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Research Paper

Availability Analysis of GNSS Orbit and Clock Files

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Abstract: Precise point positioning with Global Navigation Satellite Systems (GNSS), orbit and clock products are mandatory. Today, different analysis centers produce satellite orbit and clock products. At the same time, the latency of these products is divided into three different categories. In this study, the satellite availability analysis of the publicly available final, rapid and ultra-rapid orbit (sp3) and clock files were investigated for Global Positioning System (GPS), Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS), European Global Navigation Satellite System (Galileo), BeiDou Navigation Satellite System (Beidou-2, BeiDou-3) and Quasi-Zenith Satellite System (QZSS) satellites within a one-year period of 2021. In addition, clock biases that do not exist in orbit files have also been calculated for each system. The results show that average number of GPS and GLONASS satellites are consistent among the products, however, the average GALILEO and BeiDou satellites are significantly changing among the products. The minimum average number of Galileo satellites was calculated for the final, rapid and ultra-rapid orbit products for the Centre national d'études spatiales (CNES (final)), German Research Centre for Geosciences (GFZ (rapid)) and GFZ (ultra) analysis centers, respectively. The minimum average number of satellites for BeiDou-3 medium earth orbit (MEO) and QZSS was calculated for the CODE analysis center.

Keywords: GPS; GLONASS; GALILEO; BeiDou; orbit; clock.

1. Introduction

In addition to GPS and GLONASS systems, which have been the sole alternatives for over 30 years, the European Union's Galileo and China's BeiDou navigation satellite systems have reached full operating capacity (FOC) [1,2]. Four separate worldwide GNSS systems are now available, with Galileo and BeiDou attaining full operating capacity. Except for backup satellites, the last Galileo FOC satellite launch was in July 2018 [3], while the last BeiDou-3 FOC satellite launch was in June 2020 [4].

BeiDou satellites are divided into three phases (BDS-1, BDS-2, and BDS-3), with BDS-3 satellites serving worldwide purposes [5]. Aside from global-purpose GNSS navigation satellites, there are certain regional navigation satellites. QZSS from Japan and the Indian Regional Navigation Satellite System (IRNSS (NavIC)) from India are two examples of these systems.

Most geodetic GNSS studies require precise satellite ephemeris files in Extended Standard Product-3 (SP3c) format [6] as well as clock (clk) files in RINEX (Receiver Independent Exchange) format [7]. Satellite geocentric geostationary coordinates (km) and satellite clock errors (microseconds) in a specific time interval are included in the satellite ephemeris files provided by the analysis centers. Clock files contain the clock errors of satellites and several International GNSS Service (IGS) stations on earth in a certain time interval. Clock files often have a better temporal resolution than

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orbital files (for example, 30 seconds or 5 seconds). The goal of this high temporal resolution is to minimize interpolation error in satellite clock errors [8]. The use of clock files is critical in precise point positioning (PPP). Because satellite clock errors can be eliminated in relative positioning by establishing double differences between the receivers. However, because double differences between receivers are not established in PPP, high temporal resolution clock files are required for high precision [9].

Satellite orbit files are presented to users in terms of temporal delay, divided into three parts as final, rapid and ultra-rapid. Aside from the products' temporal differences, the GNSS systems included in the satellite orbit and clock files may also differ.

The number of satellites in the products produced by the analysis centers may differ [10]. As a result, monitoring the number of satellites becomes essential. Furthermore, the analysis centers' precise ephemeris and clock product content varies in terms of GNSS systems [11].

Previous research has examined when the analysis centers become operational and how long they actively produce satellite orbit and clock information [12]. There is, however, no study that undertakes a full availability analysis of satellite orbit and clock files supplied by analysis centers for satellite systems.

Within the scope of this study, satellite orbit and clock files published by analysis centers were read through a software developed by the authors. The average number of satellites calculated for the satellite orbit and clock files and the ratio of the clock data with no solution calculated from the orbit file are considered for the year 2021 (2021 DOY:001 – 2021 DOY:365).

2. Material and method

Table 1 contains an expansion of the abbreviations in the names of the analysis centers for easier reading of the tables below. Table 2-6 summarizes the orbital and clock products produced by the analysis centers and the GNSS systems they contain, as well as their temporal resolutions.

