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Pre-Flight Calculation of the Orbital Parameters of a Small Satellite

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Abstract. The problem of pre-flight calculation of the orbital parameters of the first nanosatellite of the Belarusian State University CubeBel-1 before launching from the Jiuquan Satellite Launch Center in China has been solved. The first nanosatellite passes over the Belarusian State University ground station were predicted based on the perturbed circular motion model. The initial TLE file was generated and published on the Internet. This allowed dozens of radio amateurs from 5 continents successfully to receive the nanosatellite telemetry on the first day after the launch on October 29, 2018 at 00:43:13.576 UTC, and the Belarusian State University ground station was the first to decode the CubeBel-1 telemetry. The obtained initial parameters were compared with the calculations in the SGP 4 model. It is shown that the absolute errors in predicting the elevation and azimuth of nanosatellite CubeBel-1 did not exceed 2° and 3°, respectively, and the absolute error in predicting the Doppler frequency shift of telemetry signals did not exceed 350 Hz, which, with appropriate receiver settings, is sufficient for successful reception of telemetry signals of satellite and their decoding.

INTRODUCTION

When universities develop their educational small satellite (SS), preflight evaluation of their orbital parameters is an urgent problem. This is necessary both for planning the satellite operation during the first day of the flight, and for its search, identification (during a group launch), and organizing initial radio communication sessions. There are many examples of launching university educational satellites when they were lost after launch [1, 2]. Usually, university SS are developed according to the Cubesat standard [3, 4]. From the analysis of the averaged orbital parameters in the TLE format, it was shown [5, 6] that there are two characteristic orbits of the Cubesat satellite associated with two ways of launching them. The first method is a launch from the International Space Station (ISS). The second method is a group launch of satellites to a sun-synchronous orbit, usually together with the main payload of the launch (with a remote sensing satellite). Usually, the launch provider provides information in the form Interface control document (ICD) for piggyback satellite and Launch Vehicle. This document contains information about the parameters of the launch vehicle, the separation time of the satellite from the launch vehicle, and the flight profile of the launch vehicle. In the first hours after the launch of a SS, it is very important to receive and decode the beacon signals to check the operation of its onboard systems, evaluate its performance, and make operational management solutions. These problems can be solved by predicting the time intervals and pass parameters of the satellite over the ground station (GS). Usually, the SGP4 model is used to predict satellite motion [7]. The SGP4 model uses two-line elements (TLE) as initial data for orbit prediction [7, 8]. These TLEs are currently provided by the North American Aerospace Defense Command (NORAD).

But in the first hours after the launch of the SS, the database of the NORAD system does not contain information on its orbital parameters. Since the communication between the low-orbit SS and the GS is limited to a few minutes 5–6 times a day, for successful operation in the first days of the flight, it is necessary to connect as many amateur radio stations around the world as possible for SS search and receive its telemetry. Therefore, a preliminary estimation and publication of the predicted orbital parameters of the launched satellite are very important for its

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successful search and organization of stable radio communication. Another problem in the first days of the flight is the identification of the satellite during its group launch. After the launch, the first TLEs of the satellite group launch are provided by the NORAD system without the satellite name, instead of which the indefinite name OBJECT A, OBJECT B, etc. is inserted. When the satellite developers make stable radio communication with it, receive and decode telemetry and confirm this information, the satellite name appears in the TLE file and it is identified in international catalogues. The Belarusian State University (BSU) nanosatellite CubeBel-1 was launched from the Jiuquan Satellite Launch Center in China by a two-stage launch vehicle Long March 2C [9, 10]. Coordinates of the Jiuquan Satellite Launch Center (JSLC) is latitude 40°58'03"N and longitude 100°16'43"E. The projected sun-synchronous orbit had inclination i = 97.5°, orbital period T = 95 min and altitude H = 520 km. Scheduled launch time October 29, 2018, 00: 40: 00 UTC. Before launching the university nanosatellite CubeBel-1, the task was set based on the analysis of launches from the Jiuquan Satellite Launch Center using two-stage Long March 2C and 2D launch vehicles to a sun-synchronous orbit to predict the orbital parameters and the first nanosatellite passes over the university GS, to create an initial TLE file and publish it on the Internet for the possibility of receiving by the international network of receiving stations Satnogs and radio amateurs around the world. This analysis will make it possible to quickly change the TLE file when the launch time changes, to solve the problem of identifying a nanosatellite in a group launch of 8 satellites.

