Orbit Determination Methods For LEO Satellites From Probabilistic Analysis, Circular Motion Model And Single Pass Doppler Measurements

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Abstract— The Doppler measurements of the telemetry radio signals nanosatellite CubeBel-1 for a single pass over the Belarusian State University ground station were carried out. Two methods for orbit determination of a small satellite are considered. The first method is based on the SGP4 model and requires additional information from the NORAD TLE catalog of the satellite orbital parameters. An unknown small satellite is identified using the NORAD TLE catalog based on a probabilistic estimation of the elevation angle and the Doppler frequency shift of receiving telemetry signals. The second method is based on processing experimental measurements of the Doppler frequency of the telemetry radio signals and Keplerian circular motion model for the small satellite. It does not require additional information from the NORAD database of satellite orbital parameters.

Keywords— small satellite, Doppler frequency shift, TLE database, orbital determination, Keplerian motion model, probabilistic analysis.

I. INTRODUCTION

For effective practical training of students, many universities develop their own educational satellites [1-2]. Usually these are small satellite (SS) weighing up to 10 kg, developed according to the Cubesat standard [2-3]. The advantages of small satellites are their low cost of development and launch, the possibility of using commercial components, fewer ground tests, speed of development, and the ability to create small satellite constellation of to solve various tasks [3-6]. Reliable and effective receiving of telemetry and forecasting future positions are important for control, tracking and radio communication with the University small satellites (USS). Due to budget constraints, a single ground station (GS) is used for control and receiving telemetry at the USS, which is located within the city and has unsatisfactory reception conditions. In addition, the communication between the GS and the low-orbit USS is limited to sessions of a few minutes 5-6 times a day [7].

Prediction of future positions of USS is important for solving problems of their control, tracking, and conducting radio communication sessions. Traditionally, the SGP4 prediction model [8, 9] is used to make these predictions for single University ground station (UGS). The SGP4 model uses averaged orbital parameters in the TLE (two-line elements) format of the NORAD (North American Aerospace Defense Command) [10-11]. As a rule, TLEs are updated daily and are available free of charge, but in the long term or in the event of military conflicts, the NORAD system has the ability to disable public access to the database of averaged orbital parameters. Less often, on board a small satellite, a navigation receiver is used to determine the exact coordinates and speed [12].

Another way to obtain initial data for USS prediction models is to measure of the orbit parameters for its pass over the UGS using the telemetry or command radio signals [13-16]. The measured parameters for the UGS are the time and the Doppler shift of the frequency of the received radio signal [16-18]. In paper [13], a general method for determining the satellite orbit was proposed, based on improving approximations for the initial components of position and velocity by means of successive differential corrections from Doppler observations. In the work [19, 20], a method for calculating satellite orbit was developed on the basis of a model of circular perturbed motion and measurements of the Doppler frequency shift of telemetry signals. Based on a probabilistic estimate of the elevation angle and Doppler frequency shift from 10–20 measurements on multiple passes of a small satellite, a set of orbital parameters are determined for the estimated time of receiving telemetry signals. Based on the analysis of the database of orbital parameters of low-orbit spacecraft, including satellites of the Cubesat standard, the applicability and correctness of the circular motion model with a reduced number of unknown orbital parameters (independent variables) from six to four is justified.

In this paper, two methods for orbit determination of a SS are considered on the example of processing experimental measurements of the Doppler frequency of the telemetry radio signals nanosatellite CubeBel-1 for a single pass over UGS. The first method is based on the SGP4 model and requires additional information from the NORAD TLE catalog of the satellite orbital parameters. A small satellite is identified using the NORAD TLE catalog based on a probabilistic estimation of the elevation angle and the Doppler frequency shift of receiving telemetry signals. The

second method is based on processing experimental measurements of the Doppler frequency of the telemetry radio signals and Keplerian circular motion model (non-perturbed motion) for single pass of SS over the UGS. It does not require additional information from the NORAD database of satellite orbital parameters.