Table 1. Analysis Centers

Analysis Center ID	Analysis Center
cod	Center for Orbit Determination in Europe (CODE)
emr	Natural Resources Canada
esa	European Space Agency
gfz	Geo Forschungs Zentrum Potsdam
grg	CNES/CLS
igs	IGSACC
jpl	Jet Propulsion Laboratory
mit	Massachusetts Institute of Technology
wum	Wuhan University

Table 2. Final clock product file GNSS systems and temporal resolutions

CLK_FINAL											
Analysis Center	**Epoch Interval (sec)**	**C2_M**	**C2_I**	**C2_G**	**C3_M**	**C3_I**	**C3_G**	**G**	**R**	**E**	**J**
cod	5							✓	✓		
com	30	✓	✓		✓	✓		✓	✓	✓	✓
emr	30							✓			
esa	30							✓	✓		
gbm	30	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
gfz	30							✓	✓		
grg	30							✓	✓		
grm	30							✓	✓	✓	
igs	30							✓			
jpl	30							✓			
mit	30							✓			
wum	30	✓	✓	✓	✓	✓		✓	✓	✓	✓

Table 3. Rapid clock product file GNSS systems and temporal resolutions

CLK_RAPID				
Analysis Center	**Epoch Interval (sec)**	**G**	**R**	**E**
cod	30	✓	✓	✓
emr	30	✓	✓	
esa	300	✓	✓	
gfz	300	✓	✓	✓
igs	300	✓		

Table 4. Final satellite orbit (ephemeris) product file GNSS systems and temporal resolutions

SP3_FINAL											
Analysis Center	**Epoch Interval (sec)**	**C2_M**	**C2_I**	**C2_G**	**C3_M**	**C3_I**	**C3_G**	**G**	**R**	**E**	**J**
cod	900							✓	✓		
com	300	✓	✓		✓	✓		✓	✓	✓	✓
emr	900							✓			
esa	900							✓	✓		
gbm	300	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
gfz	900							✓	✓		
grg	300							✓	✓		
grm	300							✓	✓	✓	
igs	900							✓			
jpl	900							✓			
mit	900							✓			
wum	900	✓	✓	✓	✓	✓		✓	✓	✓	✓

Table 5. Rapid satellite orbit (ephemeris) product file GNSS systems and temporal resolutions

SP3_RAPID				
Analysis Center	**Epoch Interval (sec)**	**G**	**R**	**E**
cod	300	✓	✓	✓
emr	900	✓	✓	
esr	900	✓	✓	
gfz	300	✓	✓	✓
igr	900	✓		

Table 6. Ultra-rapid satellite orbit (ephemeris) product file GNSS systems and temporal resolutions

SP3_ULTRA											
Analysis Center	**Epoch Interval (sec)**	**C2_M**	**C2_I**	**C2_G**	**C3_M**	**C3_I**	**C3_G**	**G**	**R**	**E**	**J**
esa	900							✓	✓		
gfz	300							✓	✓	✓	
igs	900							✓			
wum	300	✓	✓	✓	✓	✓		✓	✓	✓	

In the tables, C2_M, C2_I, C2_G, and C3_M, C3_I, C3_G represent medium-earth orbit (MEO), inclined geosynchronous orbit (IGSO), and geostationary orbit (GEO), respectively; G, R, E, J represent GPS, GLONASS, Galileo, and QZSS satellite systems, respectively. Since the ultra-rapid clock file was not produced by the analysis centers, its table could not be prepared. More detailed information about GNSS satellite systems is given in reference [13].

The temporal resolution of some analysis centers' orbit information was observed to decline from 15 minutes to 5 minutes in 2021. These are the files for the grg and grm final satellite orbits, the cod and gfz rapid satellite orbits, and the Gfz ultra-rapid satellite orbits. In Tables 2, 3, 4, 5 and 6, the current temporal resolutions of the products of the analysis centers are given.

Figure 1 depicts a work flow chart illustrating the study's process steps.

Satellite orbit and clock files published from analysis centers were downloaded using open-source software named GAMP II – GOOD (Gnss Observations and prOducts Downloader) (https://github.com/zhouforme0318/GAMPII-GOOD). A software prepared on the MATLAB 2017a platform is designed to read multiple satellite orbit and clock files. In the result file for the GPS, GLONASS, Galileo, BDS-2, BDS-3, and QZSS satellites, the software is utilized to print the average number of satellites and clock percentage rates that do not have a solution (represented as 999999.999999). BeiDou satellites are also divided into three categories: MEO, IGSO, and GEO.

The Findings section describes the results acquired for the final, rapid, and ultra-rapid orbit files, as well as the final and rapid clock files.

