Small Satellite Orbit Determination Using The University Ground Station

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Abstract— **The Doppler measurements of the unknown small satellite were carried out using Belarusian State University ground station. Small satellite orbit determination by Doppler measurements of a telemetry signal on several orbits with a limited number of data on one pass was studied using University ground station. Satellite orbital elements were predicted during week to justify the orbit determination model. Small satellite radio signal processing and orbit determination based on the perturbed circular motion model are described. A good agreement with experimental Doppler frequency shift data was achieved.**

Keywords—small satellite, Doppler 'frequency shift, TLE-database, orbital determination, radio visibility intervals, perturbed circular motion model.

I. INTRODUCTION

Currently, the role of small satellites (weighing up to 10 kg) in the exploration, development and use of near-earth space is constantly increasing. According to the forecast of international research organizations, several thousand nanosatellites (weighing up to 10 kg) and picosatellites (weighing up to 1 kg) will be in orbit by 2022, which is many times more than the expected number of large-mass satellites.

The advantages of small satellites (SS) 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 [1-2]. They are increasingly being used for science and service missions, such as atmospheric studies using a Cubesat constellation, formation flying applications, inter-satellite links, communications, Earth observation and environmental monitoring [3-5].

Prediction of the future positions of small satellites is essential for its tracking, control and communication. To perform these predictions for a single ground station the SGP4 prediction model is used [6-7]. The SGP4 model takes so-called two-line elements (TLEs) as the input for the orbit prediction. These TLEs are currently provided by NORAD (the North American Aerospace Defense Command). Typically TLEs are updated daily, and are available free of charge [8].

Less often, a navigation receiver is used onboard a small satellite to determine the exact coordinates and velocity [9]. Another way to obtain initial orbital parameters for prediction models is orbit determination based on measurements of the received radio signal from a small satellite [10-12]. The measured parameters for a low-cost ground station are the time and Doppler frequency shift of the received radio signal [13].

The orbit measurement and determination system of a ground station can measure the satellite orbit with both initially known parameters (Tracking mode) and unknown parameters (Omni-directional search mode) [14]. To process measurements in Tracking mode, orbital elements in TLE format or their own database are used as initial data. The satellite orbital prediction software based on the known initial orbit parameters calculates communication sessions, the tracking angles for antenna azimuth-elevation rotator, and the telemetry radio signal frequency. The main problem is to check the satellite orbit parameters and correction them. The differential correction method of satellite orbit parameters using relative velocity data between satellite and the ground station is used [15]. The initial orbit determination problem is solved for the satellite measuring in the Omni-directional search mode. The target small satellite frequency is searched within the Amateur radio band of 435-445 MHz The distinctive features of the radio signals of telemetry packets (frequency of packets, presence of mark, etc.) are determined. Based on the results of measurements on several passes, the radio signal frequency, the satellite period, the maximum duration of pass over the ground station, the limit of measurement errors are estimated. To process measurements on a single satellite pass over a ground station, orbit determination algorithms based on Keplerian motion model are used, and on several passes, orbit determination algorithms based on the simplest perturbed motion models are used.

For more efficient operation, University ground stations and Amateur radio stations are combined into international networks for receiving data from small satellites. This makes it possible to use the joint resources of a large number of spaced stations not only to receive information from small satellites, but also to measure its orbital parameters [16].

II. THE ANALYSIS OF ORBITAL PARAMETERS AND PASS PREDICTION OF SMALL SATELLITES USING NORAD TLE DATABASE AND UNIVERSITY GROUND STATION

Examples of small satellites are nano- and picosatellites developed according to the Cubesat standard. These low-orbit satellites (orbital altitude less than 1000 km) have an almost circular orbit (with a small eccentricity value $e \ll 1$).

In Fig. 1, we compared averaged orbital parameters (satellite altitude, inclination and period) obtained from NORAD TLE on 1.10.2019. (The total number of Cubesat satellites in the database is 180.)

