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**Research Article**

# PERFORMANCE EVALUATION OF REAL TIME PRECISE POINT POSITIONING FOR MULTI-GNSS CONCEPT

**Furkan KARLITEPE[1], Nursu TUNALIOĞLU[2], Bahattin ERDOĞAN*[3]**

[1]*Tokat Gaziosmanpasa University, Dept. of Geomatic Engineering, TOKAT;* ORCID: 0000-0003-4972-1565
[2]*Yildiz Technical University, Dept. of Geomatic Engineering, ISTANBUL;* ORCID: 0000-0001-9345-5220
[3]*Yildiz Technical University, Dept. of Geomatic Engineering, ISTANBUL;* ORCID: 0000-0002-8060-9208

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**ABSTRACT**

Today, Precise Point Positioning (PPP) technique is at the forefront of the Global Navigation Satellite Systems (GNSS) based point positioning in many applications. In particular, GNSS-based real-time PPP (RT-PPP) applications are significant for next-generation autonomous systems and geospatial industries. However, real-time corrections are required for these applications. Since 2003, International GNSS Service (IGS) has been preparing substructure for multi-GNSS applications within the context of multi-GNSS Experiment (MGEX) Project. In this study, two IGS MGEX stations were selected. These are equipped with GPS, GLONASS, Galileo and BeiDou systems' receivers, and provide real-time solutions. Then, eight scenarios were generated depending on the different satellite combinations. These scenarios were examined in terms of convergence time and positioning accuracy, and the performance of different satellite systems in RT-PPP analyses was revealed. BNC v2.12.6 software was used for all analyses. Regarding the results, it can be concluded that using the different satellite combinations results in shortening the convergence time in RT-PPP and increasing the positioning accuracy.
**Keywords:** Multi-GNSS, Real-Time PPP (RT-PPP), IGS MGEX, combined positioning, convergence time.

## 1. INTRODUCTION

Precise Point Positioning (PPP) was first introduced at the end of the 1990s as an alternative Global Navigation Satellite Systems (GNSS) based positioning technique [1]. Since PPP has provided to the users positioning accuracies at cm-dm level globally in static/kinematic mode by collecting data from a single GNSS receiver, it has drawn the attention. The method has been widely used for GNSS-based positioning applications such as geodetic-geophysical surveying, climatology, marine positioning, geohazard monitoring, and atmospheric researches [2, 3]. Especially, Real-Time PPP (RT-PPP) method comes to the forefront in the application areas of agriculture, mining, construction, energy (petroleum & gas), and auto-driving vehicles. In recent years, due to the developments on GNSS embedded chipsets (dual-frequency & multi-GNSS sensors) of mobile devices (smartphones/tablets), RT-PPP applications with them have increased as well [4].

* Corresponding Author: e-mail: berdogan@yildiz.edu.tr, tel: (212) 383 52 91

PPP method provides many advantages for both post-processing and real-time positioning. Some of the main advantages are that using a single GNSS receiver, cost-effective and no need for a reference station. From this aspect, it becomes a significant alternative to traditional relative positioning [5]. However, the most important disadvantage of the method is that the convergence time required for carrier-phase ambiguity resolution is too long. This time varies according to the satellite geometry, satellite elevation angle and data quality, and can change between 30 minutes and hours [6]. In order to eliminate this disadvantage, PPP with ambiguity resolution (PPP-AR) algorithm approach has been developed [7].

The corrections for PPP can be represented using the state-space representation (SSR) of parameters approach [8]. PPP uses SSR correction products such as precise satellite orbits, clocks, signal biases (code and phase), ionosphere, and troposphere from either commercial or/and the public that is delivered to the user via satellite and/or internet.

Traditional standard PPP uses precise satellite orbits and clock correction products. In PPP-AR method, precise satellite orbits, clocks, and signal biases (code and phase) are used. The common name of these approaches in real-time applications is RT-PPP. In PPP Real-Time Kinematic (PPP-RTK) method, ionosphere and troposphere delay correction products are used in addition to precise satellite orbits, clocks and signal biases. Though PPP estimates some of the SSR parameters, PPP-RTK estimates almost all of the SSR parameters [9]. The comparison of PPP, PPP-AR and PPP-RTK is given in Table 1.

**Table 1.** Comparison of the PPP, PPP-AR, PPP-RTK methods [9]

| Method | SSR correction products | Initialization time | Accuracy (horizontal) |
|---|---|---|---|
| PPP | Satellite orbits<br>Satellite clocks | > 40 min for float | a few cm |
| PPP-AR | Satellite orbits<br>Satellite clocks<br>Code biases<br>Phase biases | ~ 30 min | a few cm |
| PPP-RTK | Satellite orbits<br>Satellite clocks<br>Code biases<br>Phase biases<br>Ionospheric delay<br>Tropospheric delay | < 1 min | a few cm |

Today, IGS provides SSR correction products to the users free of charge with Radio Technical Commission for Maritime (RTCM v3) data format via Networked Transport of RTCM via Internet Protocol (NTRIP). Therefore, RTCM-SSR products are widely used. However, only the precise satellite orbits, clocks, and signal code bias (SCB) products are now available for the users among the RTCM-SSR products provided by International GNSS Service (IGS). The signal phase bias (SPB) and vertical total electron content (VTEC) products of IGS are still in the testing process. The RTCM-SSR products of IGS are only available for GPS and GLONASS systems, and these products for Galileo and BeiDou systems are not available yet [10].

