Chapter 30
Global Coverage Performance Analysis Based on 4 BeiDou MEO Satellites

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Abstract Constellation coverage performance is an important indicator of assessing constellation design, therefore this paper intended to provide reference for the deployment of BeiDou Navigation Satellite System in the future by analyzing the coverage performance of BeiDou navigation satellites. This paper studied two navigation constellation performance indicators which are continuous coverage and spatial configuration, and studied the design method for global coverage performance simulation based on 4 BeiDou MEO satellites constellation. Firstly, this paper analyzed global area which can be quadruple covered, time percentage of navigation availability and the PDOP average value within time of navigation availability; Secondly, this paper calculated PDOP value of observation points sharing the same longitude within one regression cycle, made statistical analysis of maximum coverage gap and average coverage gap of each point, and analyzed the variation of PDOP value in different latitudes; Finally, this paper analyzed periodic changes of global coverage area of navigation availability.

Keywords BeiDou navigation satellite system · MEO navigation satellite · PDOP value · Continuous coverage indicator · Spatial configuration indicator

30.1 Introduction

With more and more BeiDou navigation satellites launched successfully, BeiDou Navigation Satellite System basically has had the capability of providing regional passive services, and On December 27, 2011, BeiDou system declared to provide Initial Operational Capability (IOC) officially. Meanwhile, through One Launch

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Vehicle technology in launching double MEO Satellites, BeiDou System is still working on expanding service area, improving system performance and perfecting BeiDou regional constellation gradually. In line with the development plan, BeiDou system will complete the transition from regional constellation to global constellation by 2020. In view of the essential role of these 4 MEO satellites of BeiDou regional constellation in enhancing regional constellation (GEO + IGSO) and carrying-out of global constellation technology tests, the analysis of global coverage performance will be significant and provide indispensible reference value for further research.

As constellation coverage performance is an important indicator of assessing constellation design, the analysis of coverage performance of BeiDou navigation satellites in this paper will provide reference for the deployment of BeiDou Navigation Satellite System in the future. In 1970s, many experts aboard have done systematic research on the global constellation coverage, Walker [1] studied circular orbit patterns to provide continuous whole earth coverage and some different constellations to meet various performance requirements. In 1990s, many experts at home had begun to carry out the research of MEO satellite coverage performance. Sudan [2] studied the optimal method for constellation parameters of MEO communication regional satellite based on the analysis of major parameters of orbit, and analysed the global coverage capability of an optimal 5 MEO satellite constellation.

For the present however, few researches have been done on BeiDou MEO navigation satellites at home and aboard, because they are newly networked satellites. Considering that BeiDou system is still on its way to global continuous coverage due to only 4 MEO satellites launched, this paper intended to investigate the performance based on 4 BeiDou MEO satellites constellation in order to ensure its global coverage performance in future. By the simulation of continuous coverage and spatial configuration performance indicators, this paper gave preliminarily statistics of 4 BeiDou MEO satellites constellation, including worldwide coverage area, coverage period and navigation available range, in order to lay the foundation for the more in-depth studies of BeiDou global constellation and provide reference for subsequent deployment strategies of BeiDou system.

30.2 BeiDou Navigation Satellite System Development Plan

According to the overall planning of the "three-step" development strategy [3, 4], BeiDou is in the implementation of the "Phase II". Up to November 2012, there are 14 effective BeiDou navigation satellites in-orbit, including 4 GEO, 5 IGSO and 4 MEO satellites. Each satellite's design parameters are shown in Table 30.1.

Table 30.1 The designed parameters of BeiDou navigation satellite system

Satellite type	Satellite number	Orbit latitude	Orbit number	Orbit inclination	Serial number	RAAN
GEO	5	36000	1	0	GEO-1	58.75°E
					GEO-2	80°E
					GEO-3	110.5°E
					GEO-4	140°E
					GEO-5	160°E
IGSO	5	36000	5	55	IGSO-1	118°E
					IGSO-2	118°E
					IGSO-3	118°E
					IGSO-4	95°E
					IGSO-5	95°E
MEO	4	21500	2	55	MEO-1	0°E
					MEO-2	0°E
					MEO-3	120°E
					MEO-4	120°E

30.3 Simulation of 4 BeiDou MEO Satellites Constellation

30.3.1 Navigation Constellation Performance Indicators

Navigation constellation performance indicators are the fundamental basis of constellation design and navigation performance assessment, which include continuous coverage indicator, spatial configuration indicator, redundancy maintain indicator, configuration maintain indicator, independent performance indicator, etc. [5, 6]. Among them, navigation satellite systems are directly associated with the analysis of continuous coverage indicator and spatial configuration indicator. The analysis of 4 BeiDou MEO satellites constellation in this paper is mainly based on these two indicators by numerical simulation method.

