Initial Results of the Precise Orbit Determination for the New-Generation BeiDou Satellites (BeiDou-3) Based on the iGMAS Network

Bingfeng Tan,Yunbin Yuan, Mingyue Wen, Yafei Ning and Xifeng Liu

State Key Laboratory of Geodesy and Earth Dynamics, Institute of Geodesy and Geophysics, Chinese Academy of Sciences

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B.Tan: bingfengtan@whigg.ac.cn

B. Tan: bingfengtan@whigg.ac.cn
Y. Yuan: yybgps@whigg.ac.cn

Introduction

On 30 March 2015, China's first New-Generation (BeiDou-3) Navigation experimental satellite was successfully launched, which signaled the beginning of BDS's expansion from regional to worldwide coverage. By August 2016, five BeiDou-3 experimental satellites, each of which has a new navigation signal system, inter-satellite links, and other test features, have been launched, which brings the satellite navigation system closer to completion. By the end of 2018, eighteen BDS-3 satellites will be launched and eight BDS-3 satellites will be launched during 2017.

There are difficulties and limitations in the precise orbit determination of BeiDou-3 satellites. Compared to BeiDou-2 satellites, there are fewer and worse distributed tracking stations. The observations of a very limited number of 9 International GNSS (Global Navigation Satellite System) Monitoring and Assessment Service (iGMAS) stations and 52 Multi-GNSS Experiment (MGEX) stations from 16 July to 14 August 2016 are processed to determine the orbits of BeiDou-3 and BeiDou-2 satellites, respectively.

The internal consistency and satellite laser ranging (SLR) validations are conducted for the orbit validation. BeiDou-3 MEO (Medium Earth Orbit) (C33 and C34) have larger root mean square (RMS) values than those BeiDou-3 IGSO (C31 and C32), whereas BeiDou-2 MEO satellites have smaller RMS values than the BeiDou-2 IGSO satellites. Furthermore, BeiDou-3 IGSO and BeiDou-2 satellites have RMS values at identical levels, whereas BeiDou-3 MEO satellites have larger RMS values than the BeiDou-2 MEO satellites. The RMS residuals are approximately 10 cm in the radial component and approximately 25 cm in the along component for BeiDou-3 IGSO satellites. For BeiDou-3 MEO satellites, the RMS residuals are approximately 40 cm in the radial component and approximately 60 cm in the along component. The SLR validation reports that the orbit radial component can reach an accuracy on the level of 1 decimeter and 4 decimeters for BeiDou-3 IGSO and MEO, respectively.

Data Collection for BeiDou-3 Satellites POD

The BeiDou-3 satellites retain the navigation-signal-transmitting modulation system in deployment phase 1 (i.e., 1561.098 MHz (B1), 1207.140 MHz (B2), and 1268.520 MHz (B3)). Furthermore, BeiDou-3 satellites will include the migration of its civil BeiDou B1 signal from 1561.098 MHz to a frequency centered at 1575.42 MHz, which is identical to the GPS L1 and Galileo E1 civil signals, and its transformation from a quadrature phase shift keying (QPSK) modulation to a multiplexed binary offset carrier (MBOC) modulation similar to the future GPS L1C and Galileo's E1. Two frequencies of B2 (1176.45 (B2a) and 1207.14 (B2b)) and two frequencies of B3 (1278.75 (B3c) and 1268.52 (B3C)) will be candidates for the migration of civil BeiDou B2 and B3 signals. Because the new signals of BeiDou-3 satellites remain in the internal test stage, observations of old B1, B2, and B3 frequencies were selected for the BeiDou-3 satellite POD in this study.

China is developing the International GNSS Monitoring and Assessment Service (iGMAS) to monitor the nation's BeiDou satellites and other global navigation satellites to ensure the precise-orbit products of the systems in order to improve the signal availability, reliability, precision, and accuracy. In this study, 9 iGMAS stations (cf. Figure 1) were selected for the BeiDou-3 satellite POD, and the station information is listed in Table 1. For comparison, 52 MGEX stations (cf. Figure 1) were selected for BeiDou-2 satellites POD. The observation data of iGMAS and MGEX from 16 July to 14 August 2016 were processed for BeiDou-3 and BeiDou-2 satellite precise-orbit determination, respectively.

Table 1 Selected tracking stations from the International GNSS (Global Navigation Satellite System) Monitoring and Assessment Service (iGMAS).

