

# Orbit Accuracy Analysis for BeiDou Regional Tracking Network

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**Abstract** In order to evaluate the orbit accuracy of regional network of Chinese BeiDou Satellite Navigation System (BDS), we compare the orbits determined by regional network consisting of ground stations within the border of China and orbits provided by global Multi-GNSS Experiment (MGEX) covering 2-year time span from 2013 to 2014. The results show that, for GEO/IGSO/MEO, mean radial accuracies of regional network orbits are around 0.4, 0.3, and 0.2 m, respectively. The orbit accuracy degenerates significantly during eclipse and IGSO/MEO yaw-fixing season. IGSO/MEO orbit accuracies present possible quasi-periodic oscillation, but show week correlation with sun's elevations above the orbital plane. Assessment of regional network orbits by satellite laser ranging (SLR) shows, for GEO/IGSO/MEO, that the RMS values of station-satellite distance are around 0.6, 0.3, and 0.2 m, respectively, which match the orbit radial errors fairly well but contain significant systematic offsets. The characteristics presented in BeiDou satellites are quite different from those in GPS/Galileo. The dynamic modeling accuracy and orbit processing strategy on BeiDou satellites need further enhancement.

**Keywords** BDS · Regional network · Orbit evaluation · SLR

## 1 Introduction

BeiDou Satellite Navigation System (BDS) adopts mixed constellation structure which consists of satellites distributed in Geostationary Earth Orbit (GEO), Inclined Geosynchronous Orbit (IGSO), and Medium Earth Orbit (MEO). Currently, regional

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The original version of this chapter was revised: For detailed information please see Erratum. The erratum to this chapter is available at [10.1007/978-981-10-0940-2\\_66](https://doi.org/10.1007/978-981-10-0940-2_66)

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BDS which consists of 14 satellites has been put into operation stably. Global BDS has also been implemented gradually, and a few test satellites have been launched or been put into recent launch plan. The final goal of BDS construction is to form satellite navigation system which provides global coverage service. As the onboard reference of navigation system, precise satellite orbit will play important role during the BDS application and spreading in high precision fields.

The networks of monitoring stations of GPS and Galileo systems have achieved global and fairly even distribution. But limited by external conditions, the monitoring stations of BDS are located inside the border of China, which lead to poor geometry structure of carrier phase measurement, and the normal equations of orbit determination have greater probability to become ill-conditioned.

Some dynamical models in BDS orbit processing have not been perfect yet. The solar radiation pressure (SRP) model is the most important perturbation model affecting orbit determination of high-orbit and medium-orbit satellites. The practical SRP models are empirical or semi-empirical, which have been formed on the basis of long-term and large amount data analysis. At present, only for GPS, the SRP model and parameter estimation have been well developed [1, 2]. The modeling for Galileo SRP is still in the stage of investigation and improvement [3]. The modeling for BDS SRP should also been put more efforts.

The nominal coordinate of BDS onboard carrier phase center is adopted in our current data processing. Little difference would appear during the geometry correction for different frequency or to different direction. But only the fixed value is adopted now, in which application should be accompanied by a set of self-consistent parameters to avoid systematic bias of orbits.

Full understanding on accuracies and characters of BDS orbits provided by regional network is an important approach to investigate the effects of above-mentioned factors and to provide further improvement. For this purpose, comparison and analysis are carried out on the basis of 2-year orbits provided by BDS regional network consisting of a set of ground stations located within the border of China and orbits provided by the multi-GNSS experiment (MGEX) consisting of global ground stations. Multi-satellite orbit determination strategy with simultaneous estimation of orbital elements and clock errors are adopted to obtain the orbits in BDS regional network framework [4]. The external orbit validation on BDS regional network is also carried out on the basis of global satellite laser ranging (SLR) tracking provided by International Laser Ranging Service (ILRS).

## 2 Orbit Comparison

### 2.1 MGEX Orbits

MGEX is a huge experimental system organized by International GNSS Service (IGS), in which goal is to explore characters of multiple satellite navigation systems including GPS of US, GLONASS of Russia, Galileo of EU, BDS of China, and QZSS of Japan by

cooperative analysis [5, 6]. A few global satellites navigation analysis centers have joined in MGEX working group, and provide products such as orbit, clock, satellite and station hardware delay, ionospheric correction, earth orientation parameters, etc.

