Modelica-Based Modeling on LEO Satellite Constellation

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Abstract

The new generation of LEO (Low Earth Orbit) communication satellite constellations have the advantages of low latency, strong signals, and global coverage. In order to achieve global coverage, the LEO satellite constellations are often very large, with a large number of satellites, which puts forward high requirements for the overall design, operation and maintenance of the constellation. Based on the Modelica language, this paper conducts a detailed study of the LEO communication satellite constellation and built a system model of satellite constellation, and carries out a full-link simulation for the typical service of mobile communication. By analyzing the simulation results, we conclude that based on the model of satellite constellation proposed in the paper, the satellite constellation can be quickly designed and simulated.

Keywords: satellite constellation, Modelica, satellite communication, full-link simulation

1 Introduction

In recent years, as the demand for network communication has increased sharply, the idea of using LEO communication satellite constellation to provide the Internet from space has become popular again due to its low communication delay and full-area coverage. A group of LEO communication satellite constellation projects represented by OneWeb, StarLink and Iridium II have emerged in the world. Compared with HEO(High Earth Orbit), LEO satellites have a shorter lifespan, and the technical updates and iterations of the constellation system are more frequent. The existing simulation methods for satellite constellations can be mainly divided into the following two types: The first is to simulate the orbit, perturbation, structure and ground coverage characteristics of the satellite constellation based on software such as STK(Q. Wang and Xie 2021), and to support the constellation orbit and structure design; the second is based on software like OPNET(C. Hu and S. Wang 2018; Zhang 2008) to simulate the communication process of paging, inter-satellite link establishment, link switching, delay and other communication processes in the communication satellite constellation to calculate the communication link performance, thereby supporting the constellation network topology and network routing algorithm design. The two types of simulation methods are respectively aimed at constellation orbit design and communication link design. Currently, there is a lack of simulation methods that can unify the two calculations.

The core content of the paper is the construction of a multi-domain unified model for the satellite constellation system. The system model established by the Modelica language covers the ground segment, space segment and user segment equipment models. In the simulation application of mobile communication services, it can not only reflect system-level features such as constellation orbit, constellation structure, ground coverage, ISL(inter-satellite link), and satellite-to-earth links, can also simulate the energy balance, attitude control, fuel margin, and antenna gain of each satellite. The following section covers the introduction to the structure and characteristics of the LEO communication satellite constellation system. Section 3 mainly introduces the architecture of satellite constellation model and the principle of the main component model. Section 4 analyzes the simulation results of system model given example parameters. Section 5 gives conclusions.

2 Principle of LEO Satellite Constellation

LEO communication satellite constellation refers to a constellation system distributed at an orbital height of 700km to 2000km, which is usually divided into three components: space segment, ground segment, and user segment, as shown in Figure 1. Among them, the space segment refers to all satellites in the constellation; the ground segment usually includes the customs station, system control center and ground integrated network, responsible for the space segment satellite monitoring and control, and the operation and management of the space network; the user segment refers to various user terminals, including mobile terminals, shipboard terminals, vehicle terminals, and airborne terminals, etc.

There are mainly three types of links in the entire constellation system, feeder links, ISL and user links. Both the feeder link and the user link belong to the satellite-to-earth link, but the feeder link connects satellite and ground station, and the user link connects satellite and user terminal. The ISL refers to the link established between any

