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A SELECTION ALGORITHM OF ORBITAL CONSTELLATION FOR LEO HIGH DATA RATE SATELLITE SYSTEM

The article presents a research model of navigation and ballistic structure of the orbital constellation. A selection algorithm of orbital structure for multi-satellite communication system without constellation adjustment that exploits the deterministic nature of the LEO satellite topology in order to deliver QoS guarantee is proposed.
Keywords: spacecraft; satellite system; algorithm; high data rate.

Introduction

National scientific and technical space program of Ukraine for 2013–2017 determines the development of modern space technology in Ukraine as an important factor in determining the strategic location of the state in the world [1].

The altitude of the satellites in the constellation is a significant factor in determining the number of satellites required to cover the Earth. A lower altitude decreases free space loss and propagation delay, but means that the service each satellite can offer is limited to users in a smaller visible area of the ground (the satellite's footprint). To fully cover the globe, more satellites are needed. This increases frequency reuse and overall system capacity, but will also increase overall system construction and maintenance costs. Satellites at lower altitudes must move faster relative to the ground to stay in their orbits, increasing the rate of handoff and Doppler effects between terminals and satellites [3; 4].

A basis for multi-satellite LEO systems is a system of orbital spacecrafts, defined as a set of spacecrafts to be arranged in-order in orbit and jointly implement the aims of the system [1].

One of the most important requirements [1; 2] about the orbital constellation is to maintain their sustainable navigation and ballistic structure. This is due to the fact that the movement parameters of both space-crafts and the orbital group in the whole are continually changing during the process of operation. The change of the parameters of orbital constellation leads to an increase of required energy characteristics in radio channels.

This ensures high efficiency of space systems, applies the global communications network for customer service, contributes to the development of scientific and technical potential [1; 3].

The aim of this work is to develop a choice algorithm of the orbital structure model of LEO high data rate satellite system.

Main part

According to the degree of motion ordering of the spacecraft in orbit satellite systems can be divided into two types [2; 3]:

1) with an orderly deterministic motion of spacecraft in orbit;

2) with a random phase placing of spacecraft into orbit plane.

For the first type for the operation of the system is necessary to conduct periodic or permanent adjustment of the mutual position of spacecrafts. In turn a space-craft requires the power equipment which complicates and increases the weight of the structure and reduces the term of active existence due to using of consumables.

The relative position of the spacecraft is random in LEO satellite systems without adjustment (uncorrectable multi-satellite systems) which causes a shift in the periodicity of observation. However, the weight of such spacecraft is much less that allows to increase total number of satellites in the system. An arbitrary arrangement of satellites is acceptable for communication systems. The equal periodicity of satellites in orbit is provided using a uniform distribution. The increase of multiplicity of the covering area is possible when approaching several spacecrafts due to this QoS (quality of service) is increased [3].

Effective use of satellites in the orbital system can only be provided if the navigational and ballistic characteristics of all satellites in the constellation are known and stable. It is therefore necessary to explore options for the construction of the orbital constellation and to analyze orbit parameters, which requires the development of methods of construction of navigation and ballistic multi-satellite structure.

Dynamic change model of the orbital structure of LEO multi-satellite system

Selecting of navigation and ballistic structure shall take into account all the constraints and based on an analysis of quality indicators of LEO multi-satellite system with different orbital construction, such as [2-4]:

- the operational availability factor ($K_{o.a}$);
- the network connectivity coefficient ($k_{n.c}$);
- the probability of message delivery within the specified time ($P_{delivery}$);
- the average delay time of messages ($T_{a.d.t}$).