There are around 30 ground stations of BDS in MGEX framework which realized preliminary global distribution even though such distribution is not even very much. Currently, three MGEX analysis centers provide BDS orbit products. Among these, Europe CODE provides orbits of BDS IGSOs and MEOs, and German GFZ and Chinese Wuhan University provides orbits of total BDS GEOs, IGSOs, and MEOs. Preliminary orbit overlap and orbit comparison analysis for the orbit products provided by these three institutions show that 3D orbit accuracies of BDS satellites are around 1–5 m for GEOs and 20 cm for IGSOs and MEOs, in which accuracies are all significantly higher than orbits provided by regional BDS network. The orbit products provided by Wuhan University last longer than the other two centers, so we take orbits of MGEX Wuhan University as reference orbits in this work [7].

## 2.2 Comparison Results

The orbits provided by regional network and Wuhan University during whole 2013 and 2014 are compared. The evaluation indices include radial (R) accuracy, transverse (T) accuracy, normal (N) accuracy, 3D position accuracy, and user range error (URE). Detailed results are listed in Table 1, in which the comparisons are

**Table 1** Statistics of orbit comparisons

Sat type	Sat code	Orbit comparison/cm				
		R	T	N	3D pos	URE
GEO	C01	39.7	2664.0	92.6	2665.9	243.2
	C02	37.0	844.6	59.4	847.4	84.7
	C03	35.6	322.9	73.6	333.1	46.4
	C04	36.5	981.9	94.4	987.1	96.0
	C05	39.1	376.8	74.2	386.1	52.2
	mean <sup>a</sup>	37.1	631.6	75.4	638.4	69.8
IGSO	C06	29.3	113.6	94.9	150.9	32.2
	C07	30.1	95.5	87.0	132.6	32.3
	C08	32.2	111.9	113.2	162.4	35.3
	C09	28.0	107.0	82.3	137.9	30.6
	C10	31.2	106.9	83.3	139.1	33.5
	mean	30.2	107.0	92.1	144.6	32.8
MEO	C11	19.3	77.3	52.2	95.3	23.2
	C12	21.5	81.7	52.2	99.3	25.3
	C13	16.6	72.7	48.9	89.2	20.5
	C14	17.9	73.1	46.8	88.6	21.5
	mean	18.8	76.2	50.0	93.1	22.6

<sup>a</sup> The results of C01 are excluded from statistics

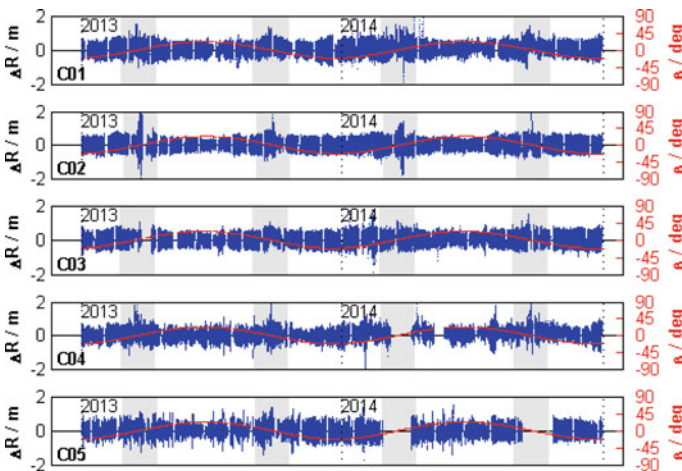
implemented not only in the visible scopes of regional network but in the whole orbits. In this table the values of C01 satellite are excluded from GEOs statistics because of its large deviation from other GEOs.

It is obvious that orbit errors are biggest in T direction and smallest in R direction. The radial errors of GEOs, IGSOs, and MEOs are around 0.4, 0.3, and 0.2 m, respectively. The orbit errors of GEOs are biggest, which attribute to their most poor and almost fixed observational geometry. Such geometry leads to strong correlation between orbit determination and clock estimation, and thus affects the orbit precision and stability seriously. The T direction accuracy of C01 in Table 1 is exceptionally low, which is possibly relevant to the radio phase center difference between its nominal value adopted in our analysis and its estimated value adopted by Wuhan University in the case of vulnerable geometric covering.

Figures 1, 2, and 3 illustrate the details of radial position comparison of GEOs, IGSOs, and MEOs. The red line in each sub-figure (scale in the right side of Y axis) show the elevation of Sun relative to satellite orbit plane ( $\beta$  angle). The shallow gray zone means the satellite is n. In the dark gray zones of Figs. 2 and 3, the  $\beta$  angle are less than  $4^\circ$ , in which the satellites' attitudes will convert into orbit normal (yaw-fixing) modes from usual yaw-steering modes.

Frequent orbit maneuvers should apply to GEOs for the maintenance of sub-satellite point' longitudes. Every maneuver could cause several-day lack of precise orbit. Week negative correlation seems appear between orbit difference and solar  $\beta$  angle in Fig. 1. Dramatic accuracy degeneration or even interruption of orbit will happen when  $\beta$  angle is close to zero.