THEORETICAL MODEL

To predict the first nanosatellite passes over the GS, it is necessary to determine its state vector at the epoch time t_e. In this paper, we consider the state vector that describes the perturbed circular motion model of the satellite [5, 6, 11]:

$$\mathbf{X}(t_e) = \left(T_e,\, i_e,\, u_e,\, \Omega_e\right), \tag{1}$$

where T_e – orbital period; i_e – inclination of the orbit to the equatorial plane; u_e – latitude argument; Ω_e – longitude of the ascending node at time t_e.

When predicting the perturbed circular motion model for the moment of time t_k, the two orbital parameters of the SS, the orbital period T and inclination i, remain unchanged

$$T\left(t_k\right) = T_e, \quad i\left(t_k\right) = i_e, \tag{2}$$

and the other two orbital parameters, the latitude argument u and the longitude of the ascending node Ω, experience secular perturbations associated with the non-centrality of the Earth's gravitational field (only the second zonal harmonic in the decomposition for the gravitational force potential was taken into account) [11, 12]:

$$\Omega\left(t_k\right) = \Omega_e - \frac{3}{2} J_2 n \left(\frac{R_E}{R}\right)^2 \cos i \left(t_k - t_e\right), \tag{3}$$

$$u\left(t_k\right) = u_e + \frac{3}{4} J_2 n \left(\frac{R_E}{R}\right)^2 \left(8\cos^2 i_e - 2\right)\left(t_k - t_e\right), \tag{4}$$

where $R = \left(\mu T^{2}\left(t_k\right)/4\pi^2\right)^{1/3}$ – the radius of the satellite orbit; R_E = 6378.137 km – mean equatorial radius of the Earth; μ = 398600.5 km^3/c^2 – the gravitational parameter of the Earth; $n = 2\pi/T(t_k)$ – angular velocity of the satellite (mean motion); J_2 = 0.0010826267 – the second zonal harmonic.

If the projected inclination of the sun-synchronous orbit i is known, then the orbital period can be estimated by the formula [13]

$$T = 2\pi R_E \left(\frac{R_E}{\mu}\right)^{\frac{1}{2}} \left(-\frac{K_0 T_S}{2\pi}\cos i\right)^{\frac{3}{7}}, \tag{5}$$

where $K_0 = \frac{3}{2} J_2 \left(\frac{\mu}{R_E^3} \right)^{1/2}$ = 2.012788·10^{-8} rad/s; T_S = 31558149.504 s – sidereal year.

As shown in [13], to estimate the longitude of the ascending node Ω at the launch time t_0 of the satellite requires information about the latitude φ_0 and longitude λ_0 of the launch site, the average sidereal time at the launch date θ_0, and the time interval of the active launch trajectory τ_a

$$\Omega = \omega_E \left(t_0 + \tau_a \right) + \lambda_0 + \theta_0 - \Delta\lambda \,, \tag{6}$$

where ω_E = 7.2921159·10^{-5} rad/s – angular velocity of the Earth's rotation; $\Delta\lambda = \arcsin\left(\frac{tg\varphi_0}{tgi} \right)$.

