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Positioning accuracy assessment for the 4GEO/5IGSO/2MEO constellation of COMPASS[†]

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Determined to become a new member of the well-established GNSS family, COMPASS (or BeiDou-2) is developing its capabilities to provide high accuracy positioning services. Two positioning modes are investigated in this study to assess the positioning accuracy of COMPASS' 4GEO/5IGSO/2MEO constellation. Precise Point Positioning (PPP) for geodetic users and real-time positioning for common navigation users are utilized. To evaluate PPP accuracy, coordinate time series repeatability and discrepancies with GPS' precise positioning are computed. Experiments show that COMPASS PPP repeatability for the east, north and up components of a receiver within mainland China is better than 2 cm, 2 cm and 5 cm, respectively. Apparent systematic offsets of several centimeters exist between COMPASS precise positioning and GPS precise positioning, indicating errors remaining in the treatments of COMPASS measurement and dynamic models and reference frame differences existing between two systems. For common positioning users, COMPASS provides both open and authorized services with rapid differential corrections and integrity information available to authorized users. Our assessment shows that in open service positioning accuracy of dual-frequency and single-frequency users is about 5 m and 6 m (RMS), respectively, which may be improved to about 3 m and 4 m (RMS) with the addition of differential corrections. Less accurate Signal In Space User Ranging Error (SIS URE) and Geometric Dilution of Precision (GDOP) contribute to the relatively inferior accuracy of COMPASS as compared to GPS. Since the deployment of the remaining 1 GEO and 2 MEO is not able to significantly improve GDOP, the performance gap could only be overcome either by the use of differential corrections or improvement of the SIS URE, or both.

PPP, real-time positioning, authorized services, orbit determination

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1 Introduction

As important space infrastructure, satellite navigation systems extend the rang of activities and promotes social connectivity by providing up-to-date weather forecasting methods and global positioning, navigation and timing services to users on or near the earth surface. China has recognized the need in this area and pursued the build-up of the COMPASS (or BeiDou-2) system for more than a decade. It's designed as a Global Navigation Satellite System (GNSS). COMPASS has followed the development roadmap of starting with regional services by the year 2013 and will expand to provide open service to global users by the year 2020. With the deployment of new satellites, COMPASS is now approaching its capability to provide high accuracy regional positioning services. The official inception of

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operational positioning, navigation, and timing (PNT) services was announced in the end of 2011, providing services to China and surrounding areas. Concurrently, test version of the Compass Interface Control Document (ICD) was released1). These developments provide opportunities for the international community to be involved in the COMPASS applications, and offer international community the possibilities to evaluate the PNT performance of the COMPASS system.

To serve its own purposes, COMPASS adopts a unique system design. Unlike other GNSS systems, COMPASS utilizes the Geostationary Earth Orbit (GEO) and Inclined Geosynchronous Satellite Orbit (IGSO) satellites which are more suitable for regional services, whose constellation is composed of 14 satellites, including 5 GEO, 5 IGSO satellites and 4 Medium Earth Orbit (MEO) satellites. As of 2012, the 13 satellites have been launched. Excepting for G2 (unusable) and M1 (testing only), the remaining 11 satellites including 4GEO+5IGSO+2MEO have successfully transmitted signals and broadcasted navigational messages, to prepare for full operation beginning in 2013 (Table 1).

Since it was first proposed by Neilan et al. [1] as a major positioning technique, Precise Point Positioning (PPP) has seen numerous important applications. Current accuracy has reached millimeter-level for GPS static positioning [2]. Accurate positioning time series are needed for the definition and maintenance of reference frame, deformation monitoring for earthquake and volcano eruption and research on atmospheric sciences [3,4].

With the construction of COMPASS satellite navigation system, many researchers had carried out studies on COMPASS application. Researchers [5,6] investigated the GEO/IGSO orbit determination accuracy. The accuracy of satellite clock rates estimates is about 1×10^{-13}–1×10^{-12}, and the laser radial Root-Mean-Square (RMS) is about 0.1 m. Adopting the triple-frequency observations [7] the investigators assessed the 2nd-order ionospheric delay effects on GNSS precise positioning. Others [8] analyzed the influence of hybrid navigation constellations with invalid satellites. Ye et al. [9] applied the COMPASS signal in SAR imaging. This work discusses the post and real-time point positioning accuracy with COMPASS navigation system.

