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Precise orbit and clock determination for BeiDou-3 experimental satellites with yaw attitude analysis

Qile Zhao[1,2], Chen Wang[1], Jing Guo[1,3*], Bin Wang[4], Jingnan Liu[1,2]

1 GNSS Research Center, Wuhan University, 129 Luoyu Road, Wuhan 430079, China

2 Collaborative Innovation Center of Geospatial Technology, Wuhan University, 129 Luoyu Road, Wuhan 430079, China

3 School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

4 Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China

(Corresponding author: jingguo@whu.edu.cn)

Abstract—Five new-generation BeiDou-3 experimental satellites, called BeiDou-3e, have been launched into inclined geosynchronous orbit (IGSO) and medium orbit (MEO) since March 2015. In addition to newly designed signals and intersatellite links, different satellite buses, updated rubidium atomic frequency standards (RAFSs), and new passive hydrogen masers (PHMs) have been used. Using 15 stations, mainly in the Asia-Pacific region, we determined orbits and clock for both the BeiDou-3e and the regional BeiDou-2 satellites using the Extend CODE (Center for Orbit Determination in Europe) Orbit Model (ECOM). The orbit consistency, indicated by 3D orbit boundary discontinuity, is 50 to 70 cm and 40 to 60 cm for BeiDou-3e IGSO and MEO satellites, respectively, and better than 15 cm in radial component. Satellite laser ranging (SLR) validation gives about 17 cm and 10 cm for BeiDou-3e IGSO and MEO satellites. The BeiDou-3e satellites orbits show slightly better performance than the BeiDou-2 satellites as indicated by SLR. However, errors depending on the sun elongation angle were identified in SLR residuals for the BeiDou-3e IGSO C32 satellite, while such errors did not exist for BeiDou-2 IGSO/MEO and BeiDou-3e MEO satellites. No orbit accuracy degeneration for BeiDou-3e IGSO and MEO satellites was observed when the elevation angle (β angle) of the sun above the orbital plane was between –4° and +4°. In that case, the BeiDou-2 IGSO and MEO satellites are in orbit normal (ON) mode. An analysis of the yaw attitude identified that BeiDou-3e satellites did not use the ON mode, but experienced midnight- and noon-point maneuvers when the β angle is approximately between –3° and +3°. Compared with BeiDou-2 satellites, the onboard clocks of the BeiDou-3e IGSO satellites showed dramatic improved performance. The stability of BeiDou-3e IGSO satellites can be compared to the latest type of RAFSs employed onboard the GPS IIF satellites as well as the PHMs used onboard the Galileo satellites.

Keywords: BeiDou-3; precise orbit determination; clock analysis; passive hydrogen masers; yaw attitude

Introduction

The development of the Chinese BeiDou Navigation Satellite System (BDS) occurs in 3 phases. In the first phase, BeiDou-1, 4 satellites were deployed to geostationary orbit (GEO) to form an experimental system. The second phase, BeiDou-2, launched a constellation of 5 satellites in GEO, 5 in inclined geosynchronous orbit (IGSO), and 4 in medium earth orbit (MEO). In this phase, the system has been providing continuous passive positioning, navigation, and timing (PNT) services for users throughout the Asia-Pacific area since December 27, 2012. In the third phase (BeiDou-3), the BDS will be completed with global navigation ability by 2020. At that time, the system will comprise a constellation of 5 GEO, 27 MEO, and 3 IGSO satellites (CSNO 2016). On March 30, 2015, the first BeiDou-3 satellite was successfully launched into IGSO, beginning the system's transition toward global coverage. Up to May 2017, there were 5 BeiDou-3 satellites in orbit, as listed in Table 1. Currently, 4 satellites (C31–C34) are already in operation and broadcasting signals, while C35 is still being tested. The purpose of the 5 satellites is to validate the new features of the BeiDou-3 satellites, including signals, intersatellite link technology, and onboard frequency standards. Hence, these 5 satellites are referred as BeiDou-3 experimental satellites, hereafter abbreviated as BeiDou-3e.

Table 1 Status of BeiDou-3e satellites (May 2017). CAS: China Academy of Science; CAST: China Academy of Space Technology

Satellite	Launch date	COSPAR ID	PRN	Orbit	Manufacturer
I1-S	Mar. 30, 2015	2015-019 A	C31	IGSO, 55° inclination	CAS
M1-S	Jul. 25, 2015	2015-037 A	C34	MEO	CAST
M2-S	Jul. 25, 2015	2015-037 B	C33	MEO	CAST
I2-S	Sep. 29, 2015	2015-053 A	C32	IGSO, 55° inclination	CAST
M3-S	Feb. 1, 2016	2016-006 A	C35	MEO	CAS

All BeiDou-2 satellites are based on the DongFangHong-3A (DFH-3A) satellite platform, which is an updated version of DFH-3 used by BeiDou-1 satellites and manufactured by the China Academy of Space Technology (CAST). The DFH-3A bus adopts a hexahedral structure, and additional equipment for C-band telecommunication and short message service have been carried by GEO satellites. The BeiDou-2 satellites also support 2-way satellite time and frequency transfer to enable the determination of satellite clock offsets.

However, BeiDou-3e satellites are based on two different satellite platforms developed by CAST and the China Academy of Science (CAS). The CAS platform weighs only approximately

848 kg. Similar to Galileo-IOV/FOC satellites, it has an elongated shape along X axis instead of a cubic one, and the elongated face with the normal direction along Z axis points to the earth's center. In addition, a star camera instead of sun and earth sensors is used to determine attitude and stabilize the satellite's orientation. On the other hand, the CAST platform has a cubic shape and weighs 2800 kg. Other improved technologies have also been used for both platforms. For example, the intersatellite link manages communication and distance measurement between the BeiDou-3e satellites to enable autonomous navigation, and improves independency and stability of BDS. With intersatellite ranging measurements, precise orbits can be determined (Yang et al. 2017). The primary frequency standards of the BeiDou-2 navigation payload are based on Chinese rubidium clocks, while European clocks serve as backup units. However, passive hydrogen masers (PHMs) developed by Shanghai Astronomical Observatory and Beijing Institute of Radio Metrology and Measurement have been used to provide the primary frequency standard for BeiDou-3 satellites. The improved Chinese rubidium atomic frequency standards (RAFSs) serve as the backup.