It is shown in Figs. 2 and 3 that for IGSOs and MEOs, the orbit accuracy may be higher when solar  $\beta$  angle is larger. The orbit accuracy usually degenerates during eclipse season. While the satellite has converted into or approaches to yaw-fixing



**Fig. 1** Radial comparisons of BDS GEO orbits

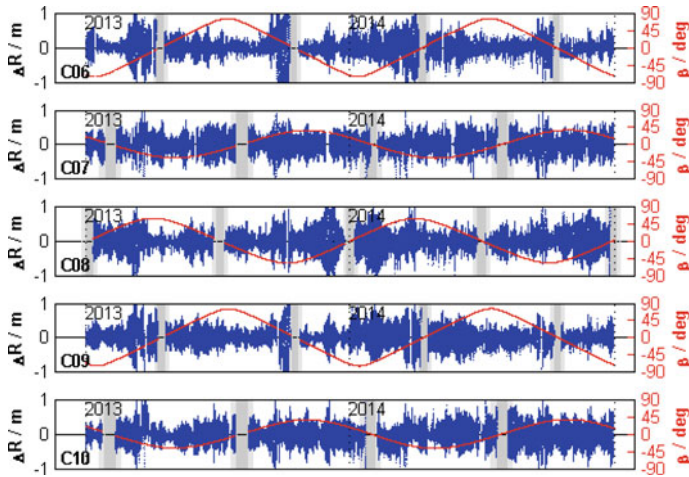


Fig. 2 Radial comparisons of BDS IGSO orbits

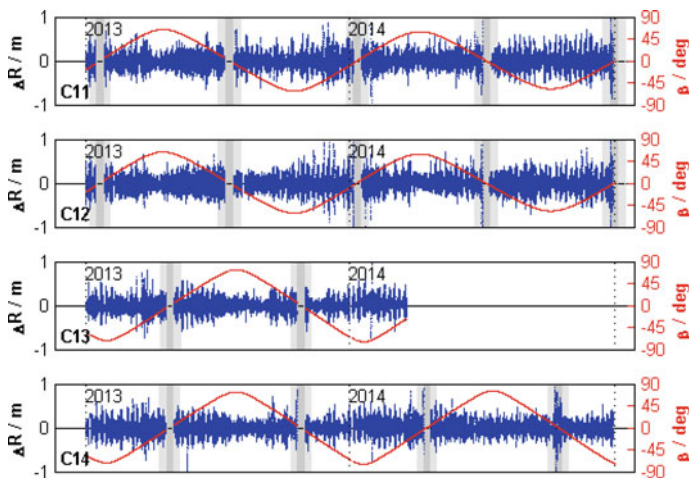


Fig. 3 Radial comparisons of BDS MEO orbits

mode, dramatic accuracy degeneration or even interruption of orbit is possible to occur.

Further detailed survey on Figs. 2 and 3 cannot reveal simple negative correlation between orbit accuracy and solar  $\beta$  angle. It is possible to experience rapid varying process of orbit accuracy during slowly varying process of  $\beta$  angle. The orbit accuracy shows some quasi-wave packet structure. This is possible to relate to parameter estimation of SRP model. Because  $\beta$  angle is taken as SRP parameter in basic frequency item and multiple frequency items, and during the SRP parameter estimation, the effects of these frequency items are involved in orbits.

### 3 SLR Validation

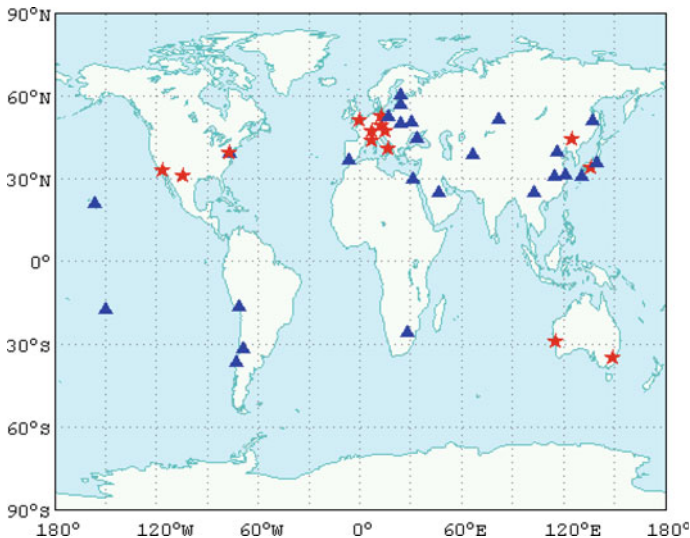
#### 3.1 SLR Observation

For navigation satellites, SLR is the unique high precision measurement independent to radio carrier phase measurement, and has been taken as an important orbit validation approach [8, 9].