In spite of this, some of the commercial companies have developed new data standards/formats to support and extend the PPP applications that can be alternative to the RTCM. For instance, a company, Sapcorda, has developed a data format, namely Safe Position Augmentation for Real-Time Navigation (SPARTN) for the autonomous industry (cars, drones, mobile/IoT, logistics etc.) [11]. Additionally, the State Space Representation Compressed Format (SSRZ) was developed by Geo++ [12]. The comparison of these data formats developed for SSR correction products can be found in Table 2.

**Table 2.** Comparison of the data formats: RTCM-SSR, SSRZ, SPARTN for correction products [12]

| SSR Group | Multi-stage/ Scalability | | RTCM-SSR | SSRZ (0.9) Geo++ 4090.7 | SPARTN (1.8.0) Sapcorda |
|---|---|---|---|---|---|
| RTCM farming | | | yes | optional | no |
| SV clock | high rate clock | | available | available | available |
| | low rate clock | | available | available | |
| SV orbit | | | available | available | available |
| SV code bias | | | available | available | available |
| SV phase bias | | | proposed/tested | available | available |
| ionosphere | global | VTEC | proposed/tested | available | available** |
| | global | STEC | under discussion | available | |
| | regional | STEC | under discussion | available | available* |
| | residual | gridded/station | under discussion | available | available |
| | global | | under discussion | in preparation | |
| troposphere | regional | | under discussion | available | available* |
| | residual | gridded/station | under discussion | available | available |
| complete SSR model | | | not yet | yes | yes |

** differs from SSRZ definition ** differs from SSRZ definition and not complementary to other stages*

While the commercial and industrial developments continue, IGS has conducted two important projects with a public approach. The projects of MGEX and Real-Time Services (RTS) conducted by IGS support and develop both the multi-GNSS concept and the widespread use of the RT-PPP.

With the MGEX Project, the products are presented to all GNSS users as experimentally and officially in four main groups, which are (1) Precise Orbit and Clock Products, (2) Broadcast Ephemerides, (3) Differential Code Biases, and (4) Real-Time Products. The MGEX Project has an integration with the RTS Project for the purpose of presenting real-time products. IGS RTS Project is critical for real-time applications on a global scale. The goal of the RTS Project is to provide all SSR products to the users with the observations collected from the MGEX stations in RTCM data format free of charge for the multi-GNSS concept in the next generation [10, 13].

While these important development dynamics continue for PPP, the convergence time and accuracy of the solutions obtained from the implementation of this technique are significant. Investigation of the approaches to shorten the convergence time and to improve the accuracy of the point positioning are important and current research issues. Today, the problem of satellite-based precise positioning starting with GPS has become a multi-GNSS structure with the integration of GLONASS, Galileo, and BeiDou systems. Now, applications for real-time high accurate positioning with a single receiver has a structure that will affect every aspect of our lives. Real-time applications are especially important for the autonomous systems that will be used effectively in the near future.

In this context, the effect of different satellite combinations for the multi-GNSS concept on both convergence time and positioning accuracy for RT-PPP applications was investigated in this study. Performance evaluations of GPS-only solution, GPS+GLONASS combined solution, GPS+GLONASS+Galileo combined solution and GPS+GLONASS+Galileo+BeiDou combined solution for RT-PPP applications were examined.

## 2. THE IMPORTANCE OF MULTI-GNSS CONCEPT FOR PPP

Additional observations gathered from GLONASS, Galileo and BeiDou satellite systems can improve the accuracy, reliability and usability of GPS-PPP. Also, RT-PPP is an innovative global positioning technique using a single receiver on the basis of real-time satellite orbit and clock products in multi-GNSS [14]. Therefore, the multi-GNSS model concept is important for both post-processing PPP (PP-PPP) and RT-PPP applications for the widespread use of the next generation multi-frequency GNSS receivers [15, 16].

Thus, public institutions such as IGS, BKG, CNES, ESA and GFZ present the SSR corrections products of GPS and GLONASS, which are especially needed to support RT-PPP applications free today. These institutions have continued their testing facilities to provide these relevant SSR products for Galileo and BeiDou systems. In order to increase the accuracy in RT-PPP, many GNSS error parameters are calculated and then added to the pseudorange (code) and carrier phase observations. In this technique, the most important parameters for determining the position accuracy in real-time are satellite orbit and clock corrections [17, 18]. In multi-GNSS, the quality of precise orbit and clock correction products is a function of the satellite system, elevation angles of Planet and the Sun, and satellite altitude [19]. However, in the traditional standard multi-GNSS RT-PPP model, inter-system bias (ISB) parameters should also be estimated in terms of accuracy and efficiency. In the transition from RT-PPP to PPP-RTK, ionosphere and troposphere delay correction products estimated in real-time are used.

As a result, efficiency in multi-GNSS RT-PPP depends mainly on total presentation of SSR correction products (precise satellite orbits and clocks, code and phase signal biases, ionosphere and troposphere). Therefore, verified and approved combined RTS products should be used instead of products delivered from a single IGS Analyses Center (AC) for RTCM-SSR.