Precise orbits and clocks are key requirements for the most demanding applications of the BDS. Much research has been done on the precise orbit determination (POD) of BeiDou-2 satellites (Zhao et al. 2013; Steigenberger et al. 2013; Lou et al. 2014). In general, the 3D RMS of orbit differences for the orbit products from the International GNSS Service (IGS) Multi-GNSS Experiment (MGEX) analysis centers (ACs) is 12 to 26 cm for MEOs, 32 to 51 cm for IGSOs, and approximately 510 cm for GEOs (Montenbruck et al. 2017). In addition, satellite laser ranging (SLR) validation demonstrates that the radial orbit accuracy for MEO, IGSO, and GEO satellites is approximately 5 cm, 10 cm, and 50 cm respectively (Montenbruck et al. 2017). However, BeiDou-2 satellites suffer solar radiation pressure (SRP) model deficiency, which is mainly caused by the attitude control mode. For BeiDou-2 IGSO and MEO satellites, 2 kinds of attitude modes are used: yaw steering (YS) and orbit normal (ON). Dramatic orbit accuracy degeneration can be observed when satellites switch the attitude mode or are in the ON mode. Based on the proper yaw attitude model for BeiDou-2 IGSO and MEO satellites (Feng et al. 2014; Guo et al. 2017a), some efforts have been done to construct a better SRP model for BeiDou-2 IGSO and MEO satellites in the ON mode (Guo 2014; Guo et al. 2017a; Prange et al. 2016). In addition, Guo et al. (2017a) identified a deficiency in the 5-parameter empirical Extended CODE Orbit Model (ECOM) SRP model (Beutler et al. 1994, Springer et al. 1999) in YS mode for BeiDou-2 IGSO satellites, and proposed that the deficiency can be overcome by using the box-wing model as the a priori SRP model. For BeiDou-2 GEO satellites, because the ON mode is used as well as almost static observation conditions with respect to ground stations, the orbit accuracy is at the meter level.

Limited research has been done on orbit and clock determination for BeiDou-3e satellites, except for Tan et al. (2016). In that work, precise orbits were determined based on 1-month data from 9 International GNSS Monitoring and Assessment System (iGMAS) tracking stations. The orbit consistency, indicated by 3D 24-h overlapping orbit differences (OODs), was found to be approximately 36 cm and 88 cm for IGSO and MEO satellites respectively. SLR validation with fewer normal points (NPs) from the International Laser Ranging Service (ILRS) (Pearlman et al. 2002) shows the radial orbit accuracy is approximately 11 cm and 40 cm for IGSO and MEO satellites respectively. Similar precision is also confirmed by the 24-h OODs in radial. Unfortunately, factors affecting orbit and clock quality have not been investigated and analyzed, such as the yaw attitude, SRP, and onboard atomic clock performance. Recently, Zhang et al. (2017) assessed the performance the BeiDou-3e satellites, and the analysis indicates that the quality of the new-generation BeiDou-3 signals is comparable to that of GPS and Galileo signals. In this study, we present the performance of the BeiDou-3e orbit and clock as determined by long-period data, and also analyze the above-mentioned factors and their impacts. In particular, we highlight the differences between BeiDou-2 and BeiDou-3e satellites in orbit, clock, and yaw attitude.

Following the section on the overview of data collection and availability, the POD strategy is described. Afterwards, the orbit boundary discontinuity (OBD) and SLR are used as the metrics to evaluate the orbit quality, while the impacts of the length of POD arc, as well as number of ECOM parameters on the orbits, will be investigated in order to obtain the best solution. And then, the yaw attitudes are estimated and analyzed with a comparison to BeiDou-2. After assessment of the stability of onboard atomic clock with modified Allan deviations (MADEVs), this study is concluded in the final section.

Data collection and availability

Signals are transmitted by BeiDou-3e satellites on as many as 5 frequencies, listed in Table 2, including the backward-compatible BeiDou-2 B1I and B3I signals. The signal bandwidth, modulation rate, and the signal modulation code structure can be founded in CSNO (2017). In this case, BeiDou-3e satellites can be easily tracked by BeiDou-2 receivers with minor modifications. In this study, 15 stations from iGMAS, BeiDou Experimental Tracking Network (BETN), and Geoscience Australia (GA) network were used. Figure 1 shows their distribution. Most of the sites are in the Asia-Pacific region, and this distribution results in relatively poor tracking conditions for MEO satellites. Table 3 summarizes the information on the location, receiver, and antenna of the 15 stations. For iGMAS stations, two kinds of receivers, CETC-54 GMR-4011 and GNSS-GGR, are used. Those are manufactured by the 20th and 54th Institute of China Electronics Technology Corporation respectively. The Ture-CORS receiver from Wuhan Navigation and LBS Inc. and the PolaRx5 receiver from Septentrio are deployed in BETN and GA networks. However, all the receivers could track only the B1I and B3I signals transmitted by the BeiDou-3e satellites.

Table 2 Frequency of BeiDou-3e satellite-transmitted signals

Frequency Band	B1I	B3I	B1C	B2a	B2b
Frequency (MHz)	1561.098	1268.52	1575.42	1176.45	1207.14

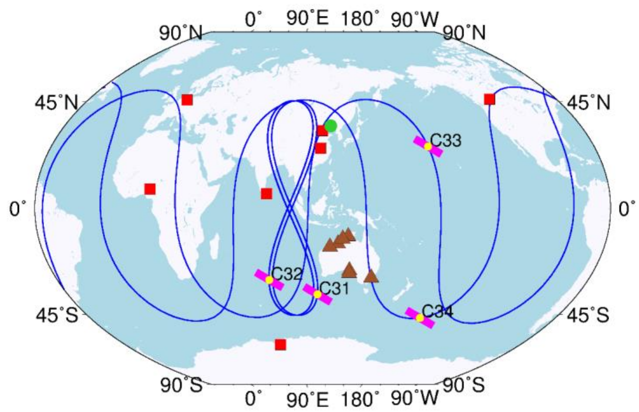

Fig. 1 Distribution of the 15 stations used and ground tracks of the BeiDou-3e satellites. Red squares indicate iGMAS, the green circle represents the BETN, and the brown triangles are GA stations

Table 3 Information of the 15 stations used in this study

Site Abbrev.	Location	Country	Receiver code	Antenna code
CEDU	Ceduna	Australia	SEPT POLARX5	AOAD/M_T NONE
STR1	Stromlo	Australia	SEPT POLARX5	ASH701945C_M NONE
KAT1	Katherine	Australia	SEPT POLARX5	LEIAR25.R3 LEIT
THEV	Thevenard	Australia	SEPT POLARX5	LEIAR25.R3 LEIT

WLAL	Wallal	Australia	SEPT POLARX5	LEIAR25.R3 LEIT
FROY	Fitzroy Crossing	Australia	SEPT POLARX5	LEIAR25.R3 LEIT
KUNU	Kununurra	Australia	SEPT POLARX5	JAV_RINGANT_DM SCIS
ABJA	Abuja	Nigeria	GNSS_GGR	RINT-8CH CETD
BJF1	Beijing	China	CETC-54GMR-4011	LEIAR25.R4 LEIT
BRCH	Braunschweig	Germany	CETC-54GMR-4011	LEIAR25.R4 LEIT
CLGY	Calgary	Canada	CETC-54GMR-4011	LEIAR25.R4 LEIT
KNDY	Kandy	Sri Lanka	CETC-54GMR-4011	GNSS-750 NONE
WUH1	Wuhan	China	CETC-54GMR-4011	LEIAR25.R4 LEIT
ZHON	Zhongshan Station	Antarctica	GNSS_GGR	LEIAR25.R4 LEIT
LIN6	Liaoning	China	Ture-CORS	LEIAR25.R4 LEIT

Precision orbit determination strategy

Three-month data from November 25, 2016 to February 25, 2017 collected by the aforementioned stations are used for precise orbit and clock determination in this study. However, due to the unstable performance of receivers, up to 5 stations have no data for several days, which affects the orbit and clock quality. During the selected period, 10 BeiDou satellites experience the eclipse period. Figure 2 shows the variations of the angle of the sun above the orbit plane (β angle) for BeiDou-2 IGSO and MEO satellites (top) as well as BeiDou-3e satellites (bottom), in which the gray bar indicates the region with a β angle between –4° and +4°, when the BeiDou-2 IGSO and MEO satellites switch to the ON orientation. Among those satellites, C11, C12, C33, and C34 are in the same orbit plane.

