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北斗三号实时精密轨道钟差估计及精度效率评定

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摘要： 作为中国自主研发的全球卫星导航系统，北斗卫星导航系统的建设从一开始就确定了三步走的战略。围绕精度和效率等性能指标，进行了几项试验以确定一个合适的地面跟踪网。结果表明，在已有 60 个测站的情况下，增加跟踪站的数量并不能继续提高北斗三号轨道和钟差产品的精度。进一步的精度提升应该更依赖于天线相位中心改正缺失和太阳光压模型不完善等模型缺陷问题的解决。

关 键 词： 北斗三号；全球卫星导航系统；轨道确定；钟差估计

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1 Introduction

Since the end of the 20th century, the construction of BeiDou navigation satellite system (BDS) has been put on the agenda by China[1]. Based on the reality of domestic economy, science, and technology, the general “three-step” strategy is finally determined to gradually develop an independent global navigation satellite system (GNSS). With the successful construction of BDS-1 and BDS-2 in 2000 and 2012 respectively, the third and final step, from Asia-Pacific regional coverage to global service, is of vital significance to the completion of such a grand system.

On July 31, 2020, BDS-3 was offcially declared operational, announcing the full availability of BDS global service. Together with GPS, GLONASS, and Galileo, BDS-3 becomes

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one of the most important pillars in the satellite-based positioning, navigation, and timing (PNT) community.

Precise point positioning (PPP) technique[2] and its transition to real-time usage have been widely used in various types of GNSS-based applications. From scientific to engineering communities, these applications include crustal deformation research, earthquake and tsunami early warning systems, GNSS-aided lane-level autonomous driving, etc[3]. With the rapid surge of available navigation satellites from single-GPS to multi-GNSS, the real-time PPP performance in terms of precision and convergence speed has been steadily improving.

For real-time PPP applications to work succussfully, real-time generation of precise GNSS orbit and clock products is an indispensable prerequisite, which provides space and time reference frames to those research- and safety-critical applications mentioned above. Therefore, it is necessary to study the real-time precise orbit and clock estimation for BDS-3 constellation from both scientific and practical perspectives. On the other side, in order to gain greater market share and obtain more economic benefits, BDS-3, as a GNSS newcomer, must have excellent orbit and clock information to be more competitive in a wider range of applications.

In order to facilitate the development of software platform, the two-step method is widely used because legacy batch-processing softwares can be fully exploited. As discussed in the literature[4], however, the filter-based estimation approach is the natural and rigorous choice for the generation of real-time GNSS orbit and clock products. The difficulty with the one-step filter-based approach lies in the substantially increased complexity when accommodating dynamical orbit parameters into the sequential estimator.

Generally, to improve the accuracy of GNSS orbit and clock as far as possible, the number of processed tracking stations is constantly increased. This strategy is relatively feasible for post-processing tasks, where the requirement of immediacy is not so significant. For real-time service providers, however, timeliness of GNSS orbit and clock corrections is no less important than accuracy at all. As a consequence, neither accuracy nor timeliness can be excluded from consideration when generating real-time orbit and clock products.

In this work, several experiments have been conducted for real-time precise orbit and clock estimation for BDS-3 constellation, in which the balance between timeliness and precision is studied. This paper is roughly divided into four parts. Following the general introduction in Section 1, some basic information about BDS-3 constellation as well as the software platform used for experiment operation is given in Section 2. Then, the processing strategy and more experimental details for BDS-3 orbit and clock estimation are described in Section 3. Meanwhile, the generated orbit and clock products are assessed in terms of accuracy and efficiency. Finally, this work is concluded in Section 4.

2 BDS-3 constellation and software platform

Currently, BDS-3 constellation consists of 24 MEO (Medium Earth Orbit) satellites, 3 IGSO (Inclined Geosynchronous Earth Orbit) satellites, and 3 GEO (Geostationary Earth Orbit) satellites. If taking the four experimental satellites into consideration, a total of 34 BDS-3 satellites have been launched into orbit. In chronological order of their launch dates, some fundamental information about these 34 satellites are listed in Table 1. Unlike IGSO and GEO satellites which were manufactured by China Academy of Space Technology (CAST), the BDS-3 MEO satellites were produced by two independent manufacturers, CAST and Shanghai Engineering Center for Microsatellites (SECM). For this reason, the two types of MEO satellites have different configurations in such aspects as mass, geometry, attitude control law, and the depolyment of onboard frequency standards, all of which are crutial in precise orbit and clock modelling.

