УДК 521.32

МОДЕЛИРОВАНИЕ ПОСТРОЕНИЯ РЕГИОНАЛЬНОЙ ГРУППИРОВКИ НАНОСПУТНИКОВ ПУТЕМ ПОПУТНОГО ЗАПУСКА С РАЗЛИЧНЫХ КОСМОДРОМОВ

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Разработана маршрутная карта построения региональной группировки наноспутников путем попутного запуска по информации китайских провайдеров. Для создания группировки наноспутников, решающей целевые задачи сбора данных с мобильных объектов и обслуживания сервисов, был разработан программный модуль, предназначенный для анализа орбитального построения глобальной группировки *Spire Global*, выполняющей аналогичные

Образец цитирования:
Спиридонов АА, Баранова ВС, Саечников ВА, Ушаков ДВ. Моделирование построения региональной группировки наноспутников путем попутного запуска с различных космодромов. *Журнал Белорусского государственного университета. Физика.* 2022;2:50–59 (на англ.).
https://doi.org/10.33581/2520-2243-2022-2-50-59

For citation:
Spiridonov AA, Baranova VS, Saetchnikov VA, Ushakov DV. The regional nanosatellite constellation modelling formation by a piggyback launch from different spaceports. *Journal of the Belarusian State University. Physics.* 2022;2:50–59.
https://doi.org/10.33581/2520-2243-2022-2-50-59

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задачи. Структура группировки наноспутников *Spire Global* изучена на основе анализа базы данных орбитальных параметров, представленных в формате TLE (*two-line element set*), а также баз данных спутниковых группировок и сайта разработчика. Для построения группировки использовались две схемы запуска – запуск с Международной космической станции и попутный запуск. Исследованы схемы развертывания наноспутников, орбитальные параметры и параметры полета. Для моделирования построения региональной группировки проанализированы запуски наноспутников с космодромов Тайюань и Цзюцюань на орбиты с наклонением около 90°, наилучшим образом соответствующие пролету над Минском ($\varphi = 53°\,54'\,27''$ с. ш., $\lambda = 27°\,33'\,52''$ в. д.). Разработан метод предполетного прогнозирования орбиты наноспутника при попутном запуске. Данный метод предполагает определение вектора состояния наноспутника в первый день полета и на начало выполнения группировкой целевой задачи. Начальные данные, необходимые для моделирования предложенным методом, включают в себя время запуска, координаты космодрома, тип ракеты-носителя, наклонение и высоту орбиты (период). Также проводился анализ истории запусков и динамики движения спутника на аналогичных орбитах. Установлено, что для организации региональной группировки со средней продолжительностью перерыва радиовидимости порядка 36 мин при максимальном значении 85 мин достаточно пяти запусков.

Ключевые слова: группировка наноспутников; попутный запуск; предполетное прогнозирование орбиты.

Благодарность. Работа выполнена при поддержке государственных программ научных исследований Республики Беларусь «Высокотехнологичные технологии и оборудование» и «Цифровые и космические технологии, безопасность человека, общества и государства».

THE REGIONAL NANOSATELLITE CONSTELLATION MODELLING FORMATION BY A PIGGYBACK LAUNCH FROM DIFFERENT SPACEPORTS

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The roadmap for constructing a regional nanosatellite constellation using the piggyback launch according to Chinese provider information has developed. For nanosatellite constellation formation to a specific purpose, it is necessary to analyse existing constellation operated similar tasks. Therefore, the software module for the Spire Global constellation orbital construction analysis was developed. The construction of Spire Global nanosatellites constellation based on orbital parameters database in the two-line element set format, satellite constellation databases and the developer site was analysed. A launch from the International Space Station and a piggyback launch were used for constellation formation. Nanosatellite deployment schemes, orbital parameters and flight parameters are investigated launches from the Taiyuan and Jiuquan Satellite Launch Centers with orbit inclination about 90°, that best correspond to the passes over Minsk ($\varphi = 53°\,54'\,27''$ N, $\lambda = 27°\,33'\,52''$ E) are analysed. The method of nanosatellite orbit preflight prediction at a passing launch has been developed. It involves a finding the nanosatellite state vector in the first flight day and at the time of constellation mission operate start. The launch time, satellite launch center coordinates, launch vehicle type, orbit inclination and altitude (period) are used in the method. In addition, the launch history and the satellite motion dynamics analysis on similar orbits is carried out. It was found that five launches are enough to organise a regional nanosatellite constellation with average radio visibility interruption time of at least 36 min with a maximum value of 85 min.

Keywords: nanosatellite constellation; piggyback launch; pre-flight orbit prediction.

Acknowledgements. This work was supported by the state programs of scientific research of the Republic of Belarus «High-tech technologies and equipment» and «Digital and space technologies, human, society and state security».

Introduction

In Belarusian State University, the development of Earth remote sensing onboard satellite equipment has been carried out for 40 years at the aerospace research department of A. N. Sevchenko Institute of Applied Physical Problems [1] and at the department of physical optics [2]. In 2010, the radio physics and computer technology faculty started specialists preparation for aerospace sector. A university nanosatellite and a ground-based control system have been developed for the quality students training [3].

Over the past decade, there has been a worldwide trend towards the nanosatellite constellations formation for various purposes [4; 5]. As of early 2022, 52 constellations were still deploying. Of these, 27 – communication constellations (radio and optical range, data transmission, Internet), 13 – remote sensing, 5 – weather phenomena research, 3 – mobile objects automatic tracking (aircrafts and ships) and 4 – scientific research constellations [6; 7]. More than 50 nanosatellite constellations are planned for the future [8], including new task specifications such as asteroid observation, solar and ionospheric research. The number of satellites in the constellation ranges from tens to thousands.