In the process of satellite launch, the spent stages or boosters of the first and second stages of the launch vehicle should fall into specially designated areas for this purpose, where they can not cause any harm [14]. The flight paths of launch vehicles with close values of the time interval of the active launch trajectory τ_a in the first minutes after launch must coincide. As a result, in the first minutes of flight after the separation of the satellite from the launch vehicle, the satellite tracks themselves must also coincide. Therefore, it is assumed that the values of the latitude argument u_{new} of satellite for new launches into a sun-synchronous orbit with similar values of the inclinations and similar launch vehicles at the time $t_0+\tau_a+\Delta t$ should coincide with the values of previous launches

$$u_{new}(t_0^{new} + \tau_a^{new} + \Delta t) = u_{old}(t_0^{old} + \tau_a^{old} + \Delta t) \,, \tag{7}$$

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

Thus, to estimate the state vector (1) at the epoch time $t_e = t_0+\tau_a+\Delta t$ from the known values of the launch time t_0, the inclination i_e, the time interval of the active launch trajectory τ_a according to formulas (5) and (6), it is necessary to find the orbital period T_e and the longitude of the ascending node Ω_e. Then, analyzing the previous satellite launches from the target site with similar launch vehicles, find an estimating value of the latitude argument u_e. Since the main problem to be solved is numerically to simulate the parameters of the first nanosatellite passes over the BSU GS, then, based on the obtained state vector (1), using the model of the perturbed circular motion of the SS [5, 6, 11], to predict the elevation el, azimuth az, and Doppler frequency shift Δf_{calc} of radio telemetry signals over the GS (at time intervals where el >0).

RESULTS AND DISCUSSION

To analyze the orbital parameters of the satellites launched using two-stage Long March 2C and 2D launch vehicles from the JSLC, 5 launches were selected [15–19] for the period from January to October 2018 to sun-synchronous orbits with inclinations i equal to 97.3°; 98°; 98.27°; 98.28°, as shown in Table 1. The Long March 2C and 2D launch vehicles have similar values for the time interval of the active launch trajectory. Initially, the orbital parameters from the satellite's TLE files for the first 20 days of the flight were averaged to avoid large errors in further modeling. This is due to the large spread of the satellite orbital parameters in the first days of the flight, obtained from the TLE files of their relative true values. For those satellites, such as LKW-4, which carried out an orbital maneuver, the averaging was carried out for the time interval before the manoeuver.

Using TLE files as the initial data for the SGP model, the satellite latitude argument u was modeled at a 10-minute interval from the launch time plus 10 minutes. Figure 1 shows the deviation of the latitude argument u of the satellites for each of the spacecraft of the group launch from 7 satellites on February 2, 2018, relative to the first satellite in the launch of Fengmaniu-1 (Fig. 1, a) and the deviation of the latitude argument u of the satellites for various launches relative to the launch of the LKW-3 satellite on 13.01.2018 (Fig. 1, b). As shown (Fig. 1, a), the deviations of the latitude argument u for satellites from one group launch differ by less than 0.2° during the simulation, which allows to consider the parameters of only one satellite from the group for predicting subsequent launches. As shown (Fig. 1, b), the values of the latitude argument u for satellites with close values of inclination (launches 13.01, 02.02, 17.03) differ by less than 0.5° during the simulation time, while the maximum deviations of the latitude argument u for satellites with a difference between inclinations of 0.72° (launch 02.06) and 0.95° (launch 09.10) reach 2.5° and 4.5°.

TABLE 1. The orbital parameters of the satellites launched by two-stage Long March 2C and 2D launch vehicles from the Jiuquan Satellite Launch Center for the period from January to October 2018

Launch date and time (UTC)	Launch vehicle	τ_a, s	Satellite name (Country)	NORAD / COSPAR number	Inclination i,°
13 January 07:10:10	Long March 2D	550	LKW-3 (China)	43146/ 2018-006A	97.33
2 February 07:51:04	Long March 2D	550	Fengmaniu-1 (China)	43192/ 2018-015A	97.33
			NuSat-5 (Argentina)	43193/ 2018-015B	97.20
			Zhangheng-1 (China)	43194/ 2018-015C	97.33
			NuSat-4 (Argentina)	43195/ 2018-015D	97.33
			GOMX-4B (Denmark)	43196/ 2018-015E	97.32
			GOMX-4A (Denmark)	43197/ 2018-015F	97.32
			Shaonian Xing (China)	43199/ 2018-015H	97.31
17 March 07:10:04.84	Long March 2D	550	LKW-4 (China)	43236 / 2018-025A	97.33
2 June 04:13:04	Long March 2D	550	Gaofen-6 (China)	43484 / 2018-048A	98.05
			Luojia-1 (China)	43485 / 2018-048B	98.05
9 October 02:43:03.81	Long March 2C	566	Yaogan -32-01A (China)	43642 / 2018-077A	98.27
			Yaogan -32-01B (China)	43643 / 2018-077B	98.28

