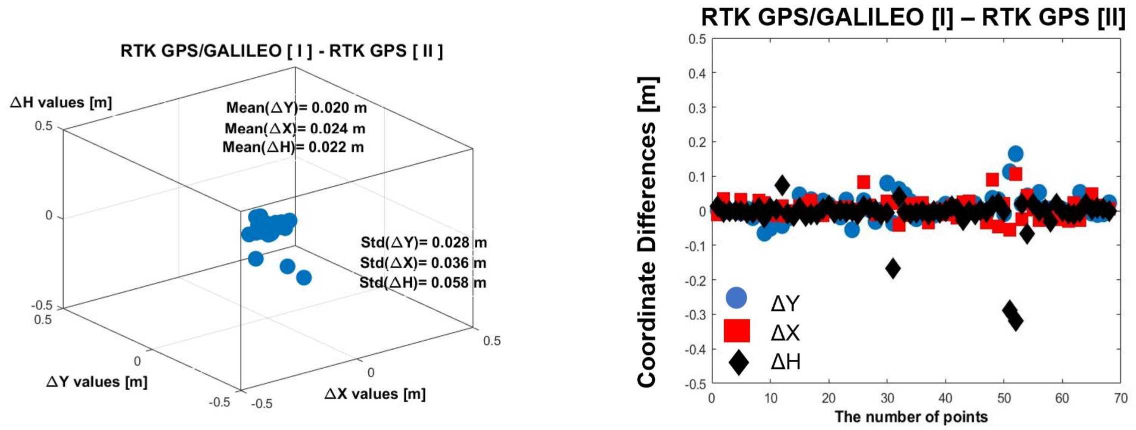


Figure 9. Comparison of the coordinates derived from Point P6 on 9 July 2021 (using RTK GPS) with the coordinates derived from Point P6 on 9 July 2021, (using RTK GPS/Galileo)

of the RTK GPS/Galileo and total station surveys. The mean values of the horizontal and vertical coordinate differences were less than 2 cm and less than 1 cm respectively. The highest differences in horizontal and vertical coordinates, as shown in Figure 12, were obtained for some points quite close to the wooded area (Pirti et al., 2009).

There was also a comparison of total station and RTK GPS/GALILEO [II] techniques (Figure 13). The discrepancy in horizontal coordinates (X, Y) ranged from a few millimetres to about 5 cm, whereas the difference in height coordinates ranged from a few centimetres to about 10 cm. Figure 13 shows mean values (1.1 – 1.9 cm) and standard deviation values (1.5 – 1.9 cm). The horizontal coordinate differences between RTK GPS/Galileo [II] and total station ranged from a few millimeters to 7 centimeters. The height coordinate discrepancies ranged from a few millimeters to roughly 8 centimeters. The results of these points in the obstructed areas (RTK GPS/Galileo) however, were not affected by the tree canopies as well as RTK GPS results.

The coordinates of RTK GPS were compared with the coordinates of the sixty-eight points obtained from the total station survey. Figures 14 and 15 illustrate the coordinate discrepancies between the RTK GPS and total station surveys. The coordinate differences were bigger in height coordinates (particularly for H coordinates due to obstructed region), according to the results of the RTK GPS and total station surveys. Figures 14 and 15 show the differences between the test points and their average values (1.1 – 2.7 cm) and standard deviation values (1.5 – 5.8 cm). The mean values of the horizontal and vertical coordinate differences were less than 3 cm and less than 2 cm respectively. The highest differences in horizontal and vertical coordinates were obtained for some points quite close to the wooded area (Pirti et al., 2009).

The results clearly show that the RTK GPS – RTK GPS/Galileo techniques are stable methods that provide dm-cm level of accuracy under various operational environments, with the exception of altering satellite geometry within woodland areas. The RTK GPS/Galileo technique, on the other hand, provides centimetre-level horizontal and vertical accuracy in woodland areas. The benefits of RTK GPS/Galileo in terms of functionality, versatility, and the capacity to operate in locations with high levels of disturbance are demonstrated in this study. In the obstructed areas where centimetre accuracy is required, the RTK GPS/Galileo technique is suitable. This study shows that in surveying applications requiring centimetre accuracy, the RTK GPS/Galileo method can replace other survey methods.

These results were consistent with prior research that found that obstructions from the environment (branches, leaves, etc.) decreased the number of satellites visible (Deckert and Bolstad, 1996; Meyer et al., 2002; Pirti et al., 2010; Sigrist et al., 1999). In addition, using multi-GNSS systems and integrating Galileo to RTK GPS surveys improved the number of satellites in both open and wooded areas (Andreas et al., 2019; ESA, 2020; Hossam-E-Haider et al., 2014; Kaartinen et al., 2015; Ogundipe et al., 2014).

