A Space-Circle Architecture Design and Performance Analysis of Spatial Backbone Network Based on Geostationary Satellite Collocation

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Abstract. With the development of satellite technology, and continuous improvement of relay, communication, navigation, remote sensing and meteorological satellite systems in China, massive heterogeneous spatial information needs for convergence, integration, storage, transmission, processing, forwarding and so on had put forward higher requirements to the construction of spatial backbone network. Proceeding from the architecture design of spatial backbone network, using the method of geostationary satellite collocation to build the backbone node was proposed. And then several typical geostationary satellite collocation styles were analyzed and compared. Using Orbital dynamics and spherical geometry theory, a fly around model with space-circle configuration was designed, and its AER performance was analyzed through simulation software and optimization algorithm. The simulation results showed that the configuration completely meet design requirements of spatial backbone network.

Keywords: Space-Circle Architecture · Geostationary satellite collocation
Spatial backbone network · Architecture design · Performance analysis

1 Introduction

The various platforms of spatial information network were distributed at different heights in the space environment, with characteristics of dynamic, complex relationships between nodes and network topology heterogeneous. As national information infrastructure, taking considering of limited in global station construction, space information network had basically taken consensus architecture shape of "backbone network + access network" in China [1–5].

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Space-based Backbone Networks (SBN) were generally composed by integrated GEO satellite backbone nodes with function of broadband access, data relay, routing and switching, information storage, processing and integration. Although the network topology was simple, but massive heterogeneous business access requirements in the future, made the single platform capacity and scarcity of orbital resources to be challenges. How to overcome these challenges, there were two solutions: one was the lager GEO platform and payload; the second was Geostationary Satellite Collocation [6].

However, lager platforms would face vexed problems such as launching, on-orbit Assembly and invulnerability etc. The structure of Geostationary Satellite Collocation means that multi-satellite shares the same orbital, and working collaboratively to recover the lack-ness of single lager platform. The ideal solution had advantages of (1) allowed space modular growth and (2) could be used in distributed computing (3) was more robust and (4) platform design and launching were simple. But Geostationary Satellite Collocation would also cause internal clusters structure optimization, reasonable designing backbone cluster node with stable structure and little maintaining cost was the first problem to be solved.

2 Research Progress

2.1 Geostationary Satellite Collocation Architecture

In terms of Geostationary Satellite Collocation architecture design, many famous Aerospace experts in the field of service and engineering were gathered by Italian Alcatel Space, Spain GMV company, Switzerland kangtelafusi company, Luxembourg SESAstra and the Canadian Telesat company. And then the SkyLAN system concept was proposed [7]. The system was actually a space network composed by multiple GEO satellites based on the standard inter-satellite communication interface. This concept was making functions of single satellite separated to multiple different, smaller satellites in the same orbit. Therefore, SkyLAN was a satellite cluster which exchange information via ISL, and execute comprehensive and integrated functions. The conceptual diagram was shown in Fig. 1.

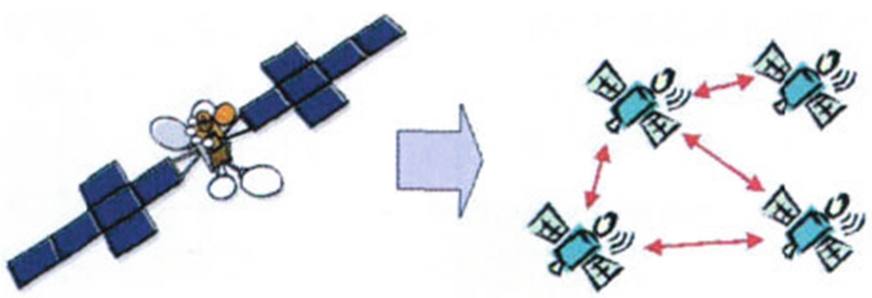

Fig. 1. SkyLAN conceptual diagram

In order to replenish and maintain military failure satellites timely in the war of future, the United States launched the operational responsive space (ORS) program, through the rapid Assembly, Integration and Test (AIT) and the deployment of small, low-cost satellites, complete development of response, enhance or supplement the space forces, enhancing the use of space and space control capabilities. In order to verify the above ideas, US DARPA proposed and invested the F6 development plan as an important part of the ORS program. The F6 program was shown in Fig. 2 [8]. F6 system put a full-function lager satellite into a few special platform groups. These small platforms exchange data wirelessly. This "plug and play" network could make updating and changing task simply by add a new satellite.