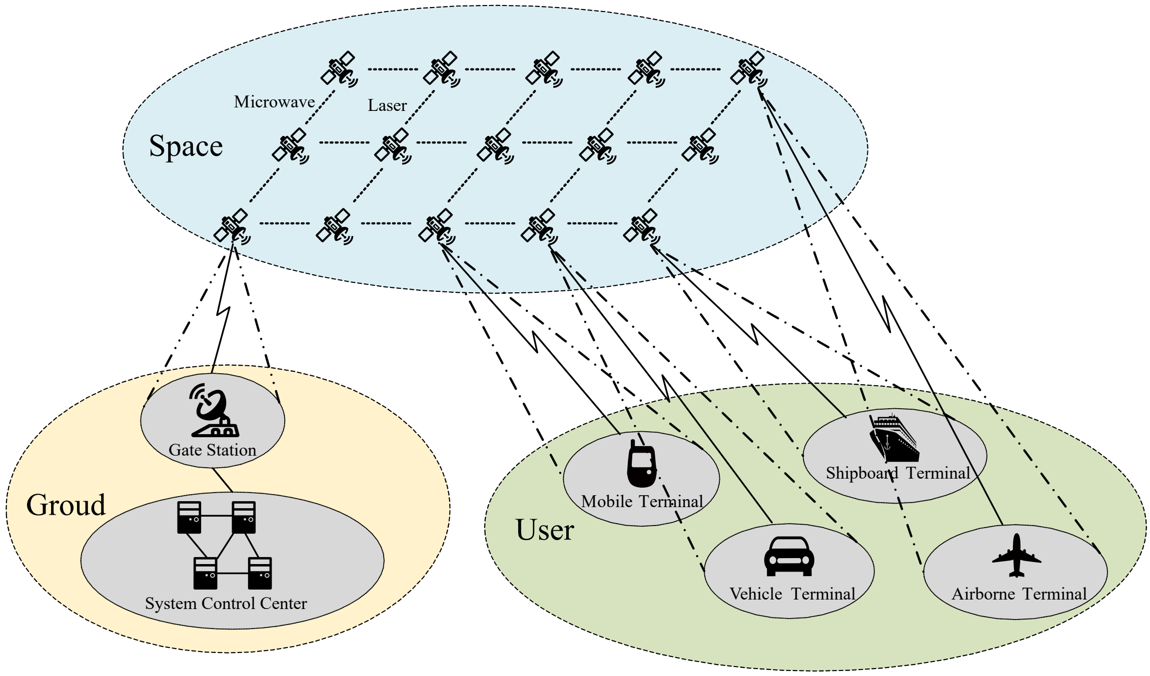


Figure 1. Schematic of a LEO communication satellite constellation.

satellite in the constellation and two adjacent satellites in the same orbital plane or between two adjacent satellites in a different orbital plane, which will occur with the switching of user links Change, the establishment of ISL generally follow the minimum hop number rule or the shortest propagation path rule.

For LEO communication satellite constellation system, the existing simulation methods are mainly based on different simulation platforms to simulate the constellation orbit coverage and communication link characteristics. Although this method can also achieve the purpose of simulation, it is not friendly for designers. And simulation tools such as STK or OPNET can only focus on system-level performance, and cannot considering the multi-domain characteristics of the satellite itself in the satellite constellation. This article uses Modelica language to establish a LEO communication satellite constellation system model. The model framework will be described in Section 3. Simulation based on this model can not only unify the constellation orbit coverage simulation and the constellation communication link simulation, but also focus on the operating status of a single satellite in the constellation system. This method not only improves the design efficiency of designers, but also facilitates the operation and maintenance of the constellation system. Simulation content is as follows:

- Constellation orbit and coverage characteristics, mainly including the position and speed of each satellite in the constellation at any time, and the overall ground coverage of the constellation.
- Communication link characteristics include two aspects, one is the margin for establishing communication links in any two places on the ground, and the other is the establishment and handover of ISL.
- Multi-domain characteristics of satellite, mainly including energy balance calculation, attitude control and orbit control maneuvers, and propellant margin calculation.

3 Unified Modeling of LEO Satellite Constellation

This section will propose a unified model architecture for constellation orbit coverage simulation, communication link simulation and satellite multi-domain simulation and introduce in detail the components of LEO satellite constellation developed by MWorks/Modelica.

3.1 Model Architecture

In order to realize the unified model of various simulation tasks of constellation, the constellation system model architecture is proposed as shown in Figure 2. Each color line with arrows in the figure represents a specific interface. The constellation orbit model calculates the number of orbital elements of each satellite in the constellation according to the given constellation design parameters. These orbital elements contain the position and speed information of the satellite and are transmitted to the ground station through the satellite-to-ground link. When user terminal 1 sends a request for establishing communication with terminal 2 to ground station, the communication request contains communication type, and the latitude