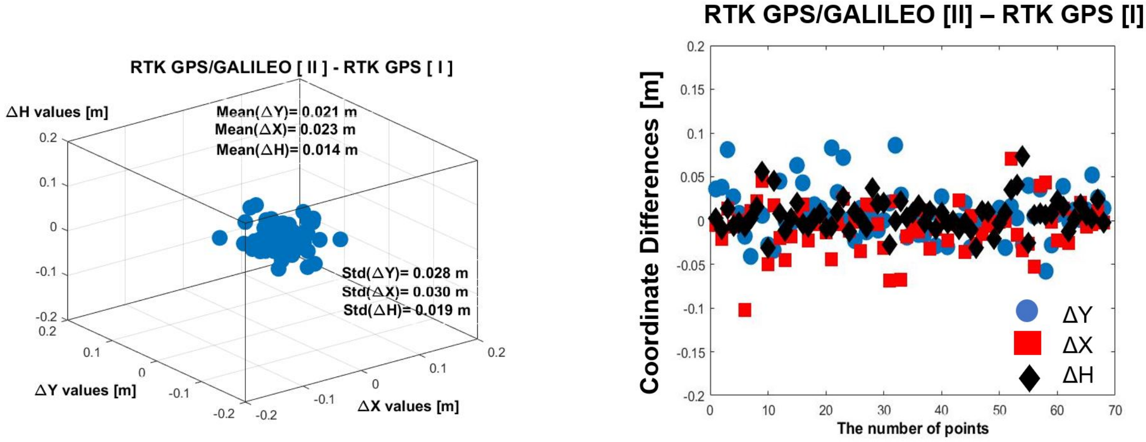


Figure 10. Comparison of the coordinates derived from Point P5 on 9 July 2021 (using RTK GPS) with the coordinates derived from Point P5 on 9 July 2021, (using RTK GPS/Galileo)

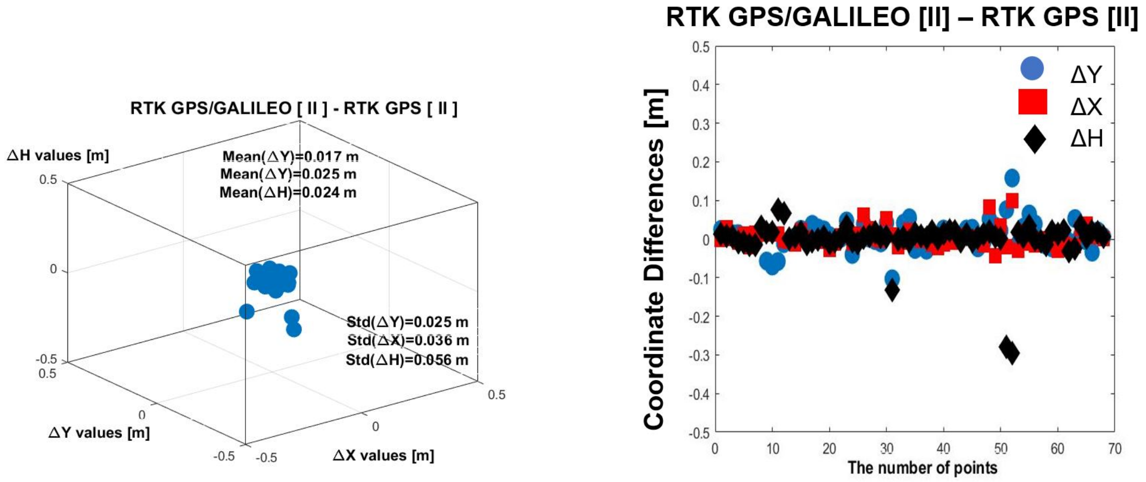


Figure 11. Comparison of the coordinates derived from Point P6 on 9 July 2021 (using RTK GPS) with the coordinates derived from Point P5 on 9 July 2021, (using RTK GPS/Galileo)

