Analysis of Inner-consistency of BDS Broadcast Ephemeris Parameters and their Performance Improvement

Conference Paper · May 2017

6 authors, including:

Junping Chen
Chinese Academy of Sciences

Sainan Yang
Chinese Academy of Sciences

Yize Zhang
Tongji University

Jungang Wang
Tongji University

Analysis of Inner-consistency of BDS Broadcast Ephemeris Parameters and their Performance Improvement

Junping Chen[1,2],Qian Chen[1,2], Bin Wang[1], Sainan Yang[1,2], Yize Zhang[1], Jungang Wang[3]
1 Shanghai Astronomical Observatory, Shanghai 200030,China
2. School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China
3 Technical University of Berlin, 10623 Berlin, Germany

BIOGRAPHIES

Prof. Junping Chen is the head of the GNSS data analysis group at Shanghai Astronomical Observatory (SHAO). He received his Ph.D. in Satellite Geodesy from Tongji University in 2007. From June 2006 to April 2011, he worked at the GFZ in Potsdam as research scientist. Since 2011, he has been supported by the "one hundred talents" program of the Chinese Academy of Sciences and works as the leader of the GNSS Analysis Center at the Shanghai Astronomical Observatory (SHAO). His research interests inlcude multi-GNSS data analysis and GNSS augmentation systems.

Qian Chen is a Ph.D. student at SHAO. Her recent research interests include GNSS augmentation and precise orbit determination.

Dr. Bin Wang is a postdoc researcher at SHAO. He finished his Ph.D. dissertation in Wuhan University and his recent research interests include GNSS augmentation and precise time transfer and syncronization.

Sainan Yang is a Ph.D. student at SHAO. Her recent research interests include BDS augmentation and ionosphere modeling.

Yize Zhang is Ph.D. at the College of Surveying and Geo-informatics Engineering at Tongji University. He works as a part-time research associate at SHAO. His recent research interests include precise point positioning (PPP) and real-time clock estimation.

Jungang Wang is a Ph.D. student at the Technical University of Berlin in Germany. He worked as a part-time research associate at SHAO from 2014-2016.

ABSTRACT

The space segment of Beidou regional navigation satellite system (BDS) consists of 5GEO/5IGSO/4MEO satellites. Orbit information of the broadcast ephemeris is obtained by the Orbit Determination and Time Synchronization (ODTS) technique based on the observations of regional tracking network, while clock information is obtained by the satellite-station Two Way Time Transfer (TWTT) technique realizing the time synchronization among satellites and monitoring stations. ODTS and TWTT are two independent techniques. TWTT makes the difference of uplink and downlink range observations to estimate satellite clock offset with respect to the BDS system time, thus satellite clock estimation is less affected by the satellite orbits error. However, due to the reason that regional monitoring network are used for the ODTS process, satellite clock parameters estimated through the ODTS process are highly correlated with the orbit parameters and partly absorb the radial orbital parameters. In this paper, the estimated satellite clocks differences between the ODTS and TWTT techniques are analyzed in detail. It is shown that the differences can be divided into two parts: firstly, the systematic offset caused by the hardware bias of the equipment; secondly, periodical terms caused by the strong correlation of satellite clock and orbits in TWTT. On this basis, a refined strategy to improve the self-consistency of satellite clock and orbit in the BDS broadcast ephemeris is developed. Experimental results show that the SISRE of the refined broadcast ephemeris is reduced by more than 60%, and pseudo-range based single-point position accuracy using the refined BDS broadcast ephemeris is improved by 29%,32% and 19% in the North, East

and Height components, respectively.

INTRODUCTION

For Global Navigation Satellite Systems (GNSSs), the accuracy of point positioning depends on the user equivalent range error (UERE) and the dilution of position (DOP) [1]. The UERE is further divided into signal-in-space range error (SISRE) and user equipment error (UEE), where SISRE describes the errors in the broadcast orbit and clock parameters and it is the key performance indicator for GNSS.