There are two types of typical Cubesat orbits. The first type of orbit is associated with nano-and picosatellites launched from the International Space Station (ISS). They have an orbital inclination about 51.6°, an orbital period from 90 to 94 min, and an orbital altitude from 330 km to 430 km. The second type of orbit is associated with nano-and picosatellites launched into a solar-synchronous orbit. They hitch rides as secondary payloads on large rockets launching with main large spacecraft. These Cubesats have an orbital inclination from 98 to 99°, an orbital period from 94 to 102 minutes, and an orbital altitude from 500 km to 800 km.

Small satellite weekly pass parameters over the University ground station (latitude φ = 53°54'27" North, longitude λ = 27°33'52" East, altitude H = 0.23 km) were predicted to justify the orbit determination model by Doppler measurements of a telemetry signal on several orbits.

For the orbit prediction the SGP4 prediction model and NORAD two-line elements as the input data were used. The South African nanosatellite nSight-1 (satellite orbit altitude about 330 km and inclination is 51.6°), which was launched and deployed from the ISS in the second quarter of 2017, was chosen as an example of the first type of Cubesat orbits.

It was shown that for a week for an almost circular orbit (eccentricity e = 0.001678) of the nanosatellite nSight-1, the inclination of the orbit i and the argument of latitude u did not experience secular perturbations. While the secular perturbations of the longitude of ascending node Ω and the orbit period T were 5° and 0.7 s per day, respectively. Michel Capderou has demonstrated [6] that the gravitational potential (J_2) is the most significant factor for secular perturbations in low earth orbit.

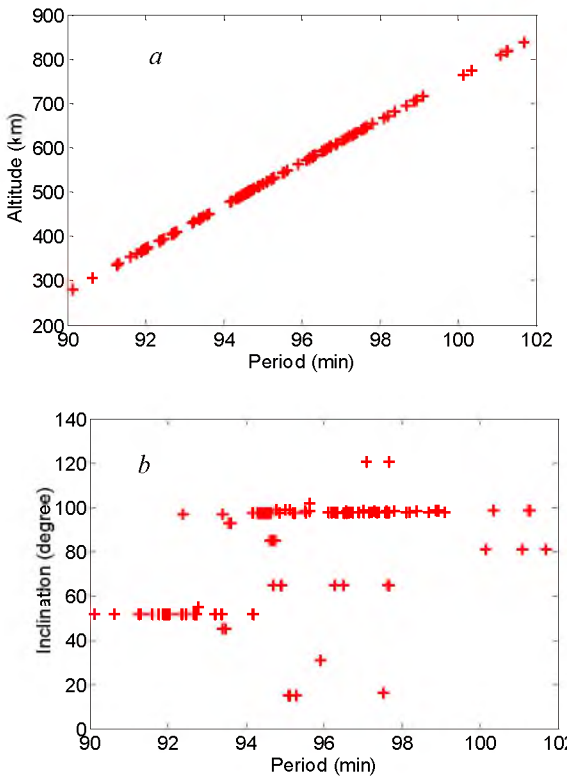


Fig. 1. Compared averaged orbital parameters (a) altitudes and (b) inclinations of the Satellites versus period.

It was shown that this nanosatellite is located 5-6 times in the radio visibility zone for the University ground station per day. In this case, the maximum pass interval during the week is less than 10 minutes, which corresponds to the maximum elevation angle of 54.22°.

The nSight-1 nanosatellite prediction results of elevation angle and Doppler frequency shift of the received telemetry signal are presented on Fig. 2 for the maximum pass interval over the University ground station. The Doppler frequency shift of the received nSight-1 telemetry radio signal varied in the range from −10.14 kHz to +10.14 kHz (for a nominal frequency of 435.90 MHz).

The Belarusian State University nanosatellite CubeBel-1, which was launched by a Chinese rocket carrier into a solar synchronous orbit on October 29, 2018, was selected as an example of the second type of Cubesat orbits.

It was shown that for a week for an almost circular orbit (eccentricity e = 0.001582) of the nanosatellite CubeBel-1, the inclination of the orbit i, the orbit period T and the argument of latitude u did not experience secular perturbations. While the secular perturbations of the longitude of ascending node Ω was 1° per day. It was shown that this nanosatellite is located 5-6 times in the radio visibility zone for the University ground station per day. In this case, the maximum pass interval during the week is about 12 minutes, which corresponds to the maximum elevation angle of 88.84°.