For satellite constellations deploying are used a launch from the International Space Station and a piggyback launch (most often in sun-synchronous orbit) as secondary payload integration [9; 10]. The information enables the satellite developers to select a suitable launch for the mission is provided by a launch service in advance. This information includes the launch time, orbit inclination and altitude, and the launch vehicle type and characteristics.

Various constellation deployment methods are used. For single-plane nanosatellite constellation configurations the necessary in-plane separation can be achieved by either the launch vehicle upper-stage, carrier vehicles [11], differential separation spring deployment, differential drag [12], or nanosatellite propulsion systems [13]. For nanosatellite constellation with multiple orbital planes the requirement for out-of-plane manoeuvring can be costly. The paper [12] proposes a method for deploying a nanosatellite constellation to several orbital planes from a single launch vehicle. The method is based on commercially available deorbit devices that are used to lower the initial orbit, and that are discarded after the correct altitude has been reached. Calculations and simulations presented in the paper are shown, that with a launch of 6 satellites to an initial 800 km sun-synchronous orbit, orbital plane separation of approximately 30° between each satellite can be achieved within five years, with each satellite in its own final 600 km orbital plane [12]. Due to the long timescales, this method is best suited for long lifetime nanosatellite missions. In the work [14] constellation deployment method using plasma drag is proposed. Analytical analysis and numerical simulation results both agree that the constellation deployment time is proportional to the inverse square root of magnetic moment, the square root of desired phase angle and the square root of satellite mass [14]. Allowable constellation deployment time one year and more, this method is the best suited for long lifetime nanosatellite missions.

When creating a nanosatellite constellation to collecting data from mobile facilities and service for a particular region with a pass frequency 15–20 times a day does not require many spacecrafts in different planes. To meet the demand of information users requests, 5–6 nanosatellite is enough, when the period of repeated observations does not exceed 1–2 h [15]. In this paper to minimise the deployment time and cost of the nanosatellite constellation formation for collecting data from mobile facilities and service over the Minsk territory, a deployment scheme by launching nanosatellites from different spaceports is proposed. It is assumed that the nanosatellites do not have a propulsion system that allowed them to be separated according to the latitude argument in one orbital plane, which they would have acquired with a joint piggyback launch. Therefore, with the help of single launch vehicle, it is advisable to launch one nanosatellite of the constellation. The nanosatellite constellation is deployed in an orbital inclinations close to 90°, to provide extensive communication coverage over Minsk region. The key parameters for nanosatellite constellation are average radio visibility interruption time of at least 40 min with a 90 min maximum value. For example, this allows to control the aircraft traffic and unmanned aerial vehicles over a certain region [16].

For nanosatellite constellation formation to a specific purpose, it is necessary to analyse existing constellation operated similar tasks. It is necessary to assess the methods of constellation formation, to analyse the orbital parameters and to carry out numerical simulation of its operation dynamics. For analyse and numerical simulation, the Spire Global constellation has chosen.

Spire Global constellation analyses

Spire Global constellation is engaged in weather phenomena research, tasks of moving objects automatic tracking – planes and ships [16; 17]. The Spire Lemur and Minas nanosatellites are Cubesat 3U standard with a mass of 4.6 kg and two years design life [16]. They have the following onboard payload: STRATOS navigational receiver for remote atmosphere and ionosphere sensing, and accurate orbit determination; SENSE receiver for ship signals; ADS-B receiver (automatic dependent surveillance-broadcasting) for aircraft tracking; various weather sensors [16; 17]. Using the GNSS (Global Navigation Satellite System) receiver STRATOS (vertical sensing resolution of the 100 m order; longitudinal 200 km; transverse 1 km) [17] and various weather sensors for remote atmosphere and ionosphere sensing, the considered constellation provides the following user services: global weather forecast at different altitudes; produces 50 weather variables; provides various time intervals for weather forecast (short-term – forecast every hour, average – forecast every 6 h, long-term – forecast of the last 3 days or more) [16]. Based on the Automatic Identification System data processing, the receiver SENSE collects data and tracks the ships. The ADS-B receiver data provides information on aircraft tracking.

This work analyses the construction of Spire Global nanosatellites constellation based on orbital parameters database in the two-line element set (TLE) format [18], satellite constellation [8] databases and the developer site [16]. A launch from the International Space Station and a piggyback launch were used for constellation formation. During the period 2016–2022, 34 nanosatellites were launched from the International Space Station (2, 4 or 8 satellites each). As of March 2022, only 14 nanosatellites are active (2 satellites are expected to deorbit shortly). The orbital parameters of these Spire Global constellation satellites are as follows: inclination 51.6°, eccentricity less than 0.001, orbital altitude from 200 to 470 km. Between 2015 and 2022, 105 nanosatellites were successfully orbiting by 20 piggyback launches (with 2, 4, 6 or 8 satellites each). There are currently 101 nanosatellites in orbit. The orbital parameters of these Spire Global constellation satellites are as follows: inclination 36.9° (8 satellites), 49.9° (1 satellite), 82.9° (2 satellites), 85.0° (2 satellites) and from 97.3° to 97.7° (88 satellites); eccentricity less than 0.001; altitude range is from 500 to 650 km.

A software for the Spire Global constellation orbital construction analysis was developed based on the simplified general perturbations model [19; 20] and initial TLE data [21]. It includes estimates for the constellation orbits formation, the modelling of nanosatellites Lemur constellation dynamics and the pass parameters prediction over the Belarusian State University ground receiving station. The orbital parameters of the 115 – satellites constellation on 14 March 2022 were modelling. It was determined that satellites altitude ranged between 200 and 650 km at the time of the simulation. Besides, had defined the satellites orbital eccentricities are close to zero that would allow the circular motion model use for further modelling. Satellites are at different orbital inclinations. The 88 satellites are in sun-synchronous orbit, with inclinations ranging from 97.3° to 97.7°. The orbital planes are almost evenly distributed along the ascending node longitude, allowing global monitoring of all longitudes from 0 to 360°. However, as shown in fig. 1, Spire Global satellites weren't observed with ascending node longitudes from 162.9° to 179.6° and from 230.1° to 256.6° at the start time of simulation on 14 March 2022.

