Modeling and Performance Analysis of Multi-layer Satellite Networks Based on STK

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Abstract. With the difference of satellite altitude, there are always some inherent defects in the traditional single-layer satellite networks. In this paper, in order to improve the performance of the single-layer networks, a multi-layer satellite network model composed of LEO/MEO/GEO and inter satellite link is proposed. In this model, the LEO and MEO layers are used as the access layer, and the data transmission is carried out to the ground. As the core layer, the GEO layer is responsible for the management of the whole network and the link assignment. Then modeling the network based on the STK satellite simulation platform and carrying out the simulation analysis of ground coverage, the performance of the inter satellite link and the link transmission. Theoretical analysis and simulation results show that the design of multi-layer satellite network is reasonable and effective, and also can be used in the construction of the integrated satellite-terrestrial networks.

Keywords: Multi-layer satellite networks · Inter satellite link
Ground coverage · Link transmission

1 Introduction

Since the concept of Multi-layer satellite networks was brought up, it has received extensive attention from various countries [1]. Up till now, most satellite systems adopt single-layer satellite network, which means that all satellites are running in the same altitude [2–5]. For instance, the famous GPS [6] satellite navigation system—Globalstar [7], applies single-layer network. However, with all satellites working on the same height, the capacity of systems will be greatly limited. The lower the satellite is, the smaller area it covers, which means it need more satellites to cover the same area. In the meanwhile, when the height of satellite declines, its speed increases, the network topology changes drastically, and the Doppler frequency increases. Comparatively, though the covered area increases when the orbit altitude of satellite augments, the transmission delay and attenuation become greater. Therefore, the single-layer satellite network is unable to satisfy our demands. If we take satellites on different altitude to constitute the system, and take advantages of each layer, it's possible to eliminate the drawbacks of single-layer network, as well as to bring some good properties.

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For most researches concerning satellite network topology, their focuses stay on the network structure design, permanent inter-satellite network and the performance of ground coverage, and very few of them model and make comprehensive estimation of the network from the perspective of ground coverage, inter-satellite network performance and network transmission features, so as to ensure the design workable and superior to others. In reference [2], the requirements for constructing permanent inter-satellite network are brought up, but it fails to give out the exact network design. In reference [3], one possible plan for designing multi-layer satellite network is brought up, but no analysis on transmission features is given out.

In this thesis, a detailed approach to how to design multi-layer satellite network and how to connect inter-satellite network is raised. Then, based on the satellite analysis toolbox—STK, analysis of ground coverage, inter-satellite network performance and transmission is carried out. Meanwhile, detailed simulation graph and data is achieved during this process. The combination of theoretical analysis and simulation proved the feasibility of the designed model of multi-layer network, and this design will give some practical suggestions on China's space-network development.

2 Multi-layer Satellite Network Modeling

2.1 Model of Multi-layer Satellite Network

The multi-layer satellite network model raised in this paper is as shown in Fig. 1. The network is divided into 3 layers, which are LEO layer, MEO layer and GEO layer. Because of the comparatively low altitude and medium coverage of LEO layer and MEO layer, they can serve as the accessing layer of the network, so as to connect to and exchange information with the ground network. GEO layer, because of its high altitude, though it has massive ground coverage, its long transmission delay and server attenuation makes it inappropriate to connect GEO layer to the ground network directly. So, it is selected as the core layer of the network, in charge of the network running and chain allocation, so as to choose the best route for data transmission among satellites [8–11].