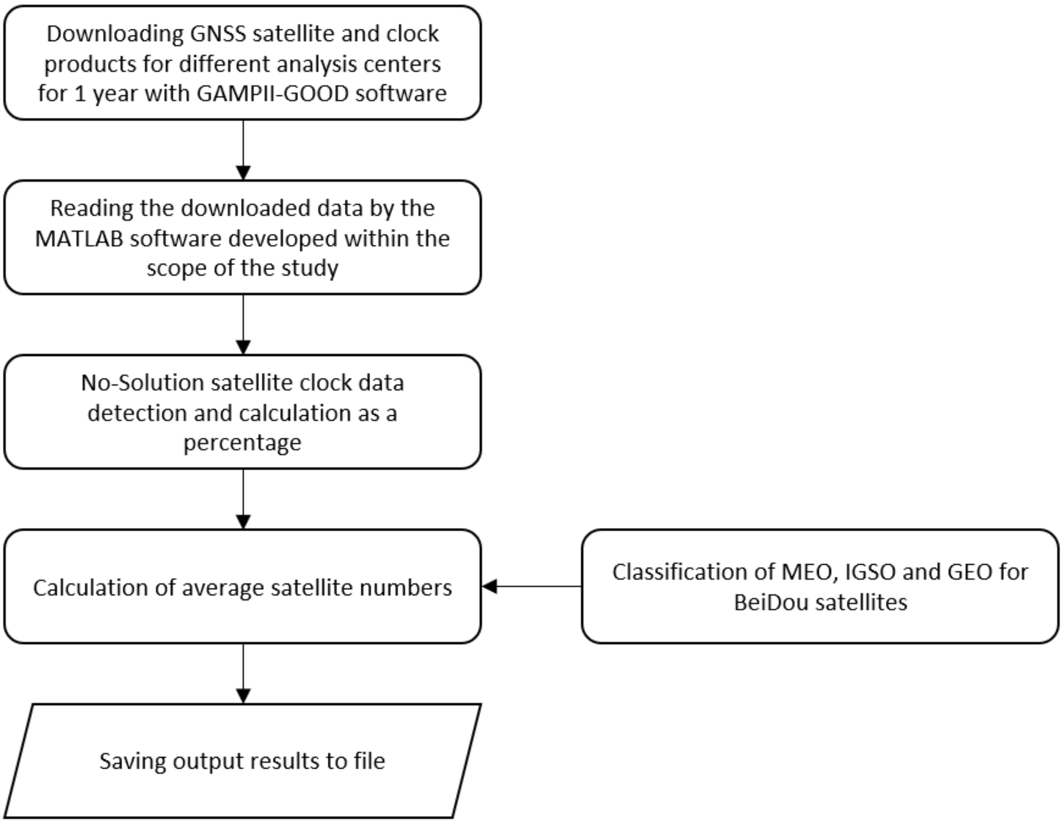

Figure 1. Work flow of the study

3. Findings

The obtained results are discussed in two parts as orbital and clock files. Tables 7-8-9 show the calculated average satellite numbers for final, rapid, and ultra-rapid orbit files.

Table 7. The average number of satellites in the final satellite orbital product file

SP3-FINAL										
	C2_M	**C2_I**	**C2_G**	**C3_M**	**C3_I**	**C3_G**	**G**	**R**	**E**	**J**
cod							31.7	20.9		
com	3	6.9		20.5	2.5		31.7	20.9	23.9	2.9
emr							31.3			
esa							31.2	20.9		
gbm	3	6.9	4.8	24	2.9	1.9	31.6	20.8	23.9	3.7
gfz							31.4	19.8		
grg							31.4	20.1		
grm							31.4	20.1	23.8	
igs							31.7			
jpl							31			
mit							31.6			
wum	3	7	4.8	24	3		31.2	20.7	23.9	3.9

Table 8. The average number of satellites in the rapid satellite orbital product file

SP3-RAPID			
	G	R	E
cod	31.7	20.9	23.9
emr	31.2	20.4	
esa	31.2	20.9	
gfz	30.8	20.4	14.9
igs	31.7		

Table 9. The average number of satellites in the ultra-rapid satellite orbital product file

SP3_ULTRA								
	C2_M	C2_I	C2_G	C3_M	C3_I	G	R	E
esa						31.2	20.9	
gfz						30.9	20	8.6
igs						31.3		
wum	2.9	5.9	4.8	23.5	2.7	30.1	20.5	22.1

When the number of satellites in 2021 is checked for the final product file (Table 7), the satellite numbers of the analysis centers are quite near to each other for GPS, GLONASS, Galileo, and BDS-2 satellites. However, the differences are significant for BDS-3 and QZSS satellites. The gbm analysis center is the sole provider of BDS-3 geostationary orbit (GEO) satellites. The com analysis center provided the minimal amount of BDS-3 mid-orbit (MEO) satellites (20.5). For gbm and wum analysis centers, this number is 24. The wum analysis center has the highest average BDS-3 inclined geosynchronous orbit (IGSO) number of 3. The minimal number of QZSS satellites for the cod analysis center was calculated to be 2.9 and 3.9 for the wum analysis center.

