Sensors & Transducers, Vol. 263, Issue 4, December 2023, pp. 98-104

Sensors & Transducers
Published by IFSA Publishing, S. L., 2023
http://www.sensorsportal.com

A Study on the Parameters Affecting Clock Comparisons Using Global Navigation Satellite Systems

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Received: 5 October 2023 / Accepted: 29 November 2023 / Published: 21 December 2023

Abstract: navigation satellites are reliable and cost-effective means that can serve as an intermediate and efficient facility for comparing remote clocks, eliminating the technical challenges associated with physically moving clocks. Historically, the Global Positioning System (GPS) was the only Global Navigation Satellite System (GNSS) that is used in clock comparisons through observing the same satellites at the same time. However, the evolution of other fully operational GNSS, has opened up alternative avenues for distant clock comparisons through the Common-View (CV) technique. Typically, there are many parameters affecting the stability and accuracy of CV clock comparisons. Some of them are related to the type of GNSS, while others are related to the laboratories and clocks being compared. So, identifying the effect of each parameter on the comparison results is always a hot topic for research. This paper builds upon a previous research work done by the author. The main focus of this paper revolves around a thorough analysis of different factors affecting CV clock comparisons using different GNSSs, including the effect of the number of the satellite vehicles utilized, the effect of the geographical distance between laboratories, and their impact on the number of common observations. Additionally, the study delves into the stability and accuracy of comparison results and the correlation between them.

To conduct this study, the timing data from ten pairs of national time and frequency laboratories were analyzed during a period of 30 days. The ten laboratories are from a total of eight countries, including the United States of America, Germany, the United Kingdom, China, the Netherlands, Kazakhstan, the Czech Republic, and Hong Kong.

Keywords: Clock comparisons, GNSS, Common-view technique, Time transfer stability, Time transfer accuracy.

1. Introduction

Atomic clocks are known for their high precision and stability; however, they can be negatively affected by vibrations and environmental changes. During international comparisons between atomic clocks, transporting one clock to the location of another may render the results invalid upon its return. Therefore, the comparison procedures should be executed without moving the clocks. Using an intermediate facility for comparing distant atomic clocks is the recommended solution. The intermediate facility can be a Geo-stationary Earth Orbit (GEO) satellite, navigation satellite, communication satellite, or optical fiber link.

There are two famous methods for comparing precise clocks via navigational satellites: the one-way method and the common-view method. There is also a third method that uses communication satellites, which is the Two-Way Satellite Time and Frequency Transfer (TWSTFT) method [1-5]. In 2020, The National Time Service Center (NTSC) at the Chinese

Academy of Sciences in Xi'an, China, devised a novel method for common-view time transfer utilizing Geostationary Earth Orbit (GEO) satellites [6].

In the one-way time transfer method, the navigational satellite emits signals carrying timing data that are received by a timing receiver hosted by the laboratory. The timing receiver receives, processes, and analyzes the signals, then extracts the time difference between the local clock, connected to the receiver, and the time scale built by the GNSS (GNSST). The calculated time difference is sent on a daily basis to the Bureau International des Poids et Mesures (BIPM) for calculating the UTC [7].

In CV clock comparisons, if the two remote clocks are in common view of at least a single satellite, then the GNSS receivers synchronized to these clocks can receive the same GNSS signals from the common satellite, process the received signals, and calculate the time difference between the local clock and the GNSS time. The common-view technique involves applying the algorithm of the one-way time transfer technique simultaneously at both sites, utilizing the same visible satellites at the same time. Actually, the CV method compares two distant standard clocks to the GNSST, and the resulting data are exchanged to calculate the time difference between the two remote clocks. The primary benefit of CV clock comparisons lies in the cancellation or minimization of common errors contributed by many sources [8, 9]. It is worth mentioning that the Common-view technique using GPS was employed by the BIPM for the calculation of UTC until 2006. [7].

The TWSTFT technique uses communication satellites, and the two remote clocks should host transponders that transmit and receive signals from the communication satellite. The TWSTFT technique is employed in situations where stability of less than a nanosecond is necessary, making it suitable for comparing distant Cesium fountains – currently recognized as the international primary frequency standards. Although sub-nanosecond accuracy can be achieved using the TWSTFT technique, the implementation cost is very high [10].

