Chapter 8
Accuracy Analyses of Precise Orbit Determination and Timing for COMPASS/Beidou-2 4GEO/5IGSO/4MEO Constellation

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Abstract Up to the end of October 2012, 14 COMPASS/Beidou-2 regional satellite navigation satellites are fully operational. Different with Global Positioning System (GPS), the space segment of COMPASS consists of Geostationary Earth Orbit (GEO) satellites, Inclined Geosynchronous Satellite Orbit (IGSO) satellites and Medium Earth Orbit (MEO) satellites, and navigation information is provided by monitoring stations limited in regional area. Besides, attitude control mode is different for each type of satellites. The predictability of satellite attitude will make broadcast ephemeris precisely predicted. In this study, satellite telemetry data are compared with nominal attitude to assess the accuracy of satellite attitude prediction. Experiments show that the accuracy is different for each type satellites, and overall prediction accuracy is better than 1°. The analyses of pseudo-range multipath noise for receivers from different manufacturers show that the random noise characteristics is significantly for the US and European manufacturers' receivers, and the magnitude is larger than domestic manufacturers', but strong daily repeatability of multipath noise characteristics is displayed for domestic receivers. The accuracy of precision orbit determination (OD) for COMPASS using regional and global monitoring stations data are compared to evaluate the impact of monitoring stations' distribution on the accuracy of satellite OD. Satellite Leaser Range (SLR) residuals are adopted to assess the satellite orbit accuracy in station line-of-sight direction. The results show that the accuracy of satellite orbit overlap is about 0.2, 1.2 and 0.6 m in R/T/N direction for regional monitor network, the accuracy for MEO overlap is slightly worse than two other type satellites, and the SLR residual is better than 1 m. The two-way satellite time

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J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2013 Proceedings*, Lecture Notes in Electrical Engineering 245,
DOI: 10.1007/978-3-642-37407-4_8, © Springer-Verlag Berlin Heidelberg 2013

frequency transfer (TWSTFT) observations are adopted to evaluate the accuracy of satellite clock error estimations. Experiments show that the standard deviation of satellite clock estimations solved by OD is about 1.4 ns. Global monitoring stations can increase the depth of coverage for MEO satellites, and the accuracy of clock estimations may be improved by about 0.6 ns. The observations from multi-constellation GNSS receiver are adopted to realize the system timing service. The results show that the stability of time system for COMPASS is consistent with GPS, the standard deviation of comparison for COMPASS and GPS precise timing is about 1.5 ns, the real time timing is about 3 ns.

Keywords COMPASS/Beidou-2 · Satellite attitude · Multi-path noise · POD · Timing

8.1 Introduction

As of October 25, 2012, a total of 16 Chinese COMPASS/Beidou-2 regional navigation system satellites has been launched [1]. Now 14 satellites are fully operational except 2 test satellites. Similar with other Global Navigation Satellite Systems (GNSS), COMPASS transmits L-band ranging signal and provides real-time broadcast ephemeris information to global area to provide real-time navigation positioning and timing (PNT) services.

Different with other GNSS, the space segment consists of GEO, IGSO and MEO satellites. The existent of GEO satellites increase correlation of orbit determination (OD) estimations, which may decrease the OD accuracy and stability. Since the monitoring stations limited to the territory of China area, and all stations located in the same side of the GEO satellite orbital plane, we rise to the challenge of mix constellation precise orbit determination. Furthermore, MEO satellite orbit can't be covered by regional tracking network. The coverage of MEO is less than 50 %, which may decrease the accuracy of MEO orbit estimations. Last, different attitude control modes are applied to each type COMPASS satellites. The satellite antenna phase center correction mode should be established accordingly in OD, positioning and timing processing.

Currently, many researchers had carried out studies for COMPASS OD and positioning. Reference [2] analyzed the code and carrier phase noise and satellite clock character for 4GEO/5IGSO constellation. The baseline vector is recovered with an accuracy of 2, 4, and 9 mm in the east, north, and up directions relative to the mean value of a GPS-based solution. Considering the highly correlation between orbital and satellite clock estimations, Ref. [3] proposed a new method for orbit accuracy assessment by two-way satellite time frequency transfer (TWSTFT) measurements. Reference [4] found that solve empirical acceleration estimations may increase the correlation of solar radiation pressure estimations and decrease orbit accuracy for 2GEO/1IGSO constellation. Reference [5] adopting regional tracking network assessed orbit accuracy and post-time and real-time positioning error. Precise Point Positioning (PPP) accuracy is about 5 and 10 cm in horizontal and vertical direction. Within Chinese regional area, three-dimensional accuracy for open and authorized service positioning is about 5 and 3 m in terms of Root-Mean-Square (RMS). Reference [6] achieved precise OD and Real-time kinematic (RTK) positioning for 2GEO/3IGSO constellation using Beidou Experimental Tracking Stations (BETS) which lay in the Asia–Pacific region and established by Wuhan University since early 2011. The overlap accuracy is 10 cm in orbital radial direction. The static PPP accuracy is about centimeter-level, relative positioning accuracy is about millimeter-level for short baseline and RTK accuracy is about 4 m.