When the results in rapid orbit products are examined, it is understood that the maximum number of GPS satellites (31.7) was produced for cod and igs analysis centers. However, the differences with other analysis centers are not significant. The changes in the number of GLONASS satellites are fairly modest. The rapid orbital products of Galileo satellites are only produced by the cod and gfz analysis centers. The number of Galileo satellites between these two analysis centers differs significantly (23.9 for cod and 14.9 for gfz). After reviewing all of the files over a one-year period, it was discovered that Galileo satellites were added to the gfz orbital files after 18.05.2021. This reduces the average number of Galileo satellites for the gfz analysis center over a one-year period. However, when the average number of Galileo satellites for the gfz analysis center is reviewed again between 18.05.2021 and 31.12.2021, it is determined that the average number of satellites is 23.9. As a result, it is shown that it approaches the same value as the cod analysis center.

When ultra-rapid orbital products were analyzed, it was discovered that the IGS analysis center had the most GPS satellites (31.3), while the wum analysis center had the fewest (30.1). The differences in the average number of GLONASS satellites are very small, and it was found that the esa analysis center had the most GLONASS satellites. The two analysis centers containing Galileo satellites in ultra-rapid orbit files are the gfz and wum analysis centers. Since the gfz analysis center introduced Galileo satellites to its ultra-rapid orbit data after 14.05.2021, the average number of satellites in 2021 has been observed to be quite low. After reanalyzing the gfz ultra-rapid orbit files after 14.05.2021, the average number of Galileo satellites was calculated to be 24. This figure was determined as 21.9 for the wum ultra-rapid product for the same dates. Ultra-rapid BDS-2 and BDS-3 (excluding GEO) orbital information is included in the wum analysis center only. When compared to the wum final orbital file, the wum ultra-rapid BDS-2 and BDS-3 satellite numbers produced similar results.

Satellite clock solutions that did not exist in the orbital files were examined independently, and the ratio of unsolved satellite clock errors to total satellite clock data is shown in Table 10-11-12.

Table 10. Unsolved satellite clock error ratio for final satellite orbit analysis centers

SP3-FINAL (%)										
	C2_M	**C2_I**	**C2_G**	**C3_M**	**C3_I**	**C3_G**	**G**	**R**	**E**	**J**
cod							0	0.1		
com	0.7	0.7		0.3	0.3		0.3	0.4	0.3	0.5
emr							0			
esa							0	0		
gbm	0.2	0.4	0.4	0	0.1	0.1	0.1	0.1	0.1	0.3
gfz							0	0.1		
grg							0	0		
grm							0	0	0	
igs							0.4			
jpl							0			
mit							0			
wum	0	0	0	0	0		0	4.1	0	0

Table 11. Unsolved satellite clock error ratio for rapid satellite orbit analysis centers

SP3-RAPID (%)			
	G	**R**	**E**
cod	0.0	0.1	0.0
emr	0.0	0.0	
esr	0.0	0.0	
gfz	0.0	0.1	0.0
igr	0.6		

Table 12. Unsolved satellite clock error ratio for ultra-rapid satellite orbit analysis centers

SP3_ULTRA (%)								
	C2_M	**C2_I**	**C2_G**	**C3_M**	**C3_I**	**G**	**R**	**E**
esa						0.0	0.0	
gfz						0.2	3.1	0.3
igs						1.6		
wum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Except for the GLONASS satellites at the wum analysis center, the rate of unsolved satellite clock errors is less than 1% when the unsolved satellite clock errors are analyzed for the final satellite orbit product. In the wum analysis center, GLONASS satellites had the highest rate (4.1%). When the wum final satellite orbit product files were checked within a year, it was discovered that the clock error of the satellite with the number R11 PRN was not present in most files. When the com analysis center for BDS-2 satellites was inspected, the files without a satellite clock solution were found at a maximum rate of 67% for BDS-2 MEO satellites and up to 57% for BDS-2 IGSO satellites. When the satellites are examined individually, it is clear that BDS-2 IGSO satellites with PRN numbers 08, 10, 13, 16, and BDS-2 MEO satellites with PRN numbers 11-12 missing clock solutions for com final product files.