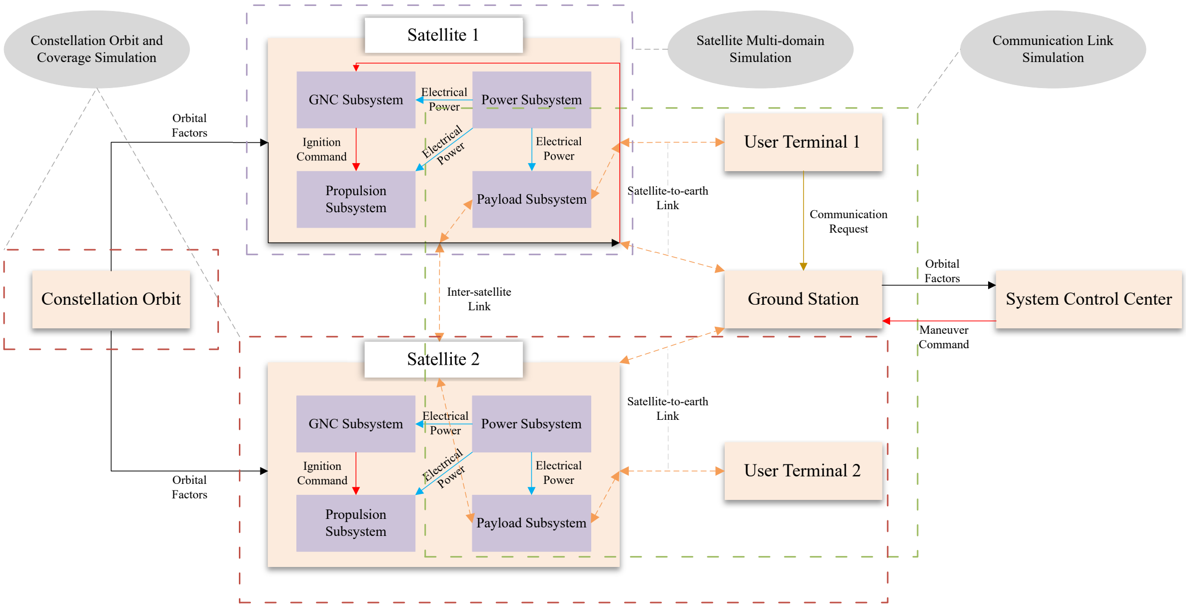


Figure 2. Model architecture of LEO communication satellite constellation system.

and longitude information of terminal 1 and terminal 2. Then ground station can establish a communication link between the two places, and calculate the link margin.

The link interface contains communication frequency, transmission rate, connection status, communication data, etc. The system control center generates the satellite orbit maneuvering control signal and transmits it to the GNC subsystem of the satellite that needs to maneuver through the satellite-to-ground link. The GNC subsystem then generates the propeller ignition command to the propulsion subsystem. With the help of the flexible component interface definition method of Modelica language, the modeling of related components can be easily carried out.

3.2 Model Implementation

Orbit, satellite and system control center are the three most important parts of LEO satellite constellation system, so this section mainly introduces the model realization of these three parts.

3.2.1 Orbit Model

The main parameters of the ideal constellation orbit model are: the number of orbits in the constellation p, the number of satellites in each orbit plane s, and orbital factors (semi-major axis a, eccentricity e, inclination i, RAAN(right ascension of ascending node) , argument of perigee and true anomaly f). The number of orbits and the number of satellites in each orbit plane determine the scale of the constellation. The semi-major axis and eccentricity of the orbit determine the size and shape of the orbit. The inclination, RAAN, and argument of perigee determine the orientation and direction of the orbit in space. The true anomaly determines the position of the satellite. Based on the above parameters, the coordinates(x,y,z) of each satellite in the geocentric inertial system can be calculated by Equation 1, so as to simulate the orbital state of the constellation at any time under ideal conditions.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{a(1-e^2)}{1+e\cos f} \cdot \begin{bmatrix} \cos\Omega\cos(\omega+f) - \sin\Omega\sin(\omega+f)\cos i \\ \sin\Omega\cos(\omega+f) - \cos\Omega\sin(\omega+f)\cos i \\ \sin(\omega+f)\sin i \end{bmatrix} \tag{1}$$

In order to simulate the state of satellite orbits in space more realistically, orbital perturbations(Chen and Lin 2020) including aspheric gravity, atmospheric drag, sun-moon gravity, sunlight pressure, and post-Newton effect are introduced, as shown in Figure 3.

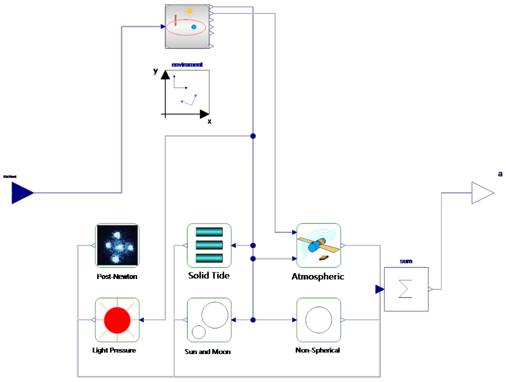


Figure 3. Orbit perturbation model.