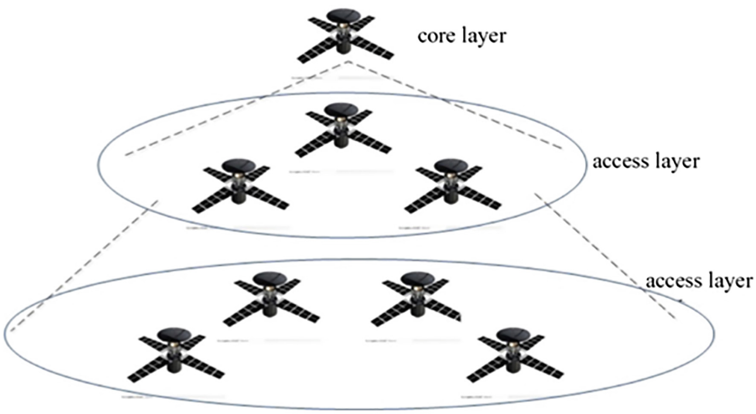


Fig. 1. Multi-layer satellite network model

2.2 Network Parameters

Quasi regression orbit is chosen in this system, which means in n2 star days, the satellite circles around the earth for n1 times, then it repeats it previous running trace. Its mathematical equation is:

$$T_s \times n_2 = T_e \times n_1 \quad (1)$$

where n_1 and n_2 are none-zero natural numbers, T_e and T_s stand for the star day length and satellite period of revolution. The exact parameters for quasi regression orbit are as shown in Fig. 2.

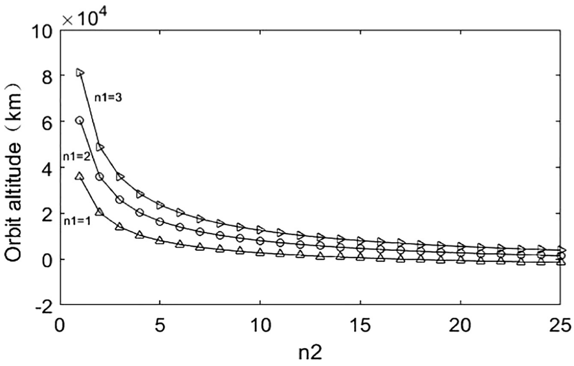


Fig. 2. Acceptable altitudes for quasi regression orbit

When the orbit altitude is h, the half geocentric-angle of covered area by satellite can be expressed as

$$\alpha = \arccos\left[\frac{R_e COSE}{h + R_e}\right] - E \quad (2)$$

where R_e is the earth radius, E is the angle of elevation from observation point to the satellite.

For the satellite network needs to realize global coverage and has to focus on China's territory, circular orbit is the best choice for this system, since satellite running on elliptic orbit can only realize steady coverage on Mid latitude region when it is at the apogee. And in terms of constellation configuration, the following drawbacks of polar orbit, which are sparse coverage on low latitude region, dense coverage on high latitude region, unbalanced coverage on different areas and high possibility of satellites crash into each other while running on the polar area, make it inappropriate for this system. Delta constellation is more appropriate for this system because of its capability of smooth coverage.

To realize globe coverage, the half geocentric angle is calculated based on the orbit height, then how many orbits are needed and how many satellites should be there on each orbit is estimated. Since Delta constellation system mainly covers the medium and low latitude areas, satellite on the LEO layer mainly cover those areas mentioned above. Then, because of the feature of massive coverage, we take advantage of satellites on the MEO layer to have supplementary coverage on the mid and low latitude area, as well as to cover the high latitude areas especially the polar area.

Finally, based on the analysis above, parameters of each orbit are calculated in combination with coverage requirements. The designed multi-layer satellite network is as show in the following Table 1:

Table 1. Parameters in the multi-layer satellite networks

Orbit	LEO	MEO	GEO
Orbit height (km)	1673	13899	35786
Orbit type	Quasi regression orbit	Quasi regression orbit	Synchronous orbit
Inclination	50°	53°	0°
Num. of orbits	4	2	1
Num. of satellite on each orbit	7	3	3
Total satellites	28	6	3

It can be seen from the table above that it takes 37 satellites in total to satisfy the coverage requirements, and the number is less than other designs of multi-layer satellite network. The declination of satellites can not only dramatically reduce the launching cost but also simplify the network management.

