



Article Identification of BDS Satellite Clock Periodic Signals Based on Lomb-Scargle Power Spectrum and Continuous Wavelet Transform

Jacek Kudrys ^{1,2}, Dominik Prochniewicz ³, Fang Zhang ², Mateusz Jakubiak ⁴ and Kamil Maciuk ^{1,2,*}

- ¹ Department of Integrated Geodesy and Cartography, AGH University of Science and Technology, 30059 Krakow, Poland; jkudrys@agh.edu.pl
- ² HNU-ASU Joint International Tourism College, Hainan University, Haikou 570228, China; 183422@hainanu.edu.cn
- ³ Faculty of Geodesy and Cartography, Warsaw University of Technology, 00661 Warsaw, Poland; dominik.prochniewicz@pw.edu.pl
- ⁴ Department of Environmental Management and Protection, AGH University of Science and Technology, 30059 Krakow, Poland; jakubiak@agh.edu.pl
- * Correspondence: maciuk@agh.edu.pl

Abstract: Onboard satellite clocks are the basis of Global Navigation Satellite Systems (GNSS) operation, and their revolution periods are at the level of 2 per day (about 12 h) in the case of the Medium Earth Orbit (MEO) satellites. In this work, the authors analysed the entire BeiDou Navigation Satellite System (BDS) space segment (BDS-2 and BDS-3) in terms of the occurrence of periodic, repetitive signals in the clock products, and checked if they coincide with the orbital periods or their multiples. The Lomb-Scargle (L-S) power spectrum was used as a tool to determine the periods present in the BDS clock products, allowing for analyses based on incomplete input data; in this case, the incomplete data were the phase data with jumps and outliers removed. In addition, continuous wavelet transform (CWT) was used to produce a time-frequency representation showing the more complex behaviour of the satellite clock products. As shown in the case of geostationary and geosynchronous inclined orbit satellites, the main period was 23.935 h, while for the Medium Earth Orbit it was 12.887 h, with the BDS satellite orbital period being 12 h 53 m (12.883 h). Some effects connected with reference clock swapping are also visible in the power spectrum. The conducted analyses showed that the BDS-2 satellite clocks have much higher noise than the BDS-3 satellite clocks, meaning that the number of designated periods is greater, but their reliability is significantly lower. BDS-3 satellites have only been in operation for a very short time, thus this is the first analysis to include this type of data. Moreover, such a wide and complex analysis has not been carried out to date.

Keywords: satellite; GNSS; period; time; clock; BeiDou

1. Introduction

The development of the Chinese BeiDou (BDS) system consisted of three stages: the demonstration system (BDS-1), the regional satellite system (BDS-2), and the global satellite system (BDS-3). Currently (status as of 11 September 2021), BeiDou consists of 44 satellites in operation (15 BDS-2 and 29 BDS-3) and 5 in the testing or experimental phase (http://www.csno-tarc.cn/en/system/constellation, Appendix A, access date: 1 June 2021). To date, BDS-2 consists of five geostationary orbit (GEO), seven inclined geosynchronous orbit (IGSO), and three Medium Earth Orbit (MEO) satellites. BDS-3 has provided services since 27 December 2018 [1] and presently consists of 3 GEO, 3 IGSO, and 24 MEO active satellites. The frequency stability of the BDS clocks is better than 2×10^{-14} per day and 3×10^{-15} per day for the rubidium clock and hydrogen maser, respectively [2].



Citation: Kudrys, J.; Prochniewicz, D.; Zhang, F.; Jakubiak, M.; Maciuk, K. Identification of BDS Satellite Clock Periodic Signals Based on Lomb-Scargle Power Spectrum and Continuous Wavelet Transform. *Energies* 2021, *14*, 7155. https:// doi.org/10.3390/en14217155

Academic Editors: Mirosław Siergiejczyk and Karolina Krzykowska-Piotrowska

Received: 22 September 2021 Accepted: 25 October 2021 Published: 1 November 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Satellite navigation systems are used in many fields and have various applications [3–8]. Time synchronisation of the clock is the base and the core in GNSS positioning. Insufficient operation or instability of the onboard clocks leads to degradation of the positioning accuracy [9–11]. The main impact on accuracy in navigation and positioning comes from the onboard satellites' clocks [12]. In recent years, research on the stability of GNSS clocks has been extensively conducted [13–15]. As clock products process data in 24-h batches, day boundary discontinuities (DBDs) occur between consecutive products. A shift or jump in the clock data is caused by the start of the new data processing package at midnight [16], and its magnitude in the case of clock products might be as high as 1 ns [17]. This kind of phenomenon must be considered when processing involves midnight—the point of the switch to the next file/processing batch. The DBDs can impact either the satellite's clock [18] or orbit [19]. As research shows, this may also affect the positioning accuracy [20,21].