30.3.1.1 Continuous Coverage Indicator

Continuous coverage indicator mainly estimates quadruple coverage capability of navigation constellation [7]. It includes some quantitative evaluation parameters, which are time percentage of navigation availability, maximum coverage gap and average gap [8].

Time percentage of navigation availability is the ratio of time with not only quadruple covered but also PDOP value under given threshold to total simulation time of point (i, j) in the grid of earth, which can be described as follows:

$$A_{tpna} = \frac{\int_{i=0}^{i=T_s} \{t|n_{tvs} \geq 4\&PDOP_i \leq k\}dt}{T_s} \times 100\,\% \tag{30.1}$$

In Eq. 30.1, n_{tvs} is the number of visible satellites, T_s is total simulation time, k is the threshold of PDOP value.

Coverage gap is the period of point (i,j) which cannot be covered by more than 3 satellites.

Maximum coverage gap is the maximum coverage gap of point (i,j) in the grid of earth during some period of time, which can be described as follows:

$$Tg_{\max} = \max\left\{Tg_{ij}^1, Tg_{ij}^2, \quad , Tg_{ij}^n\right\}, (i \in [-180, 180], j \in [-90, 90]) \tag{30.2}$$

In Eq. 30.2, Tg_{ij}^k is the k-th coverage gap of point (i,j) within total simulation time.

Average coverage gap is the ratio of total time of point (i,j) 's coverage gap and the number of coverage interrupts during some period of time, which can be described as follows:

$$Tg_{ave} = \frac{\sum_{i=1}^{i=n_{nci}} Tg_{ij}^k}{n_{nci}} \tag{30.3}$$

In Eq. 30.3, n_{nci} is the number of coverage interrupts during some period of time.

30.3.1.2 Spatial Configuration Indicator

Spatial configuration indicator mainly estimates spatial location and geometry strength of navigation satellites which are used in position calculation. We usually use dilution of precision (DOP) as metrics. DOP includes geometric dilution of precision (GDOP), horizontal dilution of precision (HDOP), vertical dilution of precision (VDOP), position dilution of precision (PDOP) and time dilution of precision (TDOP). The factors above can be calculated from locations of satellites known by users. The correspondence between DOP values and navigation performance is shown in Table 30.2 [9].

The equations of GDOP, PDOP, HDOP, VDOP and TDOP are shown as follows:

$$GDOP = (g_{11} + g_{22} + g_{33} + g_{44})^{1/2} = \sigma_g/\sigma \tag{30.4}$$

Table 30.2 The correspondence between DOP values and navigation performance

DOP value	<1	1–2	2–5	5–10	10–20	>20
Rating	Ideal	Excellent	Good	Moderate	Fair	Poor

$$PDOP = (g_{11} + g_{22} + g_{33})^{1/2} = \sigma_p/\sigma \tag{30.5}$$

$$HDOP = (g_{11} + g_{22})^{1/2} = \sigma_h/\sigma \tag{30.6}$$

$$VDOP = (g_{33})^{1/2} = \sigma_v/\sigma \tag{30.7}$$

$$TDOP = (g_{44})^{1/2} = \sigma_t/\sigma \tag{30.8}$$

In Eqs. 30.4–30.8, σ is ranging error, σ_g is geometric error, σ_p is position error, σ_h is horizontal error, σ_v is vertical error, and σ_t is time error. $g_{ii}(i = 1, \cdots, 4)$ are diagonal elements of $G = (H^T \cdot H)^{-1}$, in which H is observation matrix.

30.3.2 Simulation Design of 4 BeiDou MEO Satellites Constellation

In order to examine the impact of 4 MEO satellite on global coverage performance more clearly, BeiDou GEO an IGSO navigation satellites were not included in the simulation.

30.3.2.1 Input Variables and Conditions

As the simulation inputs, all orbital parameters of 4 BeiDou MEO satellites are shown in Table 30.1.

As the orbit of BeiDou MEO navigation satellite is the regression orbit of 7 days/13 circles, this paper set 7 days as the total simulation time, calculated grid points with the sampling frequency of every 5 min and the sampling grid of $5° \times 5°$, and set 7 as the threshold of PDOP.