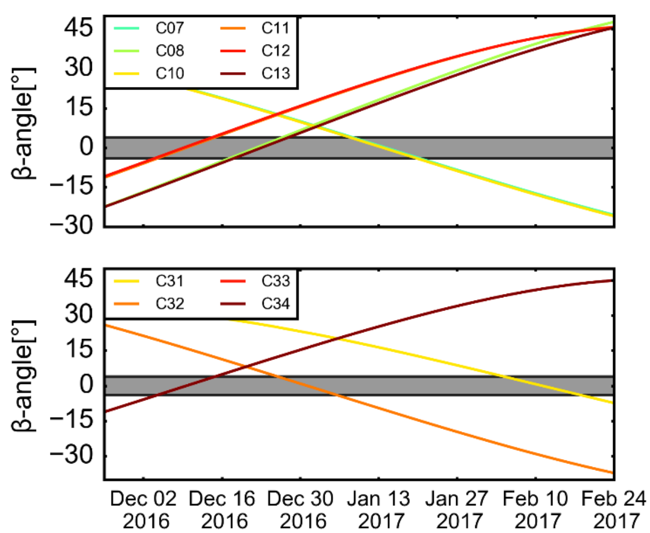

Fig. 2 Variations of the angle of the sun above the orbit plane (β angle) for BeiDou-2 IGSO and MEO satellites (top) as well as BeiDou-3e satellites (bottom). The gray bar indicates the region with a β angle between –4° and +4°, when the BeiDou-2 IGSO and MEO satellites switch to the ON orientation

To objectively compare BeiDou-2 and BeiDou-3e satellites, we determine again the orbits and clocks of BeiDou-2 with BeiDou-3e simultaneously using the 15 tracking stations. All data are processed by Position And Navigation Data Analyst (PANDA) software (Liu and Ge 2003) using a 2-step approach. In the first step, the WUM orbits, clocks, and earth orientation parameters from the IGS MGEX (Guo et al. 2015) are used for GPS/BeiDou-2 combined precise point positioning (PPP) to estimate the station coordinates, tropospheric zenith delays, and receiver clock offsets. The analysis by Guo et al (2017b) demonstrates that WUM Multi-GNSS products have the same quality as those from other IGS MGEX ACs, e.g., CODE, and GFZ. Also, SLR validation further indicates that the radial orbit accuracy for BeiDou MEO, IGSO, and GEO satellites is approximately 5 cm, 10 cm, and 50 cm respectively (Guo et al. 2017b). With this product, the obtained station coordinates repeatability reach to about 1cm in 3D. The estimated parameters from the first step are kept fixed in the second step. We use GPS/BeiDou-2 combined PPP instead of GPS only because of the poor quality of GPS data from some iGMAS stations. In the second step, the ionospheric-free combination of B1I and B3I observations are taken as input with initial orbits and clocks from broadcast ephemeris, because only the two backward-compatible signals can be tracked, as mentioned earlier. We apply a 10° cutoff elevation and elevation-dependent weighting for the observations under 30°. The satellite orbital parameters, satellite clock offsets, ambiguities, and inter system bias (ISB) are estimated. For the SRP model, a 5-parameter or 9-parameter ECOM model with a POD arc length from 2 to 5 d are applied to explore the effects of the SRP model and the POD arc length on orbit quality. In addition, an empirical constant acceleration parameter in the along-track direction with 1.0^{-10} m/s^2 constraint is estimated for each satellite, as done by Guo et al. (2015). The BeiDou-3e satellite geometry and orientation follow the conventions in Montenbruck et al. (2015) without considering yaw maneuvers, whereas the attitude model described in Guo et al. (2017a) is used for the BeiDou-2 satellites. The measurement and orbit dynamic models are summarized in Table 4, and Table 5 lists the BeiDou-3e phase center offset (PCO) values provided by the satellite manufacturers.

Table 4 Summary of precise orbit determination strategy

Observable	Undifferenced ionospheric-free code and phase combination of B1 and B3
Elevation angle cutoff	10°
Sampling rate	30 s
POD arc length	2, 3, 4, and 5 d
Weight	Elevation-dependent weighting for the observations under 30° according to 1/2 sin(E)
Initial standard deviations	2.0 m and 2.0 cm for raw code and phase
Phase center offset	BeiDou-2: estimated values (Guo 2014) BeiDou-3e: manufacturer values in Table 5
Satellite attitude model	Nominal YS model for BeiDou-3e satellites (Montenbruck et al. 2015) ON and YS for BeiDou-2 satellites (Guo et al. 2017a)
ISB	Estimated as arc-dependent constants for each receiver
Troposphere correction	Saastamoinen model for a priori dry and wet zenith delay model with estimation of wet delay

	global mapping function for dy and wet zenith delays
Tide correction	Solid earth tides, solid earth pole tides, and ocean tides as International Earth Rotation and Reference Systems Service (IERS) conventions, 2010
Geopotential	EGM2008 with 12 degrees and orders
SRP model	5-parameter or 9-parameter ECOM
Relativistic effects	IERS conventions 2010

Table 5. Manufacturer PCO values for BeiDou-3e satellites (unit: mm)

	X	Y	Z
C31	-50	0	800
C32	-110	-300	2,000
C33	-190	0	1,500
C34	-200	0	1,400

Orbit validation and analysis

To investigate the impacts of the POD arc length and the number of ECOM parameters on BeiDou-3e orbit quality, eight solutions are determined and validated by OBD and SLR. In this section, we also compared the BeiDou-2 and BeiDou-3e orbits based on the validation metrics.

Orbit boundary discontinuity

As an internal validation of orbit quality, OBD has been proposed by Griffiths and Ray (2009) using 3D position differences at a specific epoch to assess the orbit accuracy. Intrinsically, this approach is similar as OODs to validate the consistency of consecutive orbits from the same AC, but it does not give overly optimistic results since only one orbit at a specific epoch is used for comparison. In this study, the two POD arcs with only one common midnight epoch were selected. And the OBD was calculated by 3D position differences between the orbit at the last epoch of one arc and the orbit at the first epoch of another arc, as shown in Figure 3.

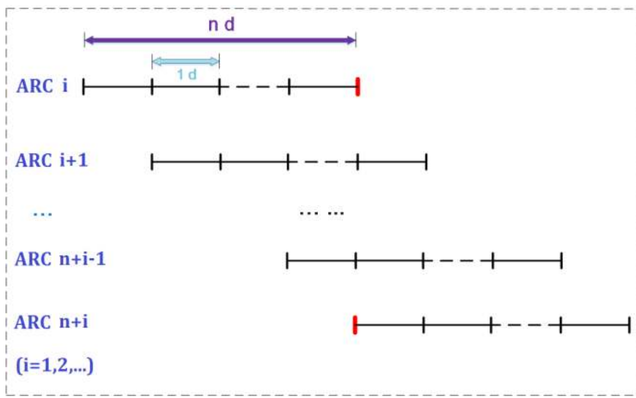

Fig. 3 Orbit arcs and orbit boundary discontinuity (OBD, red vertical bar). Two POD arcs (ARC *i* and ARC n+*i*) with only one common midnight epoch were selected. OBD is calculated by 3D position differences between the orbit at the last epoch of one arc (ARC *i*) and the orbit at the first epoch of another arc (ARC n+*i*).