- Non-spherical gravitational perturbation.

The Earth's gravitational field model adopts 70x70 Joint Gravity Model 3 (JCM3). The calculation of Non-spherical gravitational perturbation acceleration projected to the spherical coordinate component in the ground-fixed coordinate system is as follow:

$$\begin{aligned} a_N = &- \frac{\mu}{r^2 \cos\varphi} \sum_{n=2}^{\infty} \sum_{m=0}^{n} (\frac{R_e}{r})^n \{(1+n)\cos\varphi \\ &\overline{\mathbf{P}}_{\mathbf{nm}}(\sin\varphi)(\overline{C}_{nm}\cos m\lambda + \overline{S}_{nm}\sin m\lambda)e_r \\ &[n\sin\varphi \overline{\mathbf{P}}_{\mathbf{nm}}(\sin\varphi) - N_n m \overline{\mathbf{P}}_{\mathbf{n-1,m}}(\sin\varphi)] \\ &(\overline{C}_{nm}\cos m\lambda + \overline{S}_{nm}\sin m\lambda)e_\varphi + m\cdot \\ &(\overline{C}_{nm}\sin m\lambda - \overline{S}_{nm}\cos m\lambda)e_\lambda\} \end{aligned} \tag{2}$$

where e_r, e_φ and e_λ are the three orthogonal unit vectors of spherical coordinates. λ and φ denote geocentric longitude and geocentric latitude. $\overline{C}_{nm}$ and $\overline{S}_{nm}$ are the normalized gravitational coefficient. $N_{nm} = \sqrt{\frac{2n+1}{2n-1}(n+m)(n-m)}$. $\overline{\mathbf{P}}_{\mathbf{nm}}(\mathbf{u})$ is the normalized gravitational coefficient. n represents the truncation order.

- Atmospheric drag perturbation.

The acceleration of atmospheric drag on a satellite with an area-to-mass ratio is:

$$a_D = -\frac{1}{2}C_D\frac{S}{m}\rho|V|\cdot V \tag{3}$$

where C_D is damping coefficient. ρ is atmospheric density at the location of the satellite. V is the speed of the satellite relative to the atmosphere.

- Lunisolar gravitational perturbation.

The perturbation acceleration of the sun and the moon to the satellite can be expressed as:

$$a_T = -\mu_s(\frac{r-r_s}{||r-r_s||^3} + \frac{r_s}{r_s^3}) \tag{4}$$

where r and r_s are the position vector of the satellite and the sun or moon in the geocentric inertial system. μ_s is gravitational coefficient.

- Solar radiation perturbation.

The perturbation acceleration caused by solar radiation on the satellite can be expressed as:

$$a_R = KC_R\frac{S}{R}\frac{L_s}{4\pi c}\frac{r-r_s}{||r-r_s||^3} \tag{5}$$

where C_R is solar radiation coefficient. c is Speed of light. L_s represents luminosity of the sun. K is solar visibility coefficient.

- post-Newtonian effects.

The perturbation acceleration produced by the first-order post-Newtonian effect term is:

$$a_PN = \frac{\mu}{c^2r^3}[(4\frac{\mu}{r} - v^2)\dot{r} + (4\dot{v}\cdot\dot{r})\dot{v}] \tag{6}$$

where $\dot{r}$ and $\dot{v}$ are satellite position vector and velocity vector.

3.2.2 Satellite Model

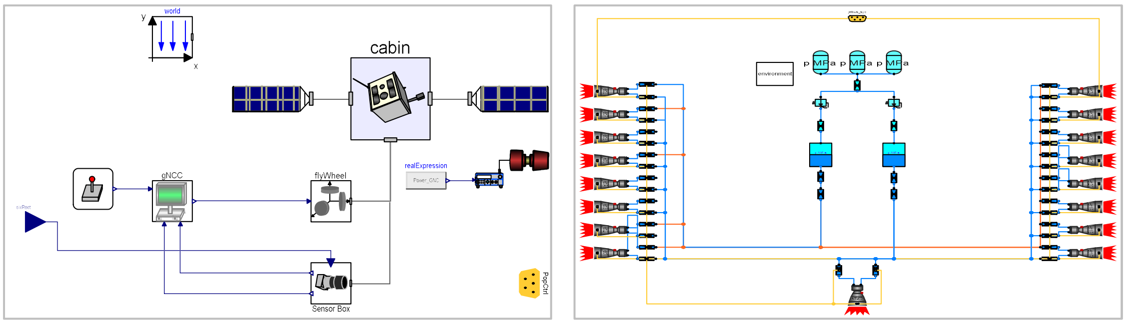
The satellite model is composed of four subsystem models, namely GNC subsystem model, propulsion subsystem model, payload subsystem model and power subsystem model.