II. Small satellite radio signal receiving and processing. Orbit determination based on the SGP4 model and the NORAD TLE database

The nanosatellite CubeBel-1 telemetry receiving and processing on a Belarusian State University GS is additionally equipped with an orbit measurement and determination system with time synchronization [7]. The GS hardware consists of: 435-438 MHz band Yagi–Uda antennas with circular polarization, receiving system based on the IC-9100 transceiver; receiving system based on the software defined radio receiver, YAESU G-5500 azimuth-elevation rotator with a control interface. The GS software includes: satellite orbital and radio signal parameter prediction software, simulation and visualization of cooperative GS scenarios and express calculation of standard ballistic information software, telemetry receiving and processing software. The orbit measurement and determination system with time synchronization for UGS consists of: GPS receiver, module for frequency and time measurements of the received radio signal based on a microcontroller for time processing and a two-channel digital oscilloscope, software for processing measurements; software for orbit determination and correction.

Measurements of the orbit parameters for a single nanosatellite CubeBel-1 pass over a UGS were performed at several points in the orbit. The satellite pass interval over a UGS is about 10 minutes. Therefore, the simplest Keplerian motion model for satellite can be used to process single pass measuring data. The nanosatellite CubeBel-1 orbit determination was made using 20 measurements of the reception time t_i and telemetry signal frequency $f_i^{\exp}$ ($i = 1...20$) on single pass for the period from 05:54:00 to 06:03:30 for 01.11.2019 (UTC) over the UGS. On one pass, the radio signals were transmitted with an interval of $\Delta t = 30$ s. Based on 20 measurements, the average reception frequency $\langle f^{\exp} \rangle$ = 436.99 MHz was estimated. The Doppler frequency shift of the radio telemetry signal is given by:

$$\Delta f_i^{\exp} = f_i^{\exp} - \langle f^{\exp} \rangle. \qquad (1)$$

An unknown SS is identified using the NORAD TLE catalog based on a probabilistic estimation of the elevation angle and the Doppler frequency shift of receiving telemetry signals. The identification of the orbital parameters of the small satellite using the TLE database of the NORAD system was carried out according to the following algorithm. For each j-th ($j = 1, 180$) Cubesat standard satellite of the orbital parameters were uploaded from the NORAD TLE catalog for 01.11.2019 (UTC). Using the SGP 4 model the elevation angle el and the Doppler frequency shift Δf_i^{calc} ($i = 1...N$) of the radio telemetry signal was modeled for $N = 20$ measurements on single pass for the period from 05:54:00 to 06:03:30 for 01.11.2019 (UTC) over the University ground station.

The probability of success β_{1j} for the j-th satellite by the data analysis on elevation angle $el > 0$ (strategy 1) was calculated as

$$\beta_{1j} = (K_{1j} / N) \cdot 100\%, \qquad (2)$$

where K_{1j} is the number of passes for the j-th satellite with the elevation angle $el > 0$.

The satellite with $\beta_{1j} > 50\%$ are sorted and selected for further analysis on the deviation of the calculated Doppler frequency shift Δf_i^{calc} from the measured Doppler frequency shift $\Delta f_i^{\exp}$. The probability of success β_{2j} for the j-th satellite by the data analysis on elevation angle $el > 0$ and $\left| \Delta f_i^{\exp} - \Delta f_i^{calc} \right| < 200$ Hz for Doppler frequency shift (strategy 2) was calculated as

$$\beta_{2j} = (K_{2j} / N) \cdot 100\%, \qquad (3)$$

where K_{2j} is the number of passes for the j-th satellite with the elevation angle $el > 0$ and the deviation of the calculated Doppler frequency shift Δf_i^{calc} from the measured Doppler frequency shift $\Delta f_i^{\exp}$ less than 200 Hz. Identification of an unknown satellite using the NORAD TLE catalog was carried out analysis on maximum value of the probability of success β_{2j}.

