Research on Backup Strategy of BeiDou Global Navigation System Constellation

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Abstract. BeiDou Global Navigation System (BDS-3) will be fully completed by 2020, and provide global users with high-quality services including positioning, navigation and timing, global short messages communication (GSMC), international search and rescue (SAR) etc. Compared with the regional navigation system, the global navigation system serves a wider area and more users, and the consequences are more serious in the event of a service outage. It is necessary to study the backup strategy of the space segment as early as possible in the early stage of system operation. Firstly, the paper analyses the effects of three kinds of satellite in different positions on the system performance, then analyses the probability distribution of multiple satellites failure, and then puts forward the satellite backup strategy. From the perspectives of improving GSMC coverage and increasing the available time of SAR, combined with the remaining life and configuration of the satellites in orbit, the orbit positions of redundancy satellites are suggested. The analysis results show that if one or two satellites are backed up in three MEO orbital planes, the robustness of the system will be improved effectively, and the availability of the system will be guaranteed even if any satellite fails. Furthermore, if four satellites equipped with SAR and GSMC load are backed up in proper phase on the first and third orbit planes, the availability of GSMC service will reach 100% in the global scope, and the availability of SAR service will be significantly improved.

1. Introduction

BeiDou Global Navigation System (BDS-3) will be fully completed by 2020, and provide global users with high-quality services including positioning, navigation and timing, global short messages communication (GSMC), international search and rescue (SAR) etc. Compared with the regional navigation system, the service areas and users of the global navigation system has increased significantly. Therefore, the global navigation system requires higher availability and continuity.

In order to ensure the high availability of global navigation system, it is necessary to maintain enough satellites in the constellation space segment all the times [1]. Due to the inevitable failure or unavailability of the satellite, it is necessary to study and implement appropriate backup strategies for the long-term operation and maintenance of navigation constellation.

Compared with other global satellite navigation systems in the world, BeiDou Global Navigation System has three kinds of orbits and can provide additional services. Previous studies mainly focused on BeiDou regional navigation system or ideal constellation system [2][3][4], but lack of the backup strategy research based on the characteristics of BeiDou global navigation system.
Starting from the effect of satellite failure on the system performance, this paper analyzes the contribution of three kinds of satellites in BeiDou Global Navigation System to the constellation performance, and then the space segment redundancy strategy is given.

2. Key considerations for constellation backup strategy
Compared with GPS, GLONASS and Galileo systems, BeiDou Global Navigation System has the following characteristics:

(1) The BeiDou Global Navigation System utilizes 3 GEO satellites, 3 IGSO satellites and 24 MEO satellites, which constitute a mixed constellation.

(2) The BeiDou Global Navigation System has two functions including navigation and positioning as well as data communication, and provides several kinds of services. Specifically, it provides three kinds of global services including RNSS, GSMC and SAR. Meanwhile, the satellite-based augmentation system (SBAS), ground augmentation system (GAS), precise point positioning (PPP) and regional short message communication (RSMC) services are provided in China and surrounding areas[5]. Short message communication service is unique to BDS.

Considering the actual characteristics of BeiDou Global Navigation System, and the requirements for system construction and constellation continuous service capability, the key factors to be considered in its backup strategy is as follows:

(1) The first consideration of backup strategy is to ensure the stability of system performance.

(2) The redundancy satellite configuration should be considered to improve the additional load performance.

(3) While ensuring the stability of the system performance, the backup satellites should gradually complete the new technology verification in order to upgrade the system.

(4) It is helpful to save the construction costs while determining the production and launch plan of the backup satellite based on the failure analysis of satellites in orbit.

(5) The launch plan of the backup satellites needs to match the construction progress of the corresponding ground system.

3. Impact of satellites failure on constellation performance
According to the target orbital position while BeiDou Global Navigation System completed, the availability worldwide reaches 100% under the condition of PDOP ≤ 3, while 3 GEO and 3 IGSO satellites have enhanced coverage in the China and surrounding area.