Looking at the rapid orbit product file results, it is clear that the rates of no-solution-satellite-clock errors for all other rapid products except the igs rapid product are quite low (and 0% for most analysis centers). When IGS rapid satellite orbit files are analyzed, it is found that GPS satellites with the numbers G11 G02 G25 G14 PRN do not generally have satellite clock solutions.

There are no unsolved satellite clock errors in the esa and wum ultra-rapid satellite orbit files when ultra-rapid satellite orbit data are examined. The rate of unsolved satellite clock errors was calculated at 1.6% for the IGS ultra-rapid analysis center, and it was revealed that satellites with the numbers G11 and G04 PRN accounted for the majority of this rate. GLONASS was determined to be the highest (3.1%) GNSS system without satellite clock solution for the Gfz analysis center. When the files were examined satellite by satellite, it was determined that the clock errors without solution did not relate to a single PRN satellite number. Tables 13 and 14 show the average GNSS satellite numbers obtained from clock files.

Table 13. Average number of GNSS satellites for final clock files.

CLK_FINAL										
	C2_M	**C2_I**	**C2_G**	**C3_M**	**C3_I**	**C3_G**	**G**	**R**	**E**	**J**
cod							31.7	20.9		
com	3.0	6.9		20.5	2.5		31.7	20.9	23.9	2.9
emr							31.3			
esa							31.2	20.9		
gbm	3.0	6.9	4.7	24.0	2.9	1.9	31.6	20.8	23.9	3.7
gfz							31.3	19.8		
grg							31.4	20.1		
grm							31.4	20.1	23.8	
igs							31.6			
jpl							31.0			
mit							31.6			
wum	3.0	7.0	4.8	24.0	3.0		31.2	19.9	23.9	3.9

Table 14. Average number of GNSS satellites for rapid clock files.

CLK_RAPID			
	G	**R**	**E**
cod	31.7	20.9	23.9
emr	31.1	20.3	
esr	31.2	20.9	
gfz	30.7	20.4	14.9
igr	31.5		

When the GNSS satellite numbers obtained from the analysis centers' final clock products are evaluated, the GPS, Galileo, BDS-2 MEO, BDS-2 IGSO, and BDS-2 GEO satellite numbers are observed to be quite close to each other. Except for the gfz and wum analysis centers for GLONASS satellites, the data from the other analysis centers are closely similar. The lowest GLONASS satellite numbers were found for the analysis centers gfz (19.8) and wum (19.9). The wum analysis center had the most QZSS satellites (3.9), while the com analysis center had the fewest (2.9). When the BDS-3 satellite results are examined, it is observed that the satellites in GEO status are only in the gbm final clock file. The lowest number of BDS-3 MEO satellites (20.5) was calculated for the com analysis center. When the results of BDS-3 IGSO satellites are reviewed, it is discovered that the com analysis center has the fewest BDS-3 IGSO satellites (2.5). Deficiencies in the number of satellites in the analysis centers have a negative impact on position accuracy [13, 14]. The BDS-3 IGSO satellite numbers (2.9/3.0) determined from the gbm and wum analysis centers were quite similar.

When the rapid clock file results are analyzed, the number of satellites calculated by other analysis centers for GPS satellites, except the gfz analysis center, is very close. The minimum number of GPS satellites (30.7) is calculated for the gfz analysis center. The GLONASS satellite numbers have been found to be relatively close to each other between the analysis centers. Analysis centers containing Galileo satellites among rapid clock files are cod and gfz analysis centers. Considering the number of Galileo satellites, it was observed that the highest number (23.9) was for the cod analysis center and the lowest number (14.9) was for the gfz analysis center. When the reason for this difference was investigated, it was observed that it was the same reason as the low number of Galileo satellites in gfz rapid orbit. From 01.01.2021 to 18.05.2021, Galileo satellites are not available in gfz rapid clock files. When the time period from 18 May 2021 to 31 December 2021 is eliminated, it can be seen that the average Galileo satellite numbers for the cod and gfz analysis centers are quite similar (23.9).

Since non-available clock solutions are not exist in the clock files, non-available clock solutions were not computed for clock files. Furthermore, because ultra-rapid clock products are not freely published on the internet, no statistics on ultra-rapid clock products are given.