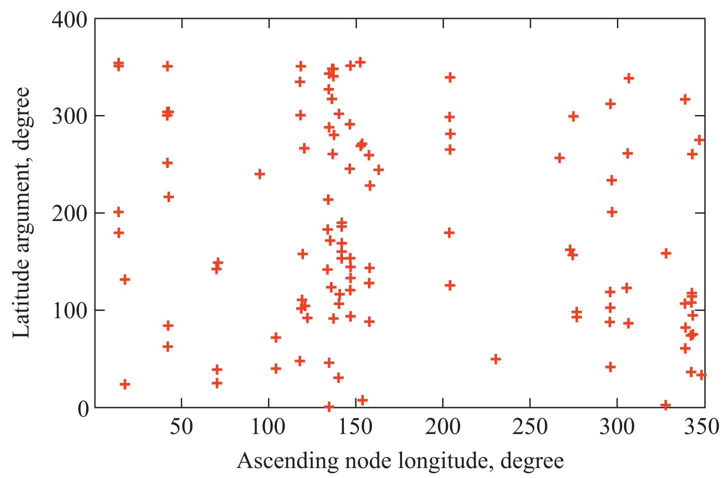

Fig. 1. The dependence of the latitude argument on the ascending node longitude for the Spire Global nanosatellite constellation

The highest number of satellites (50 %) was in the range ascending node longitude of 118.5° to 162.9°. In the plane of one orbit, the most uniform satellites distribution over the argument latitude was observed for the ascending node longitudes: 41.7°; 118.5°; 133.5°–157.4°; 203.4°; 295.8°. This allows global monitoring at all latitudes of −90° to +90° for ascending node longitude data at the time of modelling.

Pre-launch calculation orbital parameters method

In order to minimise the cost of the nanosatellite constellation formation for the purpose to solve the task of regional monitoring over the Minsk territory, a deployment scheme by launching nanosatellites from different spaceports is proposed. The mission target task begins a week after the constellation last nanosatellite launch. From the point the Belarusian State University has a positive experience with Chinese partners the information on the 2021 launches was chosen to analyse from the Chinese spaceports for the period June – November. Taking into account the Minsk geographical coordinates ($\varphi = 53° 54' 27''$ N, $\lambda = 27° 33' 52''$ E) 15 launches with an orbital inclination close to 90° were chosen from the following two launch sites: Jiuquan ($\varphi = 40° 57' 29''$ N, $\lambda = 100° 17' 28''$ E), Taiyuan ($\varphi = 38° 50' 56.71''$ N, $\lambda = 111° 36' 50.59''$ E).

In the paper [22] the satellite state vector determination method based on the perturbed circular motion for the piggyback launch into the solar-synchronous near-circular orbit has been developed. According to this method, the orbital period and satellite ascending node longitude are initially estimated from known launch time, orbital inclination and active launch path. Then, based on the launch history analysis results from the target spaceport by similar launch vehicles, using the initial TLE files, the latitude argument at the satellite launched epoch time was numerically predicted. Besides, based on the perturbed circular motion, the nanosatellite pass parameters (elevation, azimuth) and the Doppler frequency shift or radio signals necessary for successful radio communication over the ground receiving station are calculated.

In order to calculate the state vector of the constellation nanosatellites, a pre-launch orbit prediction method was developed. It involves two stages: finding the nanosatellite state vector in the first flight day and at the time of constellation mission operate start. The method flowchart is presented by fig. 2. The following input data is used in the method: the launch time, target spaceport coordinates, launch vehicles type, orbit inclination and altitude (period), as well as the history and motion dynamics analysis results of previous launches from the target spaceport to orbit with similar altitudes and inclinations.

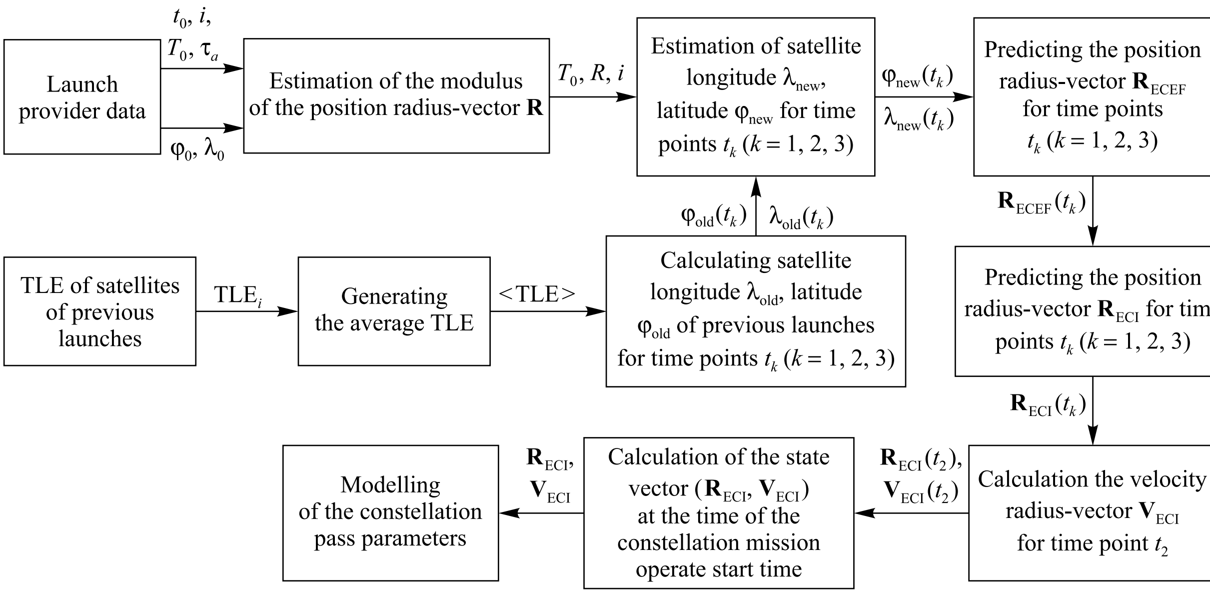

Fig. 2. Nanosatellite state vector calculation flowchart for constellation flight simulation