Among them, the GNC subsystem consists of a satellite body model, a solar wing sail model, a sensor model, a flywheel model and a controller model, as shown in Figure 4(a), which is mainly responsible for the attitude and orbit control of the satellite. In order to maintain the satellite's payload to orient or track a specific target, attitude control is required. There are two ways to achieve attitude control. Small-scale attitude control is achieved by the controller generating a control signal to the flywheel, while large-scale attitude control is realized by the controller generating the switch signal of the attitude control engine.

The main task of the propulsion subsystem is to cooperate with the GNC subsystem to complete the attitude and orbit control during the life of the satellite. According to the function, it can be divided into a gas pressurization module, a propellant storage module and a thruster unit module, as shown in Figure 4(b). The gas pressurization module is composed of three gas cylinder models, a gas orifice model and a pressure regulating valve model. The main function is to provide the gas required for constant pressure operation to maintain working pressure for the rail-controlled engine; the propellant storage module consists of two storage tank models and liquid orifice models. The main effect is to store, distribute and supply the propellant required by the engine; the unit module mainly includes one orbit control engine model and sixteen attitude control thruster models, which provide propulsion for orbit control and attitude adjustment.

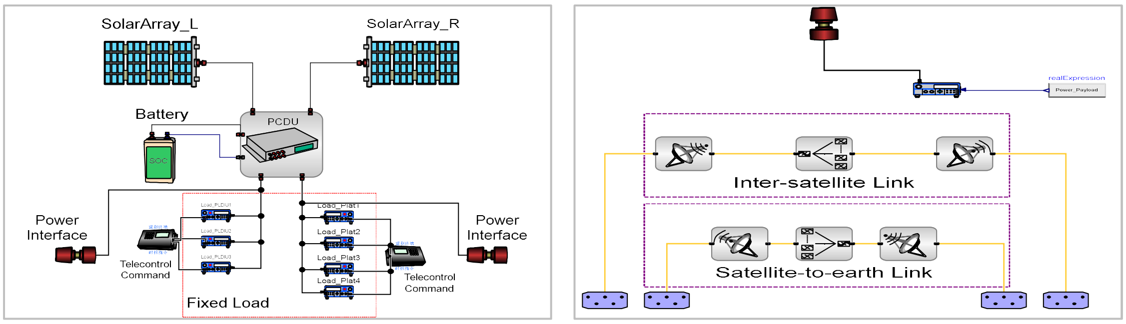
The power subsystem, as shown in Figure 4(c), includes two solar wing models, a battery model, a power controller model, and load models. The solar wing models on the left and right sides are composed of a certain number of solar cell models combined in series and parallel according to the design needs, and can generate full power under the condition of standard illumination of $1360W/m^2$. The battery model receives the electric energy output by the shunt regulator in the sunlit area for charging, and discharges when the solar wing power is insufficient for the load to maintain the stability of the bus voltage. The main function of the power controller model is to realize the distribution and regulation of solar wing power generation, battery charging and discharging, and load power, and to shunt according to needs. The load model is divided into two types, one is the fixed power load given in Figure 4(c), and the other is the load coupled in the other three subsystems. The second load is related to the working state of some equipment. For example, the power consumption of the electric load in the propulsion subsystem is related to the working status of seventeen engines.

The payload subsystem is generally composed of an-



(a) GNC subsystem model

(b) propulsion subsystem model



(c) power subsystem model

(d) payload subsystem model

Figure 4. Four main subsystem that make up satellite model in MWorks.

tenna models and transponder models, as shown in Figure 4(d). For the LEO communication satellite constellation, it is mainly used to establish ISL(L. Wang and D. Hu 2016; Yan 2010) and satellite-to-earth links. The user's communication data is received by the receiving antenna of the corresponding frequency band and then sent to the transponder. After the transponder performs gain adjustment and signal amplification processing on the data signal, it is transmitted to the transmitting antenna, and then to the next communication node through the transmitting antenna.