Research on the analysis of GNSS clock products in terms of periodic signals has already been conducted, but to a very limited extent [22–24]. The amplitude spectra of the International GNSS Service (IGS) final clock products (after removing 12-h periodic signal and daily rates) for GPS Block IIR satellites show 4 and 6 cycles per day [25], while for the whole GPS space segment, the biggest spectrum amplitudes appear for two and four cycles per day, respectively, according to Senior et al. [26] and Heo et al. [22], also based on the final IGS clock products. Moreover, such phenomena appear not only for the MEO navigational satellites such as GPS or Galileo, and IGSO satellites, e.g., QZSS [27], but also for Low Earth Orbit (LEO), e.g., GRACE [28].

The Lomb-Scargle periodogram method is well-known and is widely used for the spectral analysis of unevenly sampled time series [29]. It allows for the computation of the reliable power spectrum for unevenly sampled data or data with gaps, and has particularly broad applications in astronomy and geodynamics [30]. Usage of the Lomb-Scargle (L-S) and Continuous Wavelet Transform (CWT) methods for GNSS clock analyses has not been conducted so far. In a GNSS related field, L-S was used for coordinate time series research [31], studies on the tropospheric delay [32], and for earthquakes [33]. The CWT time—frequency analysis is commonly used for numerous field, e.g., image processing [34], signal filtering [35], astronomy [36], and geophysics [37]. For applications connected with GNSS data processing, CWT is utilised in the time series analysis for denoising and detrending [38], or for GNSS signal multipath analysis [39,40].

Herein, the authors analysed in a comprehensive way BeiDou satellites clock corrections and their periodic variation using the Lomb-Scargle periodogram [29] and CWT methods [41–43]. In the article, we present the analysis of recently available data concerning the BeiDou satellite clock. The authors prepared six steps vis a vis the pre-processing and period characteristics for each BDS satellite.

In the Material and Methods section, the data used for analysis are described along with the proposed processing methodology. Examples are presented in the Results and Discussion section, and the results for all of the analysed satellites are presented in Appendices C and D. The last section summarizes our analysis and indicates some issues for further analysis.

2. Materials and Methods

2.1. Data Source

Satellite clock corrections or satellite clock bias is a deviation of the satellite's clock reading from the adopted GNSS time scale realised by the reference clock. In this work, we focused on BeiDou clock products provided by the Wuhan University IGS Analysis Centre (WUM) in the framework of the Multi GNSS Experiment (MGEX) project (https://www.igs.org/mgex/data-products/#products, access date: 1 September 2021). Since October 2020, WUM has been providing final clock correction data for C38-C46 BDS-3 satellites, and thus precise clock correction for all active BeiDou satellites has become available from IGS MGEX data centres (Figure 1). Our analysis covers the last 88 days of 2020 (5 October 2020–31 December 2020) and was performed for BDS-2 and BDS-3 satellite

clocks. We focused on periodic effects connected with the orbital period of different types of satellites (MEO, GEO, and IGSO). The resulting analysis presents the periods in the range of 0.8–36 h. The lower limit was set to 0.8 h in order to take into account the higher harmonics of the periodic changes of the clock correction. A summary of the analysed satellite, its orbit, and clock type information are provided in Appendix A.



Figure 1. Availability of the BeiDou clock product at the WUM analysis centre in 2020. Days with clock data available are marked dark blue.

2.2. Methods

The processing algorithm is shown in the diagram in Figure 2. The subject of analysis was raw daily clock correction data (phase data) obtained from WUM with 30 s sampling intervals and was decimated in the pre-processing phase to a 300 s sampling interval. As an example of data analysis, the processing stages for satellite no. C32 are presented in Figure 3. The analysis was performed on differentiated data (frequency data).

raw clock data (phase data) δt
clock correction rate $\frac{d\delta t}{dt}$ (frequency data)
outliers removal $\frac{d\delta t}{dt} > 10^{-10} \frac{s}{s}$
jump detection and removal
polynomial trend removal
outliers removal (MAD method)
L-S periodogram and CWT time-frequency spectrogram

Figure 2. Clock data processing algorithm.

Clock metrology uses a form of phase or fractional frequency measurements relative to a reference clock. The phase reading δt is instantaneous (timestamp), while the fractional frequency reading is the difference between the two phases' values divided by their interval, according to [44]:

$$\frac{d\delta t}{dt} = \frac{\delta t_{i+1} - \delta t_i}{t_{i+1} - t_i} \tag{1}$$

The differentiation of the periodic signal changes its amplitude a and shifts phase φ by $\pi/2$, but has no impact on signal component frequency *f*. The amplitudes are scaled by $2\pi f$, according to the following equations:

$$\delta t(t) = \sum a_i \sin(2\pi f_i + \varphi_i) \tag{2}$$

$$\frac{d\delta t}{dt} = \sum 2\pi f_i a_i \sin\left(2\pi f_i + \varphi_i + \frac{\pi}{2}\right) \tag{3}$$