This study assesses the prediction accuracy of satellite nominal attitude comparing with satellite telemetry data, and provides satellite antenna phase center correction model for each type satellites. The pseudo-range noise characteristics of different manufacturers' receiver are compared. Tracking network distribution impact on OD accuracy is assessed for 4GEO/5IGSO/4MEO constellation. Satellite Laser Ranging data are adopted to evaluate orbit accuracy and verified the feasibility of orbit accuracy assessment method proposed in Ref. [3]. Multi-constellation GNSS receiver data are adopted to compare COMPASS precise and real-time timing accuracy with GPS timing service.

8.2 Algorithms

8.2.1 Satellite Attitude

Satellite attitude describes the relationship between satellite body-fix coordinate system and satellite orbit coordinate system. Define satellite mass center as the origin, satellite motion direction as X-axis, orbital plane normal direction as Y-axis, and Z-axis orthogonal to the XOY plane. The attitude angle of rotation about the X/Y/Z axis is called roll, pitch and yaw angle respectively.

Different attitude control modes are utilized for COMPASS satellites. Orbit-normal mode is applied to GEO satellites, which define satellite to center of the earth direction as Z-axis, the direction orthogonal to satellite position and velocity plan as Y-axis, and X-axis orthogonal to YOZ plane. Yaw-steering mode is applied to IGSO/MEO satellites, which define the same Z-axis as orbit-normal mode, Y-axis perpendicular to the plane of sun-earth-satellite, and X-axis orthogonal to YOZ plane. Accordingly, satellite antenna phase center should be established for each type satellite in OD processing [7]. COMPASS provides the satellite telemetry measurements. We compare it with nominal attitude prediction to evaluate the accuracy of attitude prediction. Figure 8.1 shows the yaw angel prediction errors time series for each type satellite. Since yaw angle is zero for GEO, only yaw angle measurements are figured out in first row. The bottom left two sub graphs show IGSO/MEO yaw angle time series, and the right two graphs

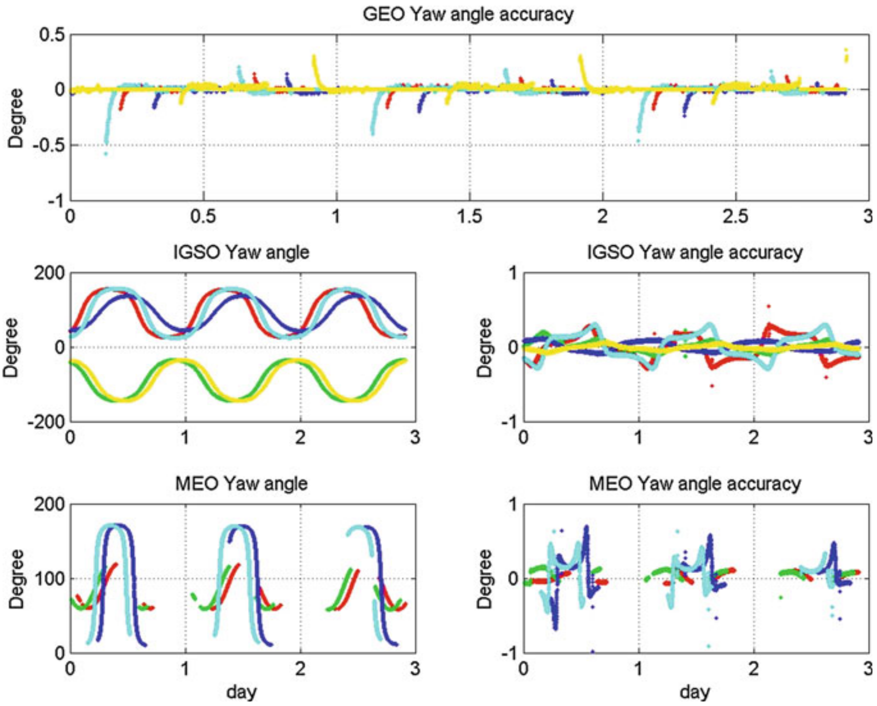

Fig. 8.1 Satellite yaw angle prediction errors time series. Different colors represent different satellites. The *top* row satellite yaw angle prediction errors. The *bottom left* two sub graphs show IGSO/MEO yaw angle time series, the *right* two graphs show IGSO/MEO yaw angle prediction errors. Unit is angle degree

show IGSO/MEO yaw angle prediction errors. Different colors represent different satellites.