It is well known that the rotational speed of GEO satellites around the Earth is equal to the rotational speed of the Earth. Hence, they appear stationary relative to any fixed point on the earth. This feature of GEO satellites makes them suitable for CV clock comparisons because they have continuous coverage over a specific area on the Earth. The precision of CV clock comparisons via GEO satellites was superior to GPS CV technique. Moreover, it was found that the root mean square (RMS) of the time difference is about 1 ns compared to TWSTFT [6, 11, 12].

The CV technique is accurate, reliable, and cheap technique for comparing distant standard clocks. Previously, GPS was the sole GNSS through which CV comparisons could be made. There are technical directives specially designed to standardize GPS time receiver software. The objective was to enhance the accuracy of GPS common-view time transfer. Now, there are many other fully operational GNSSs that can be used in standard clocks' comparisons [13-17].

In a previous study, the author demonstrated variations in the stability of one-way time transfer among different GNSS. Additionally, it was observed that satellites within the same GNSS may exhibit distinct behaviors [18]. In a recent research work done by the author, the performance of the four currently available GNSSs was studied when they are used in the common-view technique [19].

In this paper, the author validated the results obtained in the one-way clock comparisons mentioned in [18], with a focus on the CV technique. Moreover, the investigations mentioned at [19] were extended to explore the impact of the distance between laboratories on various aspects, including the number of common observations in clocks' comparison, the daily time transfer stability, and the time difference between the two clocks in the CV clock comparisons using different GNSSs.

2. The Stability of CV Clock Comparisons Using a Different Number of the Common Observed Satellite Vehicles

In a previous study done by the author [18], it was demonstrated that noticeable time transfer stability distinctions exist both among various GNSSs and among the individual satellites within the same GNSS in the one-way time transfer, Fig. 1. Galileo exhibited superior stability, while GPS showcased the highest visibility. Consequently, the conclusion was drawn that the variations in behavior among satellites within the same GNSS underline the importance of implementing selection criteria when choosing satellites for any time or frequency comparison [18].

Since the CV technique imply applying the one-way technique at both laboratories, then, in this paper, the author applied a similar analysis and calculated the instability of the CV time transfer during an observation period of 30 days (the same period used in [18]) using all the visible satellites, using the least instable satellite, using the most instable satellite, and using a group of four satellites.

Fig. 2 shows the instability of results when making a clock comparison between the British Metrology Institute (National Physical Laboratory (NPL)) and the German Metrology institute (Physikalisch-Technische Bundesanstalt (PTB)) during an observation period of 30 days, from MJD 59853 to MJD 59882. Both laboratories are operating multi-system and multi-channel dual-frequency GNSS receivers. The analyzed data of NPL is belonging to their NPL3 receiver while the analyzed data of PTB belongs to their PT13 receiver. It is worth noting that the distance between Teddington, the location of NPL, and Braunschweig, the location of PTB, is 751 Km approximately.

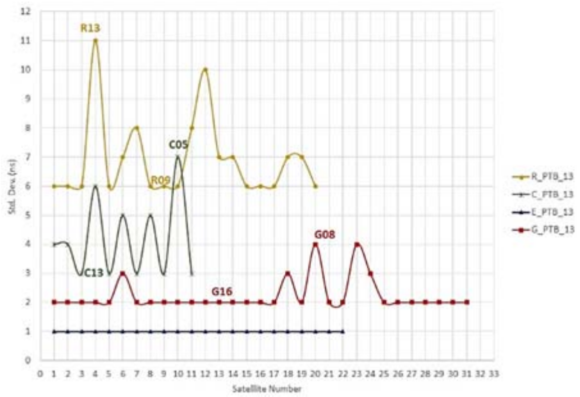

Fig. 1. The instability of the satellites in four GNSS for an observation period of 30 days. R: GLONASS; C: BeiDou-2; E: Galileo; G: GPS; PTB13: the analysed data belong to the Golden Receiver (PT13) of the German metrology institute (PTB). NRC_C4: the analyzed data belong to C4 receiver hosted by the national metrology institute of Canada (NRC) [18].

For GPS, Galileo, and GLONASS, it is clear that the least time transfer instability was obtained when we considered all the commonly visible satellites. For BeiDu-2, the time transfer instability is almost the same when using all or subset of the visible satellites, that is because the low number of the visible satellites.