Several satellites in BDS have been taken as international SLR monitoring. Fairly large amounts of SLR tracking data have been gained for one BeiDou GEO (G1, i.e., C01), two BeiDou IGSOs (I3, i.e., C08 and I5, i.e., C10), and one BeiDou MEO (M3, i.e., C11) from 2012. Current global ILRS tracking network consists of around 40 ground stations, which geographical distribution is shown in Fig. 4. On the basis of historical statistics, the observation in 14 stations illustrates the characters of large amount and high performance, so these 14 stations are selected as core stations, which are marked by asterisk symbols in Fig. 4. For BDS, among all core stations, Australian Yarragadee and Chinese Changchun occupy most of observation data, which account for more than 90 % of global sum.

#### 3.2 Validation Results

The orbits provided by regional network are validated by all observation provided by global SLR monitoring network. The precision of tropospheric model correction



**Fig. 4** Global distribution of SLR tracking network

**Table 2** Statistics of SLR validation

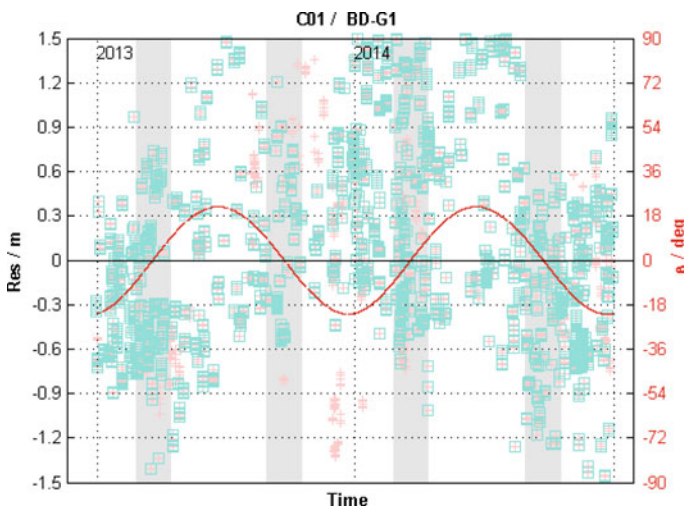
Sat type	Sat code	Cut-off elevation 20°			Cut-off elevation 60°		
		Points	Mean/cm	RMS/cm	Points	Mean/cm	RMS/cm
GEO	C01	1829	6.3	64.7	–	–	–
IGSO	C08	1820	–18.4	32.8	935	–16.6	29.7
	C10	4306	–14.3	31.0	495	–12.8	25.4
MEO	C11	4913	–0.2	22.2	1767	3.5	18.1

in SLR validation is relevant to observational elevation, so the statistics for cut-off elevation 20° and 60° are carried out separately. The ejection criterion for gross error is 1 m. Table 2 summarizes the bias and dispersion of SLR validation for all core stations.

It can be seen from Table 2 that RMS values of SLR validation show certain degree of reduction when the cut-off elevation increases from 20° to 60°. SLR validation residuals come from orbit error components along satellite–station line of sight, of which majority are orbit radial errors, but the influence of orbit transverse errors and normal errors also involved in the residuals. As shown in Table 1, significant transverse errors and normal errors exist in all satellites. With the increasing of observational elevation, the effects of transverse and normal components decrease, so the RMS values of SLR validation become a bit smaller.

For GEOs, IGSOs and MEOs, RMS values of residuals are around 0.6, 0.3, and 0.3 m. Restricted by the geometrical conditions of the regional network, the observational elevation for C01 is only around 40°, which leads to big value of RMS.

The temporal distributions of SLR validation residuals of these four satellites are illustrated in Figs. 5, 6, 7, and 8. No significant variation of residuals appears along