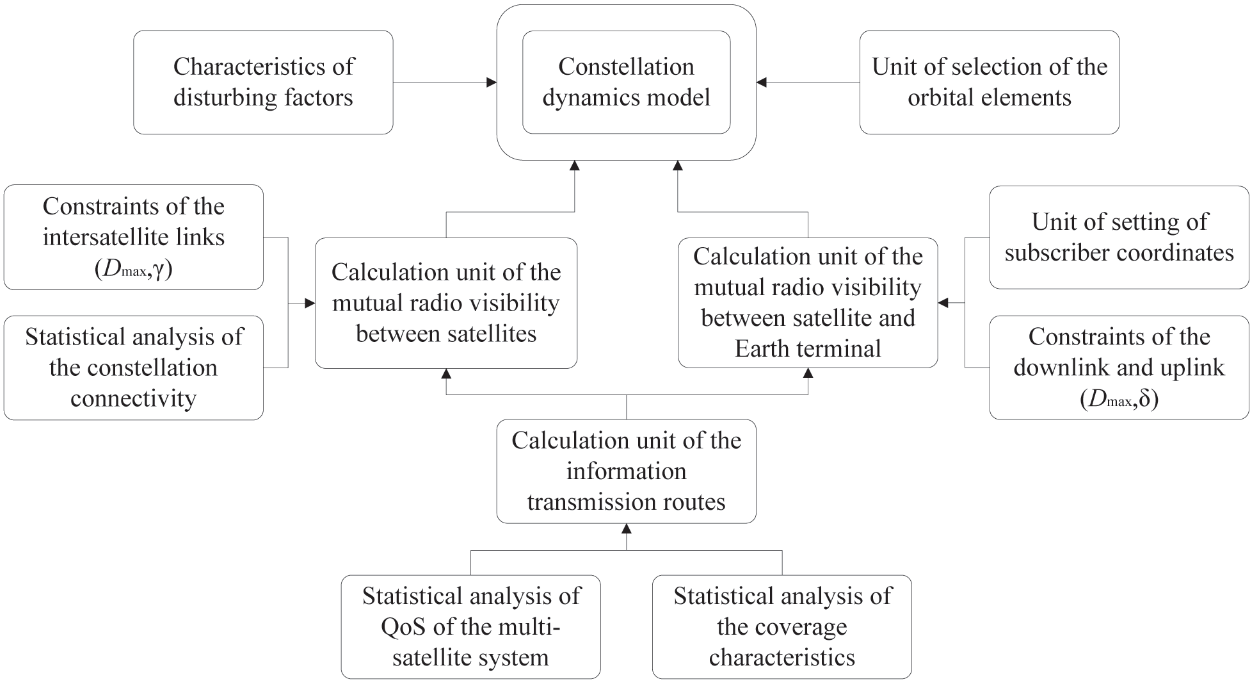

Fig. 1. Block diagram of the research model of the dynamics of the orbital spacecraft constellation

Fig. 1 shows the basic structural elements of the dynamics of the orbital spacecraft constellation.

The orbital structure of multi-satellite system is characterized by the number N of the spacecrafts and their orbital parameters. The following Keplerian elements are used as the orbital parameters [4]:

- Ω — the longitude of the ascending node;
- a — the semi-major axis (or the focal parameter p);
- i — the inclination;
- e — the eccentricity;
- ω — the argument of perigee;
- τ — the time of passage of the perigee τ.

Since $e = 0$ for circular orbits, and ω is not specified, such orbits are characterized by only four parameters: a, i, Ω, u_0. At that

$$a = r = H + R_z, \quad (1)$$

where H is the orbit altitude; r is the orbit radius.

At the stage of the research system performance simulation of the dynamics of the multi-satellite orbital network is advisable carried out in a central gravitational field, excluding air resistance, because the main reason for the instability of such networks are errors of spacecraft launch into orbit.

In turn, the impact of disturbing factors can be taken into account by means of «destruction» phased spacecraft motion in the orbital plane. In this case, the arguments of the latitude of all satellites of the constellation are distributed according to the uniform distribution in the range (0 … 360°). The relative deviation of the longitude of the ascending node of n turns is expressed in the following form [2–5]:

$$\delta\Omega_{ij} = -3\pi C_{20}\frac{R_E^2}{p_0^2} n\delta i_{ij}\sin i_0 - 6\pi C_{20}\frac{R_E^2}{p_0^3} n\delta p_{ij}\cos i_0. \quad (2)$$

Eq. (2) establishes the dependence of the relative orientation of orbit planes on the orbit insertion errors and the focal parameter $p = a(1 - e^2)$.

Calculation using the Eq. (2) shows that the relative error $\delta p_{ij}/p_0$ = 0,0001 (for a circular orbit of 1500 km altitude corresponds to the orbit insertion error of the semi-major axis about 0,8 km); δp_{ij} = 20 ang.min and the inclination i = 83°, the velocity of change of the relative orientation of the orbit will be respectively 0,0001° per day and 0,023° per day, i.e. approximately 42° of the displacement of nodes will be accumulated within 6 months.

It is noteworthy that for polar orbits ($i = 90°$), the effect of the orbit insertion errors on the focal parameter Ω is zero and is maximum for the orbit insertion errors on the inclination i. For the near-equatorial orbit ($i = 0°$) the situation is reversed.