## 3. DATA PROCESSING STRATEGY

This study investigates the performance of the combination of the different satellite systems on positioning accuracy in the RT-PPP technique. Two IGS MGEX stations, namely SCRZ and KOUG were selected. To perform RT-PPP analysis, BNC v2.12.6 software developed by BKG was used [20]. In the processing stage, the stream properties mentioned in Table 3 were implemented. Moreover, geographical coordinates and GNSS antenna types of receivers can be found in Table 4. The locations of these stations can be seen in Figure 1.

**Table 3.** RTCM v3 message types used in data processing [21]

| Products/Data Types | Message | Contents |
|---|---|---|
| Broadcast Ephemeris Streams (RTCM3EPH-MGEX) | 1019 | GPS Broadcast Ephemeris |
| | 1020 | GLONASS Broadcast Ephemeris |
| | 1042 | BeiDou Broadcast Ephemeris |
| | 1045 | Galileo F/NAV Broadcast Ephemeris |
| | 1046 | Galileo I/NAV Broadcast Ephemeris |
| Broadcast SSR Correction Streams (CLK 90) | 1059 | GPS Code Biases |
| | 1060 | GPS Combined Orbit and Clock Corrections |

**Table 4.** The geographical coordinates and antenna types of stations

| IGS MGEX Station | Latitude (°) (GRS80) | Longitude (°) (GRS80) | GNSS Antenna Type |
|---|---|---|---|
| KOUG | 5.0984709 | -52.6397502 | LEIAR25.R3 LEIT |
| SCRZ | -17.7967917 | -63.1596778 | LEIAR10 NONE |

In the study, 8 different scenarios were developed by using 2 IGS MGEX stations. 3-hour RT-PPP analyses using BNC v2.12.6 software according to different satellite combinations of GPS-only, GPS+GLONASS, GPS+GLONASS+Galileo and GPS+GLONASS+Galileo+BeiDou were carried out at station SCRZ depending on observations collected simultaneously on March 8, 2019. At KOUG station, 3-hour RT-PPP analyses similar to those in station SCRZ were performed with data collected on March 9, 2019. In all analyses, real-time coordinates of the 3-hour observations were obtained at 1-second epoch interval.

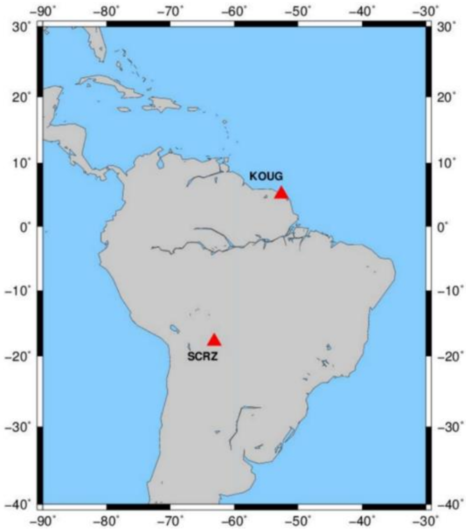


**Figure 1.** Location map of IGS Network MGEX stations: SCRZ and KOUG

During the real-time analysis, RINEX observation files for both stations were generated from RTCM streams. These observations were then used to compute the reference coordinates performing post-processing PPP (PP-PPP) analysis with GIPSY OASIS II v6.4 software. Since RT-PPP solutions were in ITRF2014 system, and reference coordinates were in ITRF2008 system, reference coordinates were converted to ITRF2014 datum. Thus, both reference coordinates and coordinates computed from real-time observations were provided in the ITRF2014 datum and observation epoch. Then, differences between reference coordinates and coordinates calculated from RT-PPP solutions for North (n), East (e) and Up directions were examined in order to investigate the effect of the different satellite combinations on convergence time and positioning accuracy in RT-PPP applications. Despite setting 3-hour observation duration, datasets with different sizes were obtained for different satellite combinations at stations SCRZ and KOUG due to data stream outages or delays in real-time applications.

Table 5 presents the total data numbers and the mean of satellite numbers for each scenario when the starting times, ending times and data outages of both stations are ignored. The scenarios state the satellite combinations. Additionally, the differences obtained from the reference coordinates are drawn separately in Figures 2-9 in order to the visual presentation of solutions.

The figures also emphasize the ±5 cm and ±10 cm limitations for the differences of n and e components in different satellite combinations.

**Table 5.** The details of the observations

| IGS MGEX Station | Scenario | Date | Start Time (UTC) | End Time (UTC) | Number of Data | Mean Number of Satellite |
|---|---|---|---|---|---|---|
| SCRZ | GPS-only | 8 March 2019 | 16:06:21 | 19:00:01 | 8551 | 10 |
| | GPS+GLONASS | | 16:05:00 | 18:58:40 | 8621 | 15 |
| | GPS+GLONASS+Galileo | | 16:08:15 | 19:01:55 | 8614 | 19 |
| | GPS+GLONASS+Galileo+BeiDou | | 16:07:15 | 19:00:55 | 8619 | 21 |
| KOUG | GPS-only | 9 March 2019 | 15:09:13 | 18:09:33 | 7497 | 9 |
| | GPS+GLONASS | | 15:11:30 | 18:11:50 | 7499 | 14 |
| | GPS+GLONASS+Galileo | | 15:04:55 | 18:05:15 | 7496 | 21 |
| | GPS+GLONASS+Galileo+BeiDou | | 15:06:39 | 18:06:59 | 7540 | 22 |