The first step of our analysis was to differentiate clock correction data δt (Figure 3a) to produce a time series of clock correction rate $d\delta t/dt$ (Figure 3b). The outliers present in the time series were removed two-fold. First, values of $d\delta t/dt$ larger than 10^{-10} s/s (arbitrarily chosen) were treated as outliers and were removed from the data set (Figure 3b). The threshold value was chosen based on the analysis of the whole data set and is adopted as 10^{-10} s/s for proper detection of the jumps in the signal (phase data). The jumps that existed in the data series were mainly caused by the day-boundary effect [18]. The maximum number of removed data points at this stage was 0.8%. Such a small amount of removed data has no impact on further data processing. After removal of the primary outliers, jumps in clock correction rate data remained identifiable for several satellites, as is visible in Figure 3C. These discontinuities were removed (Figure 3d) from the data. Next, the third order trend (polynomial) and secondary outlier detection and removal were performed. At this stage, outliers were detected with the aid of the *MAD* (median absolute deviation) method commonly used in clock stability analysis [44] (Figure 3e). The *MAD* coefficient is calculated according to:

$$MAD = med\left(\frac{|x_i - med(x)|}{0.6745}\right) \tag{4}$$

In Equation (4), x_i is the frequency data and med(x) is a median of x, and then outliers in the time series are identified if:

$$\frac{|x_i - med(x)|}{MAD} > k \tag{5}$$

In our calculations, the typical value for constant k = 5 was adopted [44], and after this stage, the maximum removed data point was 2.2%. Lastly, the Lomb-Scargle [45,46] power spectrum was calculated (Figure 3f).

Herein, we used the Lomb-Scargle method to obtain an approximation of the power spectrum of the analysed signal when gaps in the data occurred due to the removal of outliers or missing observations from the data source. In the resulting L-S spectrum, only period values for which the probability of false identification lower than P (spectrum peak | noise) = 0.00005 were selected as significant. A relatively low value of P was chosen in order to filter out spurious periods present in the analysed clock data. In Figure 3f, meaningful periods are those for which the peaks are above the orange line, i.e., 6.4 h and four peaks indicating periods over 30 h. The relevant periods for each analysed BeiDou satellite are presented as a blue mark in Appendix B.



Figure 3. Stages of data processing. (a) Original clock correction data (phase data). (b) Clock correction rate (frequency data). (c) Clock correction rate after elimination of outliers larger than 10^{-10} s. (d) Clock correction rate values after removal of the detected jump. (e) Clock correction rate after removal of the trend and outliers with the MAD method. (f) Lomb-Scargle periodogram.

As a last step of our analysis the time–frequency spectrum has been calculated using Continuous Wavelet Transform. A *CWT* is used for time series stationarity analysis. A comprehensive description of the application of the wavelet transform can be found in [47].

The Morlet wavelet was adopted as the mother wavelet. This kind of wavelet is commonly used in the time-frequency analysis and provides results with equal variance in time and frequency domains [48]. *CWT* allows for the examined signal to be presented in the form of a scalogram—a time-frequency spectrum, which permit for the identification of both frequencies present in the signal and their location in time. *CWT* is defined as a convolution of the analysed signal *s*(*t*) with scaled and shifted wavelet function $\psi(t)$ [49]:

$$CWT = \frac{1}{\sqrt{a}} \int s(t)\psi^*\left(\frac{t-b}{a}\right) dt$$
(6)

where,

a represents the scale

b denotes the translation

 ψ represents the mother wavelet, and * denotes the complex conjugate

The normalization factor $1/\sqrt{a}$ is used to preserve the direct comparability of the transform for all of the scales. The Morlet wavelet used here to calculate the time-frequency spectrum is expressed as follows:

$$\psi(t) = \frac{1}{\sqrt{\pi f_b}} exp\left(i2\pi ft - \frac{t^2}{f_b}\right) \tag{7}$$

where f denotes the center frequency and f_b represents the bandwidth.

The continuous wavelet transform method does not optimize the time and frequency resolution simultaneously. In the *CWT* analysis, a trade-off must be found between these quantities [41]. In the present study, the center frequency was taken as f = 1.5 Hz and the bandwidth parameter was $f_b = 2.0$ for all pf the clock data time series analyzed. The parameter values were selected empirically to ensure a satisfactory balance between the time and frequency resolution for the analyzed data.

3. Results and Discussion

In the analysed data (clock correction rates) after removal of the outliers and trend, numerous discontinuities are clearly visible (e.g., Figure 3e). These jumps are less visible for the older BDS-2 than for the BDS-3 satellites because of the relatively higher noise level in the clock correction time series. As the offsets are the same for all satellites (see Appendix C), their origin is also common and must be connected with some maintenance works or with a processing strategy adopted for clock correction determination. Moreover, as is indicated in the clock data files obtained, during the analysed time span, the reference clock for the WUM clock products was switched 44 times (Figure 4). The clock switch occurs at the end/beginning of the day and eight different clocks—hydrogen masers—worked as a reference clock. The switching of the reference clock leads to jumps in analysed clock data, visible for all BDS-3 satellites (e.g., Figure 3e).



Figure 4. Reference clock for the WUM clock product swapping. Vertical black lines indicate the instant of reference clock switch.