3 Inter-Satellite Link Design

The term inter-satellite link refers to the communication link between satellites, which are usually base on micro wave or light. Via inter-satellite link, information can be transmitted directly between satellites, which can dramatically reduce time-delay and attenuation caused by retransmission via station. Moreover, it can decrease the number of stations.

3.1 Inter-Satellite Link Design Within the Same Layer

For satellites on the same altitude, their visibility is shown in Fig. 3 (taking LEO as example).

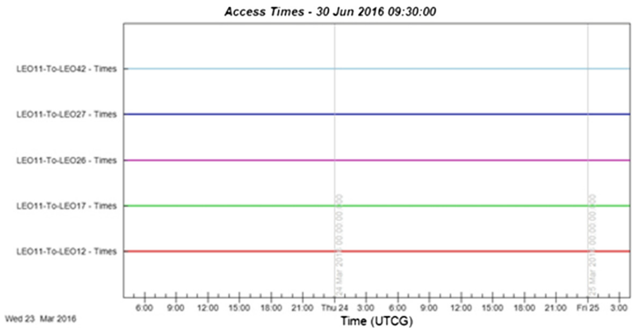


Fig. 3. Visibility within LEO layer

It can be seen from the graph that for one LEO satellite, its permanent visible to the two satellites on the same orbit with and adjacent to it. In the meanwhile, it is permanent visible to two satellites on the adjacent orbit. Therefore, each satellite on these three layers can be connected to the satellites which are permanent visible to it according to the regularity mentioned above.

3.2 Inter-Satellite Link Design Within Different Layer

Taking MEO-LEO as example, the visibility of the inter-layer link is shown in Fig. 4.

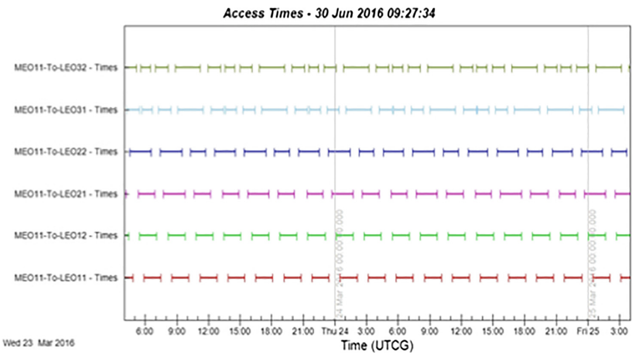


Fig. 4. Visibility within LEO layer and MEO layer

As it can be seen from the graph above, no permanent inter-satellite link can be established between satellites on different layer. However, the normal operation of inter-satellite links can be assured by the rule that satellite on the upper layer covers the satellite on the lower layer, which is to say that each satellite on the lower layer can be covered by one satellite on the upper layer. Even if in one moment that the satellite on the lower layer is not covered by the satellites on the upper layer and satellite data cannot be transmitted, the inter-satellite links can be reallocated by the system, and the data can be transmitted to a satellite covered by satellites on the upper layer, then transmitted to the upper layer.

According to this method, six MEO satellites are evenly assigned to three GEO satellites; 28 LEO satellites were assigned to six MEO satellites, where five MEO satellites are linked to five LEO Satellites, and one MEO satellite is connected to three LEO satellites. Up till now, the design of the multi-layer satellite network is accomplished, and the explicit distribution method of the inter-satellite link is shown in the following Table 2.

Table 2. Inter-satellite links allocation

Satellite orbit type	LEO	MEO	GEO
Inter-satellite link within the same layer	6	3	2
Inter-satellite within different layers	/	5 LEO and 3 LEO	2 MEO
Visibility of Inter-satellite link within the same layer	Permanent visible	Permanent visible	Permanent visible
Visibility of Inter-satellite link within different layers	/	Not permanent visible	Not permanent visible

4 Analysis and Discussion on Performance of Multi-layer Satellite Network

4.1 Coverage Analysis

For one specific area, we can make use of various satellite services only when it is covered by the satellite. And for coverage performance, we primarily care about the percentage of satellite coverage and the number of satellites can be accessed at the same time. According to introduction above, only LEO layer and MEO layer of the three layers serve as the access layer, so as to connect with the ground network. Therefore, only access layer was taken into consideration when analyze ground coverage. The percentage of covered territory of China is shown in the Fig. 5.