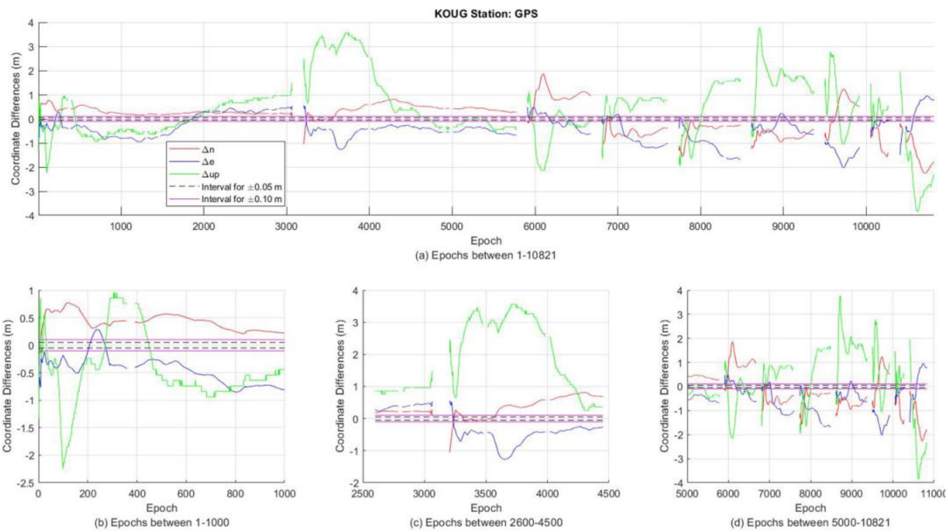


**Figure 2.** GPS-only RT-PPP solution for station KOUG

Integer ambiguity solution plays an effective role in RT-PPP applications. In case of any data stream outage, after the solution takes place in about 30 minutes, stabile progress can be seen in solutions. In the GPS-only solution, a stabile situation did not occur due to data outage at station KOUG, and the solutions did not decrease below either ± 5 cm or ± 10 cm (see, Figure 2a).

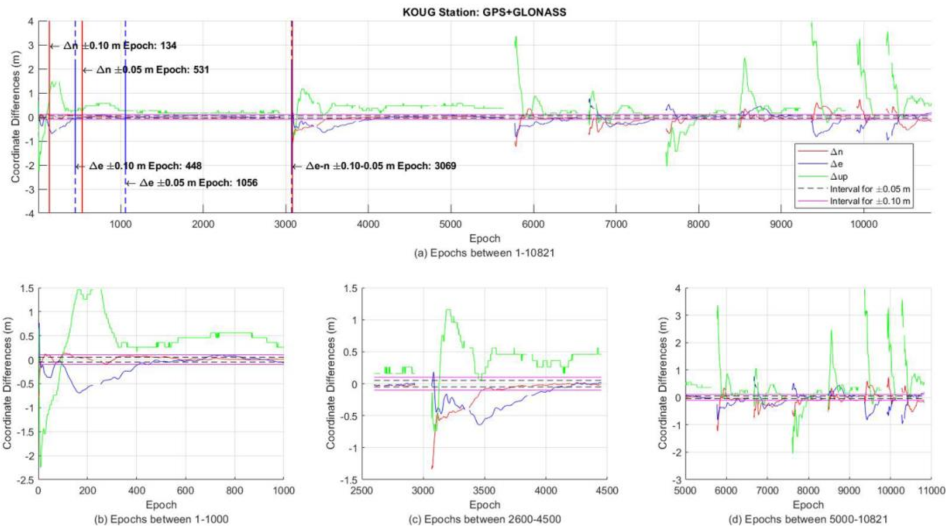


**Figure 3.** GPS+GLONASS combined RT-PPP solutions for station KOUG

The number of satellites in the GPS+GLONASS combination at station KOUG increased by 5 satellites on average compared to the GPS-only. When the coordinate differences are examined, it is seen that the differences for n and e components are reached ± 10 cm below for the first time in $134^{th}$ and $448^{th}$ seconds, respectively (see, Figure 3a). Considering the ± 5 cm interval, it decreased below this value for n and e components in $531^{st}$ and $1056^{th}$ seconds, respectively. Later, the differences exceeded the range of ± 10 cm in $3069^{th}$ second due to data outages. Considering that the differences do not fall within ± 10 cm range in the GPS-only solution, the GPS+GLONASS combination had a positive effect on the convergence time.