SISRE improvement is progressing for all GNSSs. For the GPS system, the projects like ephemeris enhancement endeavour (EEE) and legacy accuracy improvement initiative (LAII) [2] were performed, which make the SISRE reduce to 1.0 m. It is reported that SISRE of Block IIA, IIR and IIR-M satellites is 1.08, 0.42, and 0.52m respectively, during 2008-2010 period [3], and the constellation average SISRE is about 0.7m during 2012-2013 [4] and 2013-2014 period [5]. Besides, SISRE of Block IIF satellites is spectically low, which about 0.35m. For GLONASS, orbit-only contributions to SISRE are reported to be better than 1 m for 2009–2011 period [6]. While for some special GLONASS satellites, SISRE values of 1–4 m are reported [7]. An initial SISRE assessment of Galileo has been report to be 1-2m for a 14h time span from mid-May to mid-June 2013 [8].

Analyses of the broadcast ephemeris accuracy of Beidou navigation satellite system (BDS) started from 2012, many works have been published. SISRE of 0.5-1.5, 1-2 and 1-3m were reported for medium earth orbit (MEO), inclined geosynchronous orbit (IGSO) and geostationary orbit (GEO) respectively [9, 10]. These results reflect a degraded orbit determination accuracy for GEO satellites in comparison with IGSO and MEO satellites, which is mainly caused by a near-static observation geometry and affects the generation of broadcast ephemeris. While average SISRE values for BDS regional navigation satellite constellations is about 1.5 ± 0.1 m during 2013-2014 period [5]. Orbit-only contributions to SISRE, which are derived from satellite laser ranging (SLR), are reported to be 0.5-0.8m during the first quarter of 2013 [11].

Traditional method for SISRE analysis is based on the comparison between the broadcast ephemeris and precise orbit and clock products derived from the global tracking network. Different from other GNSSs, two-way radio time transfer (TWTT) among satellites and stations is used by BDS for clock synchronization [12]. Thus, BDS satellite clock offsets can be obtained through two types of techniques: the orbit determination and time synchronization (ODTS) and TWTT. By making difference between up- and down-link range observations, TWTT eliminates most common errors, including the tropospheric delay, satellite ephemeris errors etc. [13,14]. Consequently, satellite clock offsets obtained from the TWTT technique are less influenced by the satellite orbit error. Considering its high accuracy, satellite clock information of the BDS broadcast ephemeris is based on the TWTT method, meanwhile BDS broadcast orbit information is obtained through the ODTS process.In this study, clocks differences between ODTS and TWTT techniques are analyzed and a new method to improvement BDS performance, i.e. to reduce SISRE, is presented. Results show that the ODTS/TWTT clock differences could be divided into a piece-wise constant bias and periodical terms. Implementing the new method, the accuracy of BDS SISRE can be improved by around 60%.

BDS SISRE VALIDATION

For the validation of BDS SISRE of broadcast epheris, post-processing precise ephemeris based the IGS MGEX (Multi GNSS EXperiment) global network are used. In this study precise BDS ephemeris products of Wuhan university multi-GNSSs (WUM) are used, they are reported having accuracy of decimetre level, one decimetre level, and centimetre level for GEOs, IGSOs, and MEOs, respectively [15].

For the calculation of BDS SISRE, the following formula is used[15]:

$$\mathrm{SISRE} = \sqrt{(\alpha \cdot R - Clk)^2 + \beta(A + C)^2} \quad (1)$$

where terms $R, A\ and\ C$ are differences in radial, along-track and cross-track directions, respectively; and α and β are the coefficients for each orbit components, and they are defined as 0.99 and 1/126 for GEO and IGSO satellites; 0.98 and 1/154 for MEO satellites.