Station Abb.	Location	Country	Receiver	Antenna
BJF1	Beijing	China	CETC-54 GMR-4011	LEIAR25.R4 LEIT
BRCH	Braunschweig	Germany	CETC-54 GMR-4011	LEIAR25.R4 LEIT
CLGY	Calgary	Canada	CETC-54 GMR-4011	LEIAR25.R4 LEIT
GUA1	Urumqi	China	GNSS_GGR	RINT-8CH CETD
LHA1	Lhasa	China	CETC-54 GMR-4011	NOV750.R4 NOVS
TAHT	Tahiti	France	GNSS_GGR	RINT-8CH CETD
WUH1	Wuhan	China	CETC-54 GMR-4011	LEIAR25.R4 LEIT
XIA1	Xian	China	GNSS_GGR	RINT-8CH CETD
XHON	Antarctica	United Nations	CETC-54 GMR-4011	LEIAR25.R4 LEIT

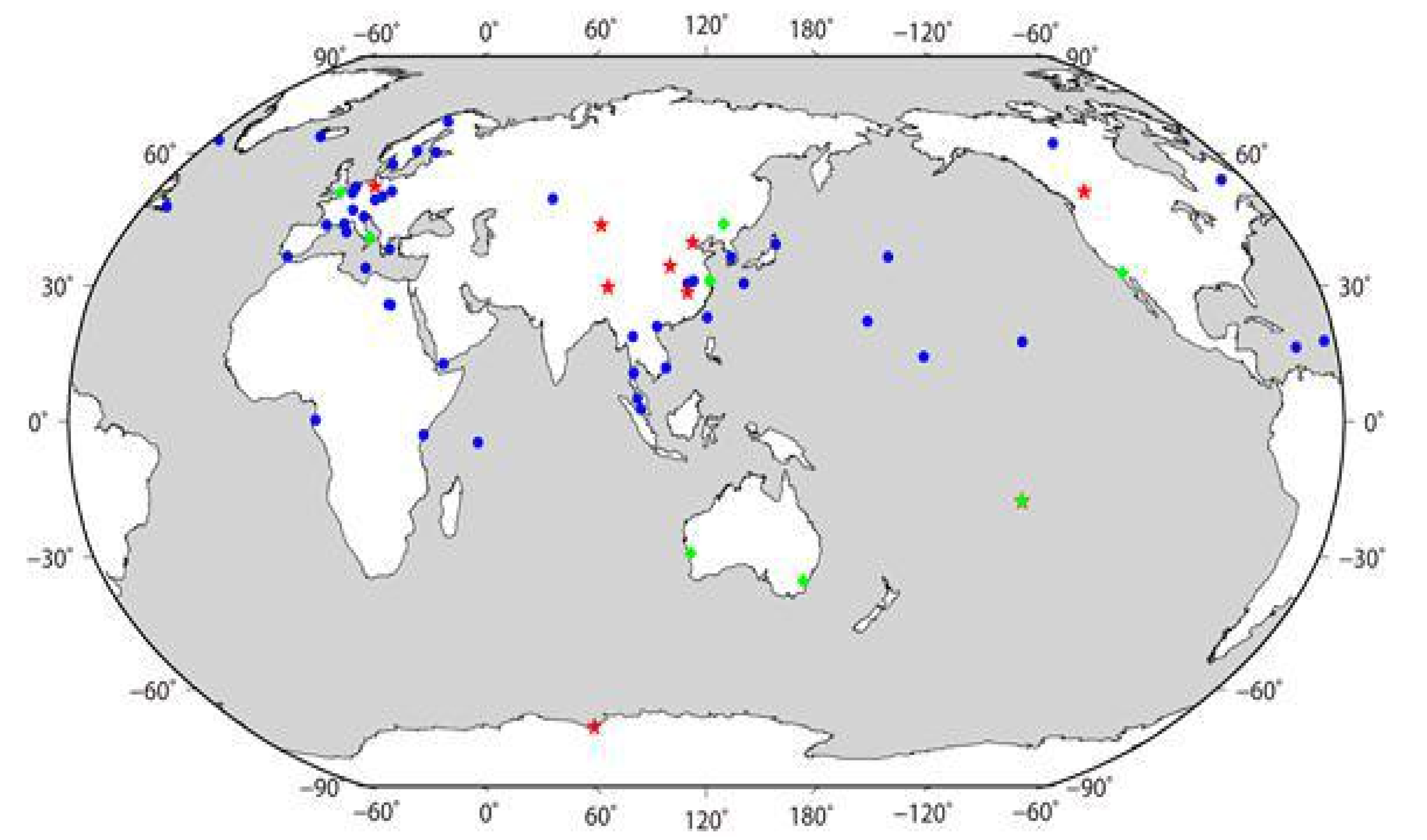

Fig. 1 Tracking stations in precise-orbit determination and satellite laser ranging (SLR) validation for BeiDou-2 and BeiDou-3 satellites. The stations are represented by red five-pointed stars, blue circles, and green diamonds for iGMAS, Multi-GNSS Experiment (MGEX), and SLR stations, respectively