For verification, if the presence of this effect had an impact on the resulting power spectrum, we performed an analysis of the simulated data. Simulated data were Gaussian noise of amplitude 2×10^{-13} s (similar to the BDS-3 satellite clock rate signal) with jumps of 0.2 ns added in the same epochs as the jumps occurring in the real data (Figure 5). These discontinuities are visible in the BDS-3 satellite clock data only. Simulated data processed the same way as real clock data (described in Section 2.2) allows us to confirm that the signals of periods of 17 h and 30–40 h are caused by frequent reference clock swapping. An L-S periodogram of the simulated data is presented in Figure 5. It shows a similar pattern for higher periods as periodograms for all of the analysed satellite clocks (Appendix C). The same effect is visible on the time–frequency spectrograms (see Appendix D).



Figure 5. Simulated data with jumps (left) and its Lomb-Scargle periodogram (right).

An example spectrogram for satellite C32 is shown in Figure 6. Visible is a component with a period of about 6.4 h, which appears from about 7200 h and continues until the end of the period analyzed.



Figure 6. CWT spectrogram for the C32 satellite.

This component is also visible in the L-S periodogram in Figure 3f. In addition, signals with periods of 18 h and over than 30 h are noticeable in the time interval 6700–8000 h. These signals are caused by frequent changes of the reference clock (cf. Figures 3e and 5). Spectrograms for all of the analyzed satellites are shown in Appendix D.

The identified periods in the clock correction rate depend on the satellite orbit type. For GEO and IGSO satellites, the main period of 23.935 h corresponding to the sidereal day is present. Moreover, higher harmonics are visible—up to the ninth in the case of the C01 satellite—which shows that the periodic changes are not sinusoidal. The orbital period for the BeiDou MEO satellites is about 12.887 h. All BDS-3 MEO satellites have dominant second harmonics for this period (Appendices B–D).

The IGSO BDS-3 satellites (C38, C39, and C40) equipped with H-maser clock exhibit many low power spectrum peaks around 24 h and 12 h. In the case of these satellites, orbital periods close to the sidereal day and its harmonics are of course natural. In the BDS-3 segment, only these three satellites are IGSO and they all have an H-maser clock. The presence of signals with periods between 12 and 24 h, which are not visible in the other BDS-3 satellites data, may depend on these factors. Several BDS-2 satellites' clock corrections oscillate with very low periods, e.g., C10, 1.02 h; C11, 1.21 h; and C14, around 1.8 h, not connected with their orbital periods.

4. Conclusions

GNSS satellite clocks are a key factor in GNSS time transfer and precise positioning. Periodic effects present in satellite clock data may transfer to the GNSS products, giving false signals in areas such as geodynamical analysis and time transfer. This is of great importance, especially in Precise Point Positioning (PPP) applications with zero-difference data processing. In this paper, the authors prove the existence of identifiable effects connected with satellite orbital periods and common for the same satellite type (MEO, GEO, and IGSO). Other effects, present in all of the analysed signals, and giving a similar spectral structure, may be connected with the processing strategy applied for clock correction determination or maintenance works in the time scale-reference clock switch. Although the jumps caused by switching the reference clock are relatively small (ca. 2 ns), it is worth noting that such effects are not clearly visible and are not documented in final products in any way. Moreover, the usage of the L-S method allows for a determination of the periods not connected with satellites orbital movement nor with the time scale maintenance in several BDS-2 satellite clocks. This kind of phenomenon needs further, extended investigation. The time-frequency analysis shows that the satellite clock behaviour may vary in time, and determined periods have variable amplitudes over the analysed time span. The analysed data may also include periodic components related to the sampling interval, but this phenomenon was not analysed in this study. The presented analysis was carried out only for the BeiDou system. In future research, it is necessary to study this type of phenomenon also for other GNSS systems, possibly with the use of special software packages developed for analysis unequally spaced data (e.g., [50]) to verify potential limitations of the methodology used.

Author Contributions: Conceptualization, J.K. and K.M.; methodology, J.K. and K.M.; software, J.K. and K.M.; validation, J.K., K.M. and M.J.; formal analysis, J.K., K.M. and M.J.; investigation, J.K. and K.M.; resources, J.K. and K.M.; data curation, J.K. and K.M.; writing—original draft preparation, J.K. and K.M.; writing—review and editing, J.K., K.M., D.P. and F.Z.; visualization, J.K. and K.M.; supervision, J.K., K.M., D.P., M.J. and F.Z.; project administration, J.K., K.M. and D.P.; funding acquisition, J.K. and K.M. Percentage author's contribution: J.K. 60%, D.P. 5%, F.Z. 5%, M.J. 5% and K.M. 25%. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Science Centre, Poland (Project No. 2016/23/D/ST10/00498); by the Initiative for Excellence Research University grant at AGH University of Science and Technology; and by the research subvention no. 16.16.150.545.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

 Table A1. BeiDou constellation status (http://www.csno-tarc.cn/en/system/constellation, access 1 June 2021).