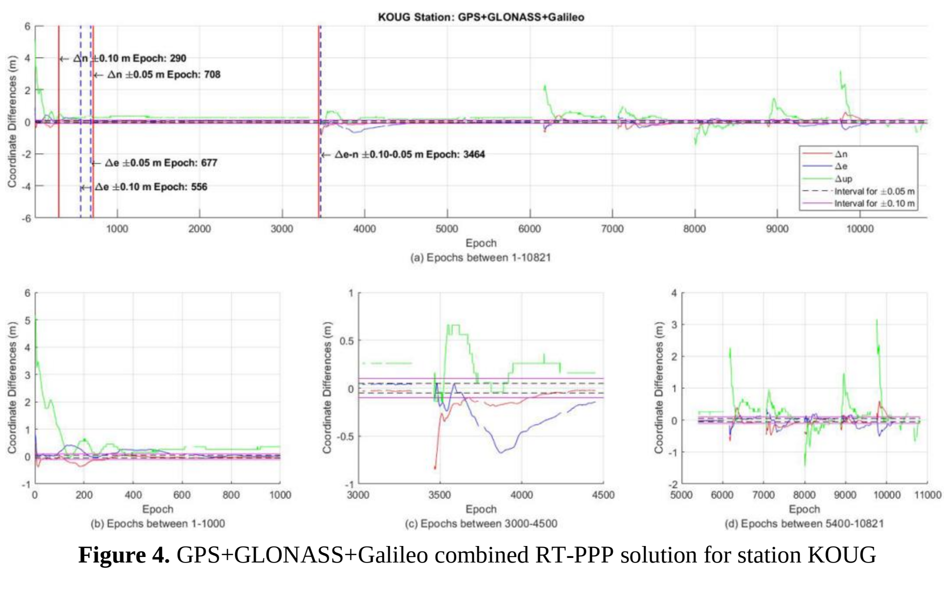


**Figure 4.** GPS+GLONASS+Galileo combined RT-PPP solution for station KOUG

At station KOUG, the number of satellites in the GPS+GLONASS+Galileo combination increased by 12 satellites on average compared to the GPS-only. The differences for n and e components reached ± 10 cm below for the first time in 290th and 556th seconds, respectively (see, Figure 4a). Moreover, it decreased below ±5 cm for component n and e in 708th and 677th seconds, respectively. Then the differences exceeded the range of ± 10 cm in 3464th second due to data outages. Although there is no improvement in the convergence time of n component compared to the GPS+GLONASS combined solution, the time to decrease within ± 5 cm range of the differences in e component has been shortened.

At station KOUG, the number of satellites in the GPS+GLONASS+Galileo+BeiDou combination increased by an average of 13 satellites compared to the GPS-only, and 1 satellite compared to the GPS+GLONASS+Galileo combination. In RT-PPP solutions, the minimum number of satellites belongs to the BeiDou system. The differences for n and e components reached ± 10 cm below for the first time in 303rd and 797th seconds, respectively (see, Figure 5a). Considering the ± 5 cm range, this value was decreased for component n and e in 637th and 891st seconds, respectively. Later, due to data stream outages, the differences increased over the range of ± 10 cm in 3381st second. Compared to the GPS+GLONASS+Galileo combined solution, no gain was achieved in terms of convergence time.