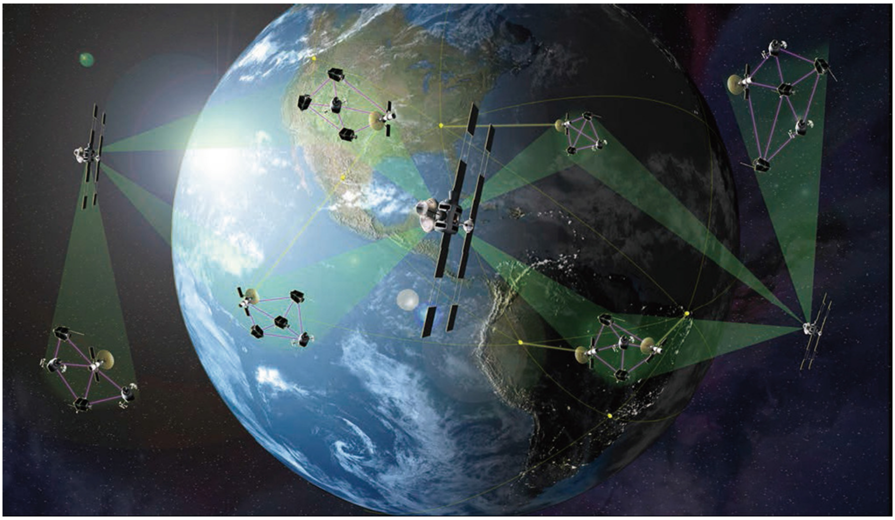

Fig. 2. The constellation diagram of F6 plan [9]

DARPA planned to implement F6 in four stages. First stage was concept design of satellite system, designing project framework using orbit dynamics. And also, contract team would develop a test-bed based on hardware in loop for software simulation on task of spacecraft module separation. Second stage was accomplishing system detail design, hardware and software development of satellite function module. Third stage was completing function module development for system integrated and ground simulation test validation. Fourth stage was launching function module, compositing satellite network, and on-orbit demonstration.

2.2 Geostationary Satellite Collocation Orbital Design

Because of the great potential technical advantages of Geostationary Satellite Collocation, it had very broad applications in military and civilian field, and was wildly researched by many experts and scholars. The fixed circular orbit model was assumed by Ross [10], and the linear mathematical expressions were given under the J2 perturbation. However, intersection node perturbation and apsides rotating under J2 perturbation making the model available only in a short time. Analytical expression for the relative motion of the satellite was given using method of unit spheres by Vadali [11]. And a linear approximate solution of near-circular orbit was given by constructing transfer matrix using the spherical geometry method by Schweighar and Sedwick [12]. A higher order moving model based on the Gauss equation was given, and a method for solution of nonlinear relative motion was proposed in [13]. A trajectory design method of distributed constellations was given and applied in Earth observation satellite systems in [14]. A least squares estimation method for satellite formation flying orbit design was given in [15], using least squares estimation method to design the orbital elements of rest concomitant satellites under reference satellite orbital elements and relative motion. A orbital phase control method to achieve orbit approach and fly-around orbit parameters design in [16]. These methods above were only suitable for distributing low-orbit remote sensing satellite orbit design, and orbit resources does not need to be considered. Taking into account the particularity of the GEO satellite with the scarcity of orbital resources, not only to ensure the stability of group structure, but also to ensure flying-around satellite cannot interfere with other satellites in orbit, Existing methods cannot meet the configuration requirements for Geostationary Satellite Collocation.

3 Backbone Network Architecture Analysis of Geostationary Satellite Collocation

3.1 Analyze Requirements

According to spatial development strategy of information network in China, as an important part of the future global information infrastructure, space-based backbone network would be the center of information gathering, management and control for space information system, and could accomplish three core functions of user, control and operation management. As the core node of space information system, the backbone network was designed to work with existing satellite system cluster together to complete the mission requirements, and accomplish interconnection of heterogeneous satellite systems, user's random access and information sharing, and could apply to modern military activities as well as Government and industry sectors. Space-based backbone network design must take into account the following factors:

- The SBN will be an information network that has regional expanding to global coverage. When designing satellite constellation, the ability of global coverage should be considered. And the GEO satellites to construct the constellation should be best choice.
- The SBN will provide various services including information gathering, integration, forward and management for various heterogeneous space platforms of spatial information network, and must have the link transmission capability of large capacity. Since lager GEO platform design, launching, assembly is facing a bottleneck, Geostationary Satellite Collocation will eliminate the disadvantages of

platform, allows modular growth of space segment, at the same time reduce the initial investment cost of the system;

- The SBN is a global coverage constellation, constricted by setting the abroad ground and TT&C stations. It requires the network running autonomously to solve the TT&C problem out of our country and to improve network survivability.

Therefore, under the analysis of space environment characteristics and the space-based platform ability, facing the different application requirements of national defense and military, a service oriented uninterrupted SDN architecture was designed. In Fig. 3, the schematic of SBN structure was given follow. It was divided to six core nodes, and each core node cluster includes 4–5 GEO satellites, those satellites work cooperatively to meet service needs for SBN.