PRN	IGS-SVN	NORADID	SVN	Satellite Type	Clock Type	Manuf	Launch Date	SatStatus	Healthy	Service Signal
1	C020	44231	GEO-8	BDS-2	Rubidium	CASC	17 May 2019	Operational	Healthy	B1I/B2I/B3I
2	C016	38953	GEO-6	BDS-2	Rubidium	CASC	25 October 2012	Operational	Healthy	B1I/B2I/B3I
3	C018	41586	GEO-7	BDS-2	Rubidium	CASC	12 June 2016	Operational	Healthy	B1I/B2I/B3I
4	C006	37210	GEO-4	BDS-2	Rubidium	CASC	1 November 2010	Operational	Healthy	B1I/B2I/B3I
5	C011	38091	GEO-5	BDS-2	Rubidium	CASC	25 February 2012	Operational	Healthy	B1I/B2I/B3I
6	C005	36828	IGSO-1	BDS-2	Rubidium	CASC	1 August 2010	Operational	Healthy	B1I/B2I/B3I
7	C007	37256	IGSO-2	BDS-2	Rubidium	CASC	18 December 2010	Operational	Healthy	B1I/B2I/B3I
8	C008	37384	IGSO-3	BDS-2	Rubidium	CASC	10 April 2011	Operational	Healthy	B1I/B2I/B3I
9	C009	37763	IGSO-4	BDS-2	Rubidium	CASC	27 July 2011	Operational	Healthy	B1I/B2I/B3I
10	C010	37948	IGSO-5	BDS-2	Rubidium	CASC	2 December 2011	Operational	Healthy	B1I/B2I/B3I
11	C012	38250	MEO-3	BDS-2	Rubidium	CASC	30 April 2012	Operational	Healthy	B1I/B2I/B3I
12	C013	38251	MEO-4	BDS-2	Rubidium	CASC	30 April 2012	Operational	Healthy	B1I/B2I/B3I
13	C017	41434	IGSO-6	BDS-2	Rubidium	CASC	30 March 2016	Operational	Healthy	B1I/B2I/B3I
14	C015	38775	MEO-6	BDS-2	Rubidium	CASC	19 September 2012	Operational	Healthy	B1I/B2I/B3I
16	C019	43539	IGSO-7	BDS-2	Rubidium	CASC	10 July 2018	Operational	Healthy	B1I/B2I/B3I
19	C201	43001	MEO-1	BDS-3	Rubidium	CASC	5 November 2017	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
20	C202	43002	MEO-2	BDS-3	Rubidium	CASC	5 November 2017	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
21	C206	43208	MEO-3	BDS-3	Rubidium	CASC	12 February 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
22	C205	43207	MEO-4	BDS-3	Rubidium	CASC	12 February 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
23	C209	43581	MEO-5	BDS-3	Rubidium	CASC	29 July 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
24	C210	43582	MEO-6	BDS-3	Rubidium	CASC	29 July 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
25	C212	43603	MEO-11	BDS-3	Hydrogen	SECM	25 August 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
26	C211	43602	MEO-12	BDS-3	Hydrogen	SECM	25 August 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b

Table A1. Cont.

PRN	IGS-SVN	NORADID	SVN	Satellite Type	Clock Type	Manuf	Launch Date	SatStatus	Healthy	Service Signal
27	C203	43107	MEO-7	BDS-3	Hydrogen	SECM	12 January 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
28	C204	43108	MEO-8	BDS-3	Hydrogen	SECM	12 January 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
29	C207	43245	MEO-9	BDS-3	Hydrogen	SECM	30 March 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
30	C208	43246	MEO-10	BDS-3	Hydrogen	SECM	30 March 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
31	C101	40549	IGSO-1S	BDS-3S	Hydrogen	SECM	30 March 2015	Experiment	-	-
32	C213	43622	MEO-13	BDS-3	Rubidium	CASC	19 September 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
33	C214	43623	MEO-14	BDS-3	Rubidium	CASC	19 September 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
34	C216	43648	MEO-15	BDS-3	Hydrogen	SECM	15 October 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
35	C215	43647	MEO-16	BDS-3	Hydrogen	SECM	15 October 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
36	C218	43706	MEO-17	BDS-3	Rubidium	CASC	19 November 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
37	C219	43707	MEO-18	BDS-3	Rubidium	CASC	19 November 2018	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
38	C220	44204	IGSO-1	BDS-3	Hydrogen	CASC	20 April 2019	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
39	C221	44337	IGSO-2	BDS-3	Hydrogen	CASC	25 June 2019	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
40	C224	44709	IGSO-3	BDS-3	Hydrogen	CASC	5 November 2019	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
41	C227	44864	MEO-19	BDS-3	Hydrogen	CASC	16 December 2019	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
42	C228	44865	MEO-20	BDS-3	Hydrogen	CASC	16 December 2019	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
43	C226	44794	MEO-21	BDS-3	Hydrogen	SECM	23 November 2019	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
44	C225	44793	MEO-22	BDS-3	Hydrogen	SECM	23 November 2019	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
45	C223	44543	MEO-23	BDS-3	Rubidium	CASC	23 September 2019	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
46	C222	44542	MEO-24	BDS-3	Rubidium	CASC	23 September 2019	Operational	Healthy	B1I/B3I/B1C/B2a/B2b
56	C104	40938	IGSO-2S	BDS-3S	Hydrogen	CASC	30 September 2015	Experiment	_	-
57	C102	40749	MEO-1S	BDS-3S	Rubidium	CASC	25 July 2015	Experiment	_	-
58	C103	40748	MEO-2S	BDS-3S	Rubidium	CASC	25 July 2015	Experiment	-	-
59	C217	43683	GEO-1	BDS-3	Hydrogen	CASC	1 November 2018	Operational	Healthy	B1I/B3I
60	C229	45344	GEO-2	BDS-3	Hydrogen	CASC	9 March 2020	Operational	Healthy	B1I/B3I
61	C230	45807	GEO-3	BDS-3	Hydrogen	CASC	23 June 2020	Testing		B1I/B3I