Figure 4 shows the average 3D root mean square (RMS) values of each solution's OBDs for the respective group, classified according to the satellite generation and types. Because the BeiDou-2 IGSO and MEO satellites suffer a marked degeneration of orbit quality in the ON mode, the arcs containing the ON mode are excluded in the statistic for analysis. No GEO is available for BeiDou-3e satellites, so the comparison is focused on IGSO and MEO satellites in the following discussion.

In general, the average RMS of 5-parameter ECOM (ECOM5) solutions is lower than that of 9-parameter ECOM (ECOM9) solutions with the same POD arc length. For the ECOM5 model, the smallest RMS values are obtained for solutions with a 3-day arc length. However, for ECOM9 solutions the RMS values almost decrease with increasing POD arc length and reach the minimum when the POD arc length is 5 days, except for BeiDou-3e IGSO satellites, which has increasing OBD values for 4-day and 5-day arcs. This indicates that the full set of ECOM model probably require a greater POD arc length to smooth the orbit dynamics compared to reduced 5 parameters. In addition, it can be observed that the IGSO satellites show a larger average RMS than that of MEO satellites for both BeiDou-2 and BeiDou-3e, although the IGSO satellites have better tracking condition because of the Asia-Pacific regional station used in this study. This can be attributed to the larger nadir angle caused by the lower orbit altitude of MEO satellites, which makes the orbit dynamic parameters easier to separate from the other estimated parameters. In addition, the long POD arc may also have helped to smooth the orbit dynamic parameters of the MEO satellites and reduce the deficiency of the data coverage. In general, the best orbits for BeiDou satellites can be determined with the ECOM5 model and a 3-day POD arc.

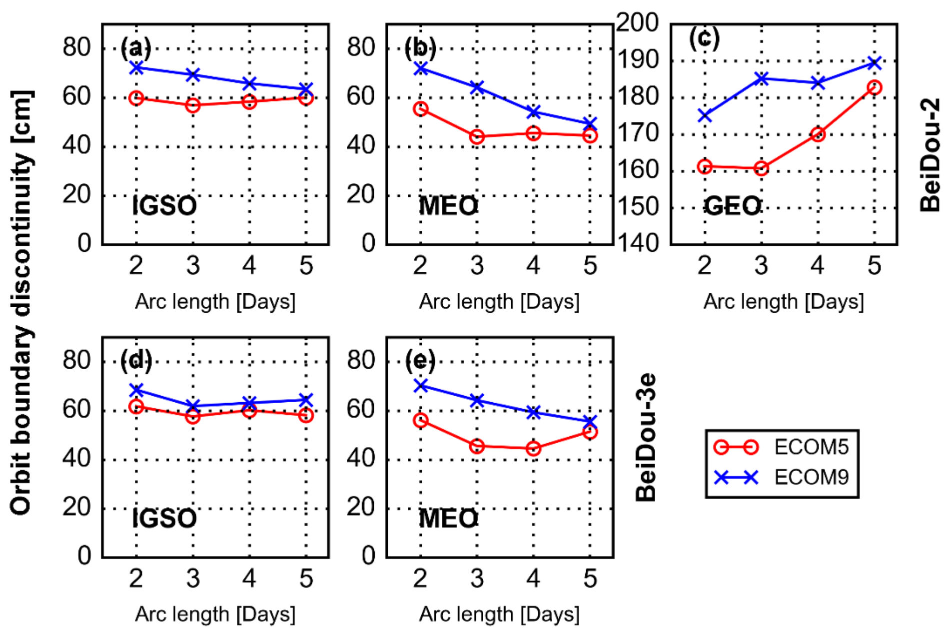

Fig. 4 Average 3D RMS values for OBDs for the respective groups classified according to the satellite generation and types. (a) BeiDou-2 IGSO, (b) BeiDou-2 MEO, (c) BeiDou-2 GEO, (d) BeiDou-3e IGSO, and (e) BeiDou-3e MEO. Five-parameter (ECOM5) and 9-parameter (ECOM9) ECOM solutions are indicated as red circles and blue crosses respectively

Furthermore, Figure 5 shows the average RMS values of OBDs for the best solutions, i.e., using the ECOM5 model with 3d data arcs, in along-track, cross-track, and radial directions. In general, the orbit consistency is approximately 30 to 50 cm, 10 to 30 cm, and 8 to 15 cm in along-track, cross-track, and radial directions respectively. Similar performance is achieved for BeiDou-2 and BeiDou-3e satellites.

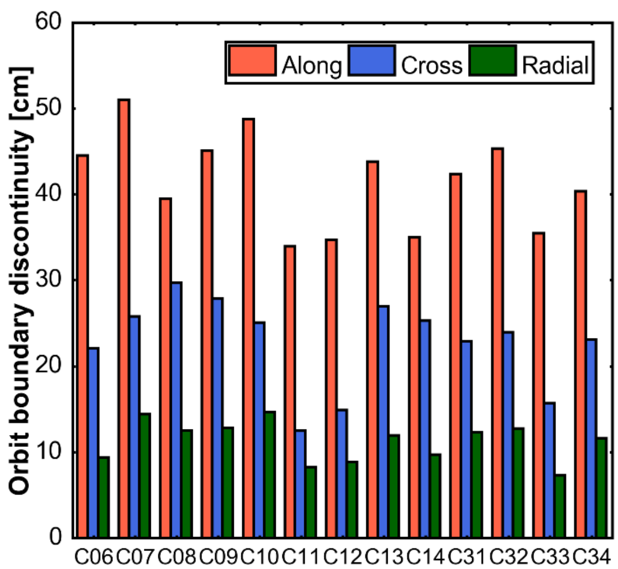

Fig. 5 Average RMS values of BeiDou-2 and BeiDou-3e OBDs for the solution determined with the ECOM5 model and a 3-d arc in along-track, cross-track, and radial directions

As mentioned earlier, the 4 MEO satellites (C11, C12, C33, and C34) are in the same orbit plane, however, different performances are observed for C33/C34 and C11/C12 as shown in Figure

5, particularly in the along-track direction. Studying the daily RMS of OBDs, marked performance differences are identified when the β angle is between –4° and +4°. Figure 6 shows the daily 3D and radial RMS for the best solution of C11 and C33 during DOY 339 to 349, 2016. It is clear that the orbit accuracy degenerates significantly after C11 switches its attitude mode, whereas C33 shows stable orbit performance. This indicates the different yaw attitude control mode used by BeiDou-3e satellites when the β angle is between –4° and +4°.