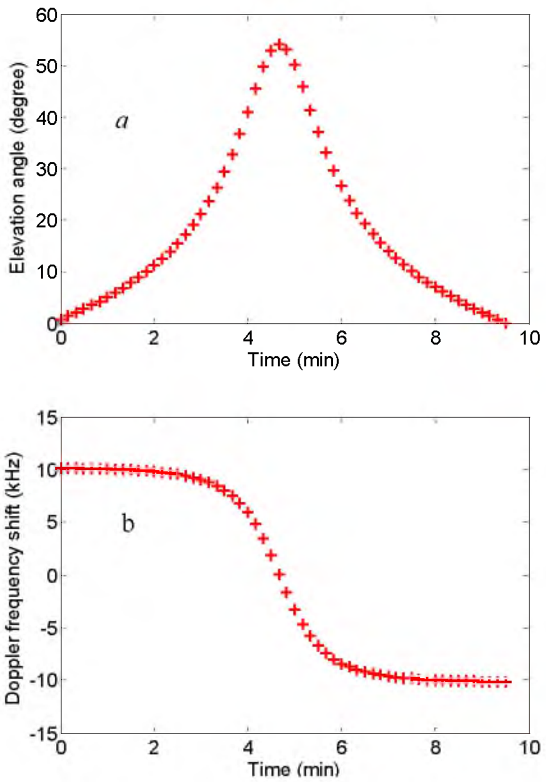


Fig. 2. (a) Elevation angle and (b) Doppler frequency shift of the nanosatellite nSight-1 versus time.

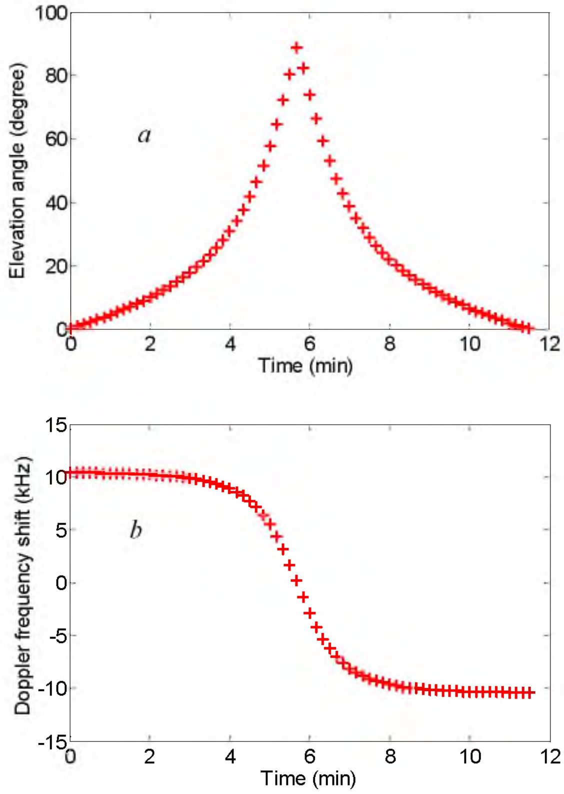


Fig. 3. (a) Elevation angle and (b) Doppler frequency shift of the Belarusian State University nanosatellite Cubebel-1versus time.

The CubeBel-1 nanosatellite prediction results of elevation angle and Doppler frequency shift of the received telemetry signal are presented on Fig. 3 for the maximum pass interval over the University ground station. The Doppler frequency shift of the received Cubebel-1 telemetry radio signal varied in the range from −10.38 kHz to +10.38 kHz (for a nominal frequency of 436.99 MHz).

III. Small Satellite Radio Signal Receiving and Processing.

The telemetry receiving and processing on a Belarusian State University ground station are performed using software and hardware of the communication system. The ground station is additionally equipped with an orbit measurement and determination system with time synchronization. The ground station 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 (SDR) receiver, YAESU G-5500 azimuth-elevation rotator with a control interface and with an additional unit of orientation detection sensors (magnetometer, accelerometer, gyroscope, controller), control computer.