表 1 Basic information about BDS-3 constellation as of August, 2021

Phase	Launch date	SVN	PRN	Orbit	Slot	Clock	Manuf.
BDS-3S	2015-03-30	C101	—	IGSO	—	PHM	SECM
	2015-07-25	C102, C103	—	MEO	—	RAFS	CAST
	2015-09-30	C104	—	IGSO	—	PHM	CAST
BDS-3	2017-11-05	C201, C202	C19, C20	MEO	B7, B8	RAFS	CAST
	2018-01-12	C203, C204	C27, C28	MEO	A4, A5	PHM	SECM
	2018-02-12	C205, C206	C22, C21	MEO	B6, B5	RAFS	CAST
	2018-03-30	C207, C208	C29, C30	MEO	A2, A3	PHM	SECM
	2018-07-29	C209, C210	C23, C24	MEO	C7, C1	RAFS	CAST
	2018-08-25	C211, C212	C26, C25	MEO	C2, C8	PHM	SECM
	2018-09-19	C213, C214	C32, C33	MEO	B1, B3	RAFS	CAST
	2018-10-15	C215, C216	C35, C34	MEO	A1, A7	PHM	SECM
	2018-11-01	C217	C59	GEO	—	PHM	CAST
	2018-11-19	C218, C219	C36, C37	MEO	C4, C6	RAFS	CAST
	2019-04-20	C220	C38	IGSO	—	PHM	CAST
	2019-06-25	C221	C39	IGSO	—	PHM	CAST
	2019-09-23	C222, C223	C46, C45	MEO	C5, C3	PHM	CAST
	2019-11-05	C224	C40	IGSO	—	PHM	CAST
	2019-11-23	C225, C226	C44, C43	MEO	A8, A6	PHM	SECM
	2019-12-16	C227, C228	C41, C42	MEO	B2, B4	RAFS	CAST
	2020-03-09	C229	C60	GEO	—	PHM	CAST
	2020-06-23	C230	C61	GEO	—	PHM	CAST

Note：Four decommissioned BDS-3 experimental satellites are also included here for completeness. SVN, PRN, orbit and slot are consistent with IGS naming conventions.

To cope with the problem of real-time multi-GNSS orbit and clock generation, a software platform must be developed. Measurement modelling, quality control, orbit modelling, numerical integration, and sequential estimation make up the framework of such a software, while various management functions are also necessary to connect these separate parts into a coherent and complete software package. Figure 1 illustrates the structural composition of our software program, and the modelling work in the software is, as far as possible, in accordance with the lastest IERS (the International Earth Rotation and Reference Systems Service) and IGS (the International GNSS Service) conventions[5]. More descriptions and details can be found in literature[4], where real-time estimation of GPS orbit and clock products has been demonstrated.

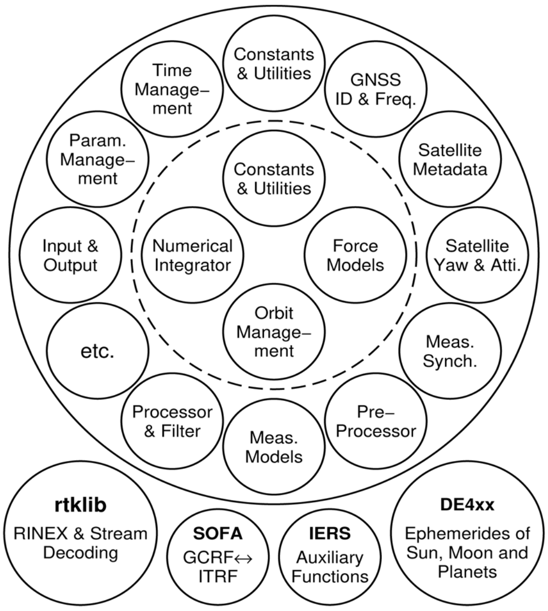
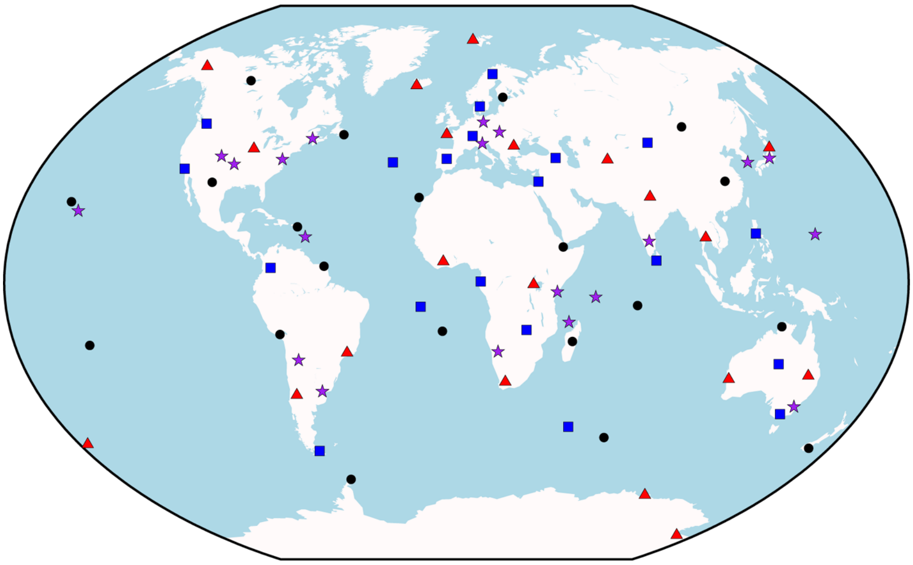