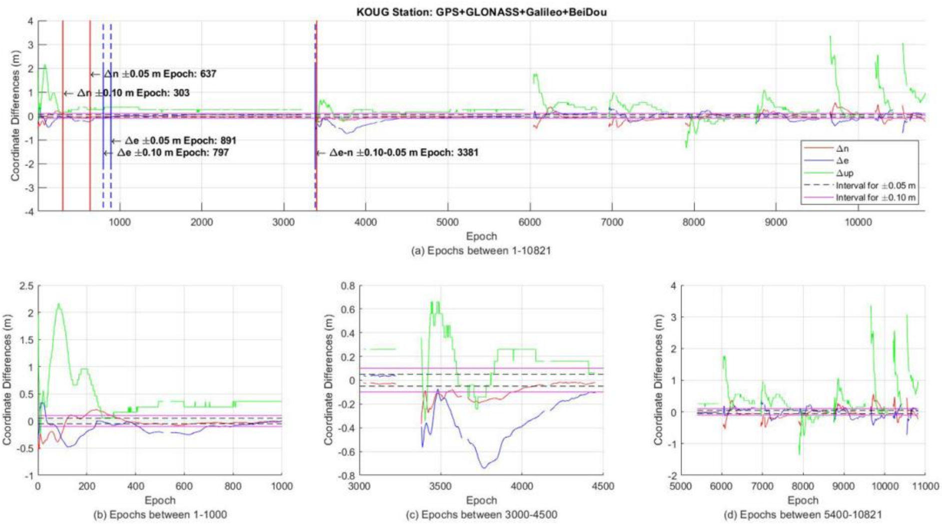


**Figure 5.** GPS+GLONASS+Galileo+BeiDou combined RT-PPP solution for station KOUG

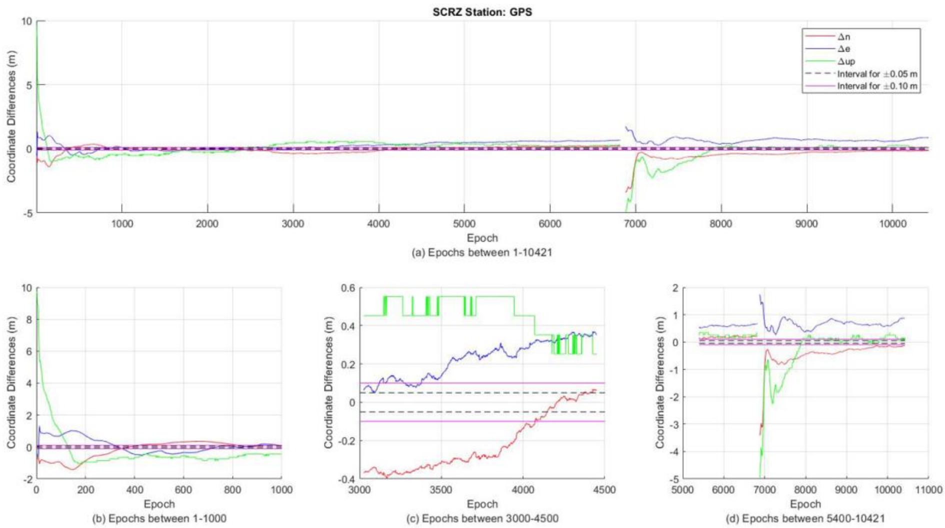


**Figure 6.** GPS-only RT-PPP solution for station SCRZ

Similar to station KOUG, analyses were carried out at station SCRZ. Although data outages are less than station KOUG, the differences obtained from the reference solutions did not fall below the ± 10 cm range when considering the GPS-only solution (see, Figure 6a).

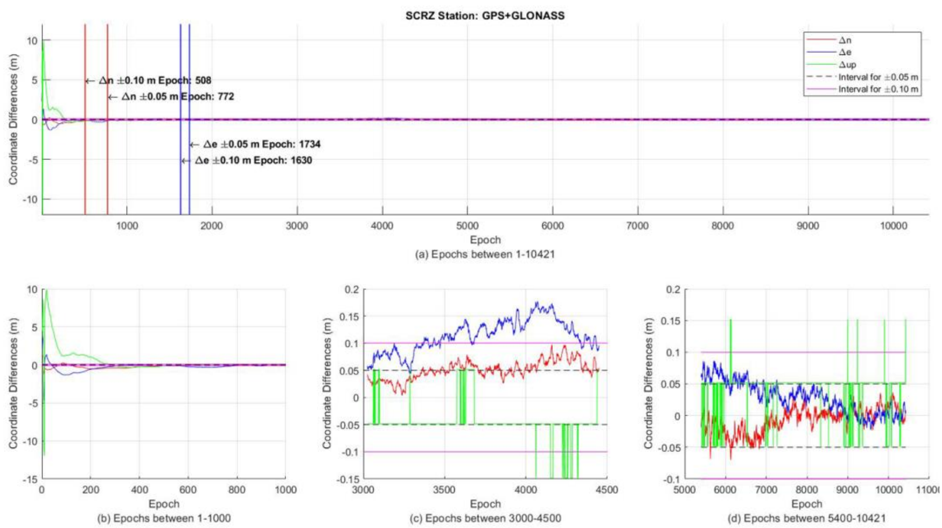


**Figure 7.** GPS+GLONASS combined RT-PPP solution for station SCRZ

The number of satellites in the GPS+GLONASS combination at station SCRZ has increased by an average of 5 satellites compared to the GPS-only. The differences for n and e components reached ± 10 cm below for the first time in 508$^{th}$ and 1630$^{th}$ seconds, respectively (see, Figure 7a). Considering the ± 5 cm interval, the value was decreased in 772$^{nd}$ and 1734$^{th}$ seconds for component n and e, respectively. Convergence times at station SCRZ are longer than station KOUG, but no data outage occurred. Considering that, the differences do not fall within ± 10 cm range in the GPS-only solution, the GPS+GLONASS combined solution had a positive effect on the convergence time at station SCRZ, as well.

The number of satellites in GPS+GLONASS+Galileo combination at station SCRZ increased by 9 satellites on average compared to the GPS-only. The differences for n and e components reached ± 10 cm below for the first time in 864$^{th}$ and 4775$^{th}$ seconds, respectively (see, Figure 8a). Considering the ± 5 cm range, it fell below this value at 4878$^{th}$ second for component n. The differences for component e were not in the range of ± 5 cm at all. Although there was an increase in the number of satellites in the GPS+GLONASS+Galileo combined solution, there was no improvement in the convergence time.

At station SCRZ, the number of satellites in the GPS+GLONASS+Galileo+BeiDou combination increased by an average of 11 satellites compared to the GPS-only, and 2 satellites compared to the GPS+GLONASS+Galileo combination. The minimum number of satellites in RT-PPP solutions belongs to the BeiDou system. The differences for n and e components reached ± 10 cm below for the first time in 390$^{th}$ and 2401$^{st}$ seconds, respectively (see, Figure 9a). Considering the ± 5 cm interval, it decreased below in 910$^{th}$ and 3864$^{th}$ seconds for component n and e, respectively. Although the differences for the component e in the GPS + GLONASS + Galileo combined solution do not fall within the range of ± 5 cm, the differences have decreased to this range as a result of the addition of the BeiDou satellite system to the combination.