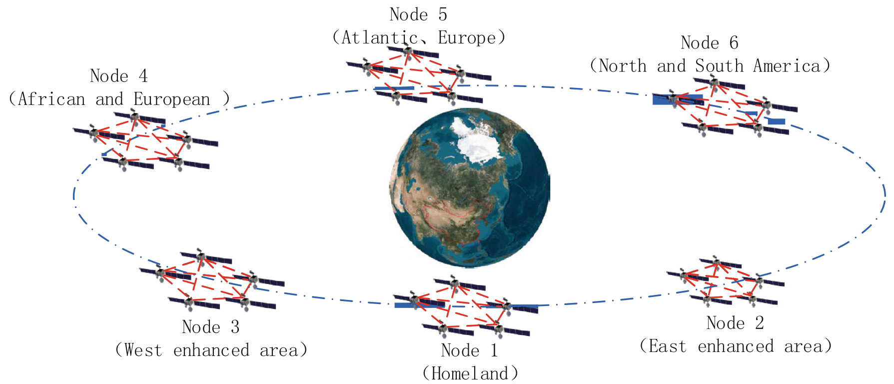

Fig. 3. Schematic of space-based backbone network structure

3.2 Configuration Analysis of Backbone Node Cluster

According to SBN design, its core node uses the configuration of distributed Geostationary Satellite Collocation cluster, this configuration can greatly improve system survivability, self-organization capability, and so on. At present, the typical cluster configuration includes fly-with, sway, fly-around, each configuration has their own advantages and disadvantages. After research and analysis, the applicable space-based trajectory design method for core node will be determined.

- Fly-by cluster configuration

The Fly-with distributed cluster configuration is shown in Fig. 4. All nodes construct a queue to form a distributed cluster, the advantage of this configuration is the constellation design simple, relatively simple position change the relationship between adjacent satellites. But for GEO constellation, this configuration occupies multiple adjacent orbital positions. Considering of GEO orbit resource scarcity currently, engineering implementation is almost impossible.

- Sway cluster configuration

The sway cluster configuration is shown in Fig. 5. All nodes are swing in one orbit position to form distributed cluster, this configuration has advantage of simply constellation design, and only occupy one GEO orbit position. But the azimuth, elevation and range between adjacent node change dramatically, taking inter-satellite high speed directional antenna for example, it is great challenge for antenna Acquisition Tracking Pointing (ATP).

- Fly-around cluster configuration

The fly-around distributed cluster is designed in Fig. 6. Setting a main fix GEO satellite node, the others fly around the fix node in circle to form a distributed cluster. The advantage of this configuration is making the relative position fixed by orbital optimization designed. And because of adding eccentricity, it can effectively avoid crash with other GEO orbital satellite. While its design is much more complex, need to optimize the orbital elements, and belong to multi-objective optimization problem.

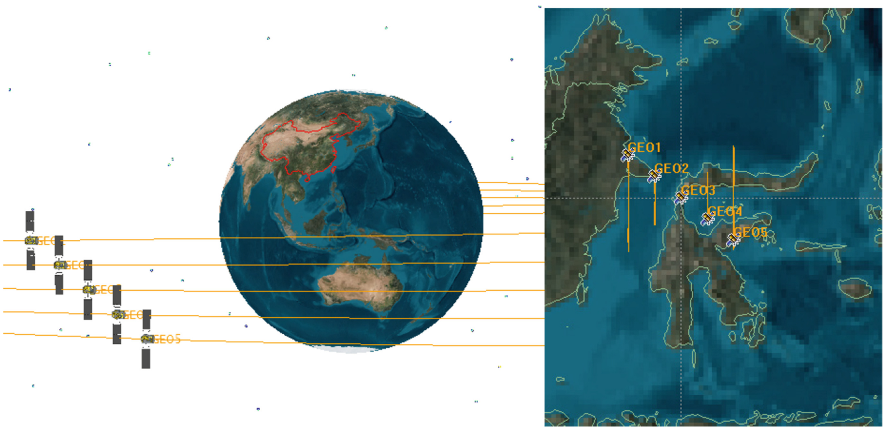

Fig. 4. Fly-with cluster configuration

From the three kinds of distributed cluster configuration analysis above, coplanar fly-around of GEO distributed cluster configuration scheme is more suitable for SBN node design. By working cooperatively between flying around node and master node, it can effectively meet the needs for space information network service, and the configuration can be lunch satellites according to the need of service to improve the scalability of the system.