The radial direction contributes the most to the SISRE calculation, where it consists of radial orbit part and satellite clocks. We define the following equation using SISRE_r to calculate radial part of SISRE:

$$\mathrm{SISRE\_r} = \sqrt{\frac{\sum_{i}^{n}(\alpha \cdot R - Clk)^2}{n}} \quad (2)$$

In equation (2), n is the total number of epochs and $\alpha \cdot R - Clk$ is the combined radial residual error. Ideally, equation (2) contains only random noise related to orbits and clocks error. However, in case that the two components are not consistent, a system bias will exist and contaiminate the SISRE.

BDS SISRE and SISRE_r calculation using equations (1) and (2) is performed for the second half of the year 2016. Furthermore, SLR measurements spanning the same period from the international laser ranging service (ILRS) network [16] are used for the validation of radial orbit accuracy.

Table 1 shows the statics of SISRE_r, SLR validation and SISRE results , where we see that the SLR validation results are around 0.5m and are much smaller than SISRE_r. SLR results reflects the radial orbits accuracy, i.e. the term R in equations (1) and (2). The discrepancy between SISRE_r and SLR results is due to the inconsistency between radial orbits and satellite clocks in broadcast ephemeris. Consequently, the SISRE of BDS is contaiminated and it is around 1-3 m with mean value of 1.58 m.

Tab. 1 Validation of BDS broadcast ephemeris in terms of SISRE_r, SLR and SISRE, where ILRS tracks C01, C08, C10 and C11 only

Sat	SISRE_r (m)	SLR(m)	SISRE(m)
C01	1.94	0.65	2.40
C02	2.70	-	2.91
C03	1.21	-	1.33
C04	2.23	-	2.37
C05	1.13	-	1.27
C06	1.83	-	1.85
C07	0.90	-	0.95
C08	0.94	0.56	0.99
C09	0.97	-	1.00
C10	0.91	0.39	0.95
C11	1.30	0.51	1.37
C12	1.59	-	1.64
C14	1.54	-	1.59
Mean(GEO)	1.84	-	2.06
Mean(IGSO)	1.11	-	1.15
Mean(MEO)	1.48	-	1.53
Mean(All)	1.48	0.53	1.58

INNER-CONSISTENCY BETWEEN BDS BROADCAST EPHEMERIS

The reason for the inconsistency between radial orbits and satellite clocks is due to the fact that satellite clock information of the BDS broadcast ephemeris is based on the TWTT technique,while the broadcast orbit information is obtained through the ODTS process. ODTS and TWTT are two independent techniques, where TWTT makes the difference of uplink and downlink ranges to estimate satellite clock offset with respect to the BDS system time,thus satellite clock estimation is less affected by the satellite orbit error. However, due to the reason that only regional monitoring network observations are used for the generation of broadcast orbits, satellite clock parameters estimated through ODTS process are highly correlated with orbit parameters and partly absorb radial orbital parameters. The satellite clock and orbit parameters from ODTS process are self-consistent as the ODTS process follows the minimum-square residuals law. The absorption of orbits into clocks makes the estimated ODTS clocks not "pure" satellite clocks and thus cause the clock differences between ODTS and TWTT.

Figure 1 shows the differences among different orbits and clocks of satellite C01. In Method1, broadcast orbits of three days are compared to the post-processing precise orbit and the differences in radial direction are plotted. For this comparison, the approximate difference of 1.1 m between the reference points have to be considered, where the reference point is phase center for broadcast and mass center for post-processing. The frequent jumps in Method1 is due to hourly updating of broadcast ephemeris. In Method3, satellite clocks are compared between ODTS and TWTT techniques. For this comparison, the differences clearly show periodical signals, which coincides with the daily revolution period of GEO satellites showing that orbit errors are partly absorbed in ODTS clocks. Additionaly, a bias of 2.82m exists, exhibiting a systematic offset between ODTS and TWTT clocks.