In the first stage, the nanosatellite state vector in the first flight day is calculated based on the minimum launch data (inclination i, altitude H_0 or period T_0, launch time t_0, target spaceport coordinates, launch vehicles type), and the launch history analysis results from the target spaceport by similar launch vehicles. In the process of satellite launch, the spent stages or boosters of the first and second launch vehicle stages should fall into specially designated areas for this purpose, where they can not cause any harm [23]. Therefore, it is assumed that the nanosatellite longitude λ_{new} and latitude φ_{new} from subsequent launches by similar vehicles at time $t_0 + \tau_a + \Delta t$ should coincide with the longitude λ_{old} and latitude φ_{old} of previous launches:

$$\lambda_{new}\left(t_0^{new} + \tau_a^{new} + \Delta t\right) = \lambda_{old}\left(t_0^{old} + \tau_a^{old} + \Delta t\right),$$

$$\varphi_{new}\left(t_0^{new} + \tau_a^{new} + \Delta t\right) = \varphi_{old}\left(t_0^{old} + \tau_a^{old} + \Delta t\right),$$

where t_0^{old}, t_0^{new} – previous and subsequent launch time; τ_a^{old}, τ_a^{new} – previous and subsequent active launch trajectory time interval; Δt – several minutes time interval.

To find the nanosatellite radius-vector and velocity vector at the epoch time t_e, the previous launches by similar vehicles are analysed, besides, nanosatellite longitude λ and latitude φ at three time moments $t_1 = t_e - \tau$, $t_2 = t_e$, $t_3 = t_e + \tau$ in the first flight day are estimated. Then, based on the orbital period T_0, the position radius-vector modulus R is calculated [8; 19]:

$$R = \mu^{1/3}\left(\frac{T_0}{2\pi}\right)^{2/3},$$

where μ is the gravitational parameter of the Earth and is equal 398 600.5 km^3/c^2.

Three nanosatellite radius-vectors $\mathbf{R}_{ECEF}\left(X_{ECEF}, Y_{ECEF}, Z_{ECEF}\right)$ in the Earth-centered, Earth-fixed (ECEF) coordinate system at times t_1, t_2, t_3 (Earth's oblateness has ignored) are figured out as follows [19]:

$$Z_{ECEF} = R\sin\varphi;\ X_{ECEF} = R\cos\varphi\cos\lambda;\ Y_{ECEF} = R\cos\varphi\sin\lambda,$$

where X_{ECEF}, Y_{ECEF}, Z_{ECEF} are coordinates of radius-vector $\mathbf{R}_{ECEF}$ in the ECEF coordinate system.

Since the greatest difference between geodesic latitude and geocentric latitude is reached at 45° latitude and is 0.192 1° = 11.315′, geocentric latitude for calculations has used.

Transforming radius-vector from the Earth-fixed to the geocentric inertial coordinate system at the time moment t_k ($i_k = 1, 2, 3$). The nanosatellite radius-vector in Earth-centered inertial (ECI) coordinate system [19]:

$$\mathbf{R}_{\text{ECI}} = \begin{pmatrix} X_{\text{ECI}} \\ Y_{\text{ECI}} \\ Z_{\text{ECI}} \end{pmatrix} = R_3\left(-\theta_{\text{GST}}\right)\mathbf{R}_{\text{ECEF}} = R_3\left(-\theta_{\text{GST}}\right)\begin{pmatrix} X_{\text{ECEF}} \\ Y_{\text{ECEF}} \\ Z_{\text{ECEF}} \end{pmatrix},$$

where $R_3\left(-\theta_{\text{GST}}\right) = \begin{pmatrix} \cos\left(-\theta_{\text{GST}}\right) & \sin\left(-\theta_{\text{GST}}\right) & 0 \\ -\sin\left(-\theta_{\text{GST}}\right) & \cos\left(-\theta_{\text{GST}}\right) & 0 \\ 0 & 0 & 1 \end{pmatrix}$ is rotate matrix; X_{ECI}, Y_{ECI}, Z_{ECI} are coordinates of radius-vector $\mathbf{R}_{\text{ECI}}$ in the ECI coordinate system; θ_{GST} is the Greenwich Sidereal Time (GST).

The Gibbs or Herrick – Gibbs method (for small time intervals values between the time moments t_i) is used to find the nanosatellite velocity vector $\mathbf{V}_{\text{ECI}}\left(t_2\right)$ from three position vectors $\mathbf{R}_{\text{ECI}}\left(t_i\right)$ [19]. Thus, the nanosatellite state vector in the first flight day at the epoch time $t_e = t_2$ is fully defined.

In the second stage, based on the nanosatellite state vector in the first flight day, the orbit prediction at the time constellation mission operate start is conducted. As known [19; 24], for a low-orbiting spacecraft, the main perturbing forces are the non-centrality Earth gravity field (mainly taking into account the second zone harmonic, that characterises the Earth polar compression) and the atmosphere resistance force.