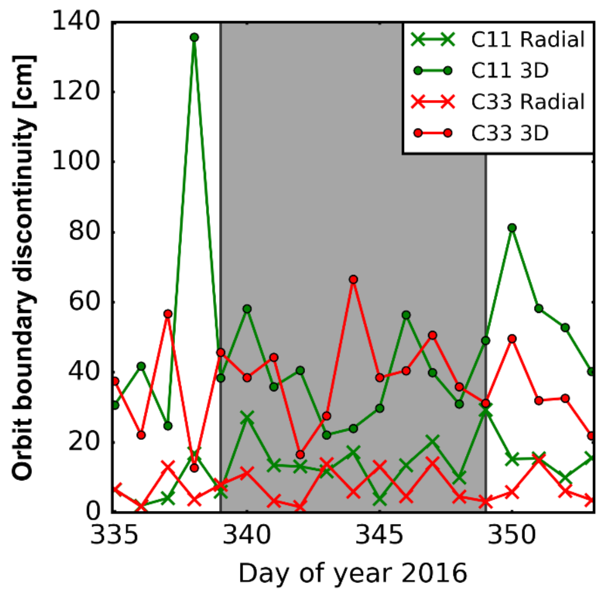

Fig. 6 Daily 3D and radial RMSs of OBDs for C11 and C33 during DOY 339 to 349, 2016, when C11 switches its attitude mode to ON mode indicated by grey block region.

Satellite laser ranging validation

SLR is used for independent validation of GNSS satellites' orbits mainly in the radial component. All launched BeiDou-3e satellites are equipped with laser retroreflectors (LRAs) and are tracked by the ILRS. The LRA coordinates in the satellite reference frame of BeiDou-3e satellites are listed in Table 6. In this study, only the first 24 h orbits in each solution are used for SLR validation. Table 7 summarizes the results. Residuals larger than 2.0 m, 1.0 m, and 1.0 m for GEO, IGSO, and MEO satellites, respectively, are treated as outliers and removed. After quality control, there are 845, 872, 714, 1130, 115, 120, and 119 NPs left for C01, C08, C10, C11, C32, C33, and C34 respectively. Unfortunately, no NPs are available for C31 during the study period. In contrast to BeiDou-2 satellites, there are fewer NPs for BeiDou-3e satellites, because the SLR tracking priority is quite low.

Table 6 LRA offsets for BeiDou-3e satellites (unit: m)

	X	Y	Z
C31	-0.973	0.184	0.637
C32	0.185	0.685	1.960
C33	0.612	-0.072	1.249
C34	0.612	-0.072	1.245

Table 7 RMS of SLR residuals for different BeiDou-2 and BeiDou-3e orbit solutions (unit: cm)

	Arc length (days)	C01	C08	C10	C11	C32	C33	C34
ECOM5	2	30.1	17.9	19.2	16.0	18.9	10.1	12.9
	3	31.6	17.2	18.9	14.3	17.1	9.8	10.5
	4	32.0	20.9	19.2	14.5	17.3	8.7	12.1
	5	32.6	23.1	19.7	14.5	18.7	10.2	12.0

ECOM9	2	33.8	32.8	32.9	43.0	44.3	14.4	18.7
	3	31.3	31.1	25.5	17.2	41.9	13.3	18.0
	4	31.7	29.2	23.2	15.0	29.7	11.1	14.2
	5	30.8	28.8	22.1	14.7	22.7	12.5	13.9

In general, from the SLR validation the same conclusion can be drawn as for OBDs: The ECOM5 solutions are superior to ECOM9 solutions with the same POD arc length, regardless of the type or generation of the BeiDou satellite. MEO satellites show better performance than that of IGSO satellites. As to the POD arc length, 3-day is the best for the ECOM5 model and 5-day for the ECOM9 model. Among all the solutions, the orbits determined with the ECOM5 model and a 3-day arc have the best performance. Similar orbit precision has been achieved for BeiDou-2 and BeiDou-3e IGSO satellites, whereas the BeiDou-3e MEO orbits show better performance than that of IGSOs as validation by OODs. The RMS value of SLR residuals for the best solution of BeiDou-3e C33 and C34 reaches to approximately 10 cm, although the eclipse season is also included.

To illustrate the results of our investigation into whether systematic error is induced by the deficiency of the SRP model in BeiDou-3e satellites, Figure 7 shows the SLR residuals of the best solution against the sun elongation angle (eps angle, the angle formed by earth–spacecraft–sun) for 2 IGSO (C08 and C32) and 2 MEO (C11 and C33) satellites. Although fewer NPs are available for C33, it can be seen that there is no systematic error in the SLR residuals, except a minor positive bias, this may be caused by the inaccuracy of LRA offsets listed in Table 5. Almost no any systematic error exists for C11. For the 2 IGSO satellites, a different pattern of SLR residuals can be observed. For C32, there is an obvious linear increasing trend in the SLR residuals that is not found for C10. This indicates that there are sun-elongation-angle-dependent systematic errors in C32 orbits, and reflects the deficiency of the ECOM SRP model for C32 POD. Similar errors have been identified for Galileo satellites (Montenbruck et al. 2015), hence an enhanced SRP model for C32 is required for further research.

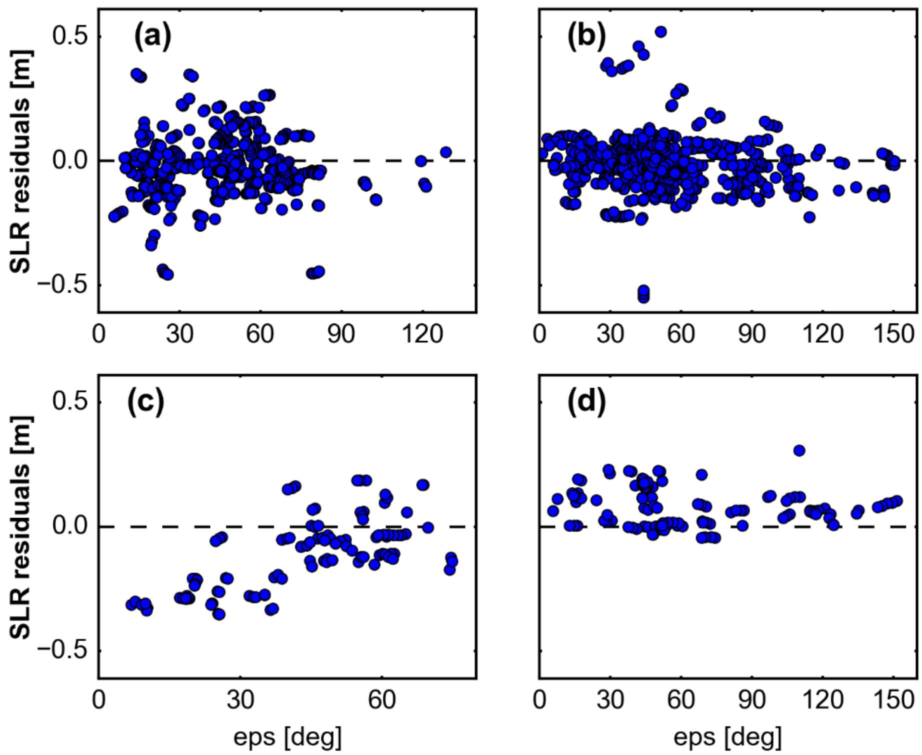

Fig. 7 SLR residuals against the Sun elongation angle (eps angle) for (a) C08, (b) C11, (c) C32, and (d) C33