Results of Method2 are the SLR validations. Both results from Method1 and Method2 show that the radial orbits of broadcast ephemeris have an accuracy of few decimeters. However the discrepency of TWTT and ODTS clocks may reach the level of 1-4 m. The discrepency contains a constant offset and periodical terms, and this is the biggest error resource for the BDS SISRE of some satellites.

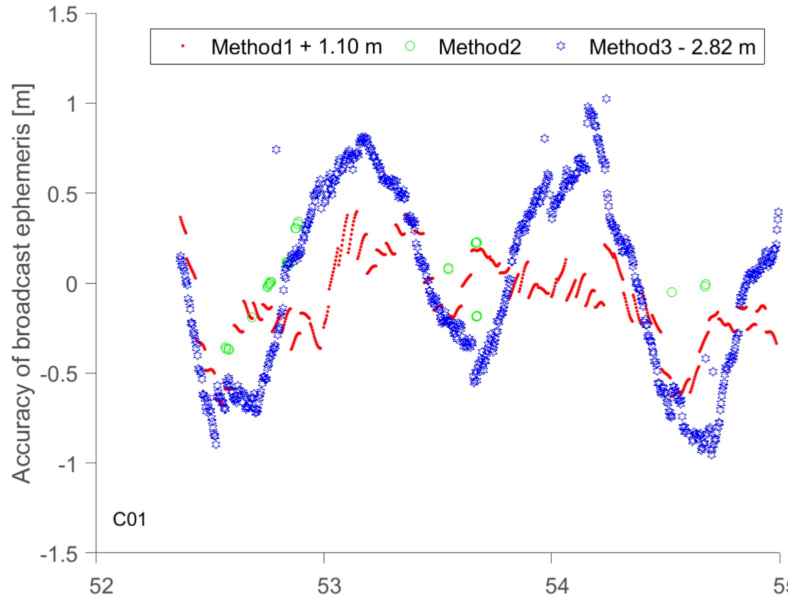

Figure 1. Comparison between different orbits and clocks for C01 satellite, showing that constant offset and periodical terms exist in the difference between ODTS and TWTT satellite clocks.

Using the data of the second half of the year 2016, offsets between ODTS and TWTT satellite clocks are derived and results are shown in table 2.

Tab. 2 Mean value and STD of offset between ODTS/TWTT satellite clocks

Sat	Mean±STD(m)	Sat	Mean±STD(m)	Sat	Mean±STD(m)
C01	-2.21±1.22	C06	-1.65±1.12	C11	0.92±1.41
C02	2.53±1.12	C07	-0.19±0.62	C12	1.63±1.03
C03	1.65±1.32	C08	0.34±0.86	C14	1.56±1.24
C04	-2.27±1.13	C09	-0.63±0.47		
C05	-1.13±1.03	C10	0.34±0.76		

From table 2, we notice that the offset of GEO satellites are relatively bigger than the other type of satellites. The standard deviation (STD) of the offsets are at the level of around 1 m, containing mainly the predicting error of TWTT clocks.

ODTS/TWTT COMBINED EPHEMERIS REFINEMENT

As shown in Figure 1 that the discrepency between orbits and clocks in BDS broadcast ephemeris consists of a constant offset and periodical terms. The periodical terms have the same peroid as satellite revolution peroid, thus we could model this periodical signal into satellite orbits. For the constant offset, either the semi-major axis of satellite orbit or satellite clock term a0 of broadcast ephemeris could be adjusted.

Following the above strategy, ephemeris refinement is performed. The procedure is defined as following: (1) firstly, constant offset and periodical terms of the ODTS/TWTT satellite clock differences are detrived by making difference between the two types of clocks; (2) constant offsets are added to the original TWTT clock time series; and (3) periodical terms are added to the original radial orbit component; (4) finally, broadcast ephemeris is fit based on the refined orbit/clock time series.