3.2.3 System Control Center Model

The system control center model belongs to the ground segment. The main function in the satellite constellation is to maintain the stability of the constellation structure. The input is orbital factors of all satellites calculated by the constellation orbit model, and the output is the speed pulse that the GNC subsystem needs to generate orbital maneuver control signal. In the satellite constellation structure, the two factors that have the greatest impact on the satellite coverage performance are the phase distribution and orbital plane distribution of the satellite, so phase control and orbital plane control are required.

The orbital plane and phase control reference of each satellite in the constellation are determined according to the following formula(Ulybyshev and Yuri 1998):

$$\Omega_0^* = \sum_{j=0}^{p-1}\sum_{k=0}^{s-1}\lambda_{jk}(\Omega_{jk} - j\cdot\frac{2\pi}{P} + j\cdot\frac{2\pi}{P}) \tag{7}$$

$$\begin{aligned} u_{00}^* = &\sum_{j=0}^{p-1}\sum_{k=0}^{s-1}\lambda_{jk}(u_{jk} - j\cdot F\cdot\frac{2\pi}{T} - k\cdot\frac{2\pi}{S}) \\ &+ j\cdot F\cdot\frac{2\pi}{T} + k\cdot F\cdot\frac{2\pi}{S} \end{aligned} \tag{8}$$

where λ_{jk} is the normalized weighting factor and the value is 1/T.

RAAN tolerance ε_Ω and phase tolerance ε_u are given in the form of model parameters. When $|\Delta u + H_u\Delta\dot{u}| > \varepsilon_u$, a phase holding maneuver is required, and the required tangential velocity pulse Δv_u is given by the following formula:

$$\Delta\dot{u}_r = \begin{cases} 0, & |\Delta u| < \varepsilon_u \\ K_u(\Delta u - \varepsilon_u), & \Delta u > \varepsilon_u \\ K_u(\Delta u + \varepsilon_u), & \Delta u < -\varepsilon_u \end{cases} \tag{9}$$

$$\Delta v_u = \frac{a}{3}(\Delta\dot{u} - \Delta\dot{u}_r) \tag{10}$$

where $\Delta\dot{u}_r$ is phase deviation change rate correction value. $\Delta\dot{u}$ is the rate of change of phase deviation, which is obtained by difference. $K_u = -1/H_u$, and H_u is the rate of change of phase deviation, which is obtained by difference.

Similarly, when $|\Delta\Omega + H_{\Omega}\Delta\dot{\Omega}| > \varepsilon_{\Omega}$, the orbital maintenance maneuver is required, and the required normal velocity pulse Δv_{Ω} is given by the following formula:

$$\Delta i = -\frac{1}{3J_2 \sin i}(\frac{a}{R_E})^2\sqrt{\frac{a^3}{\mu}}(\Delta\dot{\Omega} - \Delta\dot{\Omega}_r) \tag{11}$$

$$\Delta v_{\Omega} = 2\sqrt{\frac{\mu}{a}}\sin(i/2) \tag{12}$$

where the calculation of $\Delta\dot{\Omega}_r$ is similar to that of $\Delta\dot{u}_r$. Δi is the required change in inclination. $J2$ refers to perturbation of the earth oblateness.

4 Simulation Results

In this section, some example parameters will be injected into system model. Among them, constellation orbit parameters are from Iridium NEXT(Iridium 2017), the specific content of constellation orbit parameters is described in section 3.2.1, which will not be repeated here; satellite parameters include satellite mass, engine thrust, solar cell rated voltage, and number of string cells or parallel cells, battery capacity and antenna gain, etc.; link parameters mainly include the longitude and latitude of the communication user, communication frequency, the minimum elevation angle of satellite-to-ground communication, and the minimum clearance height of ISL. The following article will analyze the system simulation results from three aspects: orbit coverage, communication link, and satellite status.

4.1 Orbit Coverage

Orbit coverage simulation mainly focuses on satellite position change, constellation structure maintenance and ground coverage. The position change of satellites is shown by the longitude and latitude of sub-satellite points. As shown in Figure 5, the longitude of the sub-satellite point of satellite 1-1 and satellite 1-2 is between $180°W$ and $180°E$, and the latitude of the sub-satellite point is between $85°S$–$85°N$. Figure 6 and Figure 7 show that under the action of the speed pulse signal generated by the system control center, orbit deviation can be controlled within a range of $\pm 2°$. Figure 8 shows that during the normal operation of the constellation, the two places A and B with coordinates $(160°E, 20°N)$ $(100°E, 40°N)$ have always been covered by satellites, and the maximum number can reach 5 satellites.