III. Keplerian circular motion model for single pass of small satellite

The mathematical model of a small satellite motion is based on the Keplerian circular orbit approximation for single pass of small satellite over the university ground station. The motion in a circular orbit is determined by the following parameters of the state vector $\mathbf{X}$:

$$\mathbf{X} = (T, i, u, \Omega), \qquad (4)$$

where i is the orbit inclination, T is the orbital period, u is the latitude argument, and Ω is the longitude of the ascending node at time t.

The determination of the orbit of an unknown SS was carried out by the UGS based on N measurements of telemetry radio signals on single pass

$$\mathbf{Y} = (Y_1, Y_2,...Y_i...Y_N), Y_i = (t_i, \Delta f_i^{\exp}), \qquad (5)$$

where t_i is the time of receiving and $\Delta f_i^{\exp}$ is the Doppler frequency shift of the received telemetry radio signals.

For the calculated point in time t_0, the SS state vector was found $\mathbf{X_0} = (T_0, i_0, u_0, \Omega_0)$, which best meets the measurement results according to three criteria:

- the elevation angle of the SS above the UGS at the times of measurements t_i must be positive (the SS relative to the GS should be above the horizon):

$$el_i = el(t_i) > 0, \qquad (6)$$

- the Doppler frequency shift $\Delta f_i^{calc} = \Delta f_i^{calc}(t_i)$ of the telemetry radio signal obtained as a result of numerical simulation at the time moments of measurements t_i should differ from the measured one $\Delta f_i^{\exp} = \Delta f_i^{\exp}(t_i)$ by less than 200 Hz (here we consider the error associated with the frequency instability of the onboard SS transmitter):

$$\left| \Delta f_i^{\exp} - \Delta f_i^{calc} \right| < 200 \text{ Hz}. \qquad (7)$$

- the sign of the time derivative of the Doppler frequency shift corresponds to the pattern of change in the experimental Doppler curve:

$$\text{sign}\left(\frac{d\left(\Delta f_i^{calc} \right)}{dt} \right) = \text{sign}\left(\frac{d\left(\Delta f_i^{\exp} \right)}{dt} \right). \qquad (8)$$

According to the results of measurement processing, the ranges of variation $\Delta X = (\Delta T, \Delta i, \Delta u, \Delta \Omega)$ of the parameters of the state vector X_0 are determined. Next, for each obtained state vector X at the measurement time t_i the Keplerian circular motion model is used to calculate the elevation angle el_i of the SS above the GS and the Doppler frequency shift Δf_i^{calc} of the telemetry radio signal using the following algorithm. At the time of measurements t_i, we find the orbital parameters $T(t_i) = T_0$, $i(t_i) = i_0$, $\Omega(t_i) = \Omega_0$ and $u(t_i)$. In the calculations in the Keplerian circular motion model, the three parameters T, i, and Ω remain unchanged for all time points of the measurements t_i, while the latitude argument u changes according to

$$u\left(t_i \right) = u_0 + \frac{2\pi}{T_0} \left(t_i - t_0 \right), \qquad (9)$$

where u_0 is the value of the latitude argument at time t_0.

Then find the coordinates and projections of the velocity vector in the orbital coordinate system (CS) and the geocentric inertial CS. According to the coordinates of the UGS ($\varphi = 53°54'27''$ north latitude, $\lambda = 27°33'52''$ east longitude, altitude $H = 230$ m) at the time of measurement t_i we determine the radius vector of the slant range ρ and the rate of its change in the $OXYZ$ coordinate system and the vector of the slant range ρ and the projection of its velocity in the topocentric rectangular CS. Then we find the slant range ρ, the elevation angle el and the azimuth β, as well as the rate of their change at the time t_i and calculate the Doppler frequency shift