Figure 8.1 shows that the accuracy of yaw angle prediction are better than 0.5°, 0.5° and 1° for GEO/IGSO/MEO respectively. As shown in telemetry measurements, roll and pitch angle are close to zero, which are in accord with nominal attitude. Consequently, only yaw angle should be considered in satellite antenna phase center correction model. The expression can be written as:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = R_{ciscts} \cdot \begin{pmatrix} \bar{e}_x & \bar{e}_y & \bar{e}_z \end{pmatrix} \cdot \begin{pmatrix} x_{phs} \\ y_{phs} \\ z_{phs} \end{pmatrix}, \quad d\rho_{phs} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}^T \cdot \frac{\bar{r}_{sta} - \bar{r}}{|\bar{r}_{sta} - \bar{r}|} \tag{8.1}$$

where R_{ciscts} is rotation matrix between Conventional inertial system (CIS) and Conventional inertial system (CTS), $\bar{r}_{sta}$ is location of receiver, $d\rho_{phs}$ is satellite antenna center phase correction in line-of-sight direction.

For GEO satellites:

$$\bar{e}_z = -\frac{\bar{r}}{|\bar{r}|}, \ \bar{e}_y = \bar{e}_z \times \frac{\bar{v}}{|\bar{v}|}, \ \bar{e}_x = \bar{e}_y \times \bar{e}_z \tag{8.2}$$

For IGSO/MEO satellites:

$$\bar{e}_z = -\frac{\bar{r}}{|\bar{r}|}, \ \bar{e}_y = \bar{e}_z \times \frac{\bar{r}_{sun} - \bar{r}}{|\bar{r}_{sun} - \bar{r}|}, \ \bar{e}_x = \bar{e}_y \times \bar{e}_z \tag{8.3}$$

Where $\bar{r}$, $\bar{v}$ and $\bar{r}_{sun}$ are satellite position, velocity and sun position vector in CIS respectively.

Antenna phase center of COMPASS satellites relative to the mass center is mainly in Z direction, the direction from satellite to earth center. The phase center correction is meter level for ground receiver, while the nominal attitude prediction error impact on antenna correction is less 1 mm. So the nominal attitude could be used in antenna phase center correction model. Due to length limitation, corrections for are not listed.

8.2.2 Orbit Determination and Timing

In this paper, the multi-satellite orbit determination (MPOD) strategy is adopted. The estimations are orbital parameters (initial orbital elements, solar radiation pressure parameters and empirical acceleration parameters) for all satellites, receiver zenith delay and satellite and receiver clock errors for each epoch. Limited by the regional monitoring network distribution, 3 day arc with 60 s sampling pseudo-range and carrier phase ionospheric free combinations are adopted. See Ref. [2, 5] for details.

Known satellite orbit and clock errors information, receiver location and clock errors could be estimated, and simultaneously system positioning and timing service is realized. Positioning accuracy is discussed in Ref. [5], only timing accuracy is shown in this study.

Considering the correlation of receiver position and clock errors estimation, we fix receiver position and get receiver clock errors by averaging ranging residual of all visible satellite. Receiver clock errors can be written as:

$$Clk_{sta}(i) = \frac{1}{n}\sum\nolimits_{1}^{n} oc_{sta}^{j}(i) \tag{8.4}$$

Where $Clk_{sta}(i)$ is the receiver clock in epoch i, $oc_{sta}^{j}(i)$ is ranging residual from satellite j to receiver in epoch i, which can be calculated using satellite and receiver position, satellite clock error and systemic error correction models [8], n is the number of visible satellite.

Depending on the accuracy of ephemeris, system timing could be divided into precise and real-time service. Post-processing precise orbit and precise satellite clock errors are used for precise timing, and broadcast ephemeris for real-time service. Multi-constellation GNSS receiver observations are adopted to get receiver clock errors in GPS and COMPASS system. Comparing COMPASS precise receiver clock errors with GPS precise clock errors to evaluate COMPASS precise timing accuracy, and comparing real-time clock errors estimations for real-time timing accuracy.

8.3 Results

8.3.1 Observation Noise

Reference [9] shows that pseudo-range measurements are seriously affected by multi-path noise for COMPASS, especially for GEO satellites. To analyze pseudo-range multipath noise, differences between pseudo-range and carrier phase B1I/B2I ionospheric free combinations (PC-LC) are figured out. These differences include carrier phase ambiguity, dual-frequency pseudo-range and carrier phase observation noise and multi-path noise. 7 receiver made by domestic manufacturers which are located within China territory and 12 receiver made by US and European manufacturers which are located abroad are compared in this study. Foreign manufacturers' receiver and antenna type are listed in Table 8.1.