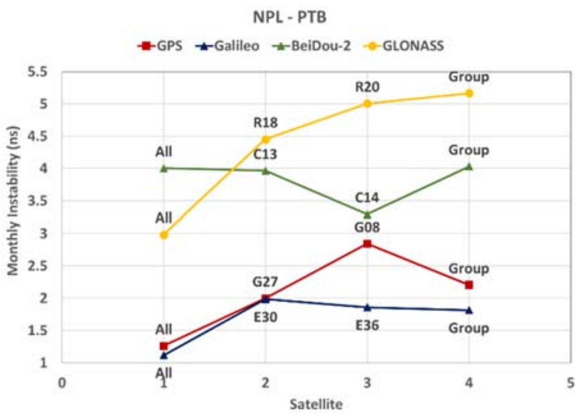

Fig. 2. The instability of the common-view clock comparison between NPL and PTB for a time period of 30 days using GPS, Galileo, GLONASS, and BeiDou-2 using all the commonly visible satellites, single satellite, and a group of four satellites.

3. The Effect of the Distance Between Laboratories on the Number of Commonly Recorded Data Points in CV Clock Comparisons

In a previous research paper [19], the author studied the instability of time transfer between NPL and PTB when using GPS, Galileo, GLONASS, and BeiDou-2. It was proven that the CV time difference instability between NPL and PTB varies among the different GNSSs, with BeiDou-2 exhibiting the least stable time transfer.

In this paper the author extends the study made at [19] and studies the effect of distance between the two laboratories on the instability of the comparison results using different GNSSs. Nine pairs of laboratories were selected to conduct this study. These pairs are as follows:

1) U.S. Naval Observatory (USNO), Washington DC, United States of America and the U.S. Naval Research Laboratory (NRL), Washington DC, United States of America;
2) U.S. Naval Observatory (USNO), Washington DC, United States of America and the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany;
3) U.S. Naval Observatory (USNO), Washington DC, United States of America and the National Time Service Center of China (NTSC), Lintong, China;
4) Dutch Metrology Institute (VSL), Delft, the Netherlands and the European Space Agency (ESA), Noordwijk, the Netherlands;
5) Dutch Metrology Institute (VSL), Delft, the Netherlands and Kazakhstan Institute of Standardization and Metrology (KZ), Astana, Kazakhstan;
6) Dutch Metrology Institute (VSL), Delft, the Netherlands and the Standards and Calibration Laboratory, Hong Kong;
7) National Time Service Center of China (NTSC), Lintong, China and Joint Atomic Time Commission (JATC), Lintong, China;
8) National Time Service Center of China (NTSC), Lintong, China and the National Institute of Metrology (Thailand), Pathumthani, Thailand;
9) National Time Service Center of China (NTSC), Lintong, China and the Institute of Photonics and Electronics, Czech Academy of Sciences (IPE/ASCR) (TP), Praha, Czech Republic.

The clocks of the first three pairs (USNO-NRL, USNO-PTB, USNO-NTSC) were compared using GPS. The clocks of the second three pairs (VSL-ESA, VSL-KZ, VSL-SCL) were compared using Galileo, and the clocks of the third three pairs (NTSC-JATC, NTSC-NIMT, NTSC-TP) were compared using BeiDou-3. Table 1 displays the model and code of the timing receiver hosted by each laboratory. Table 2 presents the distance between each pair of laboratories and the number of common data points recorded by the receivers while observing the same satellites during a testing period of 30 days (MJD 60173 to MJD 60203).

Regarding GPS, the table 2 illustrates that with an increase of 119 % in the distance between the two laboratories, the number of common data points dropped by 50 %. Additionally, an increase of 250 % in the distance resulted in 95 % drop in the common data points.

Table 1. The type and code of the timing receiver of each laboratory.

Laboratory	Receiver Model	Receiver Code
USNO	NovAtel ProPak-V3	US06
NRL	PolaRx5TR	RL5B
PTB	PolaRx5TR	PT13
NTSC	GTR55	NT03
VSL	PolaRx4TR PRO	VS06
ESA	POLARX5TR	ES07
KZ	GTR55	KZ04
SCL	PolaRx5TR	SC05
JATC	GTR55	JA02
NIMT	GTR55	MTTI
TP	GTR55	TP02

For Galileo, an increase of 152 % in the distance between the two laboratories led to a reduction of 61 % in the common data points, and an increase of 265 % resulted in 75 % drop.

In the case of BeiDou-3, an increase of 50 % in the distance between the two laboratories caused 16 % reduction in the common data points, and an increase of 252 % led to 68 % drop. Fig. 3 shows clearly the relation between the distance between laboratories and the number of the corresponding commonly recorded data points for GPS, Galileo, and BeiDou-3.

Table 2. The number of common data points and the distance between laboratory pairs.