Table 1 List of active satellites of COMPASS (Aug. 2012)

Satellite	Date	Type	Orbit
G1	2010-1	GEO	140°E
G3	2010-6	GEO	84°E
G4	2010-11	GEO	160°E
G5	2012-2	GEO	58.75°E
I1	2010-8	IGSO	118°E
I2	2010-12	IGSO	118°E
I3	2011-4	IGSO	118°E
I4	2011-7	IGSO	80–112°E
I5	2011-12	IGSO	79–110°E
M3/M4	2012-4	MEO	–

A comprehensive assessment study on COMPASS has been reported by Montenbruck et al. [10], in which signal and measurement quality, onboard frequency standards as well as tri-frequency applications were investigated and encouraging performance was observed. Following the same assessment strategy this work reports accuracy assessment with a different constellation and a different monitoring network. Two more MEO satellites have joined the constellation of 4 GEO and 5 IGSO satellites that were studied in recent reports [10] and have begun transmitting COMPASS signals. A domestic monitoring network within China was built to support the control and operation segment of COMPASS, which provided the code and carrier observations for this study. By contrast ref. [10] used a network of 6 monitoring stations that achieved the same depth of coverage as the domestic network. Focusing exclusively on post-processing positioning, one critical assessment not performed in ref. [10] was the positioning accuracy for common real-time users that replied on navigation messages broadcasted by COMPASS satellites. With the collection of all COMPASS satellites' navigation messages at the monitoring receivers, we in this work are able to assess its accuracy for both post-processing and real-time users.

2 Orbit determination and time synchronization (TS)

Different from GPS, orbital and clock information of COMPASS is generated by control segment based on data collected with a domestic monitoring network. Several challenges are facing COMPASS precise orbit determination. Firstly, strong statistic correlations between the orbit of the GEO and clock estimates can cause irregularities. Secondly, domestic monitoring network is unable to provide enough tracking coverage, particularly for MEO satellites. The depths of coverage of MEO and GEO/IGSO for the control segment monitoring network are illustrated in Figures 1(a) and (b), respectively. Color bars represent depths of coverage, or average numbers of receivers that are tracking the satellite. It is shown in Figure 1 that the coverage of MEO is less than 50% and not all GEO satellites can be observed by each receiver located in regional network. Thirdly, force models, particularly the solar radiation pressure model, are not accurately adjusted given the relatively short period of operation time. Moreover, the COMPASS measurement corrections are under development to be consistent with GPS counterparts that focus on satellite attitude and phase center models.

It is interesting to note the differences between the above

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1) China Satellite Navigation Office. BeiDou navigation satellite system signal in space interface control document (test version), www.beidou.gov.cn/

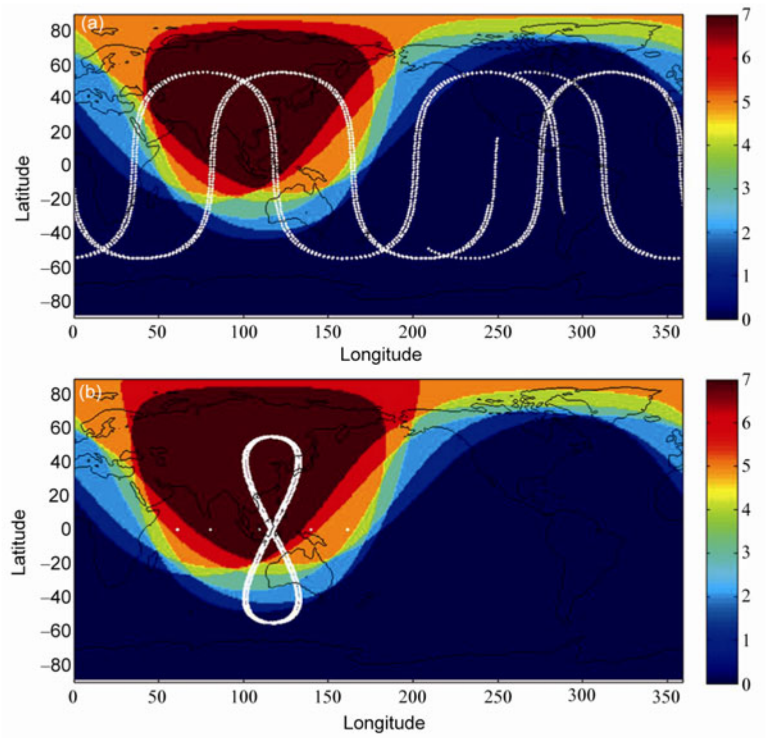

Figure 1 (a) Depth of coverage of MEO for control segment's regional network; (b) depth of coverage of GEO/IGSO for control segment's regional network.

figures with Figure 2 in Montenbruck et al. [10] which provides their depth of coverage for GEO and IGSO. With monitoring stations west (Kazan, Chennai, Singapore), north (Tanega-shima) and south (Perth and Sydney) of mainland China, it appears that better coverage is achieved for ref. [10] monitoring network, favoring more precise orbits determined.

COMPASS post-processing precise orbits and clocks are computed following the strategy [6]. A choice of 3 d data arc of ionosphere-free carrier phase and pseudo-range combination is made based on comparison experiments [6]. For COMPASS precise orbit determination, dynamic models are planetary perturbations based on JPL's planetary ephemerides of DE403/LE403, 10×10 earth non-spheric gravitation truncating EIGEN-GRACE02S, solar radiation pressure model modifying GPS T10/20 models, earth tides perturbation based on IERS 2000, oceanic tides perturbation based on FES2004 model and empirical accelerations with orbital period. The earth orientation parameters used are from IERS EOP04C, with the IAU1980 nutation model in combination with VLBI corrections. Indirect solar radiation pressure either from infrared radiation from earth or COMPASS satellite heat radiation is not modeled, which will be partly accounted for by the empirical accelerations [6].