PC-LC time series for Beijing and Curtin are shown in Fig. 8.2. The noise of Beijing (domestic manufacturer) shows multi-path characteristic obviously. The daily repeatability feature is significant for GEO satellites. IGSO/MEO also show daily repeatability and observation white noise decrease when satellites are tracked by receiver. Curtin receiver (TRIMBLE NETR9) shows white noise characteristic, and the magnitude of noise is larger than Beijing receiver. It should be noted that both PC-LC time series are combined by original observation. GEO PC-LC RMS for Beijing is 0.3 m, while for Curtin is 1.3 m. The average of 3 day arc PC-LC RMS for domestic receivers is about 0.7, 0.7 and 0.8 m for GEO/IGSO/MEO satellites respectively, and 1.1, 1.5 and 1.4 m for other receiver.

Draw PC-LC series for IGSO/MEO satellites with observation elevation angle in Fig. 8.3. The left four sub graphs represent domestic manufacturer receivers, the right represent foreign receiver. Different colors represent different located receiver. Comparing low elevation noise in the two columns, both type receivers show the noise about 10 m. With elevation angle increase, the PC-LC noise

Table 8.1 Foreign manufacturers' receiver and antenna type

Site ID	Receiver type	Antenna type	Site ID	Receiver type	Antenna type
BRST	TRIMBLE NETR9	TRM57971.00	MAR7	TRIMBLE NETR9	LEIAR25.R3
CUT0	TRIMBLE NETR9	TRM59800.00	ONS1	TRIMBLE NETR9	LEIAR25.R3
DLF1	TRIMBLE NETR9	LEIAR25.R3	REUN	TRIMBLE NETR9	TRM55971.00
GRAC	TRIMBLE NETR9	TRM55971.00	UNB3	TRIMBLE NETR9	TRM57971.00
KIR8	TRIMBLE NETR9	LEIAR25.R3	UNBS	SEPT POLARXS	TRM55971.00
LMMF	TRIMBLE NETR9	TRM55971.00	USN4	SEPT POLARX4TR	AOAD/M_T

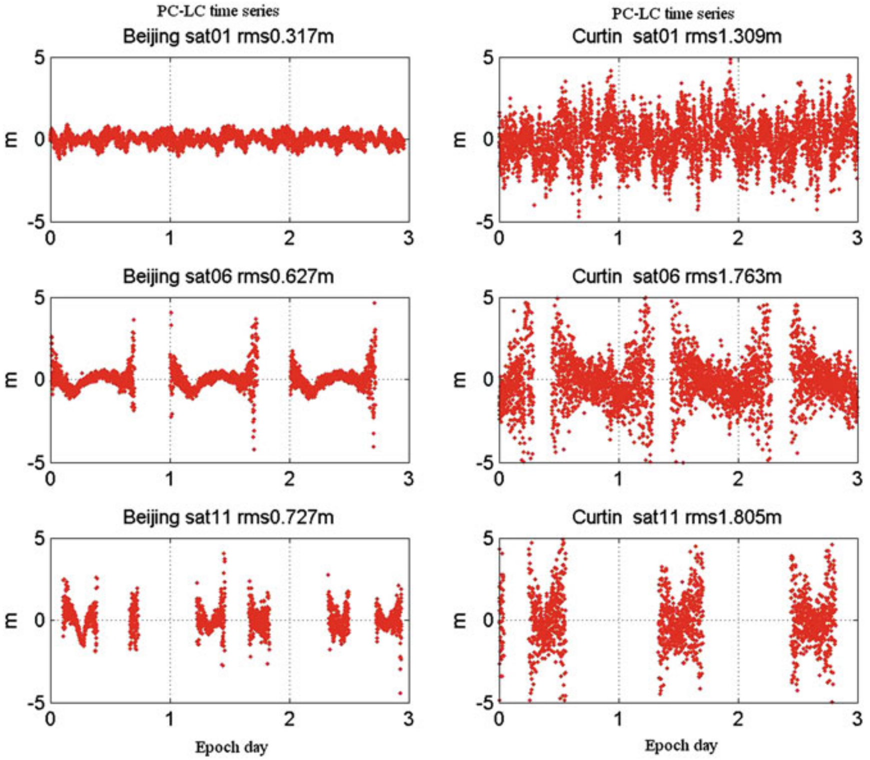

Fig. 8.2 PC-LC time series for Beijing and Curtin receiver. The *top*/*middle*/*bottom* rows represent GEO/IGSO/MEO respectively. *Left* three sub graphs represent PC-LC for Beijing and *right* for Curtin station

decrease dramatically for domestic manufacturer receiver, while slowly for foreign receivers.