图 1 Modular diagram of the software platform developed for real-time multi-GNSS orbit and clock estimation.

3 Experiments and results

3.1 Data processing

In order to have sufficient observational data of BDS-3 satellites, the first week of August, 2021 is selected as the experimental time period. By this time, the BDS-3 had officially been in operation for a full year. Thanks to the multi-GNSS experiment (MGEX) project[9] launched by IGS, there exist about 150 stations with the capability to track the full BDS-3 constellation during the chosen period. From the whole tracking network with 150 stations or so, four sub-networks are selected which contain 20, 40, 60, and 80 MGEX stations, respectively. Larger networks are expanded on the basis of the smaller, and their distributions are shown in Figure 2. Regardless of the number of stations, the distribution of each sub-network must be as evenly and globally distributed as possible. This is because continuous tracking of BDS-3 satellites is necessary in sequential processing mode.



note: 20=circle; 40=20+triangle; 60=40+square; 80=60+star.

图 2 Distribution of the four station networks used in experiments

The aim of such an experiment design is to find the appropriate size of the tracking network when estimating BDS-3 precise orbit and clock, with product accuracy and calculation efficiency as indicators. Rather than the true real-time data processing, the simulated real-time functionality is employed to filter archived RINEX files epoch by epoch. Unlike measurement modelling and orbit modelling which have been largely standardized, there is something empirical about processing strategies and filter settings. They are two important aspects in the generation of precise orbit and clock products, and Table 2 and Table 3 list processing strategies and filter settings adopted in the above experiments. These settings are consistent with those of GPS data processing[4].

3.2 Performance assessment

Due to high orbital altitude and near-static observation geometry, precise orbit determination (POD) for GEO satellites is always a big challenge for researchers, even in the post-processing data analysis. Therefore, the POD of GEO satellites itself has become an independent research subject for a rather long time. Compared with GEO satellites, the observational geometry of IGSO satellites is vastly improved. However, from figure-of-eight

表 2　**Processing strategies used for BDS-3 experiments**

Item	Strategy	
time span	From 2021-08-01 to 2021-08-07	
GNSS constellation	BDS-3	
number of stations	20/40/60/80 (Distribution in Figure 2)	
cut-off angle	10°	
sampling rate	30 s	
observation usage	Pseudo-range and carrier-phase	
	Zero-difference and ionosphere-free linear combination	
raw measurement type	C2I/L2I/C6I/L6I	
raw measurement noise	$\sigma_C = 1$ m; $\sigma_L = 0.01$ m	
observation weighting	Elevation-dependent with $\sin^2(e)$	
cycle slip detection	TurboEdit method[6]	
residual screening	Pseudo-range	$4 \times \sigma_{C,\mathrm{res}}$ as threshold
	Carrier-phase	$4 \times \sigma_{L,\mathrm{res}}$ as threshold
satellite antenna PCO/PCV	Conventional MGEX values (igs14_2194.atx)	
receiver antenna PCO/PCV	BDS-3 B1/B3 or adopted from GPS L1/L2 (igs14_2194.atx)	
reference frame	IGS14	
conventional force models		
geopotential	EGM2008 up to degree and order 12	
tidal potentials	Solid Earth, ocean, and pole tides	
third body	Moon, Sun, and all major planets	
relativistic effect	Schwarzschild term only	
solar radiation pressure	ECOM2 with 7 parameters[7]	
satellite attitude	Nominal yaw-steering model[8]	
minor perturbations		
earth albedo	Not considered	
antenna thrust	Not considered	
thermal radiation	Not considered	