The estimates are initial state vectors for all satellites, solar radiation pressure parameters (scale factor and y-bias) for each satellite, empirical accelerations on both orbital trace (T) and normal (N) directions, zenith tropospheric delay factor every 8 h for each site, phase ambiguities of the ionospheric-free combination and epoch by epoch clocks for all satellites and receivers after fixing one. The processing of orbit and clocks estimation is performed in hourly batches with a data interval of 30 s. The orbital overlap comparisons, which show the internal consistency of orbit products, present decimeter-level consistency in tangential and normal directions and centimeter-level consistency in radial direction. For more details, refer to ref. [6].

Different from GPS, independent TS of two-way radio-wave time transfer system is developed for the control segment to supplement the regional monitoring network of COMPASS system, which provides precise measurements of time differences between system time standard maintained at the master ground station and the COMPASS satellites. Specific payload is mounted on all COMPASS satellites for the space segment to support TS. For GEO and IGSO satellites, constant visibility at a few telecommunication and telemetry stations makes it possible for continuous two-way time transfer links between the satellites and system time standard. However, for MEO satellites two-way time transfer links are only possible when they are in view. Comparisons of clocks estimates and two-way radio-wave time transfer measurements show that the precision of satellite clock estimates is better than 1 ns. Since TS system provides the satellite clock predictions in navigation messages, orbital and clock information in the broadcast ephemeris is then obtained from tracking and TS data separately.

3 Dilution of precision (DOP)

DOP is one of the main factors used to specify GNSS geometry effects on user positioning accuracy. Figure 2 shows the variation of DOP for monitor stations with satellite constellation development of COMPASS. It shows that DOP is significantly improved from 3GEO/4IGSO to 4GEO/5IGSO constellation, particularly in the up component. The contribution with two more MEO addition to the DOP improvement seems marginal.

The locations of the monitor stations in Figure 2 are listed from east to west and the distributions are distinguished by two yellow bars. It indicates that DOP is improved from north area to south area, and degraded from east area to west area in China.

Compared to GPS positioning in the same service region, COMPASS has a comparative DOP value for east-west component, but less effective for DOP for north-south and height components. In addition, during a period of 24 h, variability of DOP values for GPS is significantly lower than those for COMPASS, a feather attributing to the entries and exits of IGSO and MEO satellites in view for a user (Figure 3).

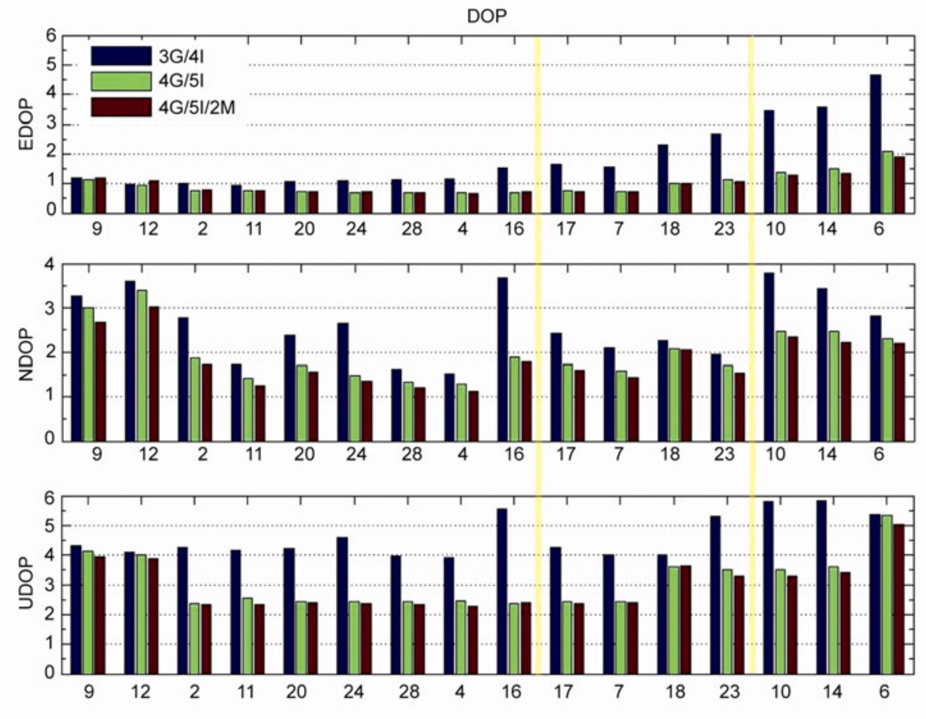

Figure 2 Variation of DOP with satellite constellation development for 16 stations in east-west, north-south, height components (3G/4I indicates DOP of 3GEO/4IGSO constellations, 4G/5I indicates DOP of 4GEO/5IGSO constellations, 4G/5I/2M indicates DOP of 3GEO/4IGSO/2MEO constellations).