8.3.2 Orbit Accuracy

Adopting regional monitor network dataset from Nov. 13th 2012 to 19th, 4GEO/5IGSO/4MEO constellation satellite orbital parameters are determined. Table 8.2 shows MPOD residual and 24 h overlap RMS in orbital radial (R), along-track (T) and orbital normal (N) direction. SAT01-05 are GEO, 06-10 are IGSO and 11–14 are MEO satellites. Pseudo-range residual is about 80 cm, and carrier phase is about 0.8 cm. The residuals differ for each type satellites, GEO residual is slightly larger than two other type satellites. Compare two 3 day arc with 24 h overlapped, three-dimension error is about meter level, GEO orbital R/T/N error are 0.2, 1.8 and 0.3 m respectively. IGSO orbital error in T direction is less than GEO, and

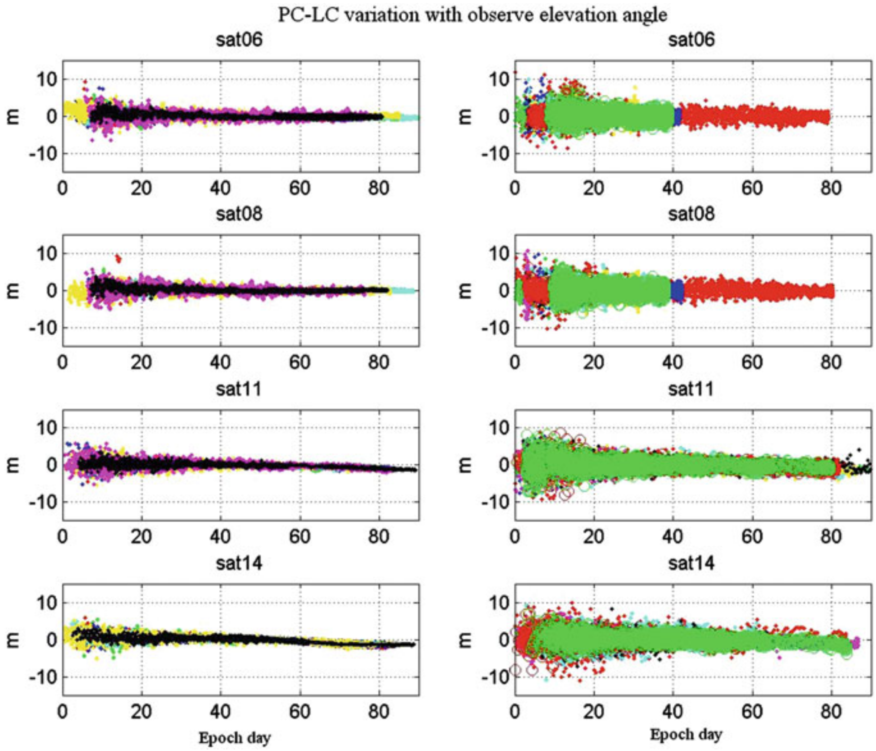

Fig. 8.3 PC-LC variation with observe elevation angle. The *top* two rows represent IGSO, *bottom* two represent MEO, *left* sub graphs are domestic and *right* are foreign receivers. *X-axis* is elevation (unit: degree), *Y-axis* is PC-LC (unit: m). Different colors represent different receivers

Table 8.2 MPOD overlap error and MPOD residual

SATID	dR/m	dT/m	dN/m	PC/cm	LC/cm
01	0.101	2.305	0.230	96.14	0.57
03	0.123	1.245	0.311	66.90	0.59
04	0.214	3.550	0.100	85.35	0.61
05	0.348	0.338	0.689	92.24	0.76
06	0.129	0.763	0.527	63.22	0.68
07	0.262	0.889	0.951	66.30	0.69
08	0.124	0.571	0.459	57.08	0.70
09	0.147	0.807	0.487	58.15	0.63
10	0.264	1.266	1.009	58.65	0.62
11	0.313	0.656	0.970	78.11	0.88
12	0.305	1.035	0.848	85.84	0.79
13	0.493	1.435	0.397	76.37	0.85
14	0.232	1.110	0.364	87.47	0.87

about 0.2, 0.8 and 0.7 m in three directions. MEO orbital error in R direction is larger than GEO and IGSO, about 0.3 m. T/N errors are 1 and 0.6 m.

SLR data are adopted to evaluate the orbit accuracy in station line-of-sight direction. Nov. 13th to 15th residual RMS is about 0.2 m for SAT08, and 0.9 m for SAT10.

8.3.3 Satellite Clock Errors Accuracy

According to Ref. [5], TWSTFT measurements can be used to assess orbital errors. Table 8.3 shows the RMS of satellite clock difference between MPOD estimations and the TWSTFT measurements. Except SAT04 whose RMS is about 3 ns, other three GEO RMS is about 1 ns, IGSO/MEO accuracy is about 1.4 ns.

Comparing SLR residual and clock errors difference obtained above in Fig. 8.4. The red lines represent clock errors difference and blue lines represent SLR residual. Three rows mean three arcs. Figure 8.4 shows that the two time series have similar variation trend.