4. Results

Within the scope of this study, the GNSS orbit and clock files, which are published free of charge by the analysis centers, are read by a software developed using the MATLAB programming language, and the average GNSS satellite numbers and the ratios of the number of satellites with coordinates in the orbital file without a clock solution are calculated for the year 2021 (01.01.2021 - 31.12.2021). The results are handled individually as orbital and clock files, as well as final, rapid, and ultra-rapid results. The following are the key points from the findings:

1-) When the GNSS satellite numbers in the final satellite orbit file (final sp3) are examined, the results in the analysis centers for GPS, Galileo, BDS-2, and BDS-3 IGSO satellites are quite similar. The gfz analysis center had the least number of GLONASS satellites (19.8), and the results of the other analysis centers were compatible with each other. The minimum number of QZSS satellites (2.9) was calculated for the com analysis center. The results of the number of QZSS satellites (3.7/3.9) in the gbm and wum analysis centers are quite consistent with each other. The results for BDS-3 MEO satellites are the same in the gbm and wum analysis centers (24.0), and this value is estimated as 20.5 in the com analysis center.

2-) When the GNSS satellite numbers in the Rapid satellite orbit file (rapid sp3) are analyzed, it is found that the gfz analysis center has the lowest number (30.8) for GPS satellites, and the results of the other analysis centers are quite compatible with each other. For all analysis centers, GLONASS satellite numbers produced similar results. The results of the cod and gfz analysis centers are equivalent in terms of the number of Galileo satellites as of 18.05.2021.

3-) When the number of GNSS satellites in the ultra-rapid satellite orbit file (ultra-rapid sp3) is checked, the wum analysis center has the fewest (30.1) GPS satellites. Other analysis centers calculated the number of GPS satellites to be around 31. When the GLONASS satellite numbers are examined, it is revealed that the minimum number (20) is calculated for the gfz analysis center, and the maximum number (20.9) is calculated for the esa analysis center. Using 14.05.2021 as a baseline, the number of Galileo satellites in the gfz and wum analysis centers is 24 and 21.9, respectively.

4-) When the rate of unresolved satellite clock errors is analyzed, it is determined that the satellite clock rates without solution are less than 1% for the final satellite orbit files, with the exception of the GLONASS satellites in the wum analysis center (4.1%). This rate is similarly very low for Rapid satellite orbit files, with a maximum of 0.6% calculated for IGR analysis center. Unsolved satellite clock errors are less than 1% for ultra-rapid files, with the exception of GPS satellites in the IGS analysis center (1.6%) and GLONASS satellites in the gfz analysis center (3.1%).

5-) When the number of GNSS satellites calculated by the analysis centers in the final clock files (final clk) is analyzed, the numbers of GPS, GLONASS, Galileo, BDS-2, and BDS-3 IGSO satellites are found to be near to each other. The lowest number of BDS-3 MEO satellites was calculated for the com analysis center (20.5). The number of BDS-3 MEOs in gbm and wum analysis centers was found to be 24. The minimum number (2.9) for QZSS satellites is calculated for the com analysis center.

6-) In rapid clock files (rapid clk), the minimum number of GPS satellites was calculated for the gfz analysis center with 30.7. The GLONASS satellite numbers calculated by the analysis centers are quite close. As of 18.05.2021, the Galileo satellite numbers for cod and gfz analysis centers were observed to be very identical to one other (23.9).

7-) Satellite clock errors are required in PPP applications since they cannot be avoided by introducing double differences between receivers, as can be done in relative position determination. Therefore, if only the satellite orbit file is used, the satellite clock rates without a solution play an important role for the stability of the PPP solution. Because the ultra-rapid clock file is not freely available on the internet, the ultra-rapid satellite orbit file must be utilized for both orbital and clock data.

It is recommended to employ the results of analysis centers with the greatest number of satellites, especially in areas where satellite visibility is limited.

GNSS systems included in the analysis center during the year should be considered in time series analyses employing multi-GNSS over several years. Analysis centers with GNSS systems (particularly for Galileo and BeiDou satellites) that are included in the analysis center from the start of the process during the time series analysis period should be favored if possible.

The authors intend to improve the MATLAB program used in this work and distribute the exe file and open-source codes to GNSS users. The open-source GAMP II program has the access address to the analysis centers' products.

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Author(s) Contributions

SÖ produced the necessary software for the evaluation of the data and wrote the article. BNÖ edited the article and contributed to the language. SA, CK, and ÖFA downloaded the data and contributed to the article writing. All five authors read and approved the final version of the article.

Conflict of Interest

The authors declare that there is no conflict of interest.

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