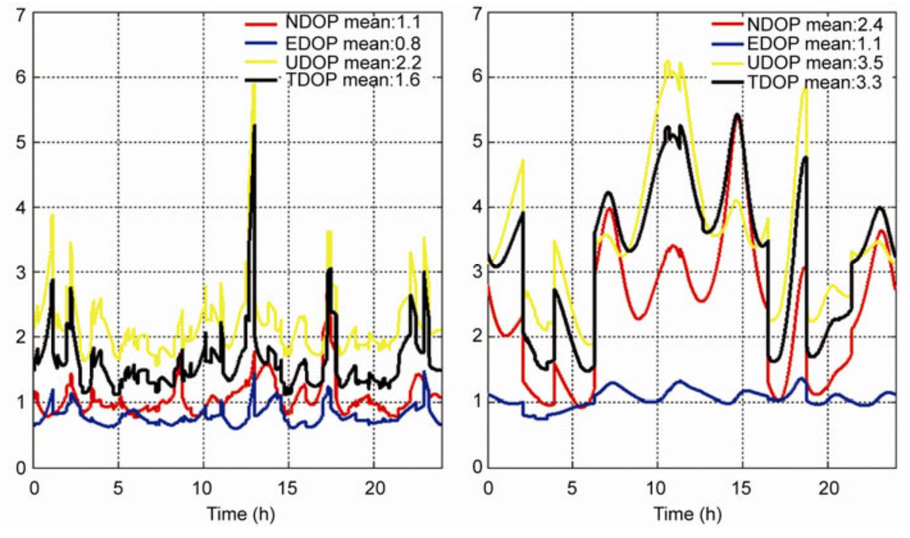

Figure 3 DOP for GPS positioning (left) and COMPASS positioning (right) at Changchun, China (Jun. 14, 2012).

4 Open and authorized services

To improve accuracy and integrity of GNSS service, additional satellite-based or ground-based augmentation systems are built. Prominent examples are WAAS (Wide Area Augmentation System) and EGNOS (European Geostationary Navigation Overlay Service). Maintained by different operating agencies and providing augmentation service to specific users, these augmentation systems are independent of GPS or other GNSS operation control systems [11–13].

One unique design of COMPASS system is that it simultaneously provides open service and authorized service using the same control and operation segment. Basic navigation information is provided by open service for free in the form of navigational messages but differential corrections and integrity information are only provided to users with authorized access. It is noteworthy that two kinds of ionospheric correction models are provided in open service, 8 parameters/14 parameters Klobuchar models [14,15]. The comparisons of two modes of services are listed in Table 2.

Orbital errors, satellite clock errors and pseudo-range measurement errors are the main error sources for positioning and timing [16,17]. Apparent positions of GEO satellites are relatively static to monitoring stations on ground, resulting in the high correlation in the determination of satellite orbits and satellite clocks. Moreover, limited geographical distribution of monitoring networks, COMPASS presents challenges in the precise orbit determination. Since independent TS system is implemented and orbits and clocks may be obtained by simultaneously processing both tracking and TS data, uncalibrated instrumental errors of TS system may degrade navigation accuracy [2]. The ionospheric delay is one of the largest and more unpredictable sources of error for single-frequency receiver users [14].

Differential corrections for orbits, clocks as well as ionospheric delay are generated by processing data from monitor receivers in a near real-time mode and then broadcasted to authorized users [15]. Given the constellation design of COMPASS, orbital and clock differential corrections are combined as one, or equivalent satellite clock error, which is computed as the average User Range Error (URE) of the service area with uniformly distributed monitor stations whose coordinates are known precisely. This differential correction is updated rapidly to account for fast changing satellite clock errors. To minimize the ionospheric delay errors for single-frequency users, authorized services provide regional ionospheric grid which is more accurate and timely than analytical function based models. The ionospheric grid could be generated by setting up uniform and densely distributed tracking monitor stations.

Significant multipath errors have been identified in pseudo-range observations of the regional satellite navigation system both in our study based on data from the COMPASS control segment monitoring network [18] and an experimental network [10]. The multipath errors may seriously degrade the estimates of differential corrections. To correct for multipath errors, we have improved the algorithm of the WAAS Code Noise and Multipath Correction (CNMC algorithm) to realize real-time correction of multipath errors [14,15].

With the application of real-time code noise and multipath correction, Cao et al. [15] showed that the RMS of pseudorange multipath errors decreased from 0.4 m to 5–6 cm. Unless stated otherwise, the pseudo-range observations are processed after the code noise and multipath correction in following real-time positioning experiments.

5 Results and discussion

COMPASS positioning experiments are carried out using data from 2012/06/18 to 2012/07/03. The preliminary positioning results of PPP and real-time positioning from COMPASS system are discussed. PPP is performed based on post-processed orbit and clock solutions. Real-time positioning is processed with broadcast navigation messages and differential corrections recovered at the receivers.

5.1 Satellite orbit and clock errors accuracy

Positioning accuracy is a function of constellation, accuracy of ephemerides, and measurements errors. To evaluate orbit and clock errors accuracy, comparison of orbit overlap and clock errors' estimations and measurements are adopted, respectively.