Yaw attitude estimation

As shown above, different performances are shown by BeiDou-2 and BeiDou-3e satellites when the β angle is between –4° and +4°. In that case, the BeiDou-2 IGSO and MEO satellites switch to the ON orientation when yaw angles (Ψ defined by the angle between the instantaneous velocity and the body-fixed x-axis) are set to zero. We infer from this that different attitude control mode is adopted by BeiDou-2 and BeiDou-3e satellites. To validate this, we estimate the yaw attitude of BeiDou-3e IGSO and MEO satellites based on the reversed kinematic PPP approach (Dillsner et al. 2011). The parameters obtained from the POD steps, i.e., the station coordinates, receiver clock offset, ZTD values, orbits, and ISB and ambiguities, are fixed in the yaw attitude estimation. In that case, only the epoch-wise satellite PCO values and clock offsets are estimated as white noise. Concerning the few decimeters of orbit accuracy achieved, the yaw attitude cannot be estimated accurately for C31, because the PCO offset in X-axis is only 5 cm for C31.

Also, one may question whether it is possible to estimate the yaw attitude correctly from only 15 stations. Hence, we have estimated the C11 yaw profile to check that possibility and the accuracy achieved. Figure 8 demonstrates the estimated yaw profile and the number of stations used for estimation on DOY 341, 2016, when the satellite is in the ON mode with an approximately –2.84° β angle. In this case, the real yaw angles are 0°. However, because less than 2 stations are available for attitude estimation from the Asia-Pacific region (0 to 50,000 s), the estimated yaw angles equal to the nominal model angle instead of 0°. Once the satellite is above the Asia-Pacific region, starting at 50,000 s, more than 5 stations track the satellite and could be used for attitude estimation. In this case, the estimated yaw angles approach 0° with better than 10° accuracy. When there are more than 7 stations, a more stable yaw estimation is obtained. The result confirms that it is possible to estimate the yaw angle within approximately 10° even with a limited number of stations.

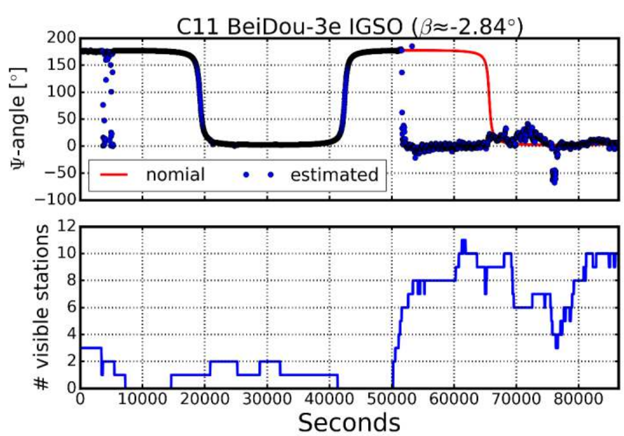

Fig. 8 C11 estimated yaw profile and the number of stations used on DOY 341, 2016 (−2.84° β angle). The red line in the top panel represents the nominal yaw angle, and the blue dots indicate the epoch-wise estimated yaw angle. The bottom panel indicates the number of stations used for attitude estimation in each epoch.

Figures 9 and 10 show the estimated yaw attitude profiles for C34 (MEO) and C32 (IGSO) when they are in deep eclipse season (−1.29° and 0.57° β angle for C34 and C32). In contrast with C11, the estimated yaw angles are almost identical to their nominal attitude and do not approach 0°. Similar phenomena are found for C33. For C32, the estimated yaw profile still obeys the nominal GNSS attitude. Hence, BeiDou-3e satellites do not use the ON mode in the eclipse season as BeiDou-2 IGSO and MEO satellites do.

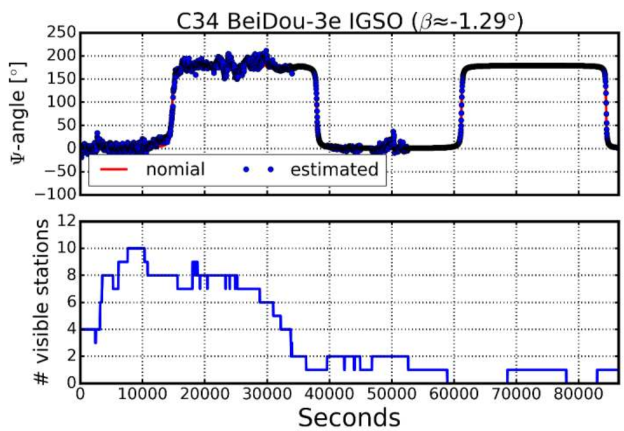

Fig. 9 C34 estimated yaw profile and the number of stations used on DOY 343, 2016 (−1.29° β angle). In the top panel, the red line represents nominal yaw angle, and the blue dots indicate the epoch-wise estimated yaw angle. The bottom panel indicates the number of stations used for attitude estimation in each epoch.

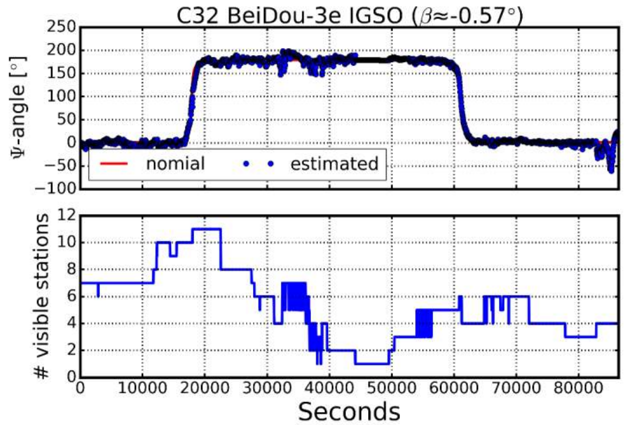

Fig. 10 C32 estimated yaw profile and the number of stations used on DOY 1, 2017 (−0.57° β angle). In the top panel, the red line represents nominal yaw angle, and the blue dots indicate the epoch-wise estimated yaw angle. The bottom panel indicates the number of stations used for attitude estimation in each epoch.

It could be argued that the inaccurate PCO values on the x- and y-axes contaminate the estimation of yaw attitudes. However, for the satellites with the mean antenna phase center located within the XZ plane, such as C31, C33, and C34, the X PCO values do not affect the yaw attitude estimation, as it is canceled when the yaw bias is estimated. For those with an antenna offset in the y-axis, the inaccurate X and Y PCOs actually result a yaw rotation with the angle between the inaccurate PCO vector and the true one in the XY plane. In this case, the angle will contaminate the estimation and show as a constant bias in the estimated yaw attitudes. However, the precision of the C32 X and Y PCO values listed in Table 4 is within 10 cm, which results in less than 1° angle biases. Considering that the yaw estimation accuracy is approximately 10°, the effect of inaccurate X and Y PCOs can be ignored.