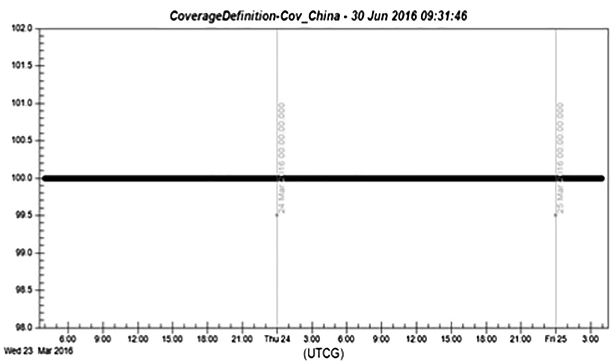


Fig. 5. Percentage of China's covered territory

It can be seen that in one cycle, satellites can reach 100% uninterrupted coverage of China. Since quasi regression orbit is adopted in this system, satellites will repeat its previous trace after one satellite circle. Therefore, the satellite network can provide coverage for China at any time, which reflects the superiority of the quasi regression orbit. Detailed information about how many satellites cover China's territory is shown in Fig. 6.

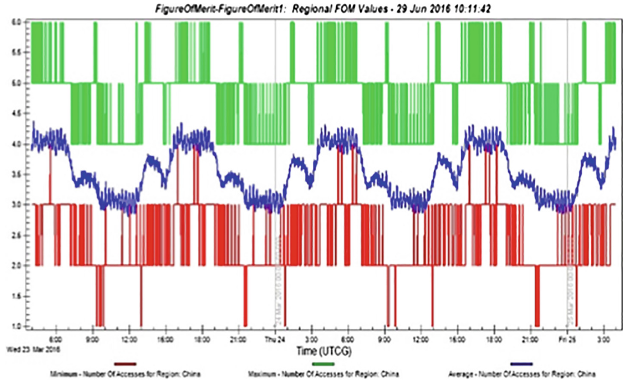


Fig. 6. No. of satellites covering China

Within one satellite cycle, the satellite network can guarantee good service for China's demands, with at most 6 satellites, at least one satellite and an average of 3.5 satellites cover China. The global coverage is as shown in Fig. 7.

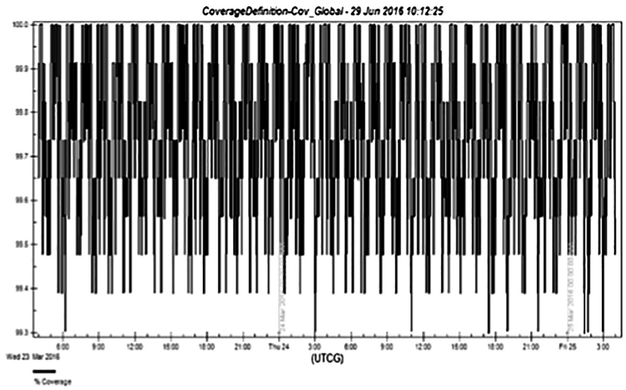


Fig. 7. Percentage of covered area on earth

In one cycle, the covered area of the globe outnumbers 99.3%, which actually promises global coverage. As for the polar area, number of satellites that covers it is as shown in Fig. 8.