As mentioned in previously, 3 d arc of ionosphere-free carrier phase and psudo-range combination are used for orbit determination. We chose two orbit determination solutions with 1 d overlapped to evaluate orbit accuracy. Table 3 shows the orbit overlap compassion in radial (R), transverse (T) and normal (N) direction. URE in Table 3 represents mean orbit error in a user's line-of-sight direction which is a function of satellite altitude. URE equations for

Table 2 Comparison of COMPASS' open and authorized services

	Open service	Authorized service
Users	public users	authorized users
Monitor stations	orbit determination stations 7 in total	orbit determination/differential stations 27 in total
Orbits and satellite clocks	navigation message	navigation messages + equivalent satellite clock errors
Ionospheric correction	8 parameters/14 parameters Klobuchar models	5°×5° ionospheric grid
Information transmitting	all satellites	GEO satellites
Updating period	1 h for orbits and satellite clocks; 2 h for ionospheric model parameters	18 s for equivalent satellite clock error; 3 min for ionospheric grid

GEO/IGSO and MEO satellite used are reported elsewhere [6].

URE for MEO is

$$\begin{aligned}\mathrm{URE} &= \sqrt{(0.99\Delta R)^2 + (0.14\Delta H)^2} \\ &= \sqrt{(0.99\Delta R)^2 + (0.14\Delta T)^2 + (0.14\Delta N)^2}.\end{aligned}$$

URE for GEO/IGSO is

$$\begin{aligned}\mathrm{URE} &= \sqrt{(\Delta R)^2 + (0.09\Delta H)^2} \\ &= \sqrt{(\Delta R)^2 + (0.09\Delta T)^2 + (0.09\Delta N)^2}.\end{aligned}$$

Table 3 shows that the orbit URE is about 1 m, and five IGSO satellites orbit accuracy is significantly better than GEO and MEO.

COMPASS is unique among all working GNSS systems to in that it incorporates a two-way TS system between all satellite clocks and system time standard, which is able to provide direct measurements of satellite clocks with accuracy better than 0.1 ns. Other than unknown biases clock measurements so obtained could be treated as “ground truth”. Zhou et al. concluded in ref. [6] that the discrepancies between estimated satellite clocks and the measured satellite clocks “ground truth”, or errors of clock estimates are useful indicators of the accuracy of orbit, with smaller discrepancy corresponds to better orbital accuracy. Table 4 shows that clock errors accuracy is about 1.7 ns and five IGSO satellite clock errors accuracy is better than others which is consistent with orbit overlap comparisons.

5.2 PPP accuracy

Two strategies may be adopted for precise positioning. Network solution processes data from all receivers, fixing those with known coordinates but simultaneously estimate orbits, clocks along with unknown coordinates. The PPP solution fixes orbits and clocks obtained with data from monitoring stations and then processes the information in other sites to estimate their coordinates. Network solution seems theoretically advantageous over PPP solution because all data contributes to estimates of orbits and clocks, while PPP solution does not need raw data from the monitoring sites, therefore making it easier to collectively process a large amount of sites. In this work, the PPP strategy is adopted.

Table 3 Orbit overlap comparison (unit: m)

SatID	R	T	N	URE
GEO1	0.284	1.915	0.518	0.659
GEO3	0.258	0.848	0.633	0.409
GEO4	0.618	2.018	1.679	1.001
GEO5	0.429	2.458	0.841	0.890
IGSO1	0.114	1.114	0.444	0.378
IGSO2	0.167	0.636	0.878	0.366
IGSO3	0.188	1.135	0.755	0.450
IGSO4	0.181	0.857	0.348	0.331
IGSO5	0.084	0.286	0.407	0.171
MEO1	0.615	1.331	1.373	0.841
MEO2	0.379	0.956	0.625	0.511

Table 4 Satellite clock estimates accuracy (unit: ns)

SatID	Accuracy	SatID	Accuracy
GEO1	2.680	IGSO3	1.357
GEO3	1.235	IGSO4	0.959
GEO4	5.103	IGSO5	0.896
GEO5	1.283	MEO1	1.203
IGSO1	1.123	MEO2	1.596
IGSO2	1.012	Average	1.677

PPP can estimate the coordinates of the receiver and its epoch-by-epoch clock error using a data arc of 24 h. Measurement errors such as tropospheric delay that cannot be precisely modeled are treated as estimates. Dual frequency ionospheric-free psudo-range and carrier phase combinations are used for better accuracy, with the phase ambiguities estimated as real number rather than integer numbers. A brief description of PPP may be found in ref. [10] except that different sites and receiver types are treated in this work.

COMPASS data from 2012/06/18 to 2012/07/03 of 51 receivers at more 20 sites are processed with PPP. Daily coordinate time series are obtained for each receiver. Repeatability is defined as:

$$\sigma = \sqrt{\frac{(v-\bar{v})\cdot(v-\bar{v})^{\mathrm{T}}}{n-1}},$$

in which v is the difference vector between COMPASS positioning and GPS surveying for east, north or height components. $\bar{v}$ is the mean value of the time series, n is the dimension of v. Table 5 below is the summary of the repeatability for some receivers. About 5% of the time series is deleted as outliers is because of either to sufficient raw data or abnormal positioning results which deviate from the mean values by more than 3 times standard deviation.