Methods and Strategies for BeiDou-3 and BeiDou-2 Satellite POD

The routine software package developed by the Analysis Centre of iGMAS at the Institute of Geodesy and Geophysics (IGGAC), Chinese Academy of Sciences has been adapted to process data for BeiDou-3 and BeiDou-2 satellites in this study.

A two-step method is adopted in this study. In the first step, the stations for BeiDou-3 and BeiDou-2 satellite POD are embodied in a GPS POD process using the ionosphere-free linear combination (LC) of L1 and L2 phase observations with IGS rapid products. Then, in the second step, the relative accurate station coordinates (CRDs), earth rotation parameters (ERPs), and zenith tropospheric delays (ZTDs), which were obtained from the GPS POD process, are further fixed in the BeiDou-3 and BeiDou-2 satellite POD process using the ionosphere-free linear combination (LC) of old B1 and B3 phase and code observations beginning with the broadcast ephemeris. In the second step, only BeiDou-3- and BeiDou-2-related parameters (i.e., six keplerian elements and five solar radiation parameters (Constants in the D-, Y-, and X-directions and periodic in the X-direction), and pseudo-stochastic orbit parameters are estimated). The BeiDou-3 satellite antenna phase center (PCO) values are provided by the Operation Control Department, and no phase center variation (PCV) values are available. The estimated PCO and PCV for BDS IGSO and MEO satellites by Dilssner et al. are used for BeiDou-2 satellites. However, the PCO and PCV for ground antennas are not available.

Results

The obtained BeiDou-3 and BeiDou-2 satellite orbits in this study are assessed in terms of both internal consistency and external validation. For internal consistency, overlap comparisons are conducted. For external validation, satellite laser ranging (SLR) observations are used to independently assess the accuracy of the BeiDou-3 satellite orbits.

The average daily root mean square (RMS) values of the 24-h overlap in the radial, along, and cross-track components for each satellite are shown in Table 2 and Figures 2–5.