4.2 Communication Link

The focus of communication link simulation is to evaluate the communication quality of the two places and the impact of inter-satellite link switching on the communication quality. Figure 9 and Figure 10 show the link attenuation of the upper satellite-to-ground link, the lower satellite-to-ground link, and the inter-satellite link, respectively. Figure 11 shows the overall communication margin of the full

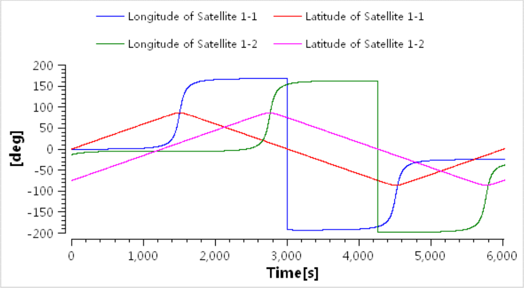


Figure 5. Longitude and latitude of sub-satellite points.

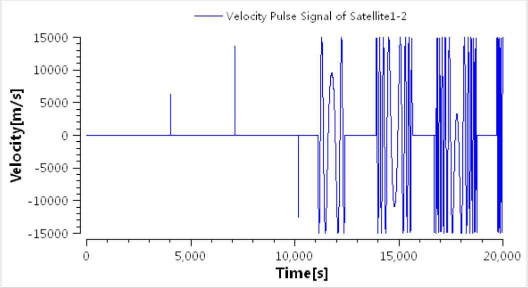


Figure 6. Tangential velocity pulse of satellite1-2.

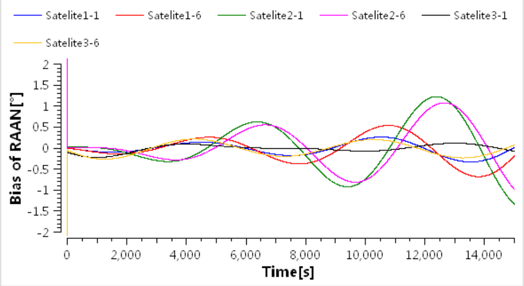


Figure 7. Deviation of orbital RAAN.

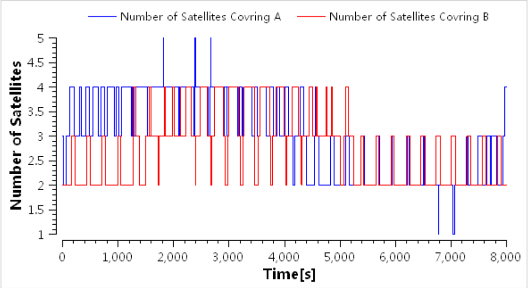


Figure 8. Number of satellites covered A and B.

link. Figure 12 shows the process of ISL switching. The simulation results show that the margin of the system can fully meet the communication needs of A and B.

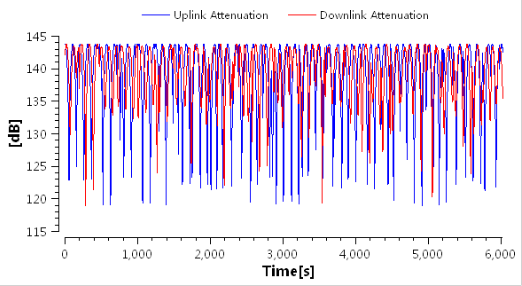


Figure 9. Satellite-to-groud link attenuation.

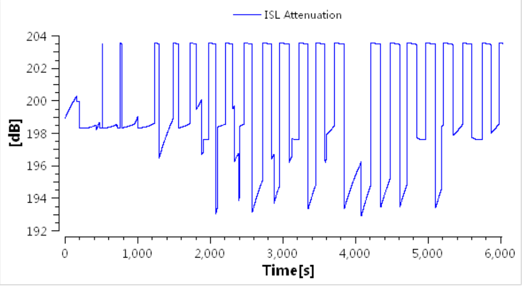


Figure 10. ISL link attenuation.