In the geocentric inertial coordinate system, the position and velocity of the spacecraft in a circular orbit at any one time (characterized by the argument of the latitude) are calculated by the following relations:

$$\begin{aligned} x_{INi} &= r(\cos\Omega \times \cos u - \sin\Omega \times \sin u_i \times \cos i); \\ y_{INi} &= r(\sin\Omega \times \cos u + \cos\Omega \times \sin u_i \times \cos i); \\ z_{INi} &= r \times \sin u_i \times \sin i; \\ V_{xINi} &= -V_u(\cos\Omega \times \sin u_i + \sin\Omega \times \cos u_i \times \cos i); \\ V_{yINi} &= -V_u(\sin\Omega \times \sin u_i - \cos\Omega \times \cos u_i \times \cos i); \\ V_{zINi} &= V_u \times \cos u_i \times \sin i. \end{aligned} \quad (3)$$

The motion of the spacecraft in the system is modeled by the discrete changes in the Eq. (3) of the initial value of the argument of latitude by adding simulation step in each cycle: $u_{i+1} = u_i + \Delta u$, at that

$$\Delta u = 2\pi\Delta t/T, \quad (4)$$

where Δt is the time step of simulation; T is the treatment period of a spacecraft.

It is convenient to use Greenwich coordinate system (taking into account the Earth's rotation around its axis) to calculate service areas, time of mutual visibility, etc. [5]:

$$\begin{aligned} x_G &= x_{IN}\cos\gamma + y_{IN} \times \sin\gamma; \\ y_G &= y_{IN} \times \cos\gamma - x_{IN} \times \sin\gamma; \\ z_G &= z_{IN}; \\ V_{xG} &= V_{xIN} \times \cos\gamma + V_{yIN} \times \sin\gamma + \Omega_E y_G; \\ V_{yG} &= -V_{xIN} \times \sin\gamma + V_{yIN} \times \cos\gamma + \Omega_E x_G; \\ V_{zG} &= V_{zIN}, \end{aligned} \qquad (5)$$

where $\gamma = \Omega_E(t - t_0)$ and $\Omega_E = 0{,}729211 \times 10^{-4} s^{-1}$ is the angular velocity of the Earth's rotation.

A calculation algorithm for LEO multi-satellite system

To ensure steady maintenance any point of the given area must be situated at least at multi-satellite LEO footprint at each period of time. The number of these zones is equal to the number of satellites in the system [5]. The service area of a spacecraft on Earth's surface is characterized by the earth central angle φ_E [6]:

$$\varphi_E = \arccos\left(\frac{R_z \times \cos\delta}{R_z + H}\right) - \delta = \\ = 90^\circ - \gamma - \arccos\left(\frac{R_z + H}{R_z} \times \sin\gamma\right). \qquad (6)$$

By the development of a steady maintenance satellite system the following assumptions are accepted [7; 8]:

- spacecrafts of multi-satellite LEO system are arranged in circular orbits;
- the location of n spacecrafts in the plane of the spacecraft is uniform;
- the orbit altitude for all spacecrafts is the same;
- the service area of all spacecrafts in the system is equal;
- polar orbit (the inclination of the orbital plane to the plane of the equator equals to $\pi/2$).

As a result, the calculation algorithm of the uncorrectable LEO satellite system can be described as the following sequence of procedures.

1. The Earth central angle of zones φ_E is determined on the basis of Eq. (6).

2. The minimum number n_{min} of satellites in the same plane (intra-plane) is calculated using the following equation (so that the adjacent zones are touched) [3; 4]:

$$n_{min} = \mathrm{E}\left[\frac{2\pi}{2\varphi_E}\right] + 1, \qquad (7)$$

where E [Y] is Antje (from the nearest integer y, that does not exceed it).

3. The half of the angular distance between subsatellite points under two adjacent spacecrafts of the same plane (see Fig. 2) a_E is defined according to the formula

$$a_E = \frac{2\pi}{2n_{min}}. \qquad (8)$$

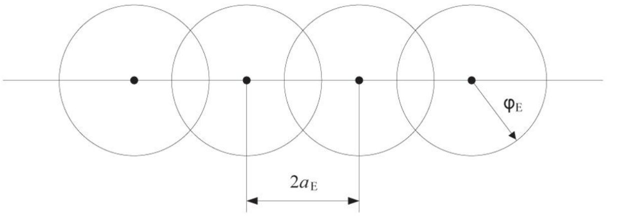

Fig. 2. By definition, the half of the angular distance between under-satellite points of two adjacent space-crafts of same plane