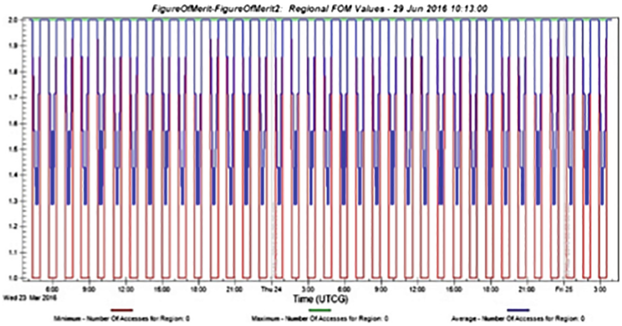


Fig. 8. No. of satellites cover the polar areas

This graph indicates that even in human population sparse polar areas that are difficult to cover, there still has 1.5 satellites in average to cover them, which satisfies the local people's daily and scientific research demands. To sum up, the designed satellite network well satisfies the designing requirements in terms ground coverage.

4.2 Performance of Inter-Satellite Link

Parameters concerning the inter-satellite link performance mainly include Azimuth Angle, Elevation Angle, and Link Range. The first two parameters determine the relative position of the satellites, as well as the complexity and direction of the satellites' antennas. The change of link range determines launching power of on-board system and its fluctuating range.

The performance of the inter-satellite links within the same layer is shown in Fig. 9.

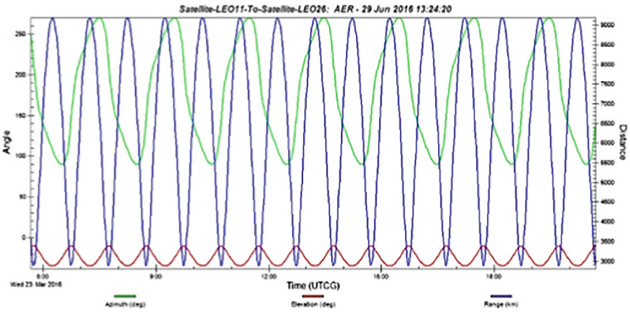
The performance of inter-satellite links between satellites from different layer is shown in Fig. 10.

Figures 9 and 10 indicate that the performance of inter-satellite links changes in a regular way. And based on this disciplinarian, the posture of satellite in space can be predicted, which will dramatically enhance the antennas tracking and capture ability.

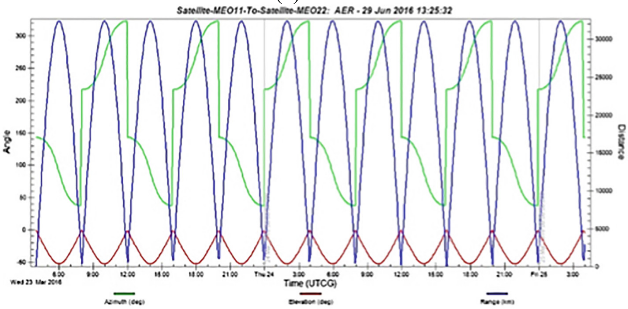
4.3 Performance of Link Transmission

The transmission of satellite network includes transmission from satellite to station and transmission within stars, in either way, signals, affected by the loss of free space loss, will attenuate during the process of transmission, which can be expressed as