Taking the same data as shown in Table 1, broadcast ephemeris refinement is carried out and the new broadcast ephemeris is compared to the post-processed precise products. Table 3 shows the refined results, where the accuracy of satellite orbit in each component is derived and SISRE is calculated for each satellite. In table 3, GEO satellites have the worst accuracy, especially the along-track direction, which is due to the near-static observation geometry. Refined broadcast orbit accuracy is around 0.5-0.7 m in radial direction and 0.8-1.8 m in cross-track direction. SISRE results show that mean SISRE is of 0.62 m, which is improved by 60% over the original 1.58 m in table 1.

Tab. 3 RMS of refined broadcast ephemeris error and SISRE

Sat	C(m)	A(m)	R(m)	SISRE(m)
C01	0.90	8.40	0.66	1.00
C02	0.91	3.54	0.66	0.73
C03	0.95	3.39	0.67	0.74
C04	1.03	7.70	0.65	0.95
C05	1.03	4.15	0.63	0.74
C06	1.39	1.95	0.54	0.58
C07	1.33	1.49	0.42	0.45
C08	1.73	1.56	0.57	0.61
C09	1.42	1.70	0.54	0.57
C10	1.44	1.39	0.43	0.46
C11	0.80	1.92	0.46	0.49
C12	0.80	2.10	0.47	0.50
C14	0.87	2.29	0.47	0.50
Mean(GEO)	0.97	5.44	0.65	0.83
Mean(IGSO)	1.46	1.62	0.50	0.53
Mean(MEO)	0.82	2.10	0.47	0.50
Mean(All)	1.08	3.05	0.54	0.62

POSITIONING ACCURACY IMPROVEMENT USING THE REFINED BROADCAST EPHEMERIS

As shown in table 3 the SISRE of the refined broadcast ephemeris is greatly reduced. To further validate the improvement of the new ephemeris, pseudo-range based single-point positioning (SPP) is performed using data of 11 IGS stations. One month data is processed and table 4 shows the positioning accuracy using original and refined ephemeris for each station. Table 4 clearly shows that SPP accuracy is improved by around 10%-40% with mean improvement of 29%,32% and 19% in the North, East and Height components, respectively.

Tab. 4 RMS of SPP in each component using original and refined broadcast ephemeris

Sta	Original ephemeris			Refined ephemeris			Improvement		
	N(m)	E(m)	U(m)	N(m)	E(m)	U(m)	N(%)	E(%)	U(%)

1	1.30	1.40	3.54	0.97	0.94	2.52	25.4	32.9	28.8
2	1.56	1.56	4.25	1.24	1.05	3.36	20.5	32.7	20.9
3	1.70	2.15	5.63	1.16	1.72	4.49	31.8	20.0	20.2
4	2.24	1.99	5.63	1.68	1.48	4.79	25.0	25.6	14.9
5	1.64	1.68	4.52	1.25	1.24	3.83	23.8	26.2	15.3
6	1.37	1.37	3.64	1.10	1.08	2.82	19.7	21.2	22.5
7	1.53	1.64	4.01	0.97	0.84	3.23	36.6	48.8	19.5
8	1.49	1.52	4.80	1.13	1.05	4.29	24.2	30.9	10.6
9	1.18	1.44	3.74	0.73	0.92	2.88	38.1	36.1	23.0
10	1.25	1.52	3.96	0.77	0.93	3.32	38.4	38.8	16.2
11	1.23	1.44	3.63	0.82	0.93	2.97	33.3	35.4	18.2
Mean	1.50	1.61	4.30	1.07	1.11	3.50	28.80	31.69	19.10

CONCLUSIONS

In this study, satellite clock differences between ODTS and TWTT are analyzed in detail. Two main error resoures of SISRE are investigated, where the systematic offset could reach 1-4 m and the amplitude of the peroidical terms could reach 1 m. A refined strategy to improve the self-consistency of satellite clock and orbit in the BDS broadcast ephemeris is developed. In the strategy, constant offsets are added to the original TWTT clock time series and periodical terms are added to the original radial orbit component. Experimental results show that the SISRE of the refined broadcast ephemeris is reduced by more than 60%, and pseudo-range based single-point position accuracy using the refined BDS broadcast ephemeris is improved by 29%,32% and 19% in the North, East and Height components, respectively.