Several typical conditions as shown in Table 1 were selected to analyze the effect of satellite failure on constellation performance in different orbits. The percentage of regions with maximum PDOP from less than 10 to less than 3 in the orbital regression cycle is analyzed to reflect the change of PDOP in case of satellite failure.
Table 1. Constellation failure conditions and the maximum PDOP global (availability = 100%)

| No. | The distribution of failed satellites                     | Max PDOP (%) |
|-----|-----------------------------------------------------------|--------------|
|     |                                                           | ≤3 | ≤5 | ≤10 |
| W1  | 1 GEO satellite failed                                   | 100| 100| 100|
| W2  | 1 IGSO satellite failed                                  | 100| 100| 100|
| W3  | 2 GEO satellites failed                                  | 100| 100| 100|
| W4  | 2 IGSO satellites failed                                 | 100| 100| 100|
| W5  | 3 GEO and 3 IGSO all failed                              | 100| 100| 100|
| W6  | 1 MEO satellite failed                                   | 45 | 98 | 99 |
| W7  | 2 MEO satellites on the same orbital plane failed        | 39 | 88 | 98 |
| W8  | 2 MEO satellites on different orbital plane failed       | 25 | 75 | 82 |
| W9  | 3 MEO satellites on the same orbital plane failed        | 35 | 73 | 78 |
| W10 | 1 MEO satellite in each of the three orbital planes failed | 20 | 52 | 71 |
| W11 | 3 MEO satellites on each two orbital planes failed       | 15 | 28 | 47 |
| W12 | 2 MEO satellites on each three orbital planes failed     | 14 | 23 | 45 |

The analysis results show that GEO, IGSO and MEO satellites failure contribute differently to constellation performance. GEO and IGSO satellites failure have little effect on PDOP on global scale, and the constellation can ensure a good position dilution of precision even when all GEO and IGSO satellites fail. While MEO satellites failure has the greatest impact on position dilution of precision worldwide. Details as follow:

1. When one MEO satellite fails, the maximum global PDOP decreases greatly. The area with PDOP < 3 decreased remarkably, but most of them met PDOP ≤ 5.
2. When two MEO satellites fail, the maximum global PDOP changes significantly. From the overall effect, the failure of two MEO satellites with different orbital plane has greater effect on the performance of the constellation than those with the same orbit.
3. When three MEO heterorbit satellites fail, the maximum PDOP in global coverage changes greatly. The area of PDOP < 3 was greatly reduced to less than 20%. PDOP > 5 occurred in more than half of the areas, and PDOP > 10 occurred in a small number of areas. Six or more MEO satellites fail, the area with PDOP ≤ 10 is less than 50% (time availability is 100%).

4. Failure probability analysis of satellites
Suppose there are n satellites in the constellation, the reliability of a satellite is \( R(t) \), and the satellite failure follows exponential distribution, then the probability of satellite failure is proportional to the working time. Assuming that the reliability of the satellite’s 10-year life is \( a \), the reliability changes during the satellite life can be expressed as [6]:

\[
R(t) = e^{-\frac{t}{10a}}
\]

(1)

Where, \( t \) is working time of the satellite. The unreliability is:

\[
F(t) = 1 - R(t)
\]

(2)

The probability of \( m \) satellites failure in constellation composed of \( n \) satellites can be expressed as:

\[
F_{n,m} = C_n^m R(t)^{n-m} F(t)^m
\]

(3)

Therefore, the probability of failure of \( m \) or more satellites in a constellation of \( n \) satellites can be expressed as:
\[ F_{n,m} = 1 - \sum_{i=0}^{m-1} C_m^i R(t)^{n-i} F(t)^i \]

Here \( i \) means the number of failure satellites.

According to BDS satellites’s performance in orbit, the constellation failure probability can be given as bellow. Assume that the inherent reliability of MEO satellite for 10 years is 0.67, while that of GEO / IGSO is 0.66. The failure probability of MEO or GEO / IGSO satellites within 10 years is shown in Table 2 and Table 3.

**Table 2.** MEO Constellation failure probability in 10 years

| Time(year) | MEO satellite reliability | Probability that the number of failed satellites | \( \geq 1 \) | \( \geq 2 \) | \( \geq 3 \) |
|------------|--------------------------|-------------------------------------------------|-------|-------|-------|
| 1          | 0.96                     | 0.61                                            | 0.24  | 0.06  |
| 2          | 0.93                     | 0.83                                            | 0.52  | 0.24  |
| 3          | 0.89                     | 0.94                                            | 0.75  | 0.49  |
| 4          | 0.85                     | 0.98                                            | 0.88  | 0.70  |
| 5          | 0.82                     | 0.99                                            | 0.95  | 0.84  |
| 6          | 0.78                     | \( \approx 1.00 \)                              | 0.98  | 0.92  |
| 7          | 0.76                     | \( \approx 1.00 \)                              | 0.99  | 0.95  |
| 8          | 0.73                     | \( \approx 1.00 \)                              | \( \approx 1.00 \) | 0.98  |
| 9          | 0.70                     | \( \approx 1.00 \)                              | \( \approx 1.00 \) | 0.99  |
| 10         | 0.69                     | \( \approx 1.00 \)                              | \( \approx 1.00 \) | 0.99  |