表 3　**Filter parameterization and noise setting (n_{sat}=27, n_{sta}=20，40，60，80)**

Parameter	Initial noise		Process noise		Number of parameters			
					n_{sta}=20	40	60	80
satellite position	10^0	m	0	m	3×27	3×27	3×27	3×27
satellite velocity	10^0	m/s	0	m/s	3×27	3×27	3×27	3×27
SRP	10^0	m/s^2	10^{-12}	m/s^2	7×27	7×27	7×27	7×27
satellite clock	10^8	m	10^8	m	1×27	1×27	1×27	1×27
receiver clock	10^8	m	10^8	m	1×20	1×40	1×60	1×80
tropospheric delay	10^0	m	10^{-4}	m	1×20	1×40	1×60	1×80
ambiguity	10^8	m	10^{-3}	m	10×20	10×40	10×60	10×80
total					618	858	1 098	1 338

ground tracks of IGSO satellites, it is apparent that the improvement of their observation geometries is mainly from the north-south component. Thus, the orbital accuracy of these two types of satellites is generally much worse than MEO satellites. Because of the above reasons and their regional feature, the three GEO satellites and an equal number of IGSO satellites are excluded when assessing the accuracy of BDS-3 orbit and clock products.

To assess BDS-3 orbit and clock information generated in this work, the final MGEX orbit and clock products provided by GFZ analysis center are selected as the reference. Orbit errors are represented in the local orbital frame, namely in the radial (R), tangential (T), and normal (N) directions. Note that the Helmert transformation is not used here. The precision of BDS-3 clock product is in terms of double-differenced clock errors, so that different clock references between GFZ and self-generated clock products can be removed. Satellite-specific orbit and clock accuracies are plotted in Figure 3 and Figure 4, where BDS-3 satellites are first divided into two groups according to their manufacturers and then three groups according to their orbital planes.