GNSS	GPS		
(Lab1 - Lab2)	USNO - NRL	USNO - PTB	USNO - NTSC
Number of common Observations	22971	11589	1174
Distance (Km)	55	6547	13772
GNSS	Galileo		
(Lab1 - Lab2)	VSL - ESA	VSL - KZ	VSL - SCL
Number of common Observations	14559	5686	3617
Distance (Km)	35	5331	9304
GNSS	BeiDou-3		
(Lab1 - Lab2)	NTSC - JATC	NTSC - NIMT	NTSC - TP
Number of common Observations	39153	33070	12346
Distance (Km)	41.7	2086	10532

4. The Effect of Distance Between Laboratories on the Stability of CV Clock Comparisons

To investigate the impact of the distance between the laboratories engaged in the comparison on the instability of results of the CV clock comparison, we conducted clock comparisons among the laboratory pairs illustrated in Table 2.

Fig. 4 illustrates the instability of the CV clock comparison when we compared three pairs of clocks that are separated by 55 km, 6547 km, and 13772 km using GPS. It is clear that the most stable results are obtained from the closest laboratories and as the distance between the two laboratories increases, the stability of the results worsens.

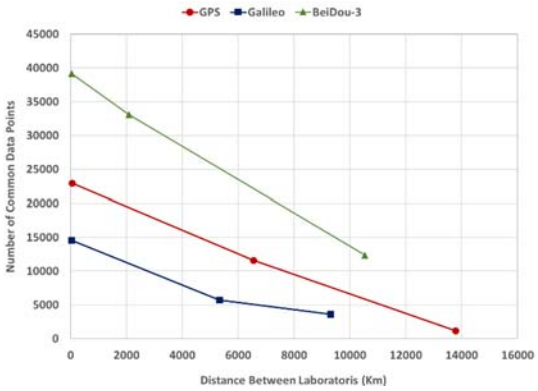

Fig. 3. The number of the common data points versus the distance between laboratories.

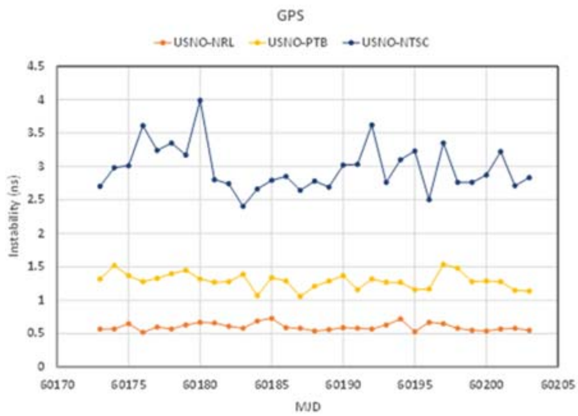

Fig. 4. The instability of the common-view clock comparison among three pairs of laboratories separated by 55 km, 6547 km, and 13772 km using all visible GPS satellites.

Fig. 5 demonstrates the instability in CV clock comparison as we compared three pairs of clocks separated by 35 km, 5331 km, and 9304 km with the use of the European GNSS, Galileo. The distance, in this case, appears to have a negligible impact on the stability of clock comparisons, especially when the distance between the two laboratories is in the range of few thousand kilometers.

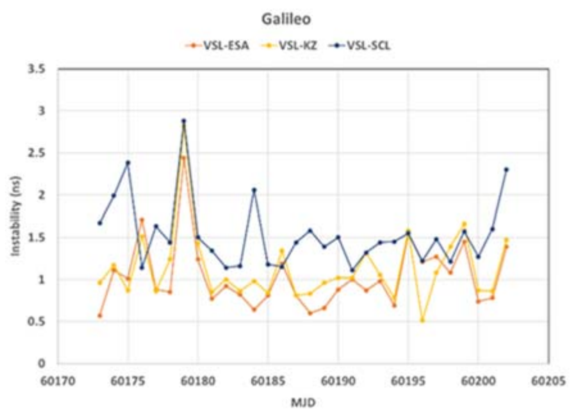

Fig. 5. The instability of the common-view clock comparison among three pairs of laboratories separated by 35 km, 5331 km, and 9304 km using all visible Galileo satellites.

Fig. 6 depicts the common-view clock comparison instability resulting from comparing clocks in three pairs of laboratories distant by 41.7 km, 2086 km, and 10532 km using the Chinese GNSS, BeiDou-3. It seems that using BeiDou-3 satellites in common-view clock comparisons yields a performance similar to that of using GPS satellites.