$$\Delta f^{calc} = -\frac{f_0}{c} \frac{d\rho}{dt}, \qquad (10)$$

where c is the speed of light in vacuum, f_0 is the nominal frequency of the onboard SS transceiver. The probability of success β_j of the given set of orbital parameters $(T_0, i_0, u_0, \Omega_0)$ for the time t_0 by estimating only the calculated elevation angle el ($j = 1$) and the elevation angle and the Doppler frequency shift Δf^{calc} ($j = 2$) at the moment of receiving the telemetry radio signal was found according to

$$\beta_j = \frac{N_j}{N} 100\%, \qquad (11)$$

where N_j is the number of calculated points that satisfy the criterion (6) for $j = 1$ and (6-8) for $j = 2$ and N is the total number of measurement points at which the numerical simulation was carried out for a given set of orbital parameters $(T_0, i_0, u_0, \Omega_0)$. The probability of success of $\beta_2 = 50\%$ means that the $N_2 = N_{total}/2$ conditions (6) $el > 0$ and (4) $|\Delta f^{\exp} - \Delta f^{calc}| < 200$ Hz are satisfied only in half of the experimental data.

IV. RESULTS AND DISCUSSION

The identification of a SS from the NORAD TLE catalog was carried out by processing 20 measurements of the reception time and telemetry signal frequency on single pass for the period from 05:54:00 to 06:03:30 for 01.11.2019 (UTC) over the UGS. First, based on the NORAD TLE catalog of the Cubesat standard satellites and SGP 4 model for each reception time t_i ($i = 1...20$) of telemetry signal, the single pass parameters over the UGS (elevation el, azimuth az, range ρ_i, range rate $d\rho_i/dt$ and Doppler frequency shift Δf_i^{calc}) were calculated for each j-th ($j = 1, 180$) satellite. An unknown SS was identified based on a probabilistic estimation of the elevation angle and the Doppler shift in the frequency of receiving telemetry signals. Second, the probability of success β_{1j} for the j-th satellite by the data analysis on $el > 0$ for elevation angle was calculated. The satellite with $\beta_{1j} > 50\%$ are sorted and selected for further analysis on the deviation of the calculated Doppler frequency shift Δf_i^{calc} from the measured Doppler frequency shift $\Delta f_i^{\exp}$, as shown in the Figure 1.
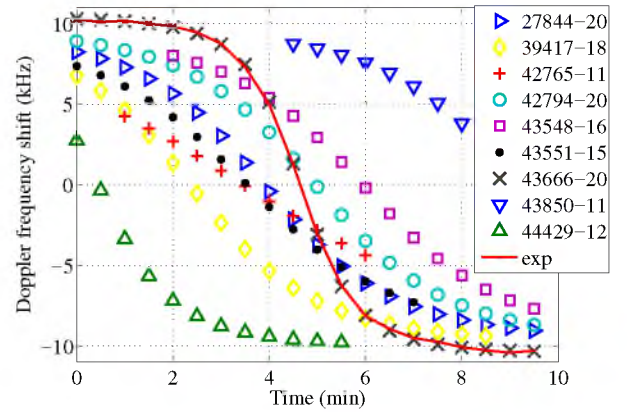

Fig. 1. Calculated Doppler frequency shift Δf^{calc} of selected satellite (with $\beta_{1j} > 50\%$) and experimental Doppler curve (red line) on the pass time over the University ground station. The inset shows the satellite catalog number in the NORAD system and number of points with $el > 0$.
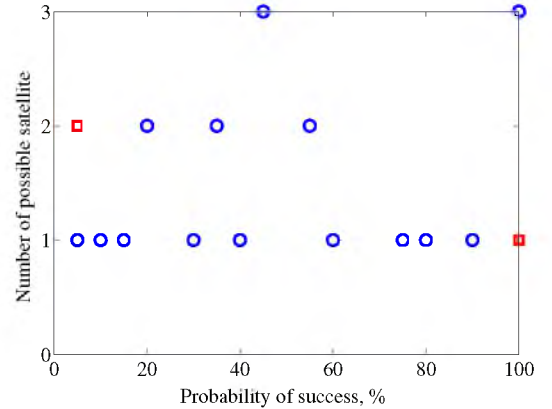

Fig. 2. The number of possible satellites versus the probability of success based on analysis of elevation β_1 (blue circles) and (b) elevation and the Doppler shift β_2 (red squares).