Since the prediction time interval can reach several months to estimate the nanosatellite state vector, a simplified perturbed motion takes into account only secular orbital parameter perturbations are used. The secular average motion perturbations (average motion derivative) based on nanosatellite motion dynamics analysis of previous launches to similar altitudes and inclinations are estimated.

Then, in the simplified perturbed nanosatellite motion model (taking into account the secular perturbations from the second zone harmonic and from the mean motion derivative), a nanosatellite state vector assessment at the constellation flight simulation beginning time are made (a week after the last constellation nanosatellite launch).

The input data in the simplified perturbed motion model for nanosatellites orbital parameters calculating at the constellation mission operate start time t, expressed in the Julian date format, are: Δt – the difference between the constellation mission operate start time and the epoch elements time t_e, expressed in the Julian date format ($\Delta t = t - t_e$); semi-major axis a_0; orbit parameter p_0; eccentricity e_0; inclination i; ascending node longitude Ω_0; perigee argument w_0; mean anomaly M_0; mean motion n_0, calculated based on nanosatellites state vector at the epoch time t_e.

First, the nanosatellite orbital parameters at the constellation mission operate start time t, taking into account the secular perturbations from the first zone harmonic and the atmosphere resistance force (the mean motion first derivative) are determined [19]:

$$a = a_0 - \frac{2a_0}{3n_0}\dot{n}\Delta t,\ e = e_0 - \frac{2\left(1 - e_0\right)}{3n_0}\dot{n}\Delta t,\ \Omega = \Omega_0 - \frac{3n_0 R_E^2 J_2}{2p_0^2}\cos\left(i\right)\Delta t,$$

$$w = w_0 + \frac{3n_0 R_E^2 J_2}{4p_0^2}\left(4 - 5\sin^2\left(i\right)\right)\Delta t,\ M = M_0 + n_0\Delta t + \frac{\dot{n}}{2}\Delta t^2,$$

$$p = a\left(1 - e^2\right),$$

where $J_2 = 0.001\,082\,626\,7$ is the second zonal harmonic; $R_E = 6378.137$ km is the mean equatorial radius of the Earth.

Then, the Kepler equation for eccentric anomaly E has been solved:

$$E - e\sin E = M.$$

After calculating the eccentric anomaly E, we find the true anomaly ϑ at the constellation operate start moment of time t [19; 24]:

$$\operatorname{tg}\frac{\vartheta}{2} = \sqrt{\frac{1+e}{1-e}}\operatorname{tg}\frac{E}{2} \text{ or } \cos\vartheta = \frac{\cos E - e}{1 - e\cos E}.$$

The current nanosatellite state vector at the constellation operate start time t in the orbital coordinate system is determined with the used the radius vector module and the true anomaly angle ϑ as [9; 19]:

$$X_{\mathrm{orb}} = R_{\mathrm{orb}} \cos\vartheta,\ Y_{\mathrm{orb}} = R_{\mathrm{orb}} \sin\vartheta,\ Z_{\mathrm{orb}} = 0,$$

$$V_{X_{\mathrm{orb}}} = -\sin\vartheta \sqrt{\frac{\mu}{p}},\ V_{Y_{\mathrm{orb}}} = \left(e + \cos\vartheta\right)\sqrt{\frac{\mu}{p}},\ V_{Z_{\mathrm{orb}}} = 0,$$

where $R_{\mathrm{orb}} = \dfrac{p}{1 + e\cos\vartheta}$ is the orbital radius vector module.

As a result, the nanosatellite position vector $\mathbf{R}_{\mathrm{ECI}}(t) = (X,\ Y,\ Z)$ and the velocity vector $\mathbf{V}_{\mathrm{ECI}}(t) = \left(V_x,\ V_y,\ V_z\right)$ in the geocentric inertial coordinate system (*OXYZ*) at the constellation operate start time are determined [9; 19]:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = R_3(-\Omega) R_1(-i) R_3(-w) \begin{pmatrix} X_{\mathrm{orb}} \\ Y_{\mathrm{orb}} \\ Z_{\mathrm{orb}} \end{pmatrix},$$

$$\begin{pmatrix} V_X \\ V_Y \\ V_Z \end{pmatrix} = R_3(-\Omega) R_1(-i) R_3(-w) \begin{pmatrix} V_{X_{\mathrm{orb}}} \\ V_{Y_{\mathrm{orb}}} \\ V_{Z_{\mathrm{orb}}} \end{pmatrix},$$

where $R_1(\alpha) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{pmatrix}$ is rotation matrix.

Results and discussion

For 15 launches from the Jiuquan and Taiyuan spaceports at 00:00:00 UTC (coordinated universal time) 11 November 2021 the nanosatellite constellation orbital parameters were calculated. As the result, the route map for the regional nanosatellites constellation formation was developed, that presented in fig. 3.

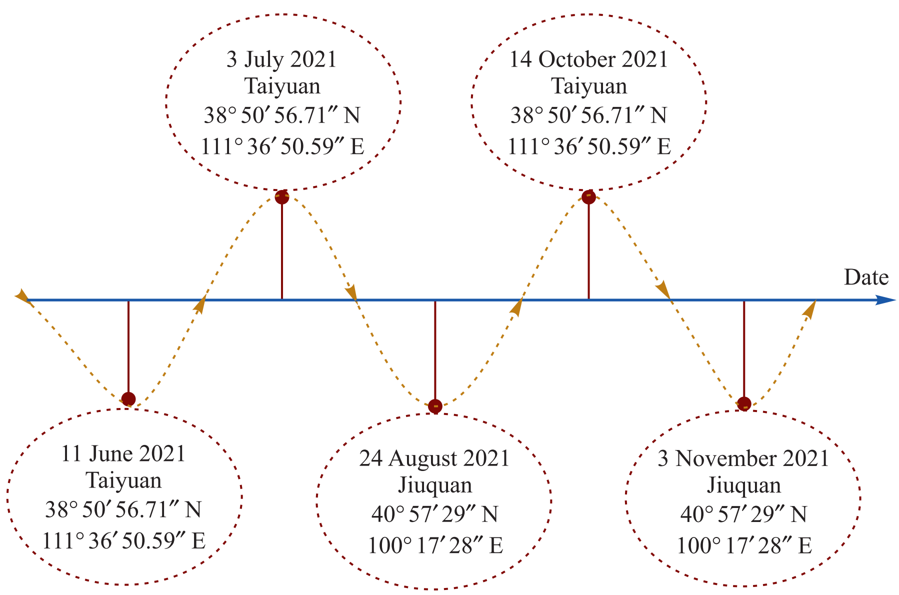

Fig. 3. Route map of the regional nanosatellites constellation formation for selected five launches from Jiuquan and Taiyuan