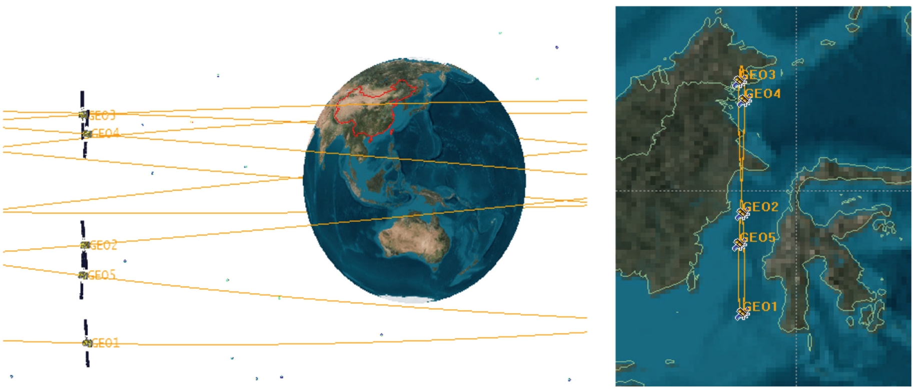

Fig. 5. Sway cluster configuration

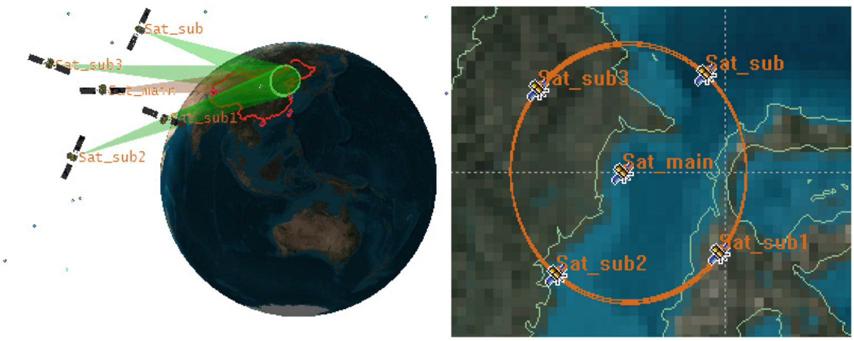

Fig. 6. Fly-around cluster configuration

4 Geostationary Satellite Collocation Design and Performance Simulation

4.1 Mathematic Model

Orbital element is a set of parameters used to describe the satellite running state, including semi-major axis a, eccentricity e, inclination i, RAAN Ω, perigee ω and mean anomaly M, represented in vector form as:

$$\vec{e} = [a, e, i, \Omega, \omega, M]^T \tag{1}$$

In formula (1), semi-major axis a and eccentricity e determine the size and shape of the orbit, inclination i, RAAN Ω and perigee ω determine the orbit space pointing, and the mean anomaly M show the instantaneous position of the satellite in orbit.

In Geostationary Satellite Collocation, each satellite node distribute into a small region, so the orbital elements except perigee ω and mean anomaly M are almost equal. In the relative motion model described by orbital elements, the relative orbital elements are used to analyze the position relationship between satellite nodes. The relative orbital elements are defined as the difference between orbital elements of each node, represented as follow:

$$\begin{aligned} \Delta\vec{e} &= \vec{e}_{cir} - \vec{e}_{ref} \\ &= [\Delta a, \Delta e, \Delta i, \Delta\Omega, \Delta\omega, \Delta M]^T \end{aligned} \tag{2}$$

The subscripts $[\cdot]_{ref}$ and $[\cdot]_{cir}$ respectively represent the relative motion of reference satellite flying-around satellite.

The relative motion relationship of reference satellite flying-around satellite is shown in Fig. 7, the O, S_{ref} and S_{cir} represent earth center, reference satellite and fly-around satellite respectively. In order to describe the trajectory of fly-around satellite relative to reference, the relative coordinate system is defined as follow: the coordinate origin is reference, x axis along the line from the earth to coordinate origin, and y axis is the direction of satellite operation, and z axis is perpendicular to the orbital plane, and x, y axis meet the right hand role.

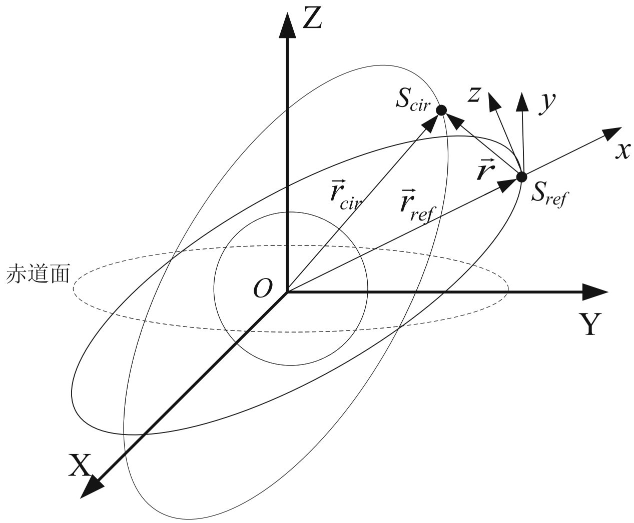

Fig. 7. The relative motion relationship of reference satellite flying-around satellite