Finally, the probability of success β_{2j} for the j-th satellite by the data analysis on $el > 0$ for elevation angle and $\left| \Delta f_i^{\exp} - \Delta f_i^{calc} \right| < 200$ Hz for Doppler frequency shift was calculated. In Fig.2 the dependencies of the number of

possible satellites on the probability of success β_1 and β_2 are presented. As shown in Fig. 1-2 according to only elevation el estimation, there are 3 satellites: CUTE-1 (NORAD 27844), DSAT (NORAD 42794), CubeBel-1 (NORAD 43666) with the probability of success $\beta_1 = 100\%$ and 9 satellites with the probability of success $\beta_1 > 50\%$. The other 12 satellites have probability of success β_1 less than 50%. At that time in Fig. 2 it is shown that according to the elevation el and the Doppler frequency shift Δf^{calc} estimation, there is only 1 satellite CubeBel-1 (NORAD 43666) with the probability of success $\beta_2 = 100\%$ and 2 satellites CUTE-1 (NORAD 27844), DSAT (NORAD 42794) with the probability of success $\beta_2 = 5\%$. The nanosatellite CubeBel-1 was determined unambiguously based on the elevation el and the Doppler frequency shift Δf^{calc} estimation.

Based on the Keplerian circular motion model for single pass of small satellite numerical simulation was carried out for the time of reception and the Doppler shift of radio telemetry at the $N = 10$ and N =20 measuring points on single pass for the period from 05:54:00 to 06:03:30 for 01.11.2019 (UTC) over the University ground station (Fig. 3). The ranges of change of the orbital period T was selected from 93 to 100 min with the step 1 s, the inclination i was from $97.13°$ to $98.43°$ with the step of $0.01°$, the argument of latitude u was from $20°$ to $180°$ with the step of $1°$ and the longitude of ascending node Ω was from 0 to $360°$ with the step of $1°$. The probability of success β_1 and β_2 of each set of orbital parameters (T, i, u, Ω) was calculated for four estimated time points $t_0 = 5{:}56{:}00$; $5{:}57{:}00$; $5{:}58{:}00$; $5{:}59{:}00$ (Fig. 3) on 01.11.2019 (UTC) based on the analysis only the elevation el (for β_1) and the elevation el and the Doppler frequency shift Δf^{calc} estimation (for β_2) of the small satellite.
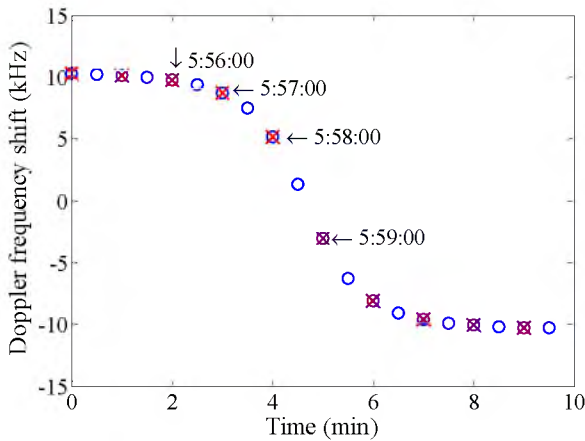

Fig. 3. Selected points of experimental Doppler curve N =10 (red squares) and N =20 (blue circles) for numerical simulation set of orbital parameters (T, i, u, Ω) for four estimated time points $t_0 = 5{:}56{:}00$; $5{:}57{:}00$; $5{:}58{:}00$; $5{:}59{:}00$ on 01.11.2019 (UTC).