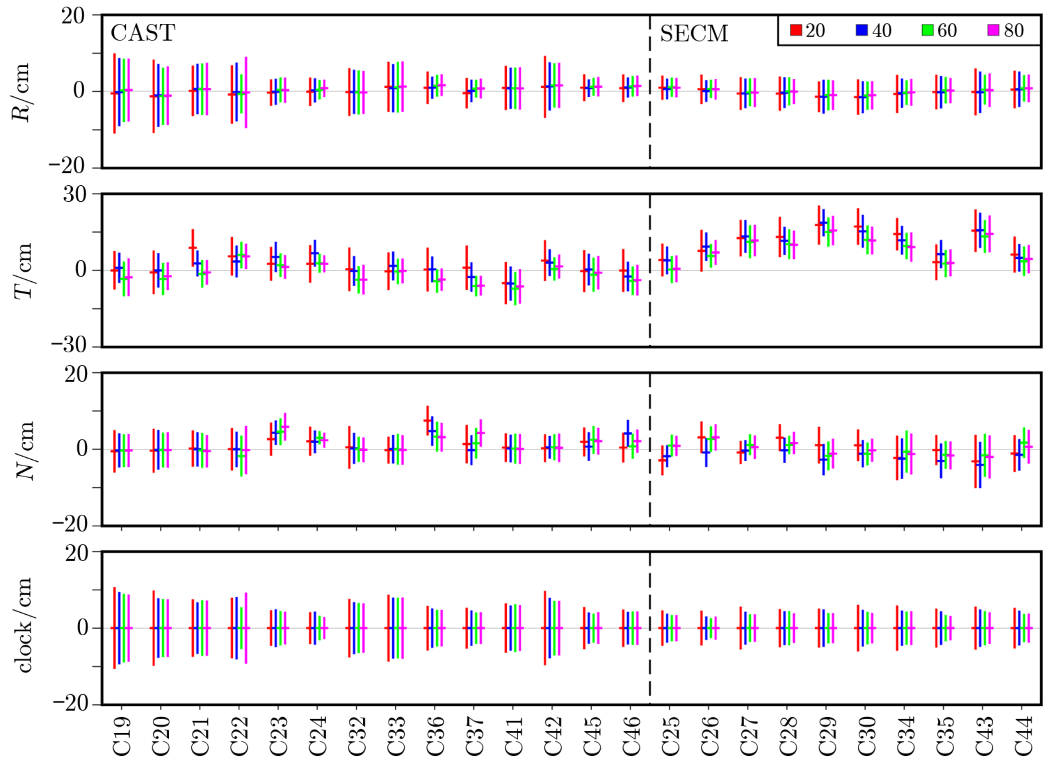


图 3 Manufacturer- and satellite-specific accuracy comparison of BDS-3 orbit and clock between the four different tracking networks

From Figure 3, there are in general no obvious manufacturer- or plane-specific patterns

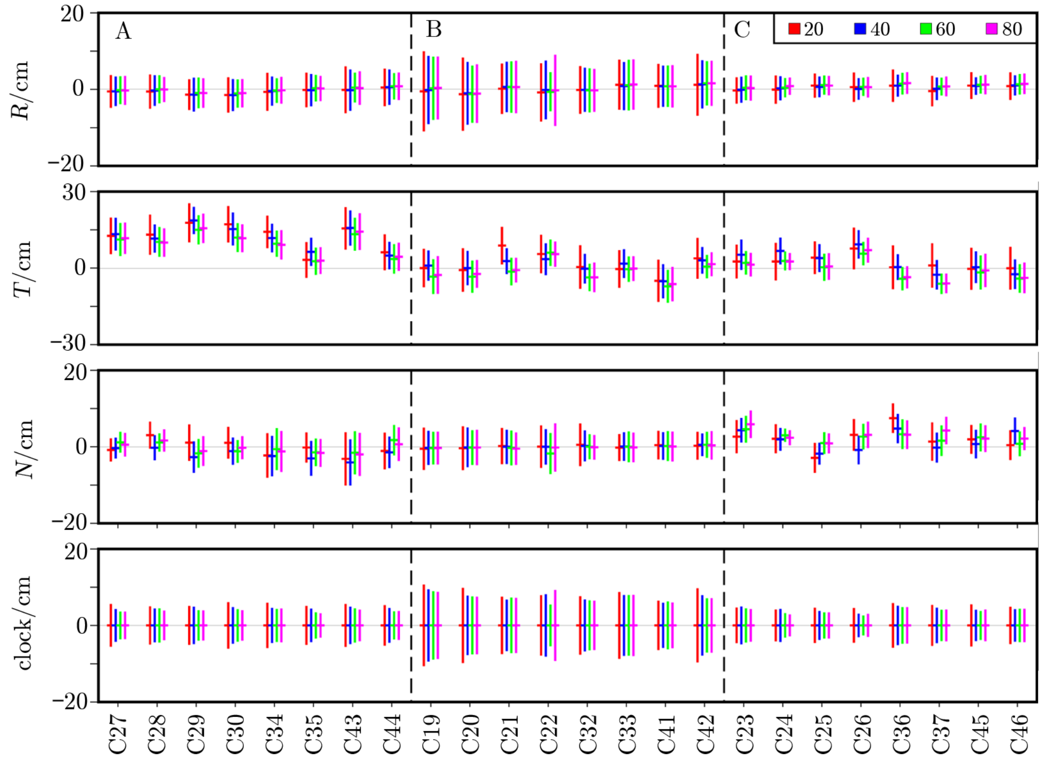


图 4　Plane- and satellite-specific accuracy comparison of BDS-3 orbit and clock between the four different tracking networks

in the BDS-3 orbit and clock accuracy. However, in radial direction in Figure 4, a clear plane-specific feature of orbit accuracy can be seen. This phenomenon is probably due to the different modeling performances of ECOM2 for orbital planes with different Sun elevations. In addition, orbit products from the four tracking networks have a rather similiar accuracy in terms of offset and standard deviation (STD) values in all three RTN directions. Increasing the number of tracking stations from 40 to 80, there is no significant improvement in orbit accuracy. This should mean that further improvement of BDS-3 orbit accuracies is mainly restricted by systematic modelling deficiencies, such as lack of phase center corrections of ground antennas and defect of existing solar radiation models. The precision of BDS-3 clock products are also presented in Figure 3 and Figure 4, which is consistent with the orbit accuracy in the radial direction. Looking at the BDS-3 MEO constellation as a whole, specific values of orbit and clock accuracy are given in Table 4. Generally speaking, BDS-3 orbit and clock products generated using 60 tracking stations have reached the accuracy ceiling for our software platform, although the accuracy is still a little bit lower than IGS real-time products.