According to Fig. 7, transferring fly-around coordinate to reference coordinate, the vector $\overrightarrow{r} = M_{ref-cir}\overrightarrow{r}_{cir} - \overrightarrow{r}_{ref}$ is gotten as the fly-around trajectory. The transfer matrix is represented as follow:

$$M_{ref-cir} = M_z\left[u_{ref}\right]M_x[-\Delta i]M_z[-u_{cir}] \\ = \begin{bmatrix} \cos\Delta u & -\sin\Delta u & -\Delta i\,\sin u_{ref} \\ \sin\Delta u & \cos\Delta u & \Delta i\,\cos u_{ref} \\ \Delta i\,\sin u_{cir} & \Delta i\,\cos u_{cir} & 1 \end{bmatrix} \tag{3}$$

In formula above, the $M_x[\cdot]$ and $M_z[\cdot]$ represent the rotation matrix of circled over x axis and z axis, the u_{ref} and u_{cir} represent the geocentric angle from relative ascending node to present position of reference satellite and fly-around satellite.

Applying formula (3) on $\overrightarrow{r} = M_{ref-cir}\overrightarrow{r}_{cir} - \overrightarrow{r}_{ref}$, by triangular transformation and further consolidation, we can get equation following:

$$\begin{cases} x = -ae_A\cos(nt+\theta) \\ y = 2ae_A\sin(nt+\theta) + a\Delta\lambda \\ z = a\Delta i\,\sin(nt+\psi) \end{cases} \tag{4}$$

In formula (4), n represents orbital angular velocity of reference satellite, and e_A, θ, $\Delta\lambda$ and Ψ are meddle variables in formula deduction progress. Form formula (4), we can conclude that: ① the component in x and y axis meet equation $\left(\frac{x}{ae_A}\right)^2 + \left(\frac{y-a\Delta\lambda}{2ae_A}\right)^2 = 1$, so the projection of fly-around trajectory in $x-y$ plane is ellipse with 2:1 long-short axle ratio. ② z axis component is an independent simple harmonic vibration, and its amplitude is $a\Delta\lambda$.

Assume the fly-around satellite as space circle configuration, its radius is r, the short axle of $x-y$ plane meets $p = ae_A = r/2$, the amplitude in z axis meet $s = a\Delta i = r\sqrt{3}/2$, the Initial phase meets $\alpha = \theta - \psi = \pi/2$ or $3\pi/2$. In actual satellite orbit design, the orbital parameters of reference satellite are usually known. Only if $\Delta\overrightarrow{e} = [\Delta a, \Delta e, \Delta i, \Delta\Omega, \Delta\omega, \Delta M]^T$ is calculated, the orbital parameters of fly-around satellite are gotten. In order to grantee the cluster could keep the original configuration after running one period, each satellite of cluster must have the same orbital semi-major axis a, as well $\Delta a = 0$. The relationship of relative motion parameters and orbital elements is given in follow equations:

$$\begin{cases} e_{cir} = \sqrt{\left(\frac{p}{a}\right)^2 + e_{ref}^2 + 2\frac{p}{a}e_{ref}\cos\theta} \\ i_{cir} = arc\,\cos\left(-\frac{\sin\Delta\Omega\,\cos(w_{ref}-\theta+\alpha)-\sin(w_{ref}-\theta+\alpha)\cos\Delta\Omega\,\cos\,i_{ref}}{\sin\,k}\right) \\ \Omega_{cir} = \Omega_{ref} + \Delta\Omega \\ w_{cir} = k + \theta - \alpha - \phi + \frac{l}{a} \\ M_{cir} = M_{ref} + \phi \end{cases} \tag{5}$$

$\Delta\Omega$ is the difference of RAAN, k and φ are middle various, and shown in follow formulas.

$$\Delta\Omega = \arctan\left(\frac{\sin(w_{ref} - \theta + \alpha)}{\cos(w_{ref} - \theta + \alpha)\cos i_{ref} + \sin i_{ref}\cot\left(\frac{s}{a}\right)}\right) \tag{6}$$

$$k = \arctan\left(\frac{\sin(w_{ref} - \theta + \alpha)}{\cos(w_{ref} - \theta + \alpha)\cos\left(\frac{s}{a}\right) + \sin\left(\frac{s}{a}\right)\cot i_{ref}}\right) \tag{7}$$

$$\phi = \arctan\left(\frac{2ape_{ref}\sin\theta}{a^2\left(e_{cir}^2 + e_{ref}^2\right) - p^2}\right) \tag{8}$$