The analysis of ranges of orbital parameter variation was carried out for N =20 and 10 selected points of experimental Doppler curve for four estimated time points t_0 as shown in Tables 1 and 2. For both sets of experimental Doppler values the number of possible sets of orbital parameters and the ranges of orbital parameters based on the Strategy 1 analysis do not depend on the choice of the estimated time points t_0. On the contrary, analysis according to Strategy 2 shows the dependence of the values of the orbital parameters on the choice of the estimated time point t_0.

It was found from Table 1, that the ranges of variation of the orbital period T and orbital inclination i with the probability of success 100% for estimated time point $t_0 = 5{:}56{:}00$ based on Strategy 2 in the comparison in Strategy 1 are reduced by 55% from 200 to 90 s and from $0.62°$ to $0.27°$, respectively. While the ranges for the latitude u and longitude of ascending node Ω with the probability of success 100% for estimated time point $t_0 = 5{:}56{:}00$ based on an estimate of the elevation angle and the Doppler frequency shift in the comparison only elevation el estimation are reduced by 92% from $13°$ to $1°$ and reduced by 94% from $53°$ to $3°$, respectively.

When the estimated time t_0 approaches the center of the Doppler curve (the Doppler frequency shift approaches zero, which corresponds to the minimum range between the satellite and the ground station), the number of possible sets of orbital parameters N_{orb} with $\beta_2 = 100\%$ decreases, and the ranges of changes in the orbital period T and inclination i become smaller. It was found that the ranges of variation of the orbital period T and orbital inclination i based on Strategy 2 with the probability of success 100% for estimated time point $t_0 = 5{:}59{:}00$ in the comparison estimated time point $t_0 = 5{:}56{:}00$ are reduced by 74% from 90 to 24 s and from $0.27°$ to $0.07°$, respectively.

Table 1. The ranges of variation of orbital parameters for different strategies 1 and 2 based on $N = 20$ measurements for four estimated time points t_0.

Orbital parameter	$t_0 = 5{:}56{:}00$	$t_0 = 5{:}57{:}00$	$t_0 = 5{:}58{:}00$	$t_0 = 5{:}59{:}00$
$\beta_1 = 100\%$				
N_{orb}	$2.05 \cdot 10^4$	$2.05 \cdot 10^4$	$2.05 \cdot 10^4$	$2.05 \cdot 10^4$
T, s	5580-5780	5580-5780	5580-5780	5580-5780
i, deg	97.13-97.75	97.13-97.75	97.13-97.75	97.13-97.75
u, deg	108-121	112-124	115-128	119-132
Ω, deg	300-353	300-353	300-353	299-352
$\beta_2 = 100\%$				
N_{orb}	48	24	21	17
T, s	5580-5670	5648-5694	5664-5704	5674-5698
i, deg	97.13-97.40	97.33-97.47	97.38-97.50	97.41-97.48
u, deg	115-116	119	123	127
Ω, deg	324, 331, 332	325	326	328

Table 2. The ranges of variation of orbital parameters for different strategies 1 and 2 based on $N = 10$ measurements for four estimated time points t_0.

Orbital parameter	$t_0 = 5{:}56{:}00$	$t_0 = 5{:}57{:}00$	$t_0 = 5{:}58{:}00$	$t_0 = 5{:}59{:}00$
$\beta_1 = 100\%$				
N_{orb}	$3.63 \cdot 10^4$	$3.63 \cdot 10^4$	$3.63 \cdot 10^4$	$3.63 \cdot 10^4$
T, s	5580-5780	5580-5780	5580-5780	5580-5780
i, deg	97.13-97.75	97.13-97.75	97.13-97.75	97.13-97.75
u, deg	107-123	111-127	115-131	119-134
Ω, deg	298-356	298-356	298-356	299-352
$\beta_2 = 100\%$				
N_{orb}	62	27	21	20
T, s	5580-5674	5646-5698	5664-5704	5674-5698
i, deg	97.13-97.41	97.33-97.49	97.38-97.50	97.41-97.48
u, deg	115-116	119	123	127
Ω, deg	324, 331-332	325	326	328