表 4 **Numerical values in centimeters of BDS-3 MEO orbit and clock products**

	R		*T*		*N*		
#Sta	offset	STD	offset	STD	offset	STD	Clock
20	0.01	5.33	5.42	7.66	0.58	4.48	6.79
40	0.10	4.67	5.21	5.80	−0.08	3.93	5.96
60	0.38	4.20	2.48	5.42	0.62	3.74	5.54
80	0.42	4.42	2.84	5.41	0.81	3.81	5.59

Figure 5 shows the comparison of single epoch time consumption between the four experiments. All the experiments are conducted on a desktop computer that is equipped with an Intel® Core™ i3-8100 CPU (@ 3.6 GHz × 4) and 12 GB RAM. The average time consumptions per epoch are, respectively, about 0.2 s, 0.6 s, 1.2 s, and 2.3 s when processing tracking networks with 20, 40, 60, and 80 stations. For single-GNSS processing, the efficiency is entirely sufficient for commonly adopted 5-second update rate even with 80 stations. While in the case of multi-GNSS, further efficiency improvements need more studies.

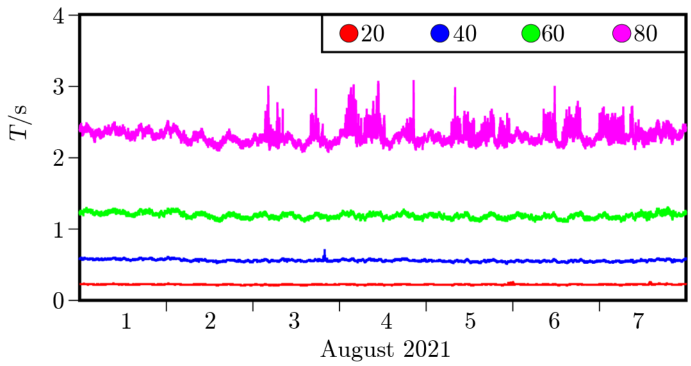


图 5 **Comparison of single epoch time consumption between experiments corresponding to the four tracking networks**

4 Discussion

BDS-3 has been fully developed and there is no doubt that its global converage will bring great benefits to PNT community around the world. For BDS-3 to play a crucial part in real-time PPP applications, real-time generation of precise BDS-3 orbit and clock products is an urgent task. In this work, several experiments are conducted to determine the size of an optimal tracking network when estimating BDS-3 products. Through the experiments, processing a tracking network with 60 stations is adequate in terms of accuracy and efficiency.

Also, experiments indicate that the factors preventing further accuracy improvement of BDS-3 orbit and clock products are modelling defects, such as lack of ground antenna phase center corrections and deficiency of solar radiation pressure models. As these modelling deficiencies are gradually resolved, it can be expected that there will be a noticeable improvement in the accuracy of real-time BDS-3 orbit and clock products.

致谢

The IGS as well as the MGEX project are acknowledged for providing raw multi-GNSS observations and precise BDS-3 orbit and clock products. All figures in this article are prepared using the Generic Mapping Tools[10].

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Real-time Precise Orbit and Clock Estimation for BDS-3 Constellation: Accuracy and Efficiency Assessment

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Abstract: BeiDou navigation satellite system (BDS) is an independent global navigation satellite system (GNSS) developed by China. The three-step strategy was adopted from the very beginning and the third and final step, BDS-3, had been officially announced operational on July 31, 2020. An essential and necessary task is to generate precise orbit and clock products in real time, only in this way can BDS-3 constellation be ready for widespread use from ordinary to high-precision real-time applications. In this work, keeping accuracy and efficiency in mind, several experiments are conducted to find an adequate size of tracking networks. It is shown that, up to 60 stations, the accuracy of BDS-3 orbit and clock products can not be improved by increasing the number of tracking stations. Further accuracy improvements should depend on solving some modelling defects such as lack of antenna phase center corrections and imperfection of solar radiation pressure models.

Key words: BDS-3; GNSS; orbit determination; clock estimation