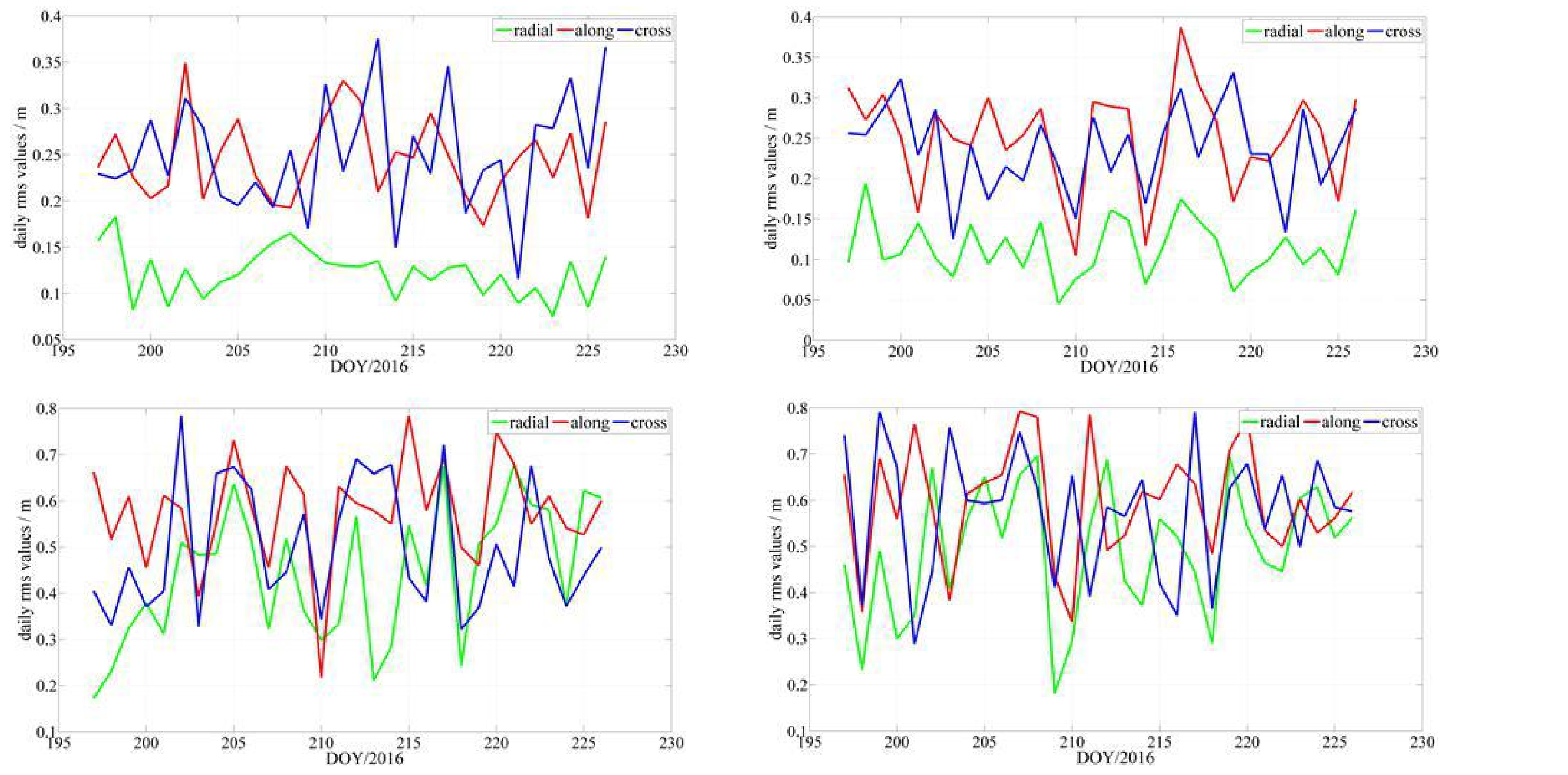

Fig. 2-5 overlap comparison in the radial, along, and cross-track components for BeiDou-3 C31, C32, C33, C34 satellites

Table 2 Averaged daily root mean square (RMS) values of 24-h orbit overlap comparison.

PRN of BeiDou Satellites	Radial (cm)	Along(cm)	Cross-track (cm)
BeiDou-3 C31 (IGSO)	12.51	24.95	23.82
BeiDou-3 C32 (IGSO)	11.88	25.81	24.32
BeiDou-3 C33 (MEO)	40.75	58.67	51.82
BeiDou-3 C34 (MEO)	41.16	59.88	59.11
BeiDou-2 C01 (GEO)	27.39	58.72	36.49
BeiDou-2 C02 (GEO)	25.72	38.79	29.09
BeiDou-2 C03 (GEO)	27.32	30.87	36.78
BeiDou-2 C04 (GEO)	41.55	69.19	47.12
BeiDou-2 C05 (GEO)	33.58	41.25	34.81
BeiDou-2 C06 (IGSO)	12.35	20.05	10.77
BeiDou-2 C07 (IGSO)	11.46	16.12	10.57
BeiDou-2 C08 (IGSO)	8.49	20.71	15.03
BeiDou-2 C09 (IGSO)	11.12	16.67	13.17
BeiDou-2 C10 (IGSO)	11.23	20.65	14.65
BeiDou-2 C15 (IGSO)	9.26	15.63	12.21
BeiDou-2 C11 (MEO)	5.69	12.45	6.37
BeiDou-2 C12 (MEO)	4.46	13.46	7.31
BeiDou-2 C14 (MEO)	5.22	14.41	12.19

The mean and RMS of SLR residuals of the middle day for orbit solutions are summarized in Table 3 and illustrated in Figures 6–9.