To study the attitude control mechanism of BeiDou-3e IGSO and MEO satellites, we further investigate the estimated yaw attitudes. No eclipse-crossing maneuvers are identified, but maneuvers near the midnight point (orbit angle μ=0°) and noon point (μ=180°) are observed. Figures 11 and 12 show the yaw profiles during eclipse phases for C32 near the midnight and noon points respectively. It can be seen that both yaw attitude maneuvers show similar variations and patterns. The yaw attitudes are symmetric to the midnight or noon point and match the nominal attitude when the satellite is in the midnight or noon point. The yaw attitudes near the midnight and noon points are also investigated for the two MEO satellites C33 and C34, where similar variations are identified. With careful analysis of the yaw profiles, we find that the yaw attitude maneuvers occur when the β angle is between -3° and 3°. Considering the 10° accuracy for the estimated yaw attitude, we do not intend to establish the attitude model but leave it for further study when more tracking stations and accurate yaw estimates will be available.

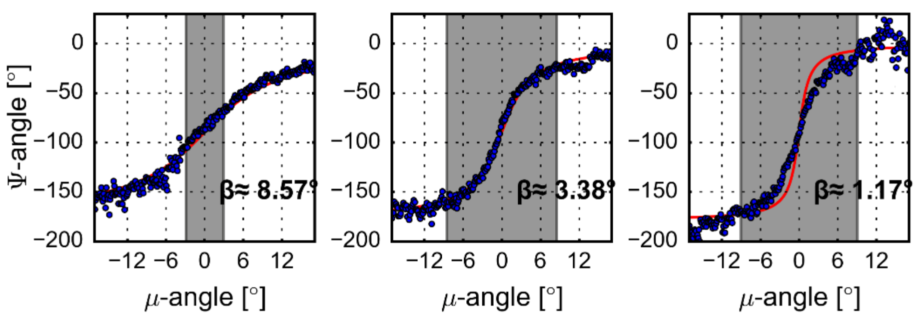

Fig. 11 Estimated (blue) and nominal (red) yaw angles of BeiDou-3e C32 passing the Earth's shadow (gray area) under different β angles

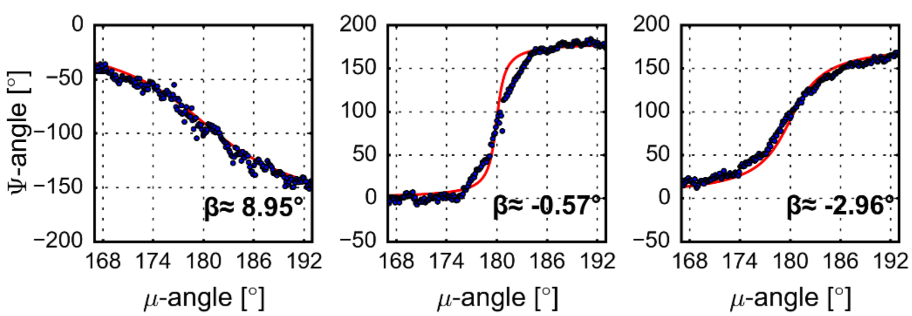

Fig. 12 Estimated (blue) and nominal (red) yaw angles of BeiDou-3e C32 passing the region around orbit noon under different β angles

Clock performance

The stability of onboard satellite clocks will affect the accuracy of the predicted clock offsets, as well as the performance of the PNT service. Therefore, highly stability atomic clocks are required. Unlike the BeiDou-2 satellites, which are equipped with rubidium clocks from manufacturers in Switzerland and China, the primary frequency standards of BeiDou-3e satellites are based on PHMs, and the improved Chinese RAFSs serve as the backup.

Power spectrum analysis of Beidou satellite clocks

Since the satellite clocks are highly correlated with the orbits, particularly in the radial, the orbit errors will be leaked to clock offsets. Hence, there may be some orbit mis-modeling errors in the apparent clock variations. In order to quantify the correlation between the orbit and clocks, a power spectrum analysis of satellite clocks has been performed. The Fourier transform method is used to identify the potential periodicity of satellite clocks. Non-equispaced or non-uniform fast Fourier transforms (NUFFT) are used in this study to avoid the impact of data gaps on the analysis result. Since the biggest influences caused by the relativistic J_2 contribution (Kouba 2014) is 33 ps and 67 ps for IGSO and MEO satellites respectively, the systematic variation is not corrected. The detrended daily data are stacked for NUFFT.

Figure 13 shows the amplitude spectrum of IGSO (top) and MEO (bottom) satellite clocks. For BeiDou-2 and BeiDou-3e IGSO satellites, the 12 h (two cycles per revolution or cpr) and 24 h (1 cpr) harmonics are significant, particularly for C06 satellites. There are noticeable signals in 8 h (3 cpr) and 6 h (4 cpr). Then, with increasing number of cpr, the amplitudes decrease gradually. Similar results have been identified in Wang et al (2016). However, a broad spectrum within 2 cpr is observed for MEO satellites, making it hard to identify the periodicity of satellite clocks. Compared with those obtained in Wang et al (2016), which shows clear periodic signals in BeiDou-2 MEO satellite clocks, this may be caused by the limitation of reginal stations used to track the MEO satellites as well as relative short period used for analysis.

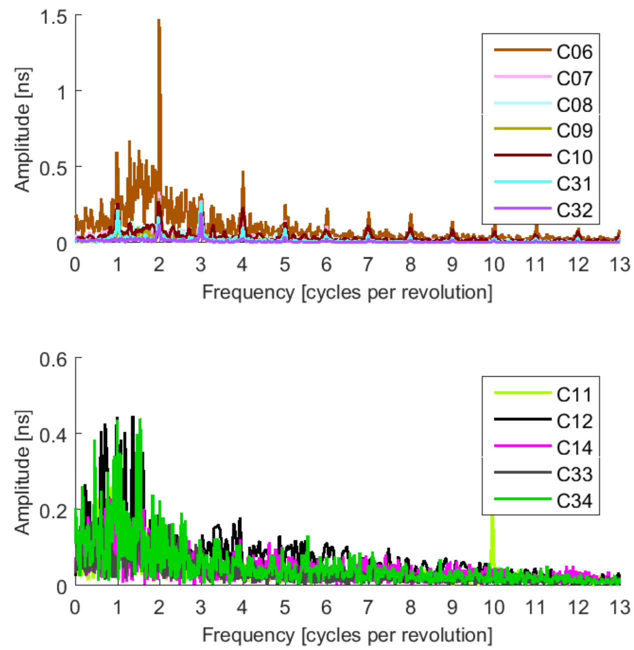

Fig. 13 Amplitude spectrum of BeDou-2 and BeiDou-3e IGSO (top) and MEO (bottom) satellite clocks

These periodic cpr signals of satellite clocks can be caused by the orbit errors. Hence, in order to make reliable assessment of the background stability of BeiDou onboard frequency standards, the following model is used to fit the periodic signals at 1-, 2-, 3, and 4-cpr of satellite clocks, as those amplitudes are most pronounced as shown in Figure 13,

$$f(t) = (a + b \cdot t) + \sum_{i=1}^{4} \left[c_i \cdot \cos(i\mu) + s_i \cdot \sin(i\mu) \right] \quad (1)$$

where a, b, c_i, and s_i are the parameters to be fitted, $f(x)$ is the fitted signals in clocks. The obtained sub-daily signals will be removed from clock offsets.