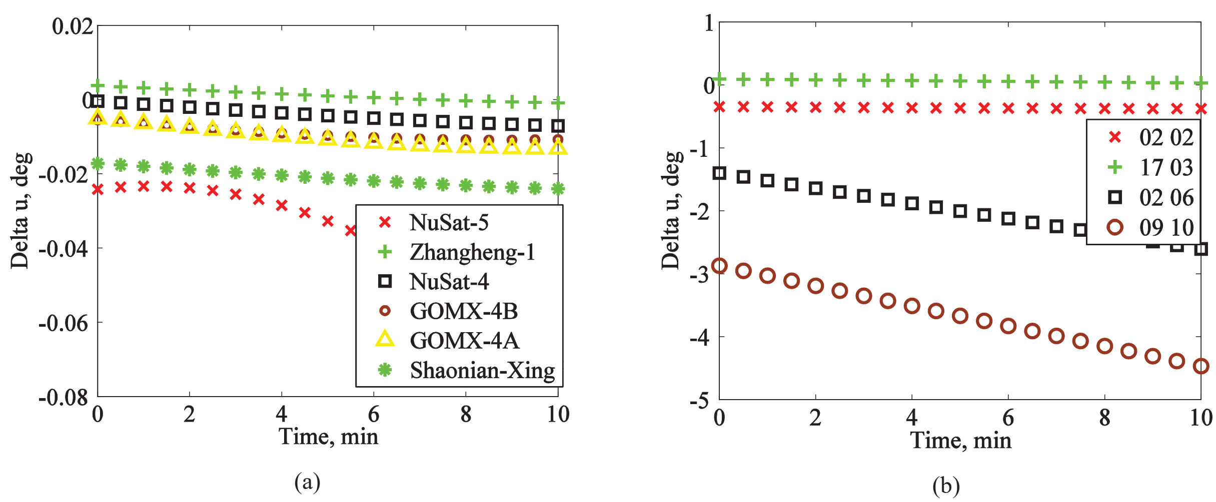

FIGURE 1. The deviation of the latitude argument (Delta u) of the satellites versus time: (a) for each of the spacecraft of the group launch from 7 satellites on February 2, 2018 relative to the first satellite in the launch of Fengmaniu-1; (b) for various launches relative to the launch of the LKW-3 satellite on 13.01.2018

To check the modeling method of the initial state vector, the state vector of the satellite GOMX-4A launched on February 2, 2018 was simulated based on the analysis of the previous launch on January 13, 2018 of the satellite LKW-3 (launch time t_0^{LKW3} = 07:10:00 UTC = 25800 s, the time interval of the active launch trajectory τ_a^{LKW3} = 550 s). The initial data for the simulation were the launch time t_0^{GOMX4A} = 07:51:04 UTC = 28260 s, the planned inclination of the orbit i = 97.3°, the time interval of the active launch trajectory τ_a^{GOMX4A} = 550 s. The planned inclination of the sun-synchronous orbit i of the satellite GOMX-4A allowed us to estimate the period of this orbit T = 94.2 min using the formula (5). The estimate of the longitude of the ascending node Ω = 165.4° of the satellite orbit at the launch time t_0 was obtained using the formula (6) based on the data on the latitude φ_0 = 40°58'03"N and longitude λ_0 = 100°16'43"E of the JSLC, the inclination i of the sun-synchronous orbit and the duration of the time interval of the active launch trajectory τ_a^{GOMX4A}. According to the launch data on January 13, 2018, of the satellite LKW-3 at time $t_0^{LKW3} + \tau_a^{LKW3} + 60$ =26410 s, the latitude argument u = 160.2° was calculated using the averaged orbital parameters, which, according to (7), is equal to the latitude argument u the satellite GOMX-4A at the epoch time t_e = $t_0^{GOMX4A} + \tau_a^{GOMX4A} + 60$ =28870 s. Thus, the state vector for the perturbed circular motion model of the satellite GOMX-4A was estimated at the epoch time t_e $\mathbf{X}(t_e) = \left(T_e,\ i_e,\ u_e,\ \Omega_e\right)$ = (94.23 min, 97.3°, 165.4°, 160.2°). The parameters of the first passes of satellite GOMX-4A over the BSU GS Minsk (latitude φ = 53°54'27" North, longitude λ = 27°33'52" East, altitude H = 0.23 km) were numerically simulated at the time interval from t_e to t_e +6 hour using the perturbed circular motion model. The first pass in the interval from 10:58:00 to 11:05:25 UTC with a maximum elevation of 5° was unsuccessful for receiving telemetry.