30.3.2.2 Definition

If the PDOP value of grid point is blow 7 at the time t, we define that this point is available for navigation; that the area formed by all the navigation available points is navigation available area; and that the point with the best PDOP in navigation available area (or the best geometric point of constellation) is the centre of navigation available area.

30.3.3 Simulation Results

30.3.3.1 Result 1

Limited by the number of BeiDou MEO navigation satellites, the coverage area and coverage time of 4 BeiDou MEO satellites constellation is small and short. Figure 30.1 shows the global area which can be quadruple covered within one regression cycle; Fig. 30.2 shows each point's time percentage of navigation availability within one regression cycle; and, Fig. 30.3 shows each point's PDOP average value within the time of navigation availability.

30.3.3.2 Result 2

The PDOP value of the observation points on the equator changed irregularly, from which we can obtain the statistics of maximum coverage gap and average gap. Figure 30.4 shows each point's PDOP value in different latitude sharing the same longitude within one regression cycle, which are (0°E, 15°N), (0°E, 10°N), (0°E, 5°N), and (0°E, 0°N).

30.3.3.3 Result 3

In one regression cycle, the geometry configuration of 4 BeiDou navigation satellites in space changes periodically. So the navigation available area, navigation available time and the centre of navigation available area also changes periodically. Figure 30.5 shows the changes of navigation available area at different times within the same cycle.

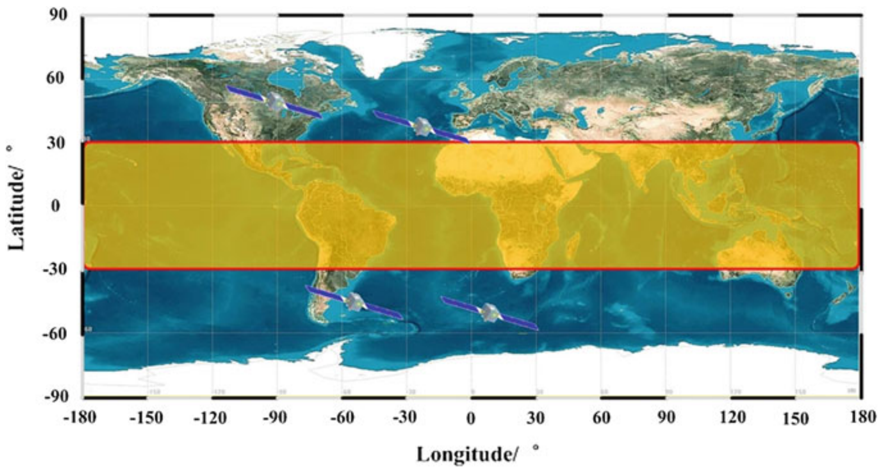

Fig. 30.1 The global area which can be quadruple covered within one regression cycle

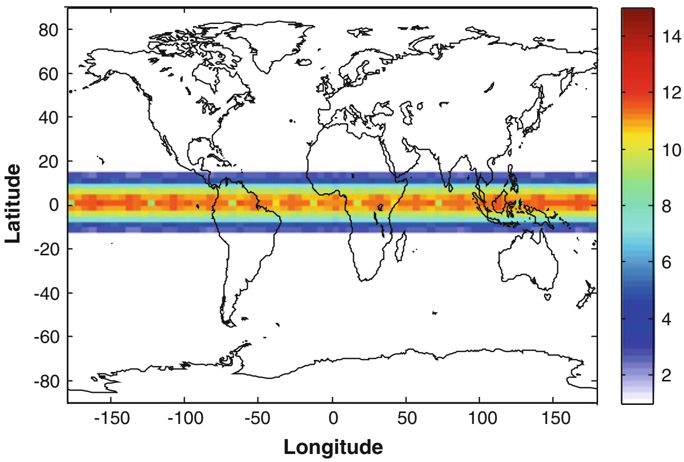

Fig. 30.2 Each point's time percentage of navigation availability within one regression cycle