Comparing orbital overlap time series with clock estimations obtained by two MPOD, shown in Fig. 8.5. Orbital difference in R/T/N direction is shown as red, green and blue line, and clock difference as light blue line. Three rows represent three type satellites. Figure 8.5 shows that the clock difference is highly correlated with orbital difference in R direction, especially for GEO and IGSO satellites. Beside, the differences in T/N direction impact the average of clock difference. Considering the high correlation between satellite orbital error in R direction and clock error estimations, we could assess orbit accuracy by comparing satellite clock estimations with TWSTFT observations.

8.3.4 Tracking Network Distribution Impact on OD Accuracy

As analysis in Sect. 8.3.2, regional tracking network can not cover MEO orbit arc, orbital overlap error for MEO is less than GEO/IGSO. To assess network

Table 8.3 Satellite clock errors difference RMS (Unit : ns)

SATID	RMS	SATID	RMS
01	1.385	09	1.555
03	1.090	10	1.799
04	2.965	11	1.021
05	0.903	12	0.842
06	1.196	13	1.887
07	1.491	14	1.265
08	1.192		

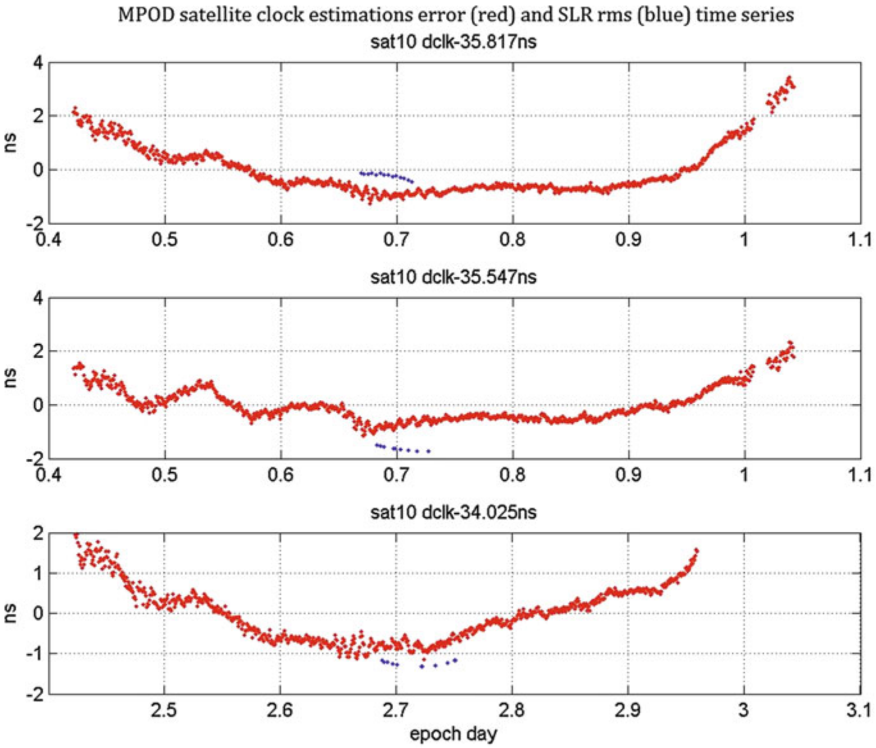

Fig. 8.4 SLR residual and clock errors difference time series. The *red lines* represent clock errors difference and *blue lines* represent SLR residual

distribution impact on OD accuracy, 12 IGS multi-constellation GNSS receiver are adopted. These receivers are distributed in Europe, American and Australia and listed in Table 8.1. Figure 8.6 shows the depth of coverage (DOC) with abroad stations. It’s obviously that these stations could increase DOC for IGSO and MEO satellites.

Table 8.4 shows the orbital overlap and clock accuracy of MPOD adopting abroad stations data. Comparing with Table 8.2, orbital overlap accuracy for IGSO is the same as regional tracking network, while R/T/N accuracy increase 0.1 m respectively for MEO satellites. Comparing clock accuracy in Table 8.4 with Table 8.3, it has been improved 0.7 and 0.4 ns for IGSO and MEO. The improvements indicate that adopting abroad station may enhance the DOC for IGSO and MEO. The reason of different improvements for IGSO and MEO is that adding abroad stations, MEO orbital arc is still not completely covered, and continuity of abroad stations observation is worse than China regional network. Hence, the clock accuracy improvement for MEO is less than IGSO satellites.