As you can see from Table 2, the ranges of variation of the orbital period T and orbital inclination i with the probability of success 100% for estimated time point $t_0 = 5{:}56{:}00$ based on Strategy 2 in the comparison with Strategy

1 are reduced by 53% from 200 to 94 s and from 0.62° to 0.28°, respectively. While the ranges for the latitude u and longitude of ascending node Ω with the probability of success 100% for estimated time point $t_0 = 5:56:00$ based on an estimate of the elevation angle and the Doppler frequency shift in the comparison only elevation el estimation are reduced by 94% from 16° to 1° and reduced by 95% from 58° to 3°, respectively.

For the Strategy 2, when the estimated time t_0 approaches the center of the Doppler curve the number of possible sets of orbital parameters N_{orb} with $\beta_2 = 100\%$ decreases, and the ranges of changes in the orbital period T and inclination i become smaller. It was found that the ranges of variation of the orbital period T and orbital inclination i for estimated time point $t_0 = 5:59:00$ in the comparison with estimated time point $t_0 = 5:56:00$ are reduced by 74% from 94 to 24 s and from 0.28° to 0.07°, respectively. The numerical simulation of orbital parameters based on the Keplerian circular motion model for single pass of small satellite over the University ground station and $N = 10$ and $N=20$ measurements of the time of reception and the Doppler shift of radio telemetry allows us to conclude that the latitude u and longitude of ascending node Ω are defined unambiguously using analysis the elevation and the Doppler frequency shift estimation. While the orbital period T and orbital inclination i were estimated in range. It was also obtained that if the estimated time t_0 approaches the center of the Doppler curve the number of possible sets of orbital parameters and the ranges of changes in the orbital period T and inclination i decreases.

To refine the state vector of small satellite based on 17 set of orbital parameters (T, i, u, Ω) with the probability of success $\beta_2 = 100\%$ was calculated the average state vector in the geocentric inertial CS $OXYZ$ $(X_0, Y_0, Z_0, V_{0x}, V_{0y}, V_{0z})$ = (-3885.3, 1607.3, 5452.7, -4.823, 3.743, -4.540) for the estimated time $t_0 = 5:59:00$ on 01.11.2019 (UTC). Based on 20 measurements Doppler frequency shift of the radio telemetry signal was to differentially correct [9] an initial approximation of the state vector in the geocentric inertial CS. The corrected state vector in the geocentric inertial CS for the estimated time $t_0 = 5:59:00$ on 01.11.2019 (UTC) is $(X_0, Y_0, Z_0, V_{0x}, V_{0y}, V_{0z})$ = (-3899.2, 1590.6, 5459.8, -4.834, 3.723, -4.537). Based on this corrected state vector and a circular perturbed motion model [18], the elevation el, azimuth az and Doppler frequency shift of radio telemetry signals Δf^{calc} were numerically simulated in the range from 0:0:0 to 23:59:59 on 02.11.2019 (UTC) of the following passes. Using the simulated data, University ground station successfully received and decoded the telemetry packets of the small satellite at the pass interval from 05:37:00 to 05:48:40 on 02.11.2019 (UTC). It was recognized small satellite nanosatellite CubeBel-1 with NORAD database.

In conclusion, we have demonstrated the potential of Belarusian State University GS for orbit determination of the unknown SS. Orbital parameters are theoretically investigated using NORAD TLE database and Keplerian circular motion model. If using the NORAD TLE catalog based on a probabilistic estimation of the elevation angle and the Doppler frequency shift of receiving telemetry signals was allowed to determine the nanosatellite CubeBel-1 unambiguously, then the method based on Keplerian circular motion model was allowed only to calculate the average state vector unknown satellite. Finally,

corrected state vector in the geocentric inertial CS was obtained based on differential correction method.

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