Frequency stability analysis of Beidou satellite clocks

To assess the performance of the BeiDou onboard clocks, MADEVs computed from the 30 s clock estimates are shown in Figure 14. Before the computation, the outliers, clock jumps, frequency steps and also the sub-daily periodics in the satellite clock offsets obtained above are carefully investigated and removed. In general, the BeiDou onboard clocks are affected by phase flicker noises in the short period (30 s to 60 s) and by frequency white noise in the medium period (60 s to 2,000 s). For an integration time beyond 2,000 s, both of BeiDou-2 and BeiDou-3e MEO satellites display complex, non-power-law behavior, and a "bump" appears at approximately 10,000 s. These may be attributed to the broad spectrum within 2 cpr signals in the clock offsets shown in the Fig. 3. Considering there are no such behaviors for BeiDou-2 MEO satellites in Wang et al (2016), the variations are unconvinced. Hence, in this study, only the MADEVs of IGSO satellites are used to assess the BeiDou-3e onboard clock performance.

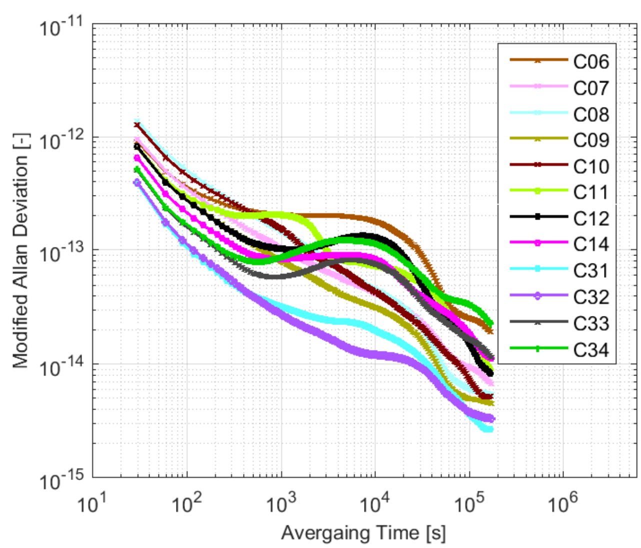

Fig. 14 Frequency stability analysis result after removing the sub-daily periodics

For BeiDou-2 IGSO satellites, at an integration time of 1,000 s, the MADEV values for all satellites are approximately $1-3\times10^{-13}$ and vary approximately as $3\times10^{-12}\cdot(\tau/s)^{-1/2}$. Similar results are shown in Montenbruck et al. (2017). However, we find a slightly worse performance in this study, because fewer stations are used for satellite clock determination. For BeiDou-3e IGSO satellites, the frequency stability of onboard clocks is better than that of the BeiDou-2, the MADEV value is approximately $2\text{-}4\times10^{-14}$ at an integration time of 1,000 s, which is better than that of BeiDou-2 IGSO satellites by almost a factor of 10. These results confirm that better RAFSs and PHMs are used by BeiDou-3e satellites. In addition, compared to the latest type of RAFSs employed onboard the GPS IIF satellites, as well as the PHMs used onboard the Galileo satellites, which exhibit stabilities of $1-2\times10^{-12}\cdot(\tau/s)^{-1/2}$ (Montenbruck et al. 2017), similar performance is achieved for BeiDou-3e onboard frequency standards, as shown by C31 and C32.

Summary and discussion

In this study, 3 months of data from GA, iGMAS, and BETN are used for orbit and clock determination of BeiDou-2 and BeiDou-3e satellites based on the ECOM SRP model. For comparison, eight solutions are determined with different numbers of ECOM SRP parameters as well as POD arc lengths. We determine that the best solution is obtained for BeiDou-3e satellites with 5-parameter ECOM and a 3-day POD arc. The 3D orbit consistency is 50 to 70 cm, and 40 to 60 cm for IGSO and MEO satellites, and better than 15 cm in teh radial. Satellite laser ranging (SLR) validation obtains to about 17 cm and 10 cm for BeiDou-3e IGSO and MEO satellites. However, sun-elongation-angle-dependent orbit errors are identified in the SLR residuals of the BeiDou-3e IGSO C32 satellite, which indicates the deficiency of the ECOM model for BeiDou-3e IGSO satellites and requires further study.

Compared with the orbits of BeiDou-2 and BeiDou-3e, similar quality of orbit consistency indicated by OBD is achieved, whereas BeiDou-3e show slightly better SLR validation, particularly for MEO satellites. Importantly, no orbit accuracy degeneration is observed for BeiDou-3e satellites when the β angle is between –4° and +4°. In an analysis of the yaw attitude, we find that BeiDou-3e satellites do not use the ON mode, but experience midnight and noon point maneuvers when the β angle is approximately between –3° and +3°. BeiDou-3e IGSO satellites show better performance than that of BeiDou-2 IGSO satellites, and can be compared to the latest type of RAFSs employed onboard the GPS IIF satellites as well as the PHMs used onboard the Galileo satellites with stability of $1-2\times10^{-12}\cdot(\tau/s)^{-1/2}$. A larger tracking network, in particular a global network, is essential for further improvement of BeiDou-3 orbits, clocks, and yaw attitude estimation. This will definitely change soon with the rapid development of Multi-GNSS activities.

Acknowledgment

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Author Biographies

Qile Zhao is a professor at GNSS Research Center of Wuhan University. He received his Ph.D. degree at Wuhan University in 2004. In 2006–2007, as a postdoctoral fellow, he did his postdoctoral program in DEOS, Delft University of Technology, the Netherlands. His current research interests are precise orbit determination of GNSS and low earth orbiting satellites, and high-precision positioning using GPS, Galileo and BDS systems.

Chen Wang is a Ph.D. student at GNSS Research Center, Wuhan University currently. He received his bachelor degree at College of Geology Engineering and Geomatics, Chang'an University in 2014. His research focuses on GNSS data processing and precise orbit determination.

Jing Guo is a postdoctoral researcher at GNSS Research Center of Wuhan University. He received his bachelor, master and doctor degrees at Wuhan University in 2009, 2011 and 2014, respectively. Currently, he works on GNSS data processing, particularly the precise orbit determination for multi- GNSS satellites, and is also responsible for the routine data processing of MGEX and iGMAS at Wuhan University.

Bin Wang is currently a postdoctoral researcher at the Shanghai Astronomy Observatory, China Academy of Science. He received his Master's and PhD degree from Wuhan University in 2011 and 2015. His current research focus is on characteristic analysis and prediction of GNSS satellite clock.

Jingnan Liu graduated from the former Wuhan College of Surveying and Mapping in 1967 and received his master's degree in 1982. He was elected Academician of the Chinese Academy of Engineering in 1999. Since 1998, he has been in charge of the National Engineering Research Center for Satellite Positioning System. He has been a member of the Science and Technology Commit- tee, Ministry of Education of China in 1997–2009 and as an editorial board member of GPS Solutions in 1998–2000. He is currently an executive member of the council, Chinese Society for Geodesy, Photogrammetry and Cartography; the editorial board member of GPS World; and the coordinator of IGS.