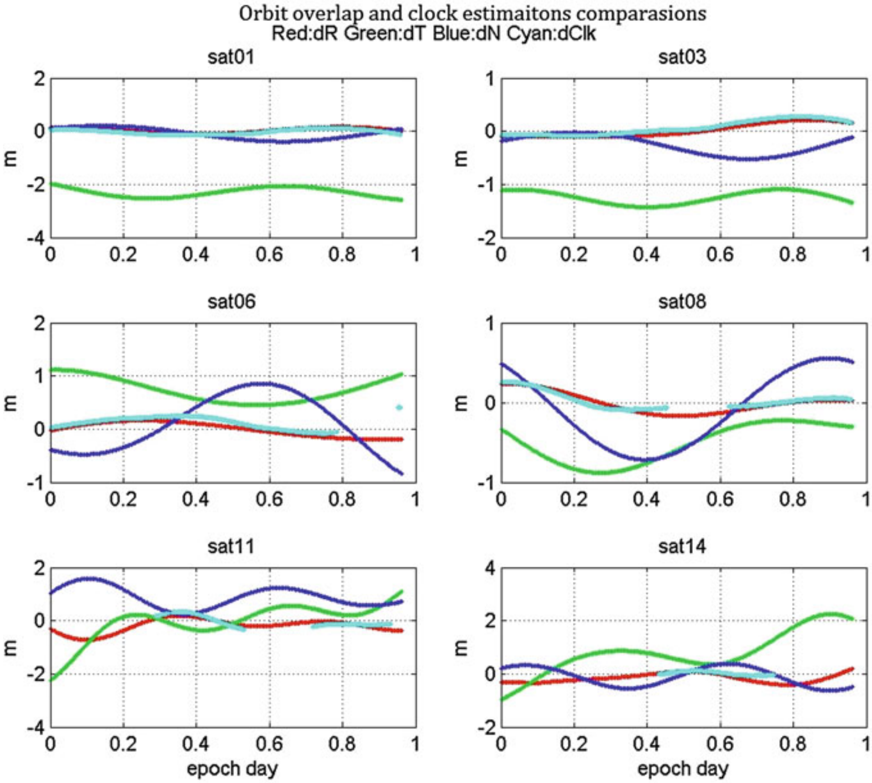

Fig. 8.5 Orbital difference in R/T/N directions and clock errors difference time series. Orbital difference in R/T/N direction is shown as *red*, *green* and *blue line*, and clock difference as light *blue line*. Three rows represent GEO/IGSO/MEO satellites. Two different satellites are drawn in the same line

8.3.5 Timing Accuracy

System timing service can be achieved by satellite orbit and clock error information. Depending on the accuracy of the ephemeris, system timing can be divided into precise and real-time service. Precise orbit and clock realize the precise timing service, and broadcast ephemeris achieves real-time service.

This study realizes system timing by precise and broadcast ephemeris respectively. In precise timing processing, PPP strategy is adopted, in which station clock errors are estimated with position parameter [5]. In real-time processing, station position is fixed and station clock errors are the average of all visible satellite UERE in each epoch, see Eq. (8.4). This strategy may reduce the impact of constellation DOP to timing accuracy.

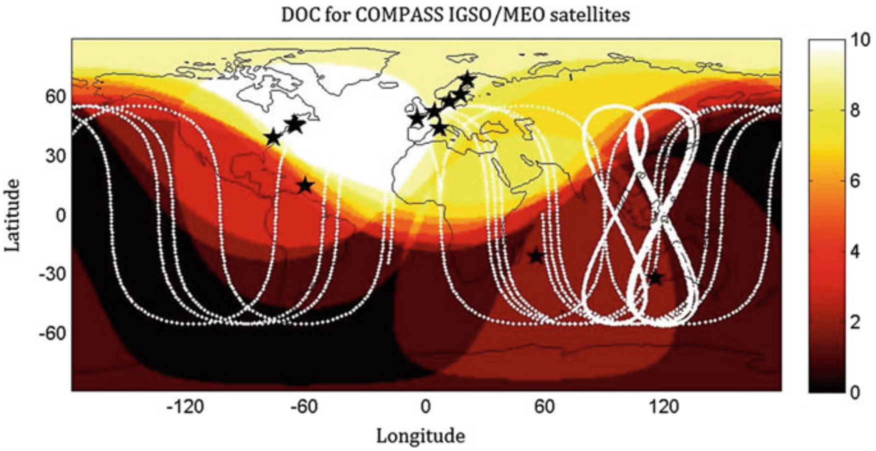

Fig. 8.6 Depth of coverage of abroad station for COMPASS IGSO/MEO. Black stars represent abroad stations, white points represent footprints of satellites. Different colors mean DOC value

Table 8.4 Orbital overlap and clock accuracy wit domestic and abroad stations

SATID	dR (m)	dT (m)	dN (m)	Clock (ns)
06	0.116	1.080	0.778	0.652
07	0.329	0.885	0.571	0.512
08	0.121	0.732	0.898	0.936
09	0.378	1.147	0.916	0.781
10	0.289	1.321	0.630	0.869
11	0.100	0.296	0.938	0.650
12	0.166	0.577	0.492	0.669
13	0.373	1.290	0.741	0.740
14	0.196	1.373	0.769	1.059

The multi-constellation GNSS station can receive navigation information from each system simultaneously. The difference of station clock error estimations by different system ephemeris include difference of time system, receiver equipment delay the orbit and clock errors of difference system and random noise. Considering the complexity of system error for station clock estimations in different navigation system, we only discuss the stability of timing service.