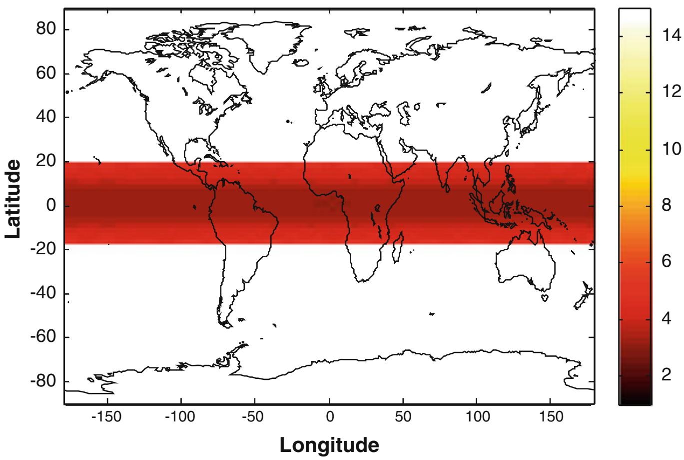

Fig. 30.3 Each point's PDOP average value within the time of navigation availability

30.3.4 Simulation Analysis

30.3.4.1 Analysis 1

From Result 1 in 3.3.1, we can obtain three points as follows:

Firstly, we can see that the global area which can be quadruple covered within one regression cycle is from 180°W to 180°E in longitude and from 20°N to 20°S in latitude; and that the navigation available area is from 180°W to 180°E in longitude and from 15°N to 15°S in latitude.

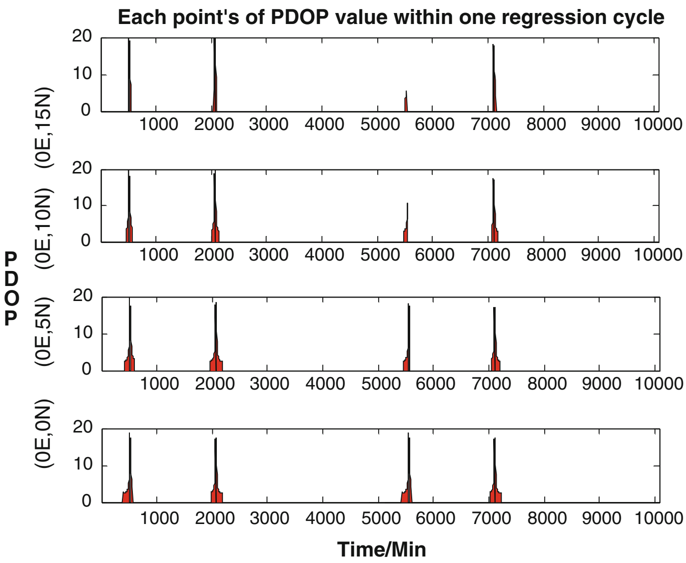

Fig. 30.4 Each point's PDOP value in different latitude sharing the same longitude within one regression cycle

Secondly, we can also see that navigation available time decreases toward both poles setting the equator as the boundary. The observation points on the equator have the longest time of navigation availability, approximately 19.5 h/7 days; meanwhile, the ones on latitude 15°N or 15°S have the shortest time of navigation availability, approximately 1.7 h/7 days.

Thirdly, we can also see that PDOP average value of the observation points within navigation available time increases toward both poles setting the equator as the boundary. PDOP average value of the observation points on the equator is the minimum, approximately 3.25; meanwhile, the one on latitude 15°N or 15°S is the maximum, approximately 4.90.

30.3.4.2 Analysis 2

From Result 2 in 3.3.2, we can obtain two points as follows: we can see that the maximum coverage gap of each observation point decreases toward both poles setting the equator as the boundary. The observation points on the equator have the shortest time of maximum coverage gap, approximately 54 h; meanwhile, the ones on latitude 15°N or 15°S have the longest time of maximum coverage gap, approximately 59 h.