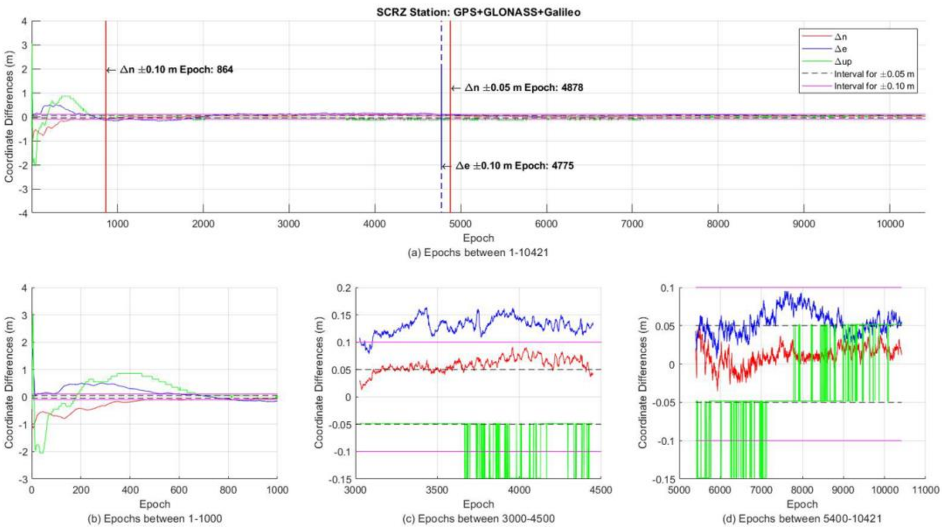


**Figure 8.** GPS+GLONASS+Galileo combined RT-PPP solution for station SCRZ

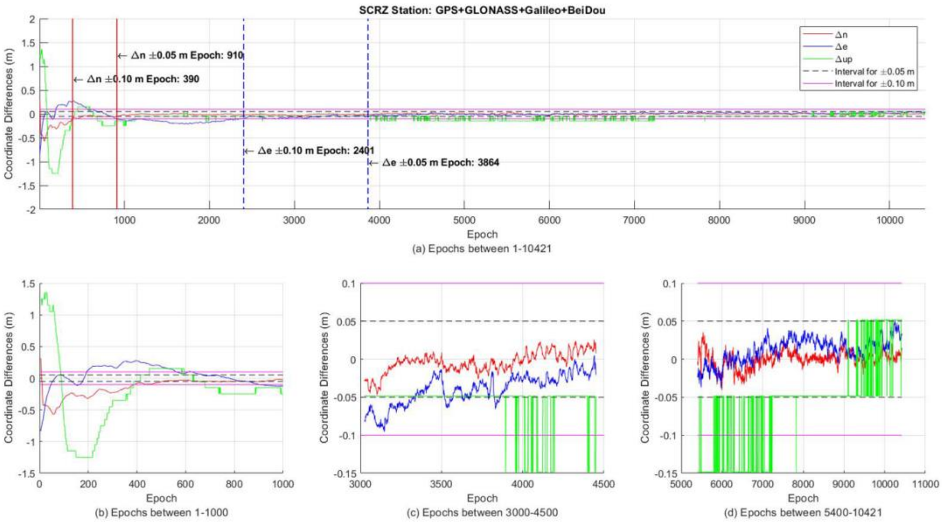


**Figure 9.** GPS+GLONASS+Galileo+BeiDou combined RT-PPP solution for station SCRZ

After examining the convergence times for different satellite combinations of RT-PPP solutions at stations KUOG and SCRZ, the means of the coordinate differences were calculated. While calculating the mean values, the first 30-minute section was not taken into consideration in the analyses (Table 6). In addition, standard deviations of these mean values as well as the mean values of the differences were calculated (Table 7). The mean of the differences in component n at station KOUG gives better results than the components e and up. The GPS+GLONASS+ Galileo+BeiDou combined solution in e component performed better than other combinations. The analysis of different satellite systems in the up component has enabled the differences to approach the reference value and the best solution has been obtained in the GPS+GLONASS+Galileo combination. The standard deviations of the mean values are higher due to data outage at station KOUG.

During the analyses, data outages were less at station SCRZ. For this reason, the standard deviations of the mean values calculated are smaller than the values obtained for station KOUG. At this station, the best results for components n and e were obtained in the GPS+GLONASS+ Galileo+BeiDou combined solution. The up component gave good overall results for all combinations. Considering these combinations, the GPS+GLONASS combined solution has the best result.

**Table 6.** Mean of coordinates' differences of stations KOUG and SCRZ for RT-PPP solutions

| | KOUG | | | SCRZ | | |
|---|---|---|---|---|---|---|
| | Mean (m) | | | Mean (m) | | |
| | n | e | up | n | e | up |
| GPS-only | 0.0144 | -0.4034 | 0.5707 | -0.1997 | 0.4644 | 0.0117 |
| GPS-GLONASS | -0.0780 | -0.0909 | 0.3799 | 0.0144 | 0.0437 | 0.0098 |
| GPS-GLONASS-Galileo | -0.0493 | -0.0662 | 0.2278 | 0.0236 | 0.0725 | -0.0472 |
| GPS-GLONASS-Galileo-BeiDou | -0.0375 | -0.0583 | 0.3013 | -0.0025 | -0.0161 | -0.0649 |