Assume the fly-around satellite number is N, the semi-major axis a, eccentricity e, inclination i and perigee ω are fixed, the relationship of RAAN Ω and mean anomaly M is shown as follow.

$$\begin{cases} M_n = \frac{n-1}{N}\pi + M_0 \\ \Omega_n = \Omega_0 + M_0 - M_n \end{cases} \tag{9}$$

Thus, the entire fly-around orbit parameters are calculated, which could provide theoretical references for data relay satellite constellation designed based on Geostationary Satellite Collocation. According to the orbital elements of the satellite constellation, we construct the constellation in the STK software, calculate the AER characteristics, and analyze its performance in detail.

4.2 Constellation Construction

Taking the GEO satellite above China for example, the initial ephemeris time set as "2016/12/02 04:00:00.000 UTCG", the fly-around satellite number is four, distributed evenly, the fly-around radius is 100 km. Using the method and formula above, the orbital parameters are given in Table 1. And its constellation configuration is shown in Fig. 8.

4.3 AER Performance Analysis

Through analyzing the inter-satellite link performance of main-sub and adjacent sub satellite, the constellation performance parameters and configuration realization will be given mathematically. The change relationship of Azimuth, Elevation and Range (AER) along with latitude between main and sub satellites is shown in Fig. 9. And its

Table 1. Orbital parameters of main and sub satellites

Satellite name	Perturbation	Semi-major axis (km)	Eccentricity	Inclination (°)	Perigee (°)	RAAN/longitude(°)	Mean anomaly (°)
Sat_main	J2	42166.3	0	0	0	249.431/118E	0
Sat_sub	J2	42166.3	0.0012	0.12	90	159.431/117.869E	0
Sat_sub1	J2	42166.3	0.0012	0.12	90	69.431/117.876E	90
Sat_sub2	J2	42166.3	0.0012	0.12	90	−20.569/117.883E	180
Sat_sub3	J2	42166.3	0.0012	0.12	90	−110.569/117.889E	270

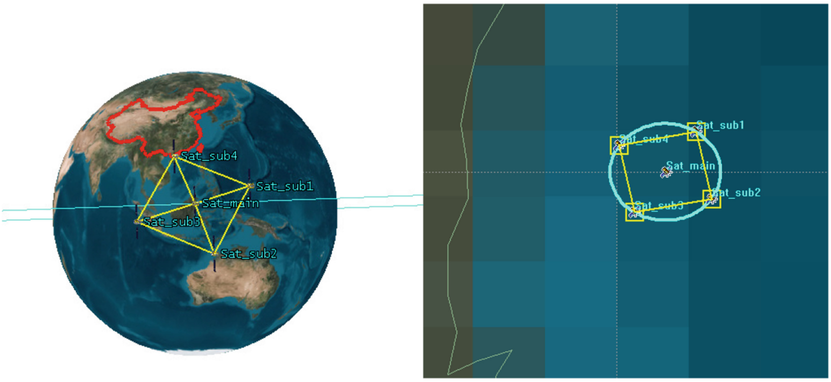

Fig. 8. Constellation configuration with four fly-around satellites

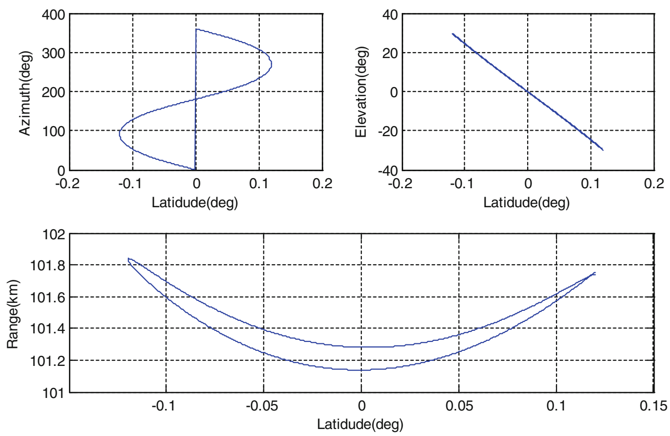

Fig. 9. AER change relationship along with latitude of main-sub satellite

relationship along with time is given in Fig. 10. From these two figures, we can find that, change region of the azimuth, elevation and range are 0 deg–360 deg, ±30 deg and 101.1 km–101.85 km respectively, can meet the configuration requirement.