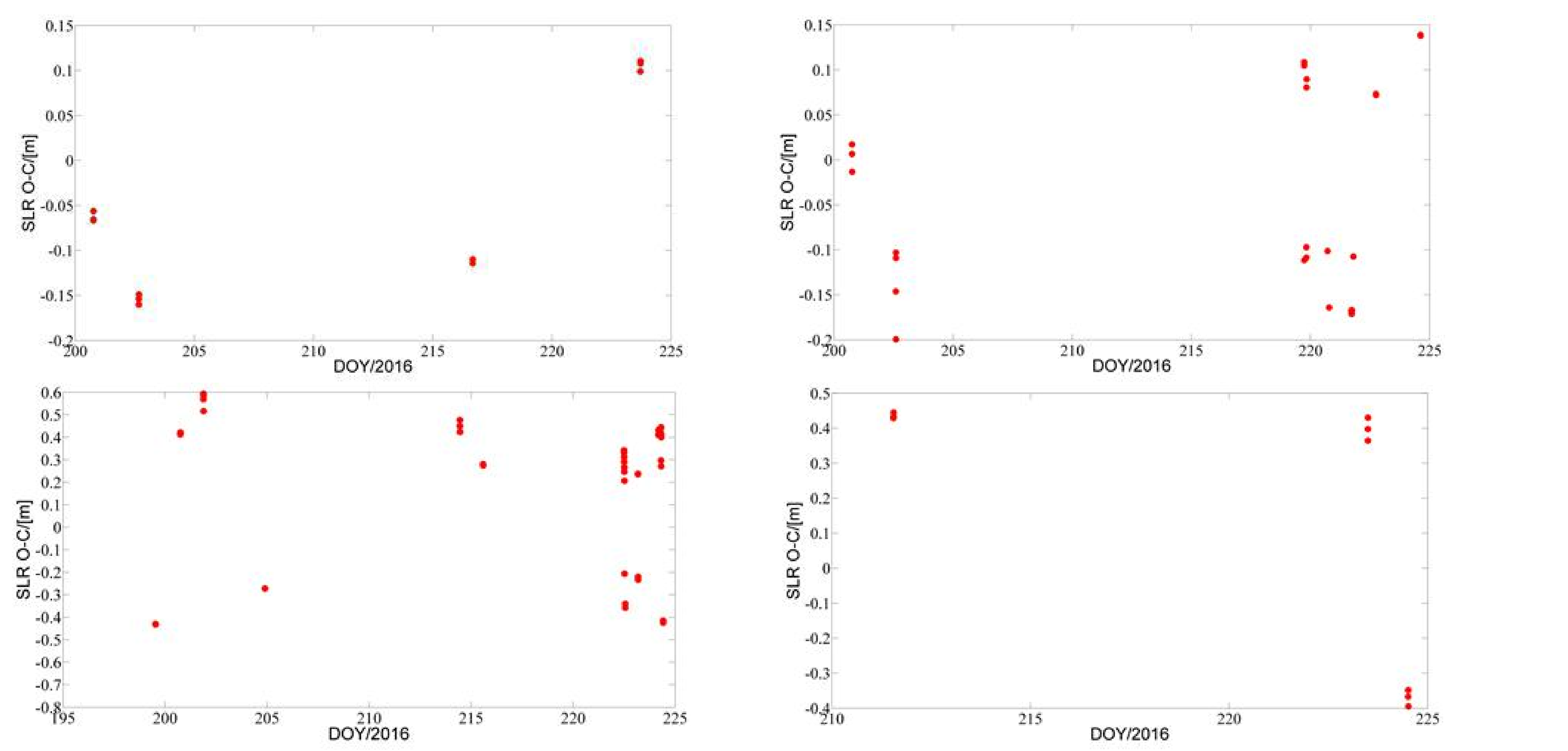

Fig. 6-9 SLR Validation for BeiDou-3 C31, C32, C33, C34 satellites

Table 3 SLR residuals of BeiDou-3 and BeiDou-2 satellites.

PRN of BeiDou Satellites	Mean (cm)	RMS (cm)
BeiDou-3 C31 (IGSO)	−3.82	11.25
BeiDou-3 C32 (IGSO)	−3.51	11.28
BeiDou-3 C33 (MEO)	15.64	38.61
BeiDou-3 C34 (MEO)	15.44	40.26
BeiDou-2 C01 (GEO)	−2.68	27.98
BeiDou-2 C08 (IGSO)	−4.27	8.51
BeiDou-2 C10 (IGSO)	−4.97	10.32
BeiDou-2 C11 (MEO)	2.92	5.91

Summary and outlook

a) We processed one month of observations from a very limited number of nine stations in the iGMAS tracking network for the precise orbit determination of BeiDou-3 satellites. Internal consistency and SLR validations were conducted, and the orbit radial component can reach an accuracy on the level of 1 decimeter and 4 decimeters for BeiDou-3 IGSO and MEO, respectively. The orbit radial component can reach an accuracy on the level of 1 decimeter and 0.5 decimeters for BeiDou-2 IGSO and MEO, respectively.

b) At present, the orbit determination performance for BeiDou-3 satellites, particularly for global BeiDou-3 MEO satellites, remains inferior to that of BeiDou-2 satellites and other GNSS constellations such as GPS and GLONASS. This problem has been attributed to the lack of a well-distributed worldwide tracking network for BeiDou-3 satellites, particularly MEO satellites. With a larger and more well-distributed global tracking network, the accuracy of BeiDou-3 satellite POD will be improved.

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