According presented road map (see fig. 3), five launches (11 June, 3 July, 24 August, 14 October, 3 November) were chosen to produce five orbital planes differing in ascending node longitude Ω (20°, 24.8°, 37.9°, 80.3°, 140.4°). For the close nanosatellite orbital planes (with $\Omega = 20°$ and $\Omega = 24.8°$), the launches spaced by the latitude argument u to diametrically opposite points of the orbit were selected, as shown in the table.

Nanosatellite orbital parameters for five selected launches

Date and lunch time (spaceport)	Nanosatellite number	*i*, degree	H, km	Ω, degree	*u*, degree
11 June 2021 (Taiyuan)	4	97.50	493	24.8	279.1
3 July 2021(Taiyuan)	5	97.52	536	20	124.4
24 August 2021 (Jiuquan)	1	86.41	1099	37.9	73.3
14 October 2021 (Taiyuan)	3	97.46	514	140.4	47.6
3 November 2021 (Jiuquan)	2	98.10	695	80.3	131.8

The constellation with five nanosatellites during its pass over the Minsk at the daily interval of 11 November 2021 was modelled. Figure 4 presents a visibility constellation nanosatellites time chart. It has been established that the largest number of times (10) in the Minsk sight area was nanosatellite 1, with a 18 min maximum interval. The rest (nanosatellites 2–5) passed 7–8 times with a 13 min maximum interval. At the same time, the constellation radio visibility interruption time was 36 min with an 85 min maximum value.

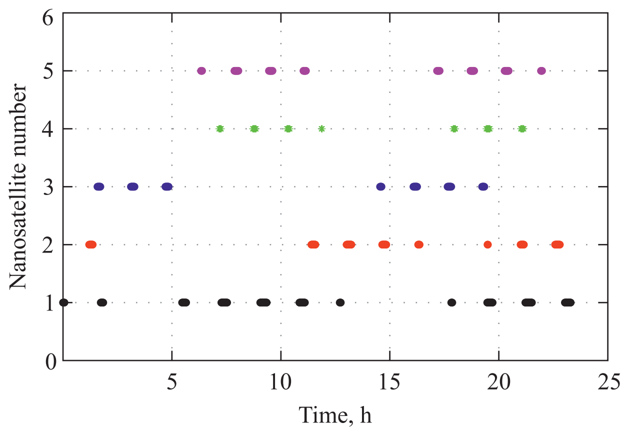

Fig. 4. The visibility constellation nanosatellites time chart

Conclusion

The software module for the nanosatellite constellation orbital construction analysis was developed. The construction of Spire Global nanosatellites constellation based on orbital parameters database in the TLE format, satellite constellation databases and the developer site information was analysed. The pre-flight piggyback launched nanosatellite orbit prediction method was developed. It involves two stages: finding the nanosatellite state vector in the first flight day and at the time of constellation mission operate start. The roadmap for constructing a regional nanosatellite constellation to collecting data from mobile facilities and service using the piggyback launch according to Chinese provider information has developed. Launches from the Taiyuan and Jiuquan Satellite Launch Centers with orbit inclination about 90°, that best correspond to the passes over Minsk are analysed. It was found that five launches are enough to organise a regional nanosatellite constellation with average radio visibility interruption time of at least 36 min with an 85 min maximum value.

Библиографические ссылки

1. Мартинов АО, Катковский ЛВ, Станчик ВВ, Беляев БИ. Исследование атмосферы с помощью сканирующего солнечного спектрополяриметра. *Журнал Белорусского государственного университета. Физика.* 2018;3:20–30.

2. Коваленко МН, Минько АА, Дидковский ЯИ, Последович МР, Шарашкин СН. Экспериментальный образец широкозахватного оптоэлектронного сканера с системой регистрации, хранения и обработки данных. *Журнал Белорусского государственного университета. Физика.* 2018;3:31–37.

3. Saetchnikov V, Semenovich S, Spiridonov A, Tcherniavskaia E, Cherny V, Stetsko I, et al. BSUSat-1 – research/educational lab – one year in orbit. In: *IEEE 7th International workshop on metrology for AeroSpace (MetroAeroSpace); 2020 June 22–24; Pisa, Italy.* [S. l.]: Institute of Electrical and Electronics Engineers; 2020. p. 111–116. DOI: 10.1109/MetroAeroSpace48742.2020.9160137.

4. Villela T, Costa CA, Brandão AM, Bueno FT, Leonardi R. Towards the thousandth cubesat: a statistical overview. *International Journal of Aerospace Engineering*. 2019;2019:5063145. DOI: 10.1155/2019/5063145.

5. Garzaniti N, Tekic Z, Kukolj D, Golkar A. Review of technology trends in new space missions using a patent analytics approach. *Progress in Aerospace Sciences.* 2021;125:100727. DOI: 10.1016/j.paerosci.2021.100727.