4. The width of the continuous in-view coverage area (by the spherical right-angled triangle) is calculated by the following equation:

$$b = \arccos\left(\frac{\cos\varphi_E}{\cos a}\right). \qquad (9)$$

5. The number of orbital planes is determined using the following equation:

$$m_{(1)} = \mathrm{E}\left[\frac{\pi}{2b}\right] + 1. \qquad (10)$$

6. The number of satellites in the system is calculated by the following formula:

$$N_{(1)} = m_{(1)} n_{min}. \qquad (11)$$

7. After this $N_{(1)}$ is memorized, then the number of satellites in the same plane is increased by one $n_{(2)} = n_{min}+1$ and the calculation is repeated starting with paragraph 3 by Eqs. (8) – (11).

8. Then $N_{(1)}$ and $N_{(2)}$ are compared and the minimum value is stored until $N_{(j+1)} > N_j$.

As a result of this algorithm, the «optimal» values $N = N_{opt}$; $m = m_{opt}$; $n = n_{opt}$ are determined.

As an example of calculation, the table shows the results of the required number of satellites in the continuous review system for altitudes (from $H = 600$ km to $H = 1500$ km), of circular orbits with the inclination i = $\pi/2$ and the minimum angle of elevation of the spacecraft above the horizon $\delta = 7°$.

The results of the calculation of the required number of satellites to ensure the continuity of service

H, km	600	750	1000	1500
n, pc	14	12	10	8
m, pc	8	7	6	5
N, pc	112	84	60	40

The maximum overlap is achieved over Earth's North and South Poles using such a construction of the system (with the orbital plane inclination to the equatorial plane is $\pi/2$). The design of inclined orbits reduces the number of satellites in the system and in this case the maximum efficiency of operation is shifted from Earth's poles to the lower latitudes.

Conclusions

The primary advantages associated with LEO satellites (compared to MEO and GEO) are a lower required transmit power, a lower propagation delay, a smaller weight of satellites, and polar coverage.

The use of satellites with a small weight and size is a promising trend of development of LEO satellite systems with high data rate equipment. LEO satellite system without constellation adjustment based on small satellites doesn't require constant control and adjustment during operation. As a result, this helps reduce required transmit power and significantly reduce the weight and size of the transceiver terminals. When deploying these satellite systems, there is no need to maintain a high accuracy of motion parameters of launch vehicles at the moment of separation of the spacecraft, which facilitates launch vehicle control system and makes launches even cheaper.

Research of the navigation and ballistic structure of LEO multi-satellite systems has allowed to develop a model of a satellite system without constellation adjustment, which takes into account the location of the satellites in circular orbits with the same altitude and inclination. In this case the network nodes are arranged in m planes of *N* satellites each. As a result, a model selection algorithm for LEO multi-satellite system without orbital constellation adjustment system has been proposed. The success of this construction is largely dependent on an implementation of routing strategies and routing algorithms and their ability to efficiently route traffic throughout the network. So further research will focus on a routing algorithm for LEO multi-satellite systems.

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АЛГОРИТМ ВИБОРУ МОДЕЛІ ОРБІТАЛЬНОЇ ПОБУДОВИ БАГАТОСУПУТНИКОВИХ НИЗЬКООРБІТАЛЬНИХ СИСТЕМ ВИСОКОШВИДКІСНОГО ПЕРЕДАВАННЯ ДАНИХ

У статті подано модель дослідження навігаційно-балістичної структури орбітального угруповання космічних апаратів. Запропоновано алгоритм розрахунку некоригованих багатосупутникових низькоорбітальних систем.

Ключові слова: космічний апарат; супутникова система; алгоритм; високошвидкісне передавання даних.

А. С. Албул

АЛГОРИТМ ВЫБОРА МОДЕЛИ ОРБИТАЛЬНОГО ПОСТРОЕНИЯ МНОГОСПУТНИКОВЫХ НИЗКООРБИТАЛЬНЫХ СИСТЕМ ВЫСОКОСКОРОСТНОЙ ПЕРЕДАЧИ ДАННЫХ

В статье представлена модель исследования навигационно-баллистической структуры орбитальной группировки космических аппаратов. Предложен алгоритм расчета некорректируемой многоспутниковой низкоорбитальной системы.

Ключевые слова: космический аппарат; спутниковая система; алгоритм; высокоскоростная передача данных.