To illustrate the PPP results, Figure 4 displays positioning time series for 9 receivers which are grouped in 3 rows following their geographic locations. The upper row shows 3 receivers co-located at a site in North China, namely these 3 receivers are about 10 m apart from each other. The middle and lower rows are for co-located receivers in south China and west China, respectively. These receivers are not

Table 5 Statistics of PPP repeatability (unit: cm)

RcvID	East	North	Up	RcvID	East	North	Up
1	2.27	1.66	4.39	8	1.31	2.01	4.59
2	2.28	1.66	4.61	9	0.25	0.45	6.66
3	2.34	1.72	4.41	10	0.25	0.58	7.90
4	0.76	1.13	2.38	11	0.33	0.53	7.93
5	0.68	1.25	2.40	12	0.61	1.23	1.96
6	0.90	1.44	1.87	13	0.85	1.21	2.02
7	0.90	1.36	3.81	14	0.80	1.39	2.40
Average	1.04	1.26	4.09	–	–	–	–

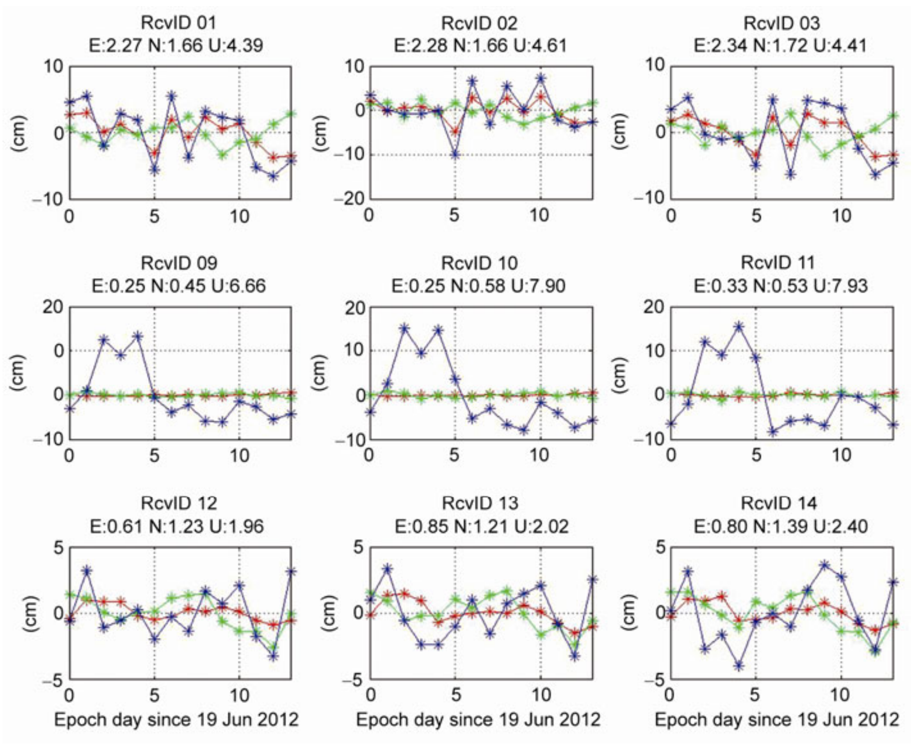

Figure 4 Co-located receivers PPP time series in different area. Red, green and blue points represent errors in east (E), north (N) and height (U) component. The base-line of the three co-located receivers in a row is less than 10 m. Three rows represent PPP time series in north, south and west of regional service area.

at monitoring sites. Different colors are used to refer to positioning components: red for east, green for north and blue for height. Units used is cm.

Figure 4 shows similar repeatability for co-located receivers. For example, for repeatability of east component, it is about 2.4 cm for receivers 1–3, about 0.3 cm for receivers 9–11, and becomes larger to about 0.7 cm for receivers 12–14. Namely the positioning accuracy in terms of repeatability displays a geographic pattern. As discussed below, this pattern is actually closely related to the COMPASS constellation. Similar pattern is found for the repeatability of North and height component.

PPP repeatability reported in this study seems consistent with findings in ref. [10] with a different monitoring network, different receivers and slightly different constellation, although longer data span is investigated in this work. Similar to the outlier of DOY 090 in Table 5 [10], obvious outliers present in Figure 4 for the up component for receivers No.9, No.10, No.11. Further investigation is needed to understand whatoccurred. As noted in ref. [10], PPP repeatability for COMPASS seems about 2 orders of magnitude lower than that for GPS.

Other than repeatability, which measures the consistency rather than accuracy, systematic differences are indeed observed between COMPASS PPP with GPS surveying results. As detailed in Table 6 the origins are not immediately clear when this study is performed. Possible attributors are antenna corrections for both the satellites and receivers, which deem a separate investigation that is currently underway.

5.3 Real-time positioning

For single-frequency users, ionospheric delays are corrected with Klobuchar 14 parameter model for open service users and ionospheric grid for authorized users, respectively. Equivalent satellite clock correction parameters are available to authorized users only as differential correction to correct their pseudo-range observations.