Simulated parameters (elevation, azimuth, Doppler frequency shift of telemetry signals) of the second pass at the time interval from 12:31:00 to 12:42:00 UTC with a maximum elevation of 49° is shown in Fig. 2, a. The accuracy of predicting of elevation, azimuth, and Doppler frequency shift of the satellite telemetry signals using the circular perturbed motion model at this reception interval is estimated in comparison with the SGP 4 model and the initial data in the TLE format, as shown in Fig. 2, b. It is shown that the absolute errors in predicting the elevation and azimuth did not exceed 2° and 4.5°, respectively, and the absolute error in predicting the Doppler frequency shift of telemetry signals did not exceed 550 Hz, which, with appropriate receiver settings, is sufficient for successful reception of telemetry signals satellite GOMX-4A and their decoding.

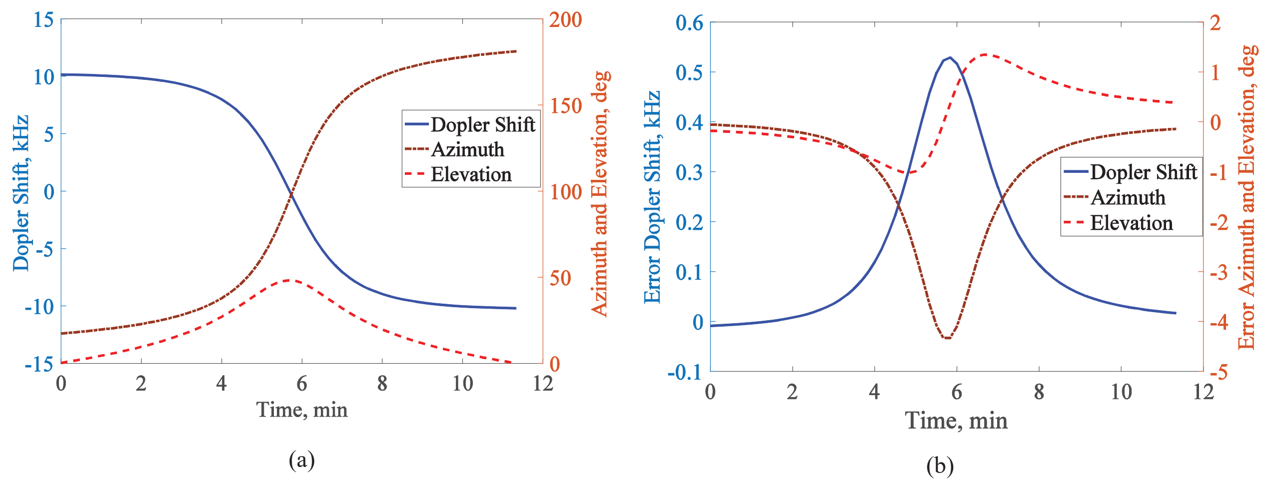

FIGURE 2. Simulated parameters versus time for the second pass of the satellite GOMX-4A over the UGS Minsk: (a) elevation, azimuth and Doppler frequency shift of telemetry signals; (b) absolute errors in predicting for the elevation, azimuth, Doppler frequency shift