$$L_f = 92.44 + 20\lg d + 20\lg f \tag{3}$$

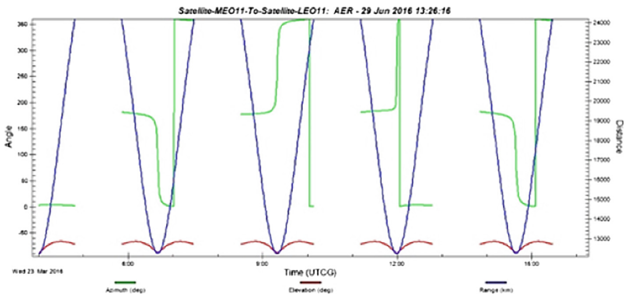


(a) LEO

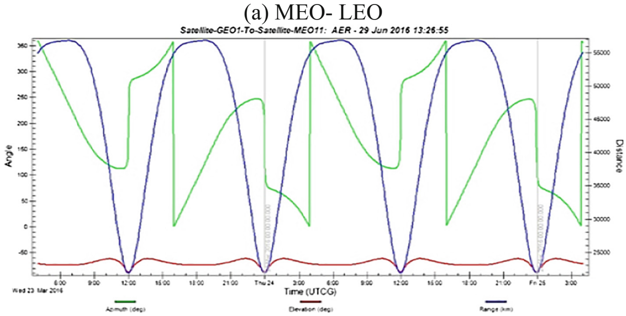


(b) MEO

Fig. 9. Performance of inter-satellite links within the same layer



(a) MEO- LEO



(b) GEO-MEO

Fig. 10. Performance of inter-satellite links within different layers

where L_f is the free space transmission loss, d is the transmission distance, f is the frequency of microwave, c is the speed of light. The relationship between free space transmission loss and transmission distance of different frequencies is shown in the graph bellow (Fig. 11).

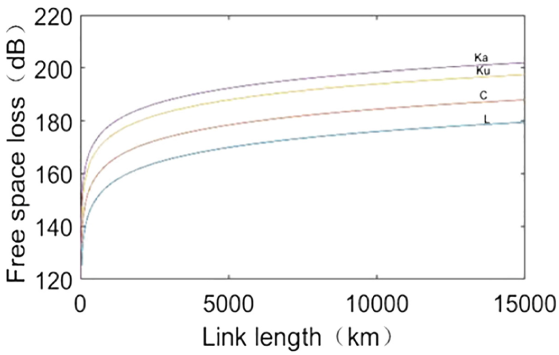


Fig. 11. The relationship between the loss of free space and the length of the link

In addition, due to the earth's unique environment, the atmospheric absorption loss and rain attenuation cannot be ignored when information is transmitted between satellites and ground station, and it should be considered in the simulation. Take Beijing station as an example, Table 3 is the simulation results which represents the transmission performance of links between Beijing station and LEO satellites.

Table 3. Transmission performance of links between Beijing station and LEO satellites

Time	Free space transmission loss	Rain attenuation	Atmospheric absorption loss	BER
23 Mar 2016 06:09:00.000	−185.8490	−6.8403	−0.1827	4.101039e−005
23 Mar 2016 06:09:20.000	−185.5830	−6.5504	−0.1706	1.135835e−005
23 Mar 2016 06:09:40.000	−185.3131	−6.2868	−0.1596	2.765264e−006
23 Mar 2016 06:10:00.000	−185.0397	−6.0466	−0.1498	5.860816e−007
23 Mar 2016 06:10:20.000	−184.7634	−5.8275	−0.1408	1.071793e−007

Atmospheric absorption loss and rain attenuation can be neglected when information is transmitted between satellites. However, the long distance between satellites usually leads to great free space transmission loss. Here, take the links between LEO satellites and MEO satellites as an example, transmission performance is simulated, which is as shown in the Table 4.

Table 4. Transmission performance of links within MEO satellites and LEO satellites

Time	Free space transmission loss	Rain attenuation	Atmospheric absorption loss	BER
23 Mar 2016 05:53:00.000	−209.4899	0	0	3.177611e−007
23 Mar 2016 05:59:40.000	−208.7834	0	0	3.293271e−008
23 Mar 2016 06:06:20.000	−207.9378	0	0	1.304739e−009
23 Mar 2016 06:13:00.000	−206.9654	0	0	1.371072e−011
23 Mar 2016 06:19:40.000	−205.9093	0	0	2.720691e−014

Simulation results show that in the process of transmission, free space loss is the main result that leads to attenuation, which can be explained that the transmission distance of space network is longer than ground network. By installing appropriate transmitters and receivers and by configuring antennas correctly, the demands of transmission can be satisfied. In the table above, parameters are fluctuating constantly due to the constant change of distance between satellites. The decrease of distance between satellites will lead to smaller transmitting loss, so as the smaller BER. And as long as the satellite is visible to each other, the BER can meet the transmitting requirements.