Figure 5 (left) shows the time series of equivalent satellite clock correction for a GEO, an IGSO and a MEO satellite updated every 18 s, displaying obviously seemingly orbital period resulting from errors of broadcast ephemeris. Abnormal corrections occurred for Sat 08, or I3 in Table 1, at about 25 h (marked with the black circle) are identified afterwards as its clock prediction errors. Compared to User

Table 6 PPP offsets between COMPASS and GPS results (unit: cm)

RcvID	East	North	Up	RcvID	East	North	Up
1	15.05	11.82	−6.48	8	0.50	5.47	33.41
2	10.37	13.22	−8.72	9	0.61	0.73	9.00
3	14.59	11.86	−8.79	10	−0.83	3.45	9.53
4	−1.13	−1.34	−1.28	11	1.01	−0.33	8.67
5	−0.79	−2.51	−0.54	12	−3.12	7.49	0.06
6	−0.82	−3.49	0.88	13	−4.20	6.93	0.04
7	−1.55	9.54	33.40	14	−0.20	9.37	1.07

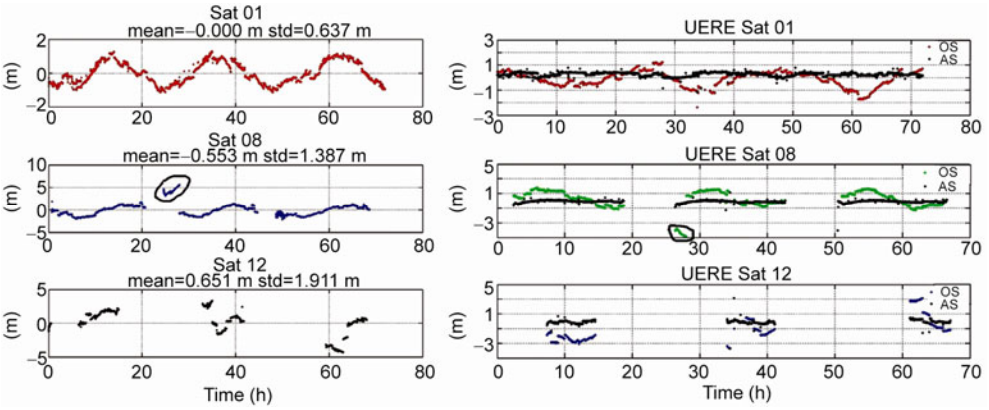

Figure 5   Time series of equivalent satellite clock correction (left) and the corresponding UERE comparison in open and authorized services (right). The *X*-axis is time, unit hour. OS is for open service, and AS is for authorized service.

Equivalent Range Errors (UERE) for open service users, UERE for authorized service users corrected with corresponding equivalent satellite clock parameters in Figure 5 (left) is significantly smaller (Figure 5 (right)). It is interesting to note that the jump of Sat 08 UERE for open service users (marked with the black circle) is removed for authorized service users.

Real-time positioning is performed using dual-frequency and single-frequency pseudo-range of monitor stations in open and authorized service, for which troposphere delay, ocean tide corrections, relativity correction, satellite and receiver antenna phase center offsets are corrected by models. The coordinates of the monitor stations are precisely determined using GPS, with accuracy better than 10 cm and are used as benchmarks to evaluate COMPASS positioning accuracy. The precision of positioning are presented in east, north and height components.

The time series of real-time positioning for Zhengzhou station are shown as an example (Figure 6). In open service, largest positioning error is in height component, reaching ~2 m. The positioning precision in east-west component is five times better than height component. Compared with open services, the three-dimensional positioning accuracy is improved by about 60% in the authorized service. The details of DOP in east, north and up directions are also displayed. It demonstrates that the largest DOP is in height component and the smallest is in east-west component. The peaks of DOP are caused by the sets and rises of non-GEO satellites.

The analysis of 18 monitor stations shows that, with dual-frequency pseudo-range observations (D-F in Figure 7), the RMS of three-dimensional positioning errors are approximately 5 m in open service, of which 4 m is in the height component. While in authorized service (Authorized D-F in Figure 7), the RMS of three-dimensional positioning errors are improved to about 3 m. Using single-frequency pseudo-range observations (S-F in Figure 7), the RMS of three-dimensional positioning errors are about 6 m in open service, of which 5 m is in the height component. In authorized service (Authorized S-F in Figure 7), the RMS of three-dimensional positioning errors are only 4 m.