For modeling the launch of the BSU nanosatellite CubeBel-1 on October 29, 2018 (launch time $t_0^{CubeBel}$ = 00:40:00 UTC = 2400 s, planned inclination i = 97.5°, time interval of the active launch trajectory $\tau_a^{CubeBel}$ = 566 s) were used data from the previous launch on January 13, 2018 of the LKW-3 spacecraft. The planned inclination of the sun-synchronous orbit CubeBel-1 allowed to estimate the orbit period T = 95.2 min using the formula (5). The estimate of the longitude of the ascending node Ω = 322.4° at the launch time t_0 of the satellite was obtained using the formula (6). According to the launch data of the satellite LKW-3, the estimate of the latitude argument $u = 160.2°$ at the epoch time t_e = $t_0^{CubeBel} + \tau_a^{CubeBel} + 60$ =3026 s was obtained. Thus, the state vector $\mathbf{X}(t_e) = \left(T_e,\ i_e,\ u_e,\ \Omega_e\right)$ = (95.2 min, 97.5°, 322.4°, 160.2°) of nanosatellite CubeBel-1 was estimated for the perturbed circular motion model at the epoch time t_e. Also, the initial TLE file of nanosatellite CubeBel-1 was generated and published on the Internet on the sites of the amateur radio community [20].

After receiving the exact launch time $t_0^{CubeBel}$ = 00:43:13.576 UTC = 2594 s on October 29, 2018 for nanosatellite CubeBel-1, the state vector was refined $\mathbf{X}(t_e) = \left(T_e,\ i_e,\ u_e,\ \Omega_e\right)$ = (95.2 min, 97.5°, 323°, 160.2°) for the perturbed circular motion model at the epoch time $t_e = t_0^{CubeBel} + \tau_a^{CubeBel} + 60$ =3220 s. Based on the state vector, the initial TLE file was also refined. Using the perturbed circular motion model, the parameters of the first passes of the nanosatellite CubeBel-1 over the BSU GS Minsk were numerically simulated at the time interval from t_e to t_e +6 hour. The first pass in the interval from 03:51:00 to 03:58:00 UTC with a maximum elevation of 5° was unsuccessful for receiving telemetry. Elevation, azimuth, Doppler frequency shift of telemetry signals of the second pass nanosatellite CubeBel-1 at the time interval from 05:24:00 to 05:35:00 UTC with a maximum elevation 50º were simulated. The accuracy of predicting elevation, azimuth, and Doppler frequency shift of the satellite telemetry signals of nanosatellite CubeBel-1 is estimated using the circular perturbed motion model at this reception interval in comparison with the SGP 4 model and the initial data in the TLE format. It is shown that the absolute errors in predicting the elevation and azimuth of nanosatellite CubeBel-1 did not exceed 2º and 3º, respectively, and the absolute error in predicting the Doppler frequency shift of telemetry signals did not exceed 350 Hz, which, with appropriate receiver settings, is sufficient for successful reception of telemetry signals of satellite and their decoding.

CONCLUSION

Finally, pre-flight calculation of the orbital parameters of a SS was carried out using the numerical analysis of 5 satellite launches with two-stage Long March 2C and 2D launch vehicles from the Chinese Jiuquan Satellite Launch Center in 2018. Prediction of the first passes of the nanosatellite CubeBel-1 over the BSU GS was performed based on the perturbed circular motion model. The initial TLE file was generated and published on the Internet on the amateur radio community sites. This made it possible to quickly change the TLE file when the launch time was changed, as well as to solve the problem of identifying a nanosatellite in a group launch of several satellites. Dozens of radio amateurs from 5 continents successfully received the nanosatellite telemetry on the first day after the launch on October 29, 2018, and the BSU GS was the first in the world to decode the CubeBel-1 telemetry. On the third day after the launch, nanosatellite CubeBel-1 was identified in international catalogues and appeared in the Cubesat satellite database on the CelesTrak website.

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