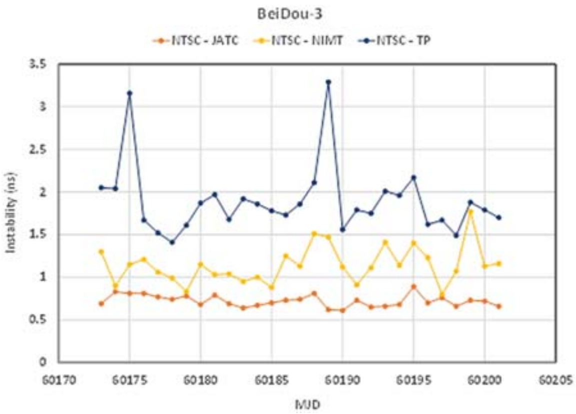

Fig. 6. The instability of the common-view clock comparison among three pairs of laboratories distant by 41.7 km, 2086 km, and 10532 km using all visible BeiDou-3 satellites.

5. The Effect of Distance Between Laboratories on the Accuracy of Clock Comparisons Using the CV Technique

Typically, the accuracy of the time difference doesn't mirror the accuracy of the GNSS satellites in CV clock comparisons, as the dominant factor affecting accuracy is the quality of calibrating the GNSS receivers at both laboratories. On the other hand, when time transfer stability is influenced by the distance between the two clocks being calibrated, it is expected that the distance between the clocks affects their time difference.

To study the effect of the distance between the laboratories on the time difference between their clocks, we need first to determine the true time difference between them. So, we have to obtain the time difference between the national time scale at each laboratory k (UTC(k)) and the Coordinated Universal Time (UTC or UTCr) calculated by the BIPM, [UTC/UTCr – UTC(k)]. Second, we calculate the true time difference between the two laboratories k1 and k2 (UTC(k1) – UTC(k2)). Then, we compare the true time difference to the time difference resulted from using the CV clock comparison.

Note: The daily values of the time differences [UTCr -UTC(k)] can be obtained from the BIPM ftp server: https://www.bipm.org/en/time-ftp/utcr. Given that UTCr is the rapid version of UTC.

To investigate how the distance between laboratories impacts the time difference between the two clocks, we selected the laboratory pairs (USNO-NRL), (USNO-PTB), and (USNO-NTSC) that are distant by 55 Km, 6547 Km, and 13772 Km respectively. A CV clock comparison was conducted between each pair using GPS.

Fig. 7 shows the time difference [UTC(USNO) – UTC(NRL)] that is calculated using the BIPM ftp server and the CV time difference between both laboratories using the data extracted from their timing receivers. Fig. 8 shows the same time difference comparison between USNO and PTB, while Fig. 9 shows the comparison results between USNO and NTSC.

In order to grasp how the distance between the laboratories influences the time difference among their clocks, we examined the correlation between Fig. 4 and Figs. 7, 8, and 9. Given that the results of the four figures are calculated during the same observation period (from MJD 60173 to MJD 60203).

The instability of time transfer between USNO and NRL, as shown in Fig. 4, exhibited the least instability that is characterized by low and semi-periodic fluctuations. These features were reflected on the time difference recorded during the common-view clock comparison, as illustrated in Fig. 7, which displayed low and semi-periodic deviations from the true time difference.

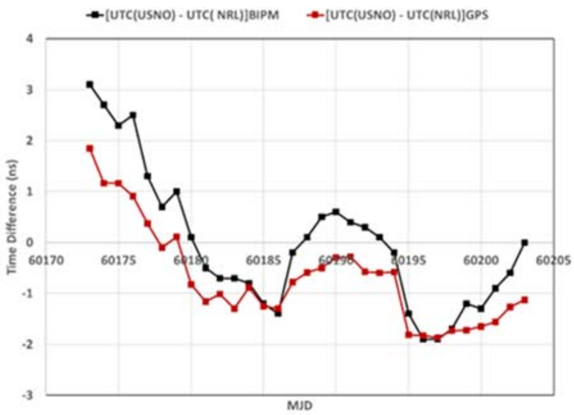

Fig. 7. The true and the CV time difference between USNO and NRL.