Appendix B

Figure A1. BeiDou BDS-2 (shaded grey) and BDS-3 satellites clock correction periodicity. The green lines correspond to BeiDou MEO satellites orbital period and its 2nd, 3rd and 4th harmonics. The orange lines correspond to GEO and IGSO satellites orbital periods and their harmonics up to 9. Spurious periods of 17 h and 30–40 h visible in the clock correction are caused by frequent jumps in the analysed signal (same as for simulated SIM data). The letters on the right side of diagram provide information on the particular satellite orbit and its clock: G—geostationary orbit, I—inclined geosynchronous orbit, M—Medium Earth orbit, R—rubidium clock, H—hydrogen maser.



Appendix C

3.2 ×10⁷

3.2 ×10⁷

3.2 ×10⁷





101

period [h]

























3.2 ×10⁷

3.2 ×10⁷

3.2 ×10⁷



9.6

9.4

10-

10-8

10-

10





4.6

4.5

4.4 4.4 *g* [s] 4.3

4.2

4.1

2.4

×10⁻⁸

2.5





9.2 9.2 9.0 8.8 8.6 2.8 t [s] 2.4 2.5 2.6 2.7 2.9 3.0 3.1 3.2 ×10⁷ C26 2020 freq. data (clock corr. rate) $\times 10^{-8}$ 1.0 0.5 &t/dt [s/s] • 0.0 -0.5 -1.02.8 t [s] 2.4 2.5 2.6 2.7 2.9 3.0 3.1 3.2 ×10⁷ ×10⁻¹³ C26 2020 freq. data detrended 4 2 δt/dt [s/s] 0 -4 3.2 ×10⁷ 2.4 2.5 2.7 2.8 2.9 3.0 3.1 2.6 t [s] C26 2020 L-S periodogram 10-1 10-2 10-LS Power 10-10-

101

period [h]

 $\times 10^{-4}$ C26 2020 phase data (clock correction)