6. Curzi G, Modenini D, Tortora P. Large constellations of small satellites: a survey of near future challenges and missions. *Aerospace.* 2020;7(9):133. DOI: 10.3390/aerospace7090133.

7. Спиридонов АА, Велиган ВА, Шалатонин ИА, Баранова ВС, Ушаков ДВ, Черный ВЕ и др. Низкоорбитальные группировки малоразмерных космических аппаратов. В: Кугейко ММ, Афоненко АА, Баркова АВ, редакторы. *Квантовая электроника. Материалы XIII Международной научно-технической конференции; 22–26 ноября 2021 г.; Минск, Беларусь.* Минск: БГУ; 2021. с. 421–424.

8. Nanosatellite & cubesat database [Internet]. [S. l.]: Erik Kulu; 2014–2022 [modified 2022 January 1; cited 2022 March 20]. Available from: https://www.nanosats.eu/database.

9. Spiridonov AA, Kesik AG, Saechnikov VA, Cherny VE, Ushakov DV. Determination of the orbit of an unknown ultra-small spacecraft based on the circular perturbed motion model and measurements of the Doppler frequency shift. *Moscow University Physics Bulletin.* 2020;75(5):488–495. DOI: 10.3103/S0027134920050203.

10. Masters D, Duly T, Esterhuizen S, Irisov V, Jales P, Nguyen V, et al. Status and accomplishments of the Spire Earth observing nanosatellite constellation. *Proceedings of SPIE. Remote Sensing.* 2020;11530:115300V. DOI: 10.1117/12.2574110.

11. McGrath C, Kerr E, Macdonald M. An analytical, low-cost deployment strategy for satellite constellations. In: Hatton S, editor. *Proceedings of the 13th Reinventing space conference.* Cham: Springer; 2018. p. 107–116. DOI: 10.1007/978-3-319-32817-1_11.

12. Leppinen H. Deploying a single-launch nanosatellite constellation to several orbital planes using drag maneuvers. *Acta Astronautica*. 2016;121:23–28. DOI: 10.1016/j.actaastro.2015.12.036.

13. Marinan A, Nicholas A, Cahoy K. Ad hoc CubeSat constellations: secondary launch coverage and distribution. In: *IEEE Aerospace conference; 2013 March 2–9; Big Sky, MT, USA.* [S. l.]: Institute of Electrical and Electronics Engineers; 2013. DOI: 10.1109/aero.2013.6497174.

14. Park JH, Matsuzawa S, Inamori T, Jeung I-S. Nanosatellite constellation deployment using on-board magnetic torquer interaction with space plasma. *Advances in Space Research*. 2018;61(8):2010–2021. DOI: 10.1016/j.asr.2018.01.038.

15. Klyushnikov VYu. Status and prospects of developing commercial nano satellite constellations for Earth remote sensing. *AIP Conference Proceedings.* 2021;2318(1):190008. DOI: 10.1063/5.0036069.

16. Harnessing space to solve problems on Earth [Internet; cited 2022 March 14]. Available from: https://spire.com.

17. Angling MJ, Nogués-Correig O, Nguyen V, Vetra-Carvalho S, Bocquet F-X, Nordstrom K, et al. Sensing the ionosphere with the Spire radio occultation constellation. *Journal of Space Weather and Space Climate.* 2021;11:56. DOI: 10.1051/swsc/2021040.

18. NORAD general perturbations (GP) element sets. Current data [Internet; cited 2022 March 14]. Available from: https://celestrak.com/NORAD/elements/.

19. Vallado DA. *Fundamentals of astrodynamics and applications*. 4th edition. Wertz J, editor. Hawthorne: Microcosm Press; 2013. 1106 p.

20. Vallado DA, Crawford P, Hujsak R, Kelso TS. Revisiting spacetrack report #3. In: *AIAA/AAS Astrodynamics specialist conference and exibit; 2006 August 21–24; Keystone, Colorado, USA.* [S. l.]: American Institute of Aeronautics and Astronautics; 2006. DOI: 10.2514/6.2006-6753.

21. Wang R, Liu J, Zhang QM. Propagation errors analysis of TLE data. *Advances in Space Research*. 2009;43(7):1065–1069. DOI: 10.1016/j.asr.2008.11.017.

22. Spiridonov AA, Saetchnikov VA, Ushakov DV, Cherny VE. Pre-Flight calculation of the orbital parameters of a small satellite. *AIP Conference Proceedings*. 2022;2456(1):030037. DOI: 10.1063/5.0074461.

23. Лысенко ЛН, Бетанов ВВ, Звягин ФВ. *Теоретические основы баллистико-навигационного обеспечения космических полетов.* Лысенко ЛН, редактор. Москва: Издательство МГТУ имени Н. Э. Баумана; 2014. 518 с.

24. Capderou M. *Satellites orbits and missions*. Paris: Springer; 2005. 564 p. DOI: 10.1007/b139118.

References

1. Martinov AO, Katkouski LV, Stanchick VV, Beliaev BI. Investigation of the atmosphere with a scanning solar spectropolarimeter. *Journal of the Belarusian State University. Physics*. 2018;3:20–30. Russian.

2. Kovalenko MN, Minko AA, Didkovsky YI, Pasliadovich MR, Sharashkin SN. Prototype of a wide-angle optoelectronic scanner with a system for data recording, storage, and processing. *Journal of the Belarusian State University. Physics.* 2018;3:31–37. Russian.

3. Saetchnikov V, Semenovich S, Spiridonov A, Tcherniavskaia E, Cherny V, Stetsko I, et al. BSUSat-1 – research / educational lab – one year in orbit. In: *IEEE 7th International workshop on metrology for AeroSpace (MetroAeroSpace); 2020 June 22–24; Pisa, Italy.* [S. l.]: Institute of Electrical and Electronics Engineers; 2020. p. 111–116. DOI: 10.1109/MetroAeroSpace48742.2020.9160137.