Figure 8.7 shows the comparison time series of station clock estimations between COMPASS and GPS in precise and real-time mode. The two rows represents the real-time and precise mode respectively, the standard deviation is about 2.5 and 1.5 ns. It indicates that both post and real-time ephemeris can realize system timing service, and are consistent with GPS results. Except the constant bias, there is no other systemic relative variation between two navigation systems (linear or higher degree). Consequently, it illustrates that the stability of two systems is consistent with each other.

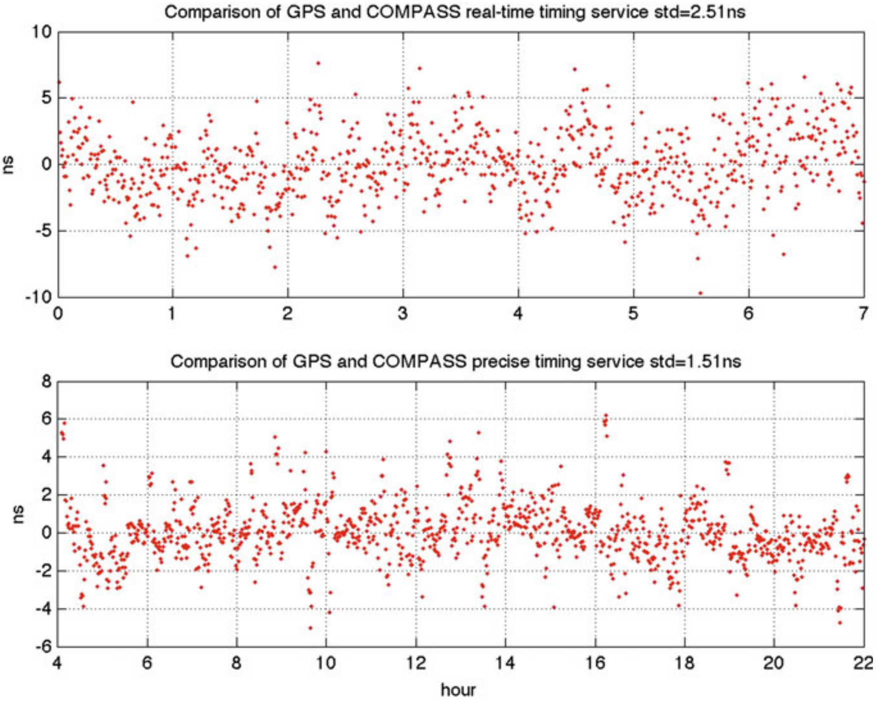

Fig. 8.7 Comparison of COMPASS and GPS timing. The *top* row is real-time results and the *bottom* is post results

8.4 Conclusions

In this study, the accuracy of satellite nominal attitude prediction is assessed, COMPASS satellite orbit parameters are determined adopting regional and global tracking network datasets, the accuracy of satellite orbit is evaluated by orbital overlap, SLR residual and TWSTFT, the accuracy of system timing service are also discussed. Conclusions are as followed:

1. Different attitude control modes are applied to GEO and IGSO/MEO satellites. It's necessary to establish satellite antenna phase center correction model for each type satellites in OD processing. The overall accuracy of nominal attitude prediction is better than 1° which can be used to establish antenna phase center correction model.
2. The characteristics of pseudo-range noise for domestic and foreign manufacturer receivers are quite different. It shows multipath characteristics for domestic receivers, while shows white noise for foreign receiver and the magnitude is larger than domestic receiver.
3. The pseudo-range and carrier phase RMS for 4GEO/5IGSO/4MEO constellation MPOD is about 80 and 0.8 cm. Since the regional tracking network can't

cover all MEO orbital arc, the overlap accuracy for MEO is slight less than GEO and IGSO satellites.

4. Adding abroad stations can increase depth of coverage for IGSO and MEO satellites, and both of overlap and satellite clock errors accuracy can be improved. Satellite clock errors accuracy increases 0.7 and 0.4 ns for IGSO and MEO respectively.
5. System timing service can be realized by precise or real-time ephemeris. The stability of COMPASS is consistent with GPS, the standard deviation of comparison for COMPASS and GPS precise timing is about 1.5 ns, the real time timing is about 3 ns.

Acknowledgments We would like to thank Beijing Global Information Application and Development Center for providing the observations of COMPASS and navigation messages. The differential and integrity information have also kindly been made available from them. The authors would gratefully acknowledge the support of all individuals and institutions that have supported this study. This paper is supported by the Natural Sciences Foundation of China (Grant No. 11103064), the Shanghai Committee of Science and Technology, China (Grant No. 11ZR1443500), the National High Technology Research and Development Program of China (Grant No. 2013AA122402) and China Satellite Navigation Conference (Grant No. CSNC2011-QY-01).

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