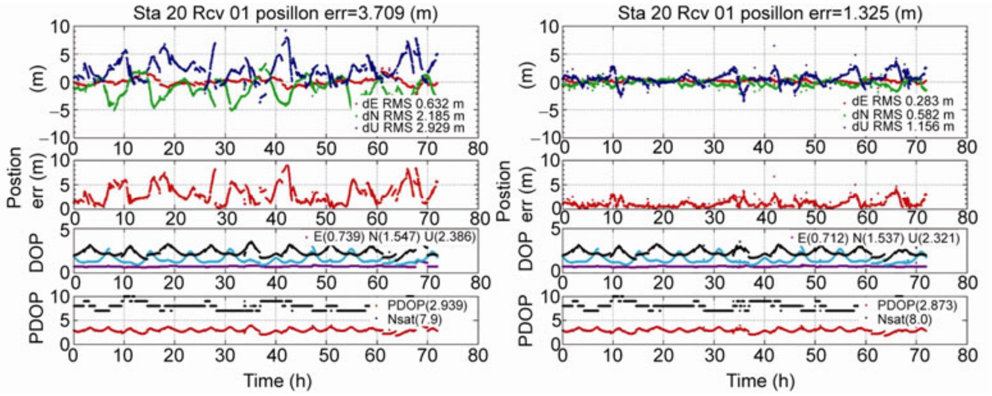

Figure 6   Positioning errors of a dual-frequency receiver at Zhengzhou in open (left) and authorized (right) services. Top subplot: red, green and blue lines are errors in east-west, north-south and height components, respectively. Middle subplot: three-dimensional positioning errors. Lower subplot: pink, blue and black lines are DOP values in east-west, north-south and height components, respectively. Bottom subplot: red line is the PDOP value and black line the number of satellites in view.

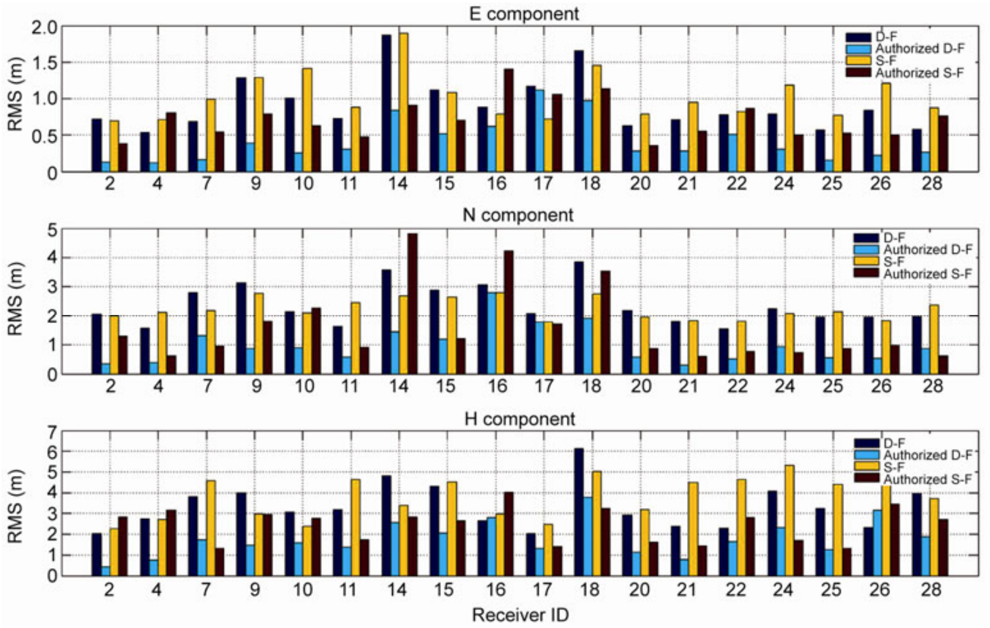

Figure 7 Positioning errors in east-west, north-south, height components for 18 stations (D-F indicates double-frequency receivers in open service. Authorized D-F indicates double-frequency receivers in authorized service, S-F indicates single-frequency receivers in open service, and authorized S-F indicates single-frequency receivers in authorized service.

6 Conclusions

This work uses COMPASS observations for accuracy evaluation of both post-processing and real time positioning performance. Results show that the accuracy of post-processing daily PPP has reached centimeter level for the 4GEO/5IGSO/2MEO constellation, while meter level pseudo-range based single point positioning accuracy is realized in real-time COMPASS navigation.

The orbit determination strategy of COMPASS control segment is able to obtain precise orbit and satellite/receiver clock estimates, with orbit URE better than 1 m, and satellite clock accuracy about 1.7 ns. IGSO satellites' orbits and clocks are better estimated than for GEO and MEO satellites'.

Fixing precise orbits and clock estimates, PPP repeatability for a receiver that is able to collect both carrier phase and pseudo-range observations is better than 2 cm, 2 cm and 5 cm in the east, north and up components, respectively. Interestingly, PPP accuracy exhibits a pattern strongly correlated with the geographic distribution of the constellation's ground tracks, with PPP accuracy of south China higher than the west and north regions.

For non-geodetic common users, accuracy of dual-frequency and single-frequency positioning is of 5 m and 6 m in terms of RMS under the open service. In the case of authorized service, the differential corrections are able to remarkably improve positioning accuracy with accuracy of dual-frequency and single-frequency positioning improved to 3 m and 4 m (RMS), respectively. Positioning accuracy will be improved further by using "phase smoothed pseudo-range" technique. The largest positioning error exists in the height component reaching 3–5 m under open service, and differential corrections provided to the authorized service are able to significantly errors in height component.

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