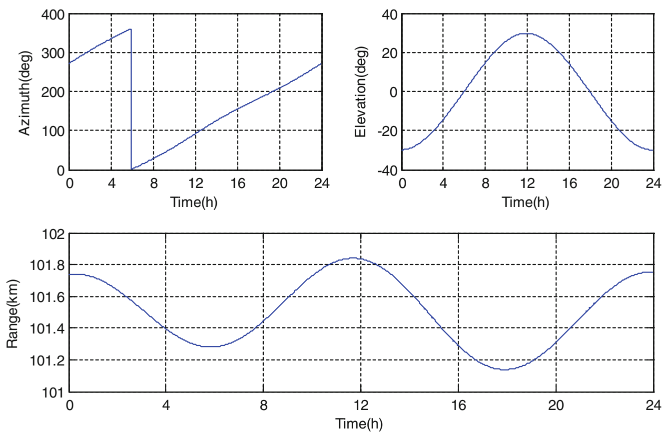

Fig. 10. AER change relationship along with time of main-sub satellite

The AER rate change relationship along with latitude between main and sub satellites is shown in Fig. 11. And its relationship along with time is given in Fig. 12. From these two figures, we can find that, change region of the azimuth rate, elevation rate and range rate are 6.1×10^{-5}deg/s–8×10^{-5}deg/s, $\pm 3.5 \times 10^{-5}$deg/s and $\pm 0.75 \times 10^{-6}$ km/s respectively. AER rate is in 10^{-5} magnitude, and the links are stable to meet the ATP requirement.

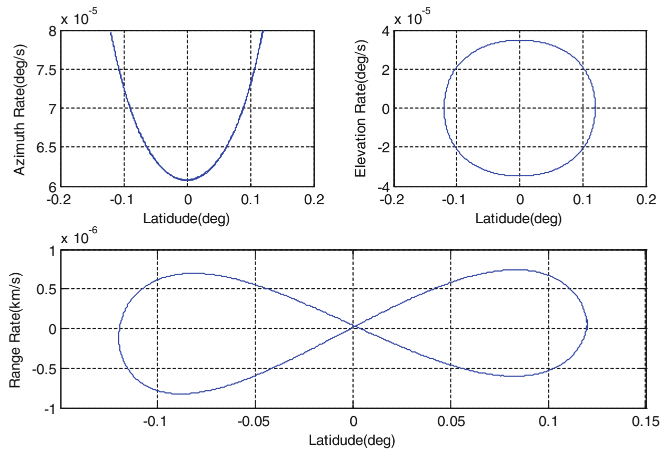

Fig. 11. AER rate change relationship along with latitude of main-sub satellite

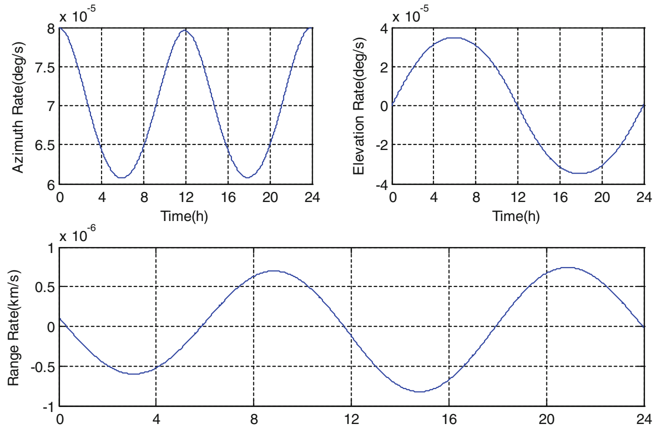

Fig. 12. AER rate change relationship along with time of main-sub satellite

The AER change relationship along with latitude between adjacent sub satellites is shown in Fig. 13. And its relationship along with time is given in Fig. 14. From these two figures, we can find that, change region of the azimuth, elevation and range are 0 deg–360 deg, ±30 deg and 143.1 km–143.9 km respectively, can meet the configuration requirement.