5 Conclusion

In this study, the integration of the Galileo satellite system into RTK GPS techniques was evaluated. The study indicated that the obstructions (i.e., leaves, branches) in woodland environment have a significant impact on the accuracy, precision and performance of RTK GPS but not RTK GPS/Galileo. In general, the results also showed that the multi-GNSS RTK (GPS/Galileo) technique offers higher positional accuracy in both open areas and woodland areas compared to RTK GPS method. The RTK GPS surveys on sixty-eight points took a very long time to collect the required number of epochs because tree leaves and branches in some points and that caused inability to receive the signals from GPS satellites. This degrades the accuracy of GPS positions by affecting both the signal quality and the computed position. Even though the receiver can still track signals from both GPS and GPS/Galileo, the ambiguity resolution time showed differences. It took approximately 41′ (41 minutes) – 56′ (56 minutes) with RTK GPS and 30′ (30 minutes) and 35′ (35 minutes) with RTK GPS/Galileo for the test points in our study. Under these circumstances, the integration of Galileo satellites on 9 July 2021 transmitting multi-frequency signals could be particularly beneficial for high-precision RTK survey. This article demonstrates the benefits of Galileo integration for high-precision real-time kinematic (RTK), taking into account GPS and GPS/Galileo, multipath impact, and tree canopy.

The Galileo is a newer technology and provides more robust functionality. The use of Galileo systems along with GPS will provide about 60 satellites, which is double the number of available signals for all user segments. Hence, Galileo positioning is expected to be significantly more accurate than GPS. Also, the higher signal strength of Galileo will improve the precision and accuracy of location information under forest canopy cover. The Galileo system developer asserts that practitioners can use a GNSS in dense forests. Also, availability of more satellites might be useful for addressing multi-path problems. Thus, it is expected that the Galileo system will provide more benefits to the users for various purposes after complete deployment.

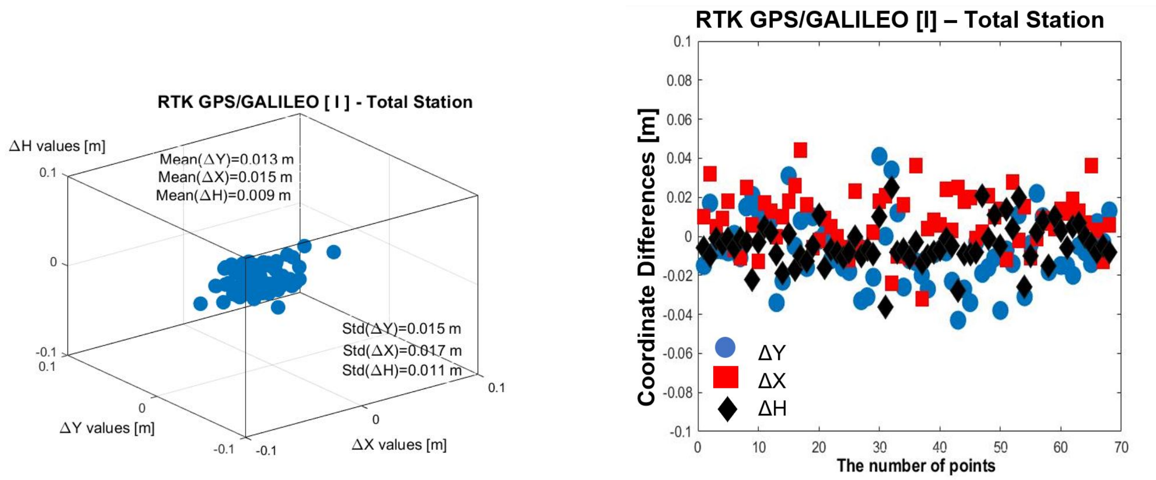


Figure 12. Comparison of the coordinates of the 68 points in the project area between total station survey and RTK GPS/Galileo (Point P5 (9 July 2021)) survey