4. Villela T, Costa CA, Brandão AM, Bueno FT, Leonardi R. Towards the thousandth cubesat: a statistical overview. *International Journal of Aerospace Engineering*. 2019;2019:5063145. DOI: 10.1155/2019/5063145.

5. Garzaniti N, Tekic Z, Kukolj D, Golkar A. Review of technology trends in new space missions using a patent analytics approach. *Progress in Aerospace Sciences.* 2021;125:100727. DOI: 10.1016/j.paerosci.2021.100727.

6. Curzi G, Modenini D, Tortora P. Large constellations of small satellites: a survey of near future challenges and missions. *Aerospace.* 2020;7(9):133. DOI: 10.3390/aerospace7090133.

7. Spiridonov AA, Veligan VA, Shalatonin IA, Baranova VS, Ushakov DV, Cherny VE, et al. Low-orbit constellations of small sized satellites. In: Kugeiko MM, Afonenko AA, Barkova AV, editors. *Kvantovaya elektronika. Materialy XIII Mezhdunarodnoi nauchno-tekhnicheskoi konferentsii; 22–26 noyabrya 2021 g.; Minsk, Belarus'* [Quantum electronics: materials of the 13th International scientific and technical conference; 2021 November 22–26; Minsk, Belarus]. Minsk: Belarusian State University; 2021. p. 421–424. Russian.

8. Nanosatellite & cubesat database [Internet]. [S. l.]: Erik Kulu; 2014–2022 [modified 2022 January 1; cited 2022 March 20]. Available from: https://www.nanosats.eu/database.

9. Spiridonov AA, Kesik AG, Saechnikov VA, Cherny VE, Ushakov DV. Determination of the orbit of an unknown ultra-small spacecraft based on the circular perturbed motion model and measurements of the Doppler frequency shift. *Moscow University Physics Bulletin.* 2020;75(5):488–495. DOI: 10.3103/S0027134920050203.

10. Masters D, Duly T, Esterhuizen S, Irisov V, Jales P, Nguyen V, et al. Status and accomplishments of the Spire Earth observing nanosatellite constellation. *Proceedings of SPIE. Remote Sensing.* 2020;11530:115300V. DOI: 10.1117/12.2574110.

11. McGrath C, Kerr E, Macdonald M. An analytical, low-cost deployment strategy for satellite constellations. In: Hatton S, editor. *Proceedings of the 13th Reinventing space conference.* Cham: Springer; 2018. p. 107–116. DOI: 10.1007/978-3-319-32817-1_11.

12. Leppinen H. Deploying a single-launch nanosatellite constellation to several orbital planes using drag maneuvers. *Acta Astronautica*. 2016;121:23–28. DOI: 10.1016/j.actaastro.2015.12.036.

13. Marinan A, Nicholas A, Cahoy K. Ad hoc CubeSat constellations: secondary launch coverage and distribution. In: *IEEE Aerospace conference; 2013 March 2–9; Big Sky, MT, USA.* [S. l.]: Institute of Electrical and Electronics Engineers; 2013. DOI: 10.1109/aero.2013.6497174.

14. Park JH, Matsuzawa S, Inamori T, Jeung I-S. Nanosatellite constellation deployment using on-board magnetic torquer interaction with space plasma. *Advances in Space Research*. 2018;61(8):2010–2021. DOI: 10.1016/j.asr.2018.01.038.

15. Klyushnikov VYu. Status and prospects of developing commercial nano satellite constellations for Earth remote sensing. *AIP Conference Proceedings.* 2021;2318(1):190008. DOI: 10.1063/5.0036069.

16. Harnessing space to solve problems on Earth [Internet; cited 2022 March 14]. Available from: https://spire.com.

17. Angling MJ, Nogués-Correig O, Nguyen V, Vetra-Carvalho S, Bocquet F-X, Nordstrom K, et al. Sensing the ionosphere with the Spire radio occultation constellation. *Journal of Space Weather and Space Climate.* 2021;11:56. DOI: 10.1051/swsc/2021040.

18. NORAD general perturbations (GP) element sets. Current data [Internet; cited 2022 March 14]. Available from: https://celestrak.com/NORAD/elements/.

19. Vallado DA. *Fundamentals of astrodynamics and applications*. 4th edition. Wertz J, editor. Hawthorne: Microcosm Press; 2013. 1106 p.

20. Vallado DA, Crawford P, Hujsak R, Kelso TS. Revisiting spacetrack report #3. In: *AIAA/AAS Astrodynamics specialist conference and exibit; 2006 August 21–24; Keystone, Colorado, USA.* [S. l.]: American Institute of Aeronautics and Astronautics; 2006. DOI: 10.2514/6.2006-6753.

21. Wang R, Liu J, Zhang QM. Propagation errors analysis of TLE data. *Advances in Space Research*. 2009;43(7):1065–1069. DOI: 10.1016/j.asr.2008.11.017.

22. Spiridonov AA, Saetchnikov VA, Ushakov DV, Cherny VE. Pre-Flight calculation of the orbital parameters of a small satellite. *AIP Conference Proceedings*. 2022;2456(1):030037. DOI: 10.1063/5.0074461.

23. Lysenko LN, Betanov VV, Zvyagin FV. *Teoreticheskie osnovy ballistiko-navigatsionnogo obespecheniya kosmicheskikh poletov* [Theoretical foundations of ballistic and navigation support for space flights]. Lysenko LN, editor. Moscow: Izdatel'stvo MGTU imeni N. E. Baumana; 2014. 518 p. Russian.

24. Capderou M. *Satellites orbits and missions*. Paris: Springer; 2005. 564 p. DOI: 10.1007/b139118.

Received 26.04.2022 / revised 04.05.2022 / accepted 05.05.2022.