3.2 ×10⁷

3.1 3.2 ×10⁷

> 3.2 ×10⁷

























Appendix D











References

- 1. Su, K.; Jin, S.; Jiao, G. Assessment of multi-frequency GNSS PPP models using GPS, Beidou, GLONASS, Galileo and QZSS. *Meas. Sci. Technol.* **2020**, in press. [CrossRef]
- 2. Han, C.; Cai, Z. Relativistic effects to the onboard BeiDou satellite clocks. Navig. J. Inst. Navig. 2019, 66, 49-53. [CrossRef]
- Lewinska, P.; Dyczko, A.; Matula, R. Integration of Thermal Digital 3D Model and a MASW (Multichannel Analysis of Surface Wave) as a Means of Improving Monitoring of Spoil Tip Stability. In Proceedings of the 2017 Baltic Geodetic Congress (BGC Geomatics), Gdansk, Poland, 22–25 June 2017; pp. 232–236. [CrossRef]
- 4. Lewińska, P.; Dyczko, A. Thermal digital terrain model of a coal spoil tip—A way of improving monitoring and early diagnostics of potential spontaneous combustion areas. *J. Ecol. Eng.* **2016**, *17*, 170–179. [CrossRef]
- 5. Nistor, S. The influence of different types of noise on the velocity uncertainties in GPS time series analysis. *Acta Geodyn. Geomater.* **2016**, *13*, 387–394. [CrossRef]
- 6. Nistor, S.; Buda, A.S. Evaluation of the ambiguity resolution and data products from different analysis centers on zenith wet delay using PPP method. *Acta Geodyn. Geomater.* **2017**, *14*, 205–220. [CrossRef]
- 7. Kampczyk, A.; Dybeł, K. Integrating surveying railway special grid pins with terrestrial laser scanning targets for monitoring rail transport infrastructure. *Meas. J. Int. Meas. Confed.* **2021**, *170*, 108729. [CrossRef]
- 8. Ai, Q.; Yuan, Y.; Xu, T.; Zhang, B. Time and frequency characterization of GLONASS and Galileo on-board clocks. *Meas. Sci. Technol.* **2020**, *31*, 065003. [CrossRef]
- 9. Borowski, L.; Banas, M. Application of Robust Estimation in Polynomial Modelling. In Proceedings of the 2018 Baltic Geodetic Congress (BGC Geomatics), Gdansk, Poland, 21–23 June 2018; pp. 62–66.
- 10. Ye, Z.; Li, H.; Wang, S. Characteristic analysis of the GNSS satellite clock. Adv. Sp. Res. 2021, 68, 3314–3326. [CrossRef]
- 11. Shi, J.; Wang, G.; Han, X.; Guo, J. Impacts of Satellite Orbit and Clock on Real-Time GPS Point and Relative Positioning. *Sensors* **2017**, *17*, 1363. [CrossRef]
- 12. Leick, A.; Rapoport, L.; Tatarnikov, D. *GPS Satellite Surveying*, 4th ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2015; ISBN 9781119018612.
- 13. Wu, Z.; Zhou, S.; Hu, X.; Liu, L.; Shuai, T.; Xie, Y.; Tang, C.; Pan, J.; Zhu, L.; Chang, Z. Performance of the BDS3 experimental satellite passive hydrogen maser. *GPS Solut.* **2018**, *22*, 1–13. [CrossRef]
- 14. Steigenberger, P.; Montenbruck, O. Galileo status: Orbits, clocks, and positioning. GPS Solut. 2017, 21, 319–331. [CrossRef]
- Hauschild, A.; Montenbruck, O.; Steigenberger, P. Short-term analysis of GNSS clocks. *GPS Solut.* 2013, *17*, 295–307. [CrossRef]
 Steigenberger, P.; Hugentobler, U.; Loyer, S.; Perosanz, F.; Prange, L.; Dach, R.; Uhlemann, M.; Gendt, G.; Montenbruck, O. Galileo orbit and clock quality of the IGS Multi-GNSS Experiment. *Adv. Sp. Res.* 2015, *55*, 269–281. [CrossRef]
- 17. Defraigne, P.; Bruyninx, C. On the link between GPS pseudorange noise and day-boundary discontinuities in geodetic time transfer solutions. *GPS Solut.* 2007, 11, 239–249. [CrossRef]
- 18. Rovira-Garcia, A.; Juan, J.M.; Sanz, J.; González-Casado, G.; Ventura-Traveset, J.; Cacciapuoti, L.; Schoenemann, E. Removing day-boundary discontinuities on GNSS clock estimates: Methodology and results. *GPS Solut.* **2021**, *25*, 35. [CrossRef]