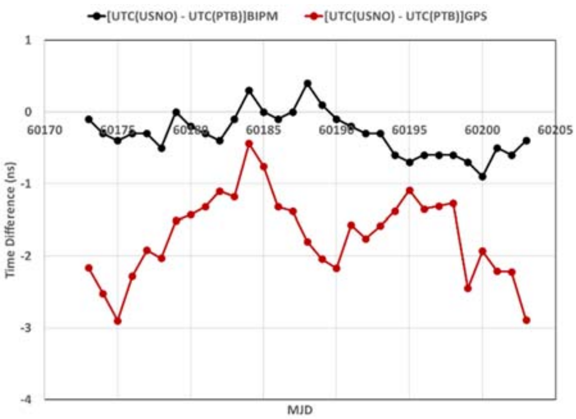

Fig. 8. The true and the CV time difference between USNO and PTB.

Fig. 4 reveals that the time transfer instability between USNO and PTB is higher than the instability between USNO and NRL and displaying semi-periodic fluctuations too. These characteristics are evident in the time difference recorded during the common-view clock comparison in Fig. 8, where there are consistent high and semi-periodic deviations from the true time difference.

Fig. 4 reveals the highest instability in time transfer between USNO and NTSC that is characterized by very high fluctuations. This instability is mirrored in the time difference during common-view clock comparison shown in Fig. 9.

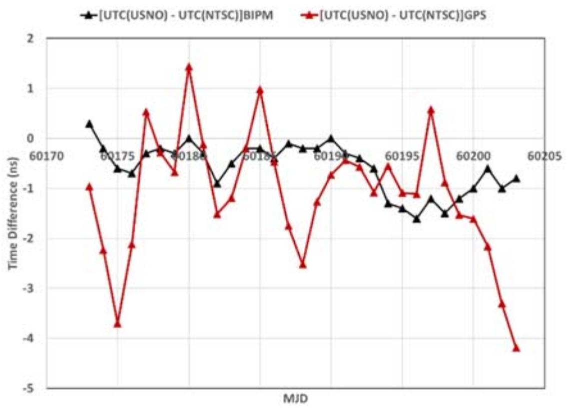

Fig. 9. The true and the CV time difference between USNO and NTSC.

6. Conclusion

Navigation satellites stand out as a reliable and cost-effective facility to be used in clock comparisons. In the past, the CV clock comparisons were primarily utilizing GPS for comparing distant clocks. However, with the advent of multiple fully operational GNSSs, including GLONASS, Galileo, and BeiDou, these systems have become viable alternatives for conducting distant clock comparisons through the common-view technique.

This paper validates previous one-way clock comparison results presented in [18], with a specific focus on the common-view technique. Moreover, extending the investigations outlined in paper [19]. The core emphasis of this research lies in scrutinizing the influence of various factors on the results of the CV clock comparisons, such as the number of satellite vehicles used and the distance between laboratories and their impact on the number of common observations as well as the stability and accuracy of the comparison results.

For GPS, Galileo, and GLONASS, the most stable results were achieved when considering signals from all observable satellites. Conversely, for BeiDu-2, the stability of results remains nearly unchanged, whether considering all visible satellites or only a subset, this is attributed to the limited number of satellites in BeiDu-2. For all GNSSs, the findings of this research indicate that the number of commonly observed data points is directly affected by the geographical separation between laboratories. BeiDou-3 demonstrated the highest count of common data points for small, medium, and large distances (up to 10,000 km), followed by GPS and then Galileo.

In the case of Galileo, the effect of the distance between laboratories is almost negligible on the stability of the comparison results. However, it negatively affects the stability in the case of GPS and BeiDou-3, given their similar performance.

For GPS, the relationship between the distance between laboratories and the accuracy of the results is evidently correlated with the stability of time transfer. A considerable correlation is observed between the stability curve and the accuracy curve.

In summary, enhancing the stability of the one-way clock comparisons can be achieved by exclusively selecting the most stable satellites. However, when it comes to CV comparisons, it is advisable to include all commonly visible satellites in the clock comparison process. The stability of the CV clock comparisons using BeiDou-3 is comparable to GPS but BeiDou-3 exhibits a higher number of common data points than GPS over the same observation period. The geographical distance between laboratories does not impact considerably the stability of CV clock comparisons when Galileo is utilized.

Acknowledgements

The author would like to thank the teamwork of the BIPM FTP server for making the time data available to the community of time metrology. Additionally, the author would like to express gratitude to colleagues at USNO, NRL, PTB, NPL, NTSC, VSL, ESA, KZ, SCL, JATC, NIMT, and TP for maintaining dual-frequency GNSS receivers and consistently sending this data to the BIPM for UTC calculation and for contributing to the enrichment of the research work.

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