5 Conclusions

In this paper, a tri-layer satellite network of LEO/MEO/GEO is analyzed and established. Firstly, the type of orbit and the type of constellation are decided. Then, detailed parameters of the network including satellites' altitude, number of orbits and numbers of satellites on each orbit are selected. Eventually, a multi-layer satellites network system consisting of 28 LEO satellites, 6 MEO satellites and 3 GEO satellites is adopted.

Inter-satellite links are established in this thesis. Firstly, visibility of satellites in three circumstances, which are on the same orbit, on adjacent orbit of the same layer and orbit of different layers is analyzed. Then, permanent inter-satellite links and none-permanent inter-satellite links are established, so as to ensure that each satellite is connected to the satellite adjacent to it, as well as ensuring that satellites on the upper layer can fully cover the satellites of the lower layer.

Detailed simulation graphs and statistics from the aspects of ground coverage, performance of inter-satellite link and transmission performance are achieved based on the satellite analysis toolbox—STK. Simulation results can be expressed as follow: the approach raised in this thesis can realize full coverage around the globe, as well as continuous coverage of China; curves of inter-satellites links' performance is achieved, so as satellites' running disciplinarian, which can be used to predict satellites' relative position, as well as providing convenience for antennas on-board to track its target. Transmission performance of inter-satellite link is simulated, and the bit-error-rate can still satisfy the transmission requirements when taking free space loss and the environmental factors on earth into consideration. All these work done above Verifies the validity and superiority of the multi-layer satellite network designed in this paper.

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References

1. Li, D., Shen, X.: On construction of China's space information network. Geomat. Inf. Sci. Wuhan Univ. **40**(6), 711–715 (2015)
2. Wang, Z., Wang, P.: Research on permanent inter-satellite-links in satellite networks. J.-China Inst. Commun. **27**, 129–133 (2006)
3. Wang, Z.: Architecture design and analysis of multi-layer satellite networks. Doctor's thesis, Harbin Institute of Technology, Harbin, China (2007)
4. Liang, J.: Research on inter-satellite networks design of satellite communication system. Master's thesis, National University of Defense Technology, Changsha, China (2006)
5. Gao, L., Zhao, H., Jiang, T.: Modeling and simulation for dynamic topology network of SIS. J. Syst. Simu. 69–72 (2006)
6. Dogan, U., Uludag, M., Demir, D.O.: Investigation of GPS positioning accuracy during the seasonal variation. Measurement, 212–242 (2014)
7. Somov, Y.I., Butyrin, S.A., Anshakov, G.P.: Dynamics and flight support of a vehicle ikar control system at orbiting globalstar satellites. Control. Eng. Pract. **11**(5), 585–597 (2003)
8. Kimura, K., Inagaki, K., Karasawa, Y.: Double-layered inclined orbit constellation for advanced satellite communication network. IEICE Trans. Commun. **E80-B**(1), 93–102 (1997)
9. Kimura, K., Inagaki, K.: Global satellite communication network using double-layered inclined-orbit constellation with optical inter-satellite links. In: Proceedings of SPIE. 12–23 (1996)
10. Lee, K., Kang, S.: Satellite over satellite (SoS) network: a novel architecture for satellite network. In: Proceedings of 2000 IEEE Conference on Computer Communications (INFOCOMM), Tel Aviv, Israel, 26–30 March 2000, vol. 1, pp. 131–136 (2000)
11. Dasha, J.S., Durresi, A.: Routing of VoIP traffic in multi-layered satellite networks. In: Proceedings of SPIE, pp. 65–75 (2003)
12. Zhu, L., Wu, Y.: Introduction to Satellite Communication. Electronic Industry Press, Beijing (2015). pp. 35–76