**Table 3.** GEO/IGSO Constellation failure probability in 10 years

| Time (year) | GEO/IGSO satellite reliability | Probability that the number of failed satellites | \( \geq 1 \) | \( \geq 2 \) | \( \geq 3 \) |
|-------------|--------------------------------|-------------------------------------------------|-------|-------|-------|
| 1           | 0.96                           | 0.21                                            | 0.02  | 0.00  |
| 2           | 0.92                           | 0.38                                            | 0.07  | 0.01  |
| 3           | 0.89                           | 0.51                                            | 0.14  | 0.02  |
| 4           | 0.85                           | 0.62                                            | 0.22  | 0.05  |
| 5           | 0.81                           | 0.71                                            | 0.31  | 0.08  |
| 6           | 0.78                           | 0.78                                            | 0.40  | 0.13  |
| 7           | 0.75                           | 0.82                                            | 0.47  | 0.17  |
| 8           | 0.72                           | 0.86                                            | 0.54  | 0.23  |
| 9           | 0.69                           | 0.89                                            | 0.61  | 0.28  |
| 10          | 0.66                           | 0.92                                            | 0.66  | 0.33  |

According to Table 2 and Table 3, the inherent reliability of the three types of satellites decreases gradually with the increase of service time and the probability of failure increases.
Figure 2. The probability of the number of failure satellites more than i (i=1,2,3) changed with time.

The probability of one MEO satellite failure exceeds 0.6 within one year, and the value increases to 0.9 within three years. The probability of one satellite failure is close to 1 within 5 years. The probability of two satellites failure transcends 0.7 within three years, and the value surpasses 0.9 within 5 years. The probability of failure of three satellites exceeds 0.8 at the same time. While the probability of one GEO / IGSO satellite failure exceeds 0.5 within 3 years, the value transcends 0.6 within 10 years, and the probability of two satellites failure exceeds 0.6 with the same period.

5. Analysis of redundancy strategy of BDS global space segment
Based on the analysis Chapter 3 and Chapter 4, the following conclusions can be drawn:

(1) The failure of MEO satellites has the most significant impact on the performance of global system constellations.
(2) The failure probability of MEO satellites in orbit is greater than that of GEO / IGSO satellites.

Based on the above two points, we should first consider backing up MEO satellites in orbit. With reference to GPS and GALILEO system construction experience, at least one or two satellites per MEO orbital plane should be backed up to improve the robustness and ensure continuous and stable services of the system. Considering that MEO satellites are launched with double satellites, it is recommended to back up at least two satellites per orbital plane.

Considering the remaining life of the satellites in orbit and the improvement of the additional load coverage performance of the satellite, a scheme of reissue orbit and phases is given.

5.1. Suggestion of replacement orbit based on satellite development status
BeiDou Global MEO satellites launch time and configurations are shown in Table 4 and Figure 3[7]. In the table below, A, B and C represent orbital planes, and 1 to 8 represent phases. In this paper, the first satellite is selected as A1 phase.
Table 4. Launch time and load configuration of BeiDou global MEO Navigation System

| Project number | Launch time | Orbital plane and phase | RNSS + |
|----------------|-------------|-------------------------|--------|
| 1, 2           | 2017-11-5   | A1,A2                   |        |
| 3, 4           | 2018-1-12   | C6,C7                   |        |
| 5, 6           | 2018-2-12   | C4,C5                   |        |
| 7, 8           | 2018-3-30   | A7,A8                   |        |
| 9, 10          | 2018-7-29   | B1,B3                   |        |
| 11, 12         | 2018-8-25   | B2,B4                   | GSMC   |
| 13, 14         | 2018-9-19   | A4,A6                   | GSMC   |
| 15, 16         | 2018-10-15  | C1,C3                   | GSMC   |
| 17, 18         | 2018-11-19  | B6,B8                   | GSMC   |
| 19, 20         | 2019-9-23   | B5,B7                   | GSMC,SAR |
| 21, 22         | 2019-11-23  | C8,C2                   | GSMC,SAR |
| 23, 24         | 2019-12-16  | A3,A5                   | GSMC,SAR |

As can be seen from Table 4 above, the first to eighth satellites were launched earlier. Without considering the sudden failure, the eight satellites fail earlier than others. Priority should be given to the redundancy satellites near this orbit.