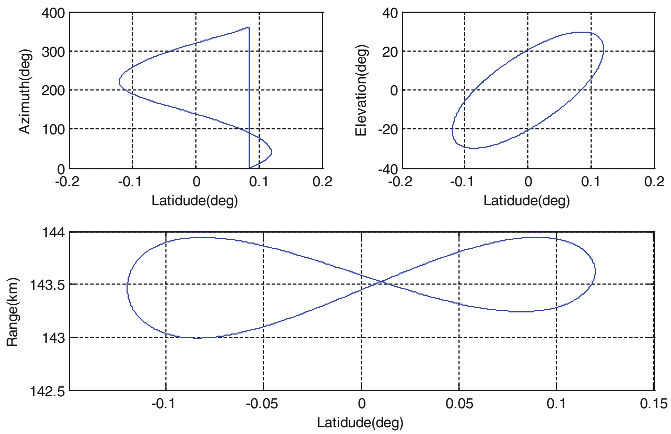

Fig. 13. AER change relationship along with latitude of adjacent sub satellite

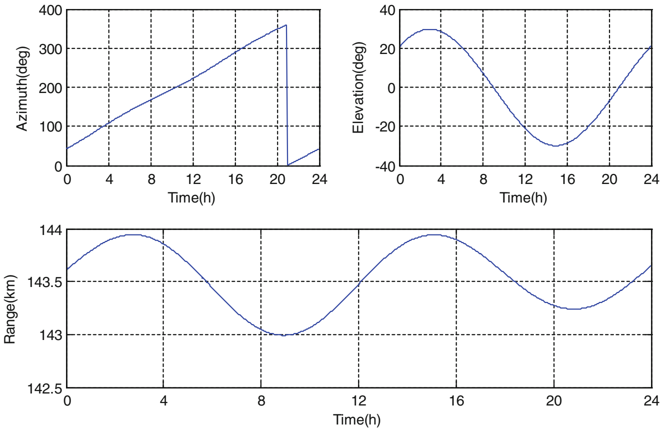

Fig. 14. AER change relationship along with time of adjacent sub satellite

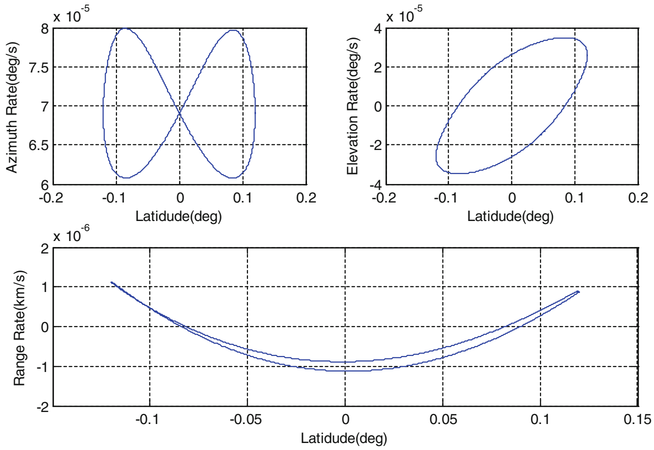

Fig. 15. AER rate change relationship along with latitude of adjacent sub satellite

The AER rate change relationship along with latitude between main and sub satellites is shown in Fig. 15. And its relationship along with time is given in Fig. 16. From these two figures, we can find that, change region of the azimuth rate, elevation rate and range rate are 6.1×10^{-5}deg/s–8×10^{-5}deg/s, $\pm 3.5 \times 10^{-5}$deg/s and $\pm 1.2 \times 10^{-6}$ km/s respectively. AER rate is in 10^{-5} magnitude, and the links are stable to meet the ATP requirement.

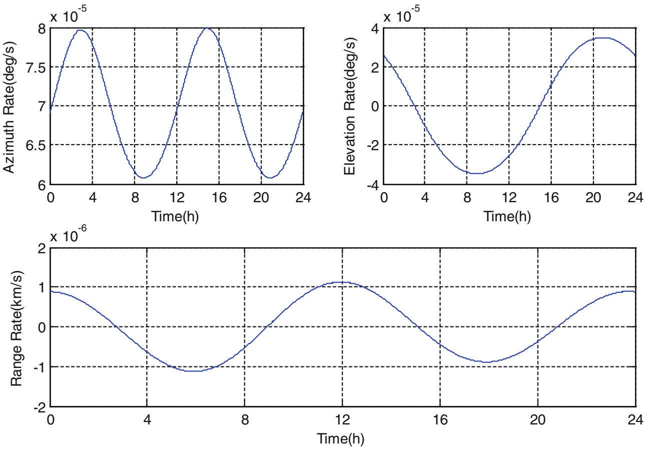

Fig. 16. AER rate change relationship along with time of adjacent sub satellite

5 Conclusion

Based on the actual application, facing on present urgent needs of spatial information networks efficient networking and mass information transformation, drawing on the latest technology and latest achievements, the method that using Geostationary Satellite Collocation mechanism to construct SBN is proposed in this paper. Multi-satellite coordination may improve the survivability and organizational ability of backbone nodes, meanwhile could significantly reduce satellite platform launch and design costs, and could provide theoretical support for the current problems of less capacity of single satellite and orbit resource scarce.

Therefore, based on analysis of three typical Geostationary Satellite Collocation configurations, using the orbital dynamics theory and spherical Geometry methods, the space-circle configuration is analyzed in detail. Then a fly-around constellation orbital design example is given, which is lying above China with 100 km radius. Then the AER performance of main-sub and adjacent sub satellite is simulated in detail. The simulation result shows that this configuration is best with little AER change character, and total meeting the antenna ATP requirement.

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