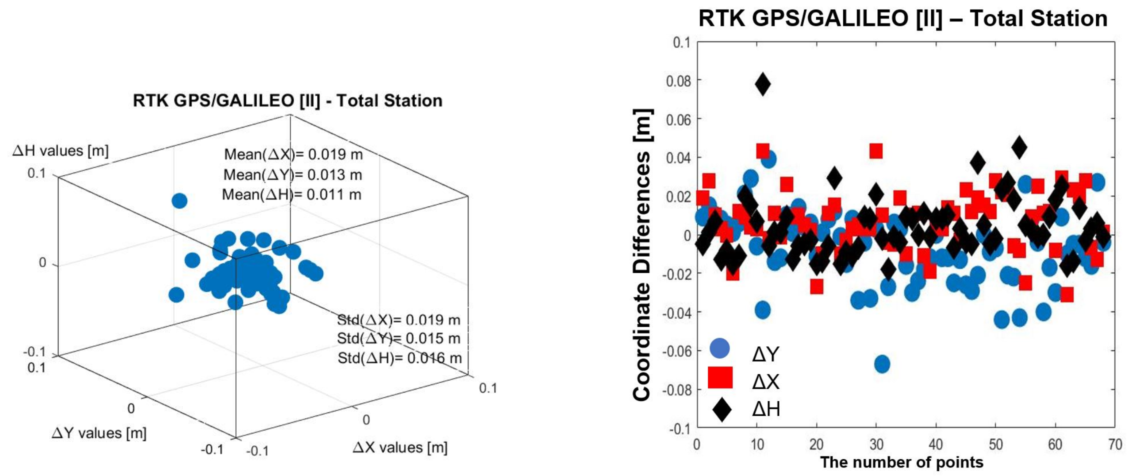


Figure 13. Comparison of the test points coordinates obtained from Total station surveys with the RTK GPS/GALILEO method (Point P6 (9 July 2021)) survey

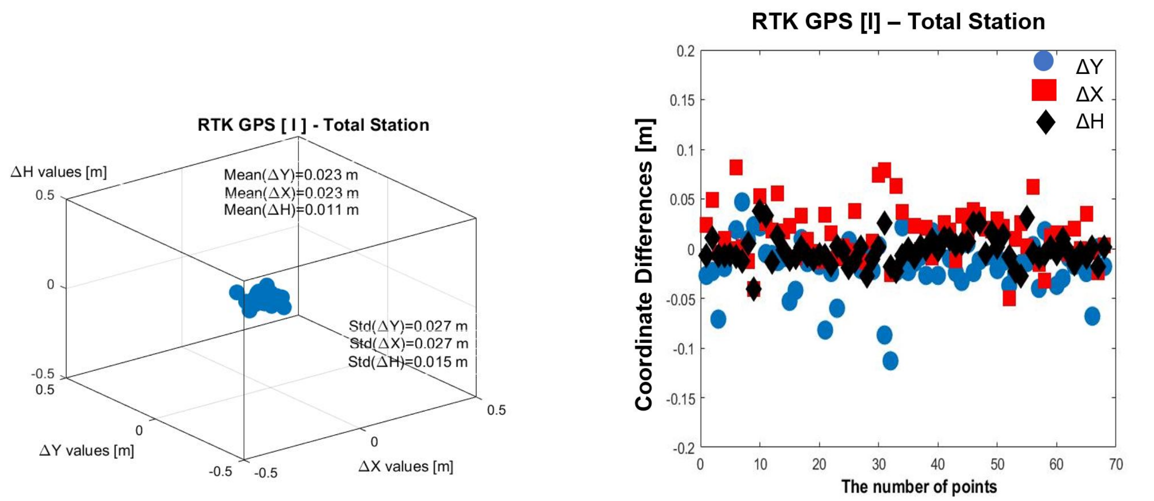


Figure 14. Comparison of the test points coordinates obtained from Total station surveys with the RTK GPS survey by using Point P6 on 9 July 2021

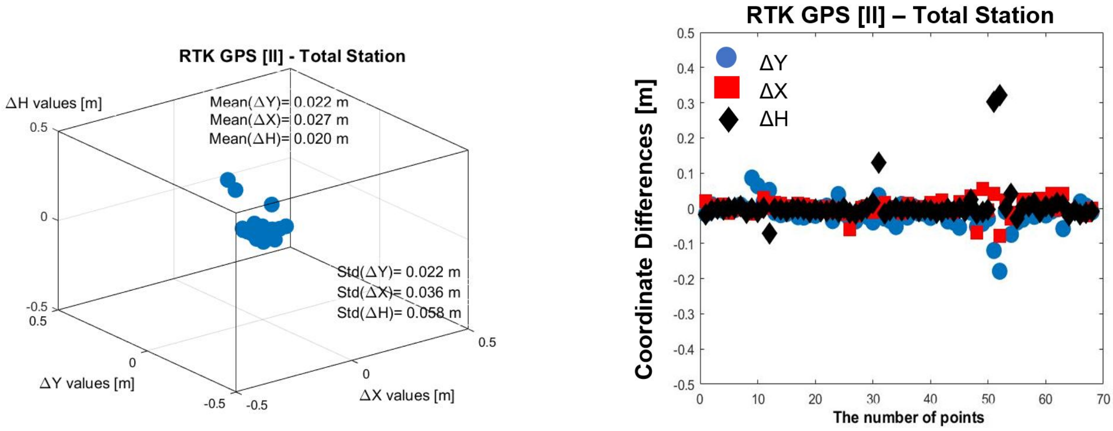


Figure 15. Comparison of the test points coordinates obtained from Total station surveys with the RTK GPS survey by using Point P6 on 9 July 2021

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