Figure 3. The schematic diagram of BeiDou MEO load configuration and phases in orbit

After analysis, when two satellites are added to each of the tree orbital plane, the global PDOP is less than 2.8 under 100% availability, and can also be guaranteed to be less than or equal to 3 in the event of any satellite failure.
5.2. Suggestion of redundancy phase based on improvement of additional load coverage performance

According to the satellite configuration in Table 4, the double coverage of the GSMC load of 14 satellites is analyzed. At an elevation angle of 15 degrees, the time availability reaches 95%. While considering 100% time availability, the global double coverage ratio is only 23%.

**Figure 4.** 14 MEO can achieve double coverage in 23% of regions worldwide (availability=100%)

**Figure 5.** Add 4 redundancy MEO satellites can achieve double coverage in 100% of regions worldwide (availability=100%)

By adding A1, A2, C4, C7 satellites configured GSMC load from the recommended redundancy orbit in Section 5.1, the availability of global double coverage at an elevation angle of 15 degrees reaches 100%.

According to the satellite configuration in Table 4, this article analyzes the time ratio simultaneously visible to the ground station at least 3 satellites, and the result is only 19% at an elevation angle of 5 degrees.

**Figure 6.** The time ratio of simultaneously seeing 3 of 6 MEO satellites in Beijing reaches 19%

**Figure 7.** The time ratio of simultaneously seeing 3 of 10 MEO satellites in Beijing can reaches more than 70%

If the redundancy satellite is equipped with SAR, the coverage performance will be improved. The coverage capacity of SAR is analyzed and compared by selecting different phases from the recommended redundancy orbit in Section 5.1.
Table 5. The time ratio of simultaneously seeing 3 MEO satellites in Beijing by adding SAR loads at different phase

| Plan number | Redundancy satellites in orbit phases | Time ratio of simultaneously seeing 3 satellites |
|-------------|--------------------------------------|--------------------------------------------------|
| Plan 1      | C4, C5, A1, A2                       | 67%                                               |
| Plan 2      | C4, C6, A1, A2                       | 69%                                               |
| Plan 3      | **C4, C7, A1, A2**                   | **72%**                                           |
| Plan 4      | C5, C6, A1, A2                       | 68%                                               |
| Plan 5      | C5, C7, A1, A2                       | 71%                                               |

After analysis, by adding a search and rescue load on the same A1, A2, C4 and C7 satellites, the time ratio of simultaneously seeing three satellites increases to more than 70%.

Based on the launch orbit and configuration of Table 4, and the conclusions of sections 5.1 and 5.2, the orbital phase of MEO redundancy satellites is recommended to be near A1, A2, C4 and C7, and the phase interval is appropriate to meet the interval of phase maintenance during the life period. This redundancy method can take into account both the constellation reliability and the coverage performance of additional loads.

6. Conclusion

By analysing the effects of three kinds of satellites in different positions of BeiDou Global Navigation System and the failure probability of satellites in orbit, the conclusion is as follows:

(1) MEO satellite failure has the most obvious effect on the performance of global system constellation.

(2) The failure probability of MEO satellite in orbit is higher than that of GEO / IGSO satellite.

Based on the above conclusion, this paper proposes to backup two satellites respectively in three orbital planes of MEO, which will effectively improve the robustness of the system and the availability of the system will be guaranteed even if any satellite fails.

Furthermore, from the point of view of improving the GSMC coverage and the available time of SAR, combined with the remaining life and configuration of satellites in orbit, this paper proposes the redundancy orbit location. After analysis, four satellites equipped with GSMC and SAR load are backed up in proper phase on the first and third orbit planes, the availability of GSMC service will reach 100% globally, and the availability of SAR service will be significantly improved at the same time.

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