ACKNOWLEDGMENTS

This paper is supported by the National Natural Science Foundation of China (NSFC) (Grant No. 11673050 and 11273046), the National High Technology Research and Development Program of China (Grant No. 2014AA123102,2013AA122402) and the 100 Talents Programme of The Chinese Academy of Sciences.

REFERENCES

1.Misra, P. and P. Enge, Global positioning system: signals, measurements, and performance. 2006, Lincoln: Ganga-Jamuna Press.
2.Creel, T., A. Dorsey, P. Mendicki, et al. Summary of accuracy improvements from the GPS legacy accuracy improvement initiative (L-AII). in Proceedings of ION GNSS 2007. 2007.
3.Heng, L., G.X. Gao, T. Walter, et al., Statistical Characterization of GPS Signal-In-Space Errors, in Proceedings of the 2011 International Technical Meeting of the Institute of Navigation. 2011: San Diego, CA. p. 312-319.
4.Cooley, B. GPS program updates. in Proceedings of ION GNSS+ 2013. 2013. Nashville, TN.
5.Montenbruck, O., P. Steigenberger, and A. Hauschild, Broadcast versus precise ephemerides: a multi-GNSS perspective. GPS Solutions, 2015. 19(2): p. 321-333.
6.Heng, L., G.X. Gao, T. Walter, et al. Statistical characterization of GLONASS broadcast ephemeris errors. in Proceedings of ION GNSS 2011. 2011. Portland, OR.
7.Heng, L., Safe satellite navigation with multiple constellations: global monitoring of GPS and GLONASS signal-in-space anomalies. 2012, Standford University.
8.Lucas, R.R. Galileo IOV status and results. in Proceedings of ION GNSS 2013+. 2013. Nashville, TN.
9.Chen, L., W. Jiao, X. Huang, et al., Study on Signal-In-Space Errors Calculation Method and Statistical Characterization of BeiDou Navigation Satellite System, in China Satellite Navigation Conference (CSNC) 2013 Proceedings, J. Sun, et al., Editors. 2013, Springer Berlin Heidelberg. p. 423-434.
10.Hu, Z., G. Chen, Q. Zhang, et al., An Initial Evaluation About BDS Navigation Message Accuracy, in China Satellite Navigation Conference (CSNC) 2013 Proceedings, J. Sun, et al., Editors. 2013, Springer Berlin Heidelberg. p. 479-491.
11.Montenbruck, O. and P. Steigenberger. The BeiDou Navigation Message in International Global Navigation Satellite Systems Society IGNSS Symposium 2013 2013. Qld, Australia
12.Han, C., C. Zhiwu, L. Yuting, et al., Time Synchronization and Performance of BeiDou Satellite Clocks in Orbit. International Journal of Navigation and Observation, 2013. 2013: p. 5.

13.Liu, L., L.-F. Zhu, C.-H. Han, et al., The Model of Radio Two-way Time Comparison between Satellite and Station and Experimental Analysis. Chinese Astronomy and Astrophysics, 2009. 33(4): p. 431-439.
14.He, F., S. Zhou, X. Hu, et al., Satellite-station time synchronization information based real-time orbit error monitoring and correction of navigation satellite in Beidou System. Science China Physics, Mechanics & Astronomy, 2014. 57(7): p. 1395-1403.
15.Guo, J., X. Xu, Q. Zhao, et al., Precise orbit determination for quad-constellation satellites at Wuhan University: strategy, result validation, and comparison. Journal of Geodesy, 2016. 90(2): p. 143-159.
16.Pearlman, M.R., J.J. Degnan, and J.M. Bosworth, The International Laser Ranging Service. Advances in Space Research, 2002. 30(2): p. 135-143.