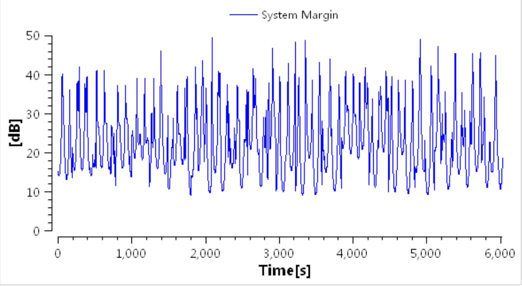


Figure 11. Link margin.

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Satellites Covering A: Satellite 1-5 Satellite 1-10 Satellite 6-4 Satellite 6-11

Satellites Covering B: Satellite 3-7 Satellite 4-1 Satellite 4-8

Minimum Hop Path:  Satellite 1-5---->Satellite 2-5---->Satellite 3-5---->Satellite 3-6---->Satellite 3-7

Satellites Covering A: Satellite 1-3 Satellite 1-5 Satellite 1-10 Satellite 6-4 Satellite 6-11

Satellites Covering B: Satellite 4-1 Satellite 4-8

Minimum Hop Path:  Satellite 1-3---->Satellite 2-3---->Satellite 3-3---->Satellite 4-3---->Satellite 4-2----
>Satellite 4-1

Satellites Covering A: Satellite 1-3 Satellite 1-10 Satellite 6-4 Satellite 6-9 Satellite 6-11

Satellites Covering B: Satellite 4-1 Satellite 4-8

Minimum Hop Path:  Satellite 6-9---->Satellite 5-9---->Satellite 4-9---->Satellite 4-8

Satellites Covering A: Satellite 1-3 Satellite 1-10 Satellite 6-4 Satellite 6-9

Satellites Covering B: Satellite 4-1 Satellite 4-6 Satellite 4-8

Minimum Hop Path:  Satellite 6-9---->Satellite 5-9---->Satellite 4-9---->Satellite 4-8
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Figure 12. ISL link swtiching.

4.3 Satellite Status

During the operation of the satellite constellation, the energy balance characteristics of 3 satellites in constellation are shown in Figure 13 and Figure 14. It can be seen that the state of charge of the three satellites remains above 80% and the output power of the solar array during the period with sunshine reaches 3000W, indicating the satellites energy system can satisfy the energy consumption under working conditions. Figure 15 shows the result of satellite attitude adjustment, the attitude angle is controlled within 1°.

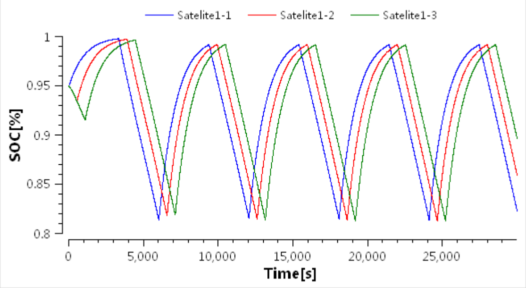

Figure 13. Results for SOC of batteries.

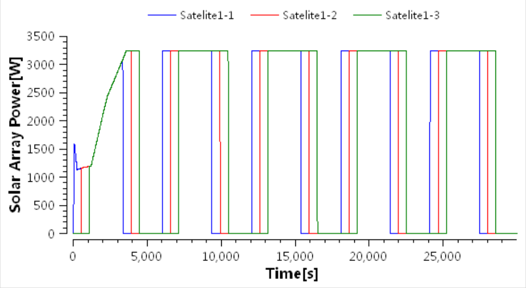

Figure 14. Results for output power of solar arrays.

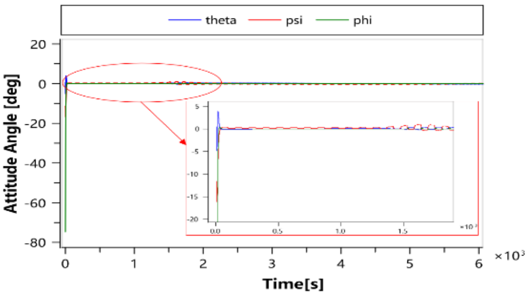

Figure 15. Results for satellite attitude angle.

5 Conclusions

In this paper, a system model of LEO communication satellite constellation is established, and a simulation analysis of typical service is carried out. The conclusions are as follows:

1. The system model established by the unified modeling language Modelica can support rapid design and verification of satellite constellation system.

2. The established system model can unify constellation orbit simulation, communication link performance simulation, and satellite status simulation.

3. The simulation application examples show that the constellation system model not only supports the characteristic analysis of key components, but also supports the overall performance evaluation of the system.

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