- 19. Qing, Y.; Lou, Y.; Dai, X.; Liu, Y. Benefits of satellite clock modeling in BDS and Galileo orbit determination. *Adv. Sp. Res.* 2017, *60*, 2550–2560. [CrossRef]
- 20. Zhang, X.; Guo, J.; Hu, Y.; Sun, B.; Wu, J.; Zhao, D.; He, Z. Influence of precise products on the day-boundary discontinuities in gnss carrier phase time transfer. *Sensors* **2021**, *21*, 1156. [CrossRef]
- Qin, W.; Ge, Y.; Wang, W.; Yang, X. An Approach for Mitigating PPP Day Boundary with Clock Stochastic Model. In Proceedings of the IFCS-ISAF 2020—Joint Conference of the IEEE International Frequency Control Symposium and IEEE International Symposium on Applications of Ferroelectrics, Keystone, CO, USA, 19–23 July 2020; Volume 6, pp. 53–66.
- 22. Heo, Y.J.; Cho, J.; Heo, M.B. Improving prediction accuracy of GPS satellite clocks with periodic variation behaviour. *Meas. Sci. Technol.* **2010**, *21*, 073001. [CrossRef]
- 23. Li, H.; Liao, X.; Li, B.; Yang, L. Modeling of the GPS satellite clock error and its performance evaluation in precise point positioning. *Adv. Sp. Res.* 2018, *62*, 845–854. [CrossRef]
- 24. Yang, H.; Xu, C.; Gao, Y. Analysis of GPS satellite clock prediction performance with different update intervals and application to real-time PPP. *Surv. Rev.* 2019, *51*, 43–52. [CrossRef]
- 25. Kouba, J. Improved relativistic transformations in GPS. GPS Solut. 2004, 8, 170–180. [CrossRef]
- Senior, K.L.; Ray, J.R.; Beard, R.L. Characterization of periodic variations in the GPS satellite clocks. GPS Solut. 2008, 12, 211–225. [CrossRef]
- Xie, W.; Huang, G.; Cui, B.; Li, P.; Cao, Y.; Wang, H.; Chen, Z.; Shao, B. Characteristics and performance evaluation of QZSS onboard satellite clocks. *Sensors* 2019, 19, 5147. [CrossRef]
- Tseng, T.P.; Shum, C.K.; Yang, T.Y. Characterizing receiver clock behaviors onboard Low Earth Orbiters: A case study of GRACE satellites. *Geod. Geodyn.* 2019, 10, 276–281. [CrossRef]
- 29. VanderPlas, J.T. Understanding the lomb-scargle periodogram. Astrophys. J. Suppl. Ser. 2018, 236, 16. [CrossRef]
- 30. Robitaille, T.P.; Tollerud, E.J.; Greenfield, P.; Droettboom, M.; Bray, E.; Aldcroft, T.; Davis, M.; Ginsburg, A.; Price-Whelan, A.M.; Kerzendorf, W.E.; et al. Astropy: A community Python package for astronomy. *Astron. Astrophys.* **2013**, *558*, A33. [CrossRef]
- Dai, X.; Jiang, S.; Wu, C.; Jia, H. GPS time series analysis of Chengdu station based on the Lomb-Scargle algorithm. *Arab. J. Geosci.* 2021, 14, 1746. [CrossRef]
- Baldysz, Z.; Nykiel, G.; Araszkiewicz, A.; Figurski, M.; Szafranek, K. Comparison of GPS tropospheric delays derived from two consecutive EPN reprocessing campaigns from the point of view of climate monitoring. *Atmos. Meas. Tech.* 2016, *9*, 4861–4877. [CrossRef]
- 33. Xiang, Y.; Yue, J.; Tang, K.; Li, Z. A comprehensive study of the 2016 Mw 6.0 Italy earthquake based on high-rate (10 Hz) GPS data. *Adv. Sp. Res.* 2019, 63, 103–117. [CrossRef]
- Antoine, J.-P.; Carrette, P.; Murenzi, R.; Piette, B. Image analysis with two-dimensional continuous wavelet transform. *Signal Processing* 1993, 31, 241–272. [CrossRef]
- Penedo, S.R.M.; Netto, M.L.; Justo, J.F. Designing digital filter banks using wavelets. *EURASIP J. Adv. Signal Process.* 2019, 2019, 33. [CrossRef]
- 36. Bravo, J.P.; Roque, S.; Estrela, R.; Leão, I.C.; De Medeiros, J.R. Wavelets: A powerful tool for studying rotation, activity, and pulsation in Kepler and CoRoT stellar light curves. *Astron. Astrophys.* **2014**, *568*, A34. [CrossRef]
- Galiana-Merino, J.J.; Rosa-Herranz, J.L.; Rosa-Cintas, S.; Martinez-Espla, J.J. SeismicWaveTool: Continuous and discrete wavelet analysis and filtering for multichannel seismic data. *Comput. Phys. Commun.* 2013, 184, 162–171. [CrossRef]
- 38. Shen, N.; Chen, L.; Liu, J.; Wang, L.; Tao, T.; Wu, D.; Chen, R. A Review of Global Navigation Satellite System (GNSS)-based Dynamic Monitoring Technologies for Structural Health Monitoring. *Remote Sens.* **2019**, *11*, 1001. [CrossRef]
- 39. Wang, G.; de Jong, K.; Zhao, Q.; Hu, Z.; Guo, J. Multipath analysis of code measurements for BeiDou geostationary satellites. *GPS Solut.* **2015**, *19*, 129–139. [CrossRef]
- 40. Kudrys, J. Spectral analysis of multi-year GNSS code multipath time-series. Bud. i Archit. 2020, 18, 015–022. [CrossRef]
- 41. Lang, W.C.; Forinash, K. Time-frequency analysis with the continuous wavelet transform. *Am. J. Phys.* **1998**, *66*, 794–797. [CrossRef]
- 42. Torrence, C.; Compo, G.P. A Practical Guide to Wavelet Analysis. Bull. Am. Meteorol. Soc. 1998, 79, 61–78. [CrossRef]
- 43. Tary, J.B.; Herrera, R.H.; van der Baan, M. Analysis of time-varying signals using continuous wavelet and synchrosqueezed transforms. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2018**, *376*, 20170254. [CrossRef] [PubMed]
- 44. Riley, W.J. *Handbook of Frequency Stability Analysis*; US Department of Commerce: Washington, DC, USA, 2008; Volume 31, ISBN 3019753058.
- 45. Lomb, N.R. Least-squares frequency analysis of unequally spaced data. Astrophys. Space Sci. 1976, 39, 447–462. [CrossRef]
- 46. Scargle, J.D. Studies in astronomical time series analysis. II-Statistical aspects of spectral analysis of unevenly spaced data. *Astrophys. J.* **1982**, 263, 835. [CrossRef]
- 47. Keller, W. Wavelets in Geodesy and Geodynamics; De Gruyter: Berlin, Germany, 2009.
- 48. Brewer, K.E.; Wheatcraft, S.W. Wavelets in Geophysics; Elsevier: London, UK, 1994; Volume 4, ISBN 9780080520872.
- 49. Teolis, A. Computational Signal Processing with Wavelets; Birkhäuser Boston: Boston, MA, USA, 1998; ISBN 978-1-4612-8672-1.
- 50. Ghaderpour, E. JUST: MATLAB and python software for change detection and time series analysis. *GPS Solut.* **2021**, *25*, 85. [CrossRef]