**Fig. 5** SLR validation sequence of C01 (GEO) orbit



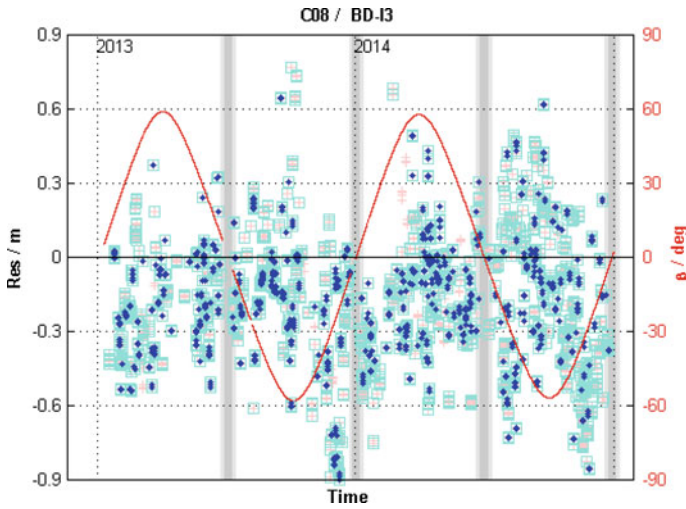


Fig. 6 SLR validation sequence of C08 (IGSO) orbit

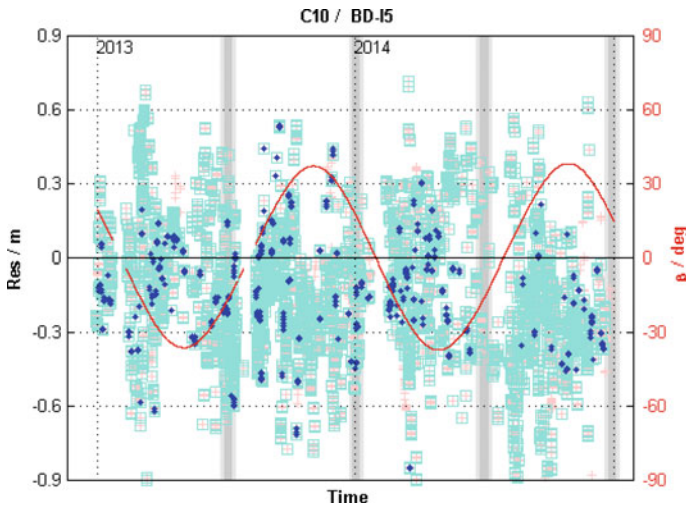


Fig. 7 SLR validation sequence of C10 (IGSO) orbit

with the variation of solar  $\beta$  angle. This is one of BDS' distinctive features because significant negative correlation between residual dispersion and  $\beta$  angle can be seen in GPS and Galileo systems.



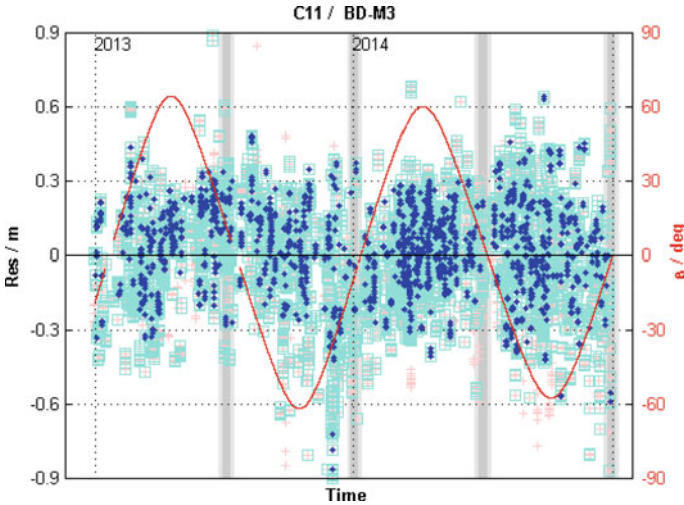


Fig. 8 SLR validation sequence of C11 (MEO) orbit

## 4 Summary

The accuracies of 2-year orbits from 2013 to 2014 provided by BDS regional network are evaluated by orbit comparison and SLR validation. The main results are as follows:

1. The comparisons with MGEX Wuhan University orbits show, for GEOs, that the 3D orbit accuracies are slightly better than 10 m, and the radial accuracies are around 0.4 m; for IGSOs, the 3D orbit accuracies are around 1–2 m, and the radial accuracies are around 0.3 m; for MEOs, the 3D orbit accuracies are better than 1 m, and the radial accuracies are better than 0.2 m. No significant negative correlation relation exists between orbit accuracy and solar elevation relative to orbit plane, which is different from GPS and Galileo satellites. Orbit accuracies degenerate during eclipse season or attitude mode change.
2. SLR validation accuracies of GEO/IGSO/MEO orbits of regional network are 0.6, 0.3, and 0.2 m, respectively, which are roughly equivalent to orbit radial accuracies. Orbit transverse and normal errors also throw certain effects on validation accuracies.

The evaluations of regional network orbits illustrate that BDSs contain different characters from GPS and Galileo satellites. Further dynamic models and estimation strategy suitable for BDS should be developed.

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