**Table 7.** Standard deviations of means of coordinates' differences for stations KOUG and SCRZ for RT-PPP solutions

| | KOUG | | | SCRZ | | |
|---|---|---|---|---|---|---|
| | Standard Deviation (m) | | | Standard Deviation (m) | | |
| | n | e | up | n | e | up |
| GPS-only | 0.7121 | 0.5811 | 1.3463 | 0.3997 | 0.2784 | 0.6554 |
| GPS-GLONASS | 0.2046 | 0.2315 | 0.6082 | 0.0348 | 0.0626 | 0.0521 |
| GPS-GLONASS-Galileo | 0.1391 | 0.1684 | 0.3638 | 0.0218 | 0.0389 | 0.0549 |
| GPS-GLONASS-Galileo-BeiDou | 0.1282 | 0.1735 | 0.4303 | 0.0125 | 0.0512 | 0.0855 |

In order to examine the distribution of different combination solutions, standard deviation values were also calculated using the differences obtained from the reference coordinates. When the standard deviation values in Table 8 are analyzed, it can be seen that generally, different satellite systems make a significant contribution to the GPS-only at both stations. At station KOUG, the lowest standard deviation for the n component was obtained in the GPS+GLONASS+Galileo+BeiDou combined solution, and the lowest standard deviation for the e and up components was obtained in the GPS+GLONASS+Galileo combined solution. Similar to station KOUG, the lowest standard deviation for the n component was obtained from the GPS+GLONASS+Galileo+BeiDou combined solution at station SCRZ. The lowest standard deviation in the e and up components was calculated in the GPS+GLONASS combined solution. Although the GPS+GLONASS combined solution for these components has the lowest standard deviation, the values are very close to GPS+GLONASS+Galileo+BeiDou combination.

**Table 8.** Standard deviations of stations KOUG and SCRZ for RT-PPP solutions

| | KOUG | | | SCRZ | | |
|---|---|---|---|---|---|---|
| | Standard Deviation (m) | | | Standard Deviation (m) | | |
| | n | e | up | n | e | up |
| GPS-only | 0.7122 | 0.7074 | 1.4622 | 0.4468 | 0.5414 | 0.6555 |
| GPS-GLONASS | 0.2190 | 0.2487 | 0.7171 | 0.0316 | 0.0448 | 0.0512 |
| GPS-GLONASS-Galileo | 0.1475 | 0.1810 | 0.4292 | 0.0321 | 0.0822 | 0.0724 |
| GPS-GLONASS-Galileo-BeiDou | 0.1336 | 0.1831 | 0.5252 | 0.0122 | 0.0487 | 0.0557 |

## 4. CONCLUSION

This study investigates the effect of different satellite combinations on RT-PPP solutions in the multi-GNSS concept. By selecting the stations KOUG and SCRZ from IGS-MGEX, each combination of the stations was analyzed in real-time with 3-hour observations collected simultaneously, and data with 1-second interval were analyzed with BNC v2.12.6 software. During the analyses, RINEX files obtained from the observation data were created and evaluated in GIPSY OASIS II v6.4 software with the GPS-only in the form of PP-PPP, and these solutions were used as reference coordinates. Coordinate differences were obtained by subtracting reference coordinates from RT-PPP solutions. The performance of different satellite combinations was examined by using these coordinate differences.

The aim of this study is to investigate how positioning accuracy of RT-PPP solutions and convergence time are affected by the different satellite combinations. When approximately 3-hour analyses were examined, it was observed that the coordinate differences in the GPS-only solutions did not fall between ± 5 cm and ± 10 cm. However, it is seen that the solutions fall within these ranges if different satellite combinations are considered. Considering the convergence time, it is seen that the GPS+GLONASS+Galileo and GPS+GLONASS+Galileo+BeiDou combinations have positive effects in general.

In the study, the means of the coordinate differences and the standard deviations of the mean values were also examined. In cases where multiple satellite combinations are used, the mean values of the differences appear closer to zero. As with the convergence time, it is seen that the GPS+GLONASS+Galileo combination in n and up components has a great contribution compared to the GPS-only. Especially for n component, the GPS+GLONASS+Galileo+BeiDou combined solution gives the best result. A small number of satellites from the BeiDou satellite system has been used in the analyses. This occurs because the e and up components are most affected by the satellite configuration.

In addition, when standard deviations calculated using reference coordinates are examined, a significant improvement in the standard deviation values was observed when multiple satellite combinations were used. Moreover, when analyses at stations KOUG and SCRZ were compared, data outages at station KOUG were experienced. Even if convergence occurs in the solutions despite these data outages, deteriorations have been observed in the following process. In addition, the standard deviations calculated at station KOUG are higher than the values computed for station SCRZ. Data outages at station SCRZ were much less than station KOUG.

As a result, the multi-GNSS concept represents a new and important formation/structure for RT-PPP solutions today and in the future (next generation). RT-PPP and PPP-RTK techniques will be used widely and effectively in the geospatial industry and applications (e.g. autonomous systems) in the near future. Therefore, it is important that the multi-GNSS concept provides interactive, continuous, and holistic service. In particular, the development, dissemination, and improvement of the accuracy of the data and products (as part of MGEX and RTS projects) offered by IGS publicly and free of charge for GPS+GLONASS+Galileo+BeiDou are critical. Considering this dynamic process, according to the results obtained in this study, data outage has an important place in the accuracy of RT-PPP applications. In addition, the use of different satellite combinations for the solution is an important factor in terms of shortening the convergence time and increasing the position accuracy obtained.

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