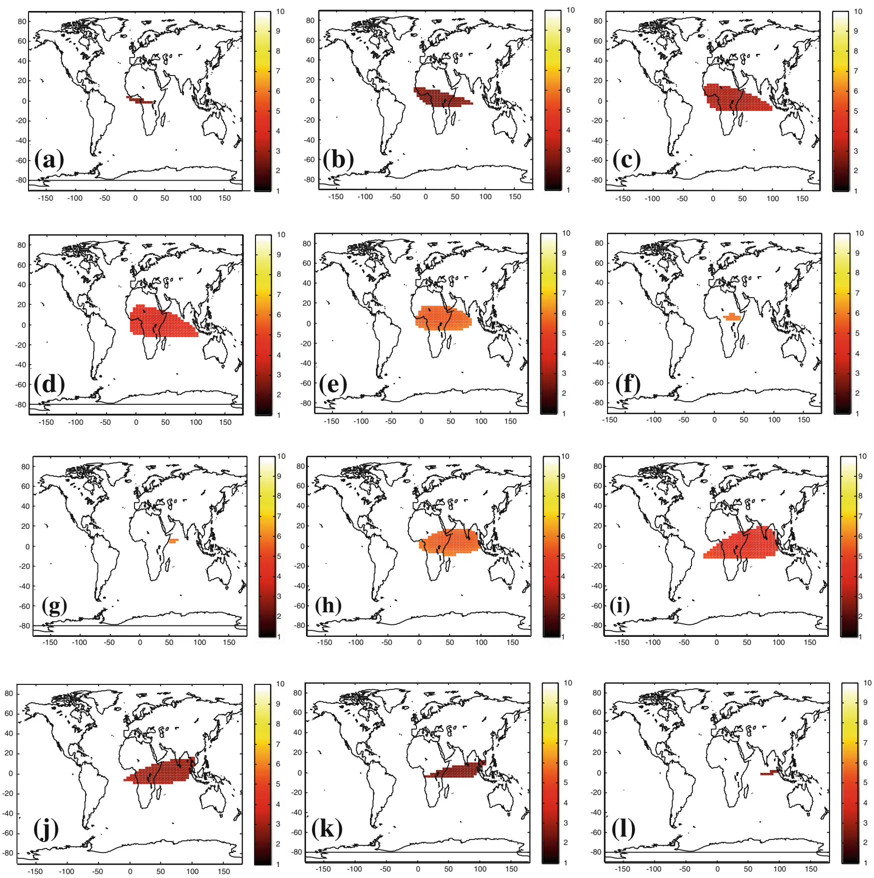

Fig. 30.5 The changes of navigation available area at different times within the same cycle. **a** t = 0 min. **b** t = 65 min. **c** t = 95 min. **d** t = 110 min. **e** t = 122 min. **f** t = 124 min. **g** t = 170 min. **h** t = 172 min. **i** t = 180 min. **j** t = 205 min. **k** t = 235 min. **l** t = 300 min

30.3.4.3 Analysis 3

From Result 3 in 3.3.3, we can obtain the periodic variation of navigation available area in different time:

The variation period is approximately 12.9 h, as same as the time of MEO satellite orbiting the earth one circle. The centre of navigation available area moves $14\pi/13$ westward in longitude during the variation period.

We can see in terms of the variation tendency of the size of navigation available area. In the beginning, the area appeared and expanded slowly until the maximum, and then reduced rapidly until disappeared, and after that it appeared again after a vanished period and expanded rapidly until the maximum, and then reduced slowly until disappeared again.

We can also see the variation tendency of the centre of navigation available area is that the centre firstly moved $2\pi/13$ westward in longitude during the first expansion period, and then moved $\pi/13$ westward in longitude during the first reduction period, and secondly moved $\pi/13$ westward in longitude during the first vanished period, and thirdly moved $\pi/13$ westward in longitude during the second expansion period, and then moved $2\pi/13$ westward in longitude during the second reduction period, and finally moved $8\pi/13$ westward in longitude during the second vanished period.

30.4 Conclusions

To sum up the simulation results above, we can come to four conclusions as follows:

1. 4 BeiDou MEO satellites constellation can offer discontinuous PNT services in navigation available area, which is from 180°W to 180°E in longitude and from 15°N to 15°S in latitude. In region of navigation available area, the navigation available time of each point is from 1.7 to 19.5 h per 7 days, within which the PDOP average value is below 5.
2. During the regression cycle, setting the equator as the boundary, the navigation available time of each point in navigation available area decreases toward both poles; and the PDOP average value of each point in navigation available area within its navigation available time increases toward both poles; and the maximum coverage gap of each point in navigation available area decreases toward both poles; and the average coverage gap of each point in navigation available area decreases toward both poles.
3. The variation period of navigation available area is approximately 12.9 h, as same as the time of MEO satellite orbiting the earth in one circle. During the variation period, the size of navigation available area expands and reduces twice, and the centre of navigation available area moves $14\pi/13$ westward in longitude.
4. Although 4 BeiDou MEO satellites cannot meet the requirement of global continuous coverage temporarily, they are enough to perform a variety of in-orbit test missions such as multi-satellite positioning test, heterogeneous satellite networking test, navigation signal debugging and so on.

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