The ground station software includes: satellite orbital and radio signal parameter prediction software, simulation and visualization of cooperative ground station scenarios and express calculation of standard navigation and ballistic information software, telemetry receiving and processing software. The orbit measurement and determination system with time synchronization for University ground station consists of: GPS receiver, module for frequency and time measurements of the received radio signal based on a microcontroller (MCU) for time processing and a two-channel digital oscilloscope, software for processing measurements; software for orbit determination and correction.

The block chart for measuring of small satellite telemetry radio signal parameters for a ground station is shown in figure 4. Radio signals of telemetry packets after conversion to an intermediate frequency in the analog part of the SDR receiver are transmitted for further processing in the ADC SDR and 2 input of a two-channel digital oscilloscope. At a time of t_1 the telemetry packet arrival signal is come from the SDR receiver trigger to the input of the time processing MCU. The GPS module receives and processes radio signals from navigation satellites and transmits 1PPS signals and NMEA packets to 1 input of the two-channel digital oscilloscope and to the time processing MCU input. 1PPS signals are synchronized with the time scale of GLONASS or GPS satellite navigation system. NMEA packets contain information about the exact coordinates of the receiving GPS antenna, the system time of satellite navigation system at the NMEA packet arrival time, and the exact 1PPS signal arrival time.

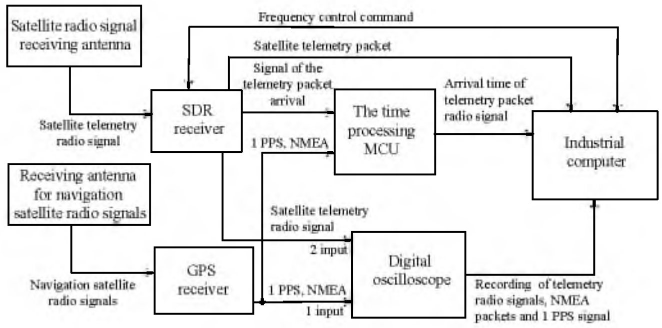


Fig. 4. The block chart for measuring of small satellite telemetry radio signal parameters.

The telemetry packet arrival signal from the SDR receiver trigger turn on the time processing MCU timer that measures the time interval τ between the arrival of the next 1PPS signal from the GPS receiver. In the NMEA packet that follows the 1PPS signal, its exact arrival time $t_1+\tau$ is recorded. The time processing MCU calculates the arrival time t_1 of the telemetry packet radio signal and transmits it to the industrial computer. The radio signal time diagram for telemetry packets, NMEA packets and 1PPS signals is recorded by a digital oscilloscope and transmitted to an industrial computer for processing and calculating the telemetry radio signal frequency and checking its arrival time measurements.

Measurements of the orbit parameters for a single satellite pass over a ground station can be performed at either one point or at several points in the orbit. The maximum satellite pass interval over a ground station is from 10 to 12 minutes for an orbit altitude of 350 to 600 km. Therefore, the simplest Keplerian motion model for satellite can be used to process single pass measuring data over a ground station. Orbit measurements can also be performed on several satellite passes over a ground station. The satellite orbit period for an altitude of 300 to 800 km is from 90 to 102 minutes. After three consecutive satellite passes over the ground station, there is a break with an interval of 8-9 hours. Therefore, to process measuring data on several passes over a ground station, it is necessary to use perturbed motion models for the satellite.

The unknown small satellite orbit determination was made using 25 measurements of the reception time t_i and telemetry signal frequency f_i (i = 1…25) on several orbits for the period from 06.10.2019 to 09.10.2019 (UTC) over the University ground station which was built on the basis of commercial components.

Based on 25 measurements, the average reception frequency $\langle f \rangle$ = 437.25 MHz, the intervals between radio signals Δt_1 on one pass, and the intervals between radio signals Δt_2 on neighboring passes were estimated. The Doppler frequency shift of the radio telemetry signal was calculated

$$\Delta f_i = f_i - \langle f \rangle.$$

On one pass, the radio signals were transmitted with an interval of Δt_1 equal to 6 minutes or 12 minutes in two consecutive packets, which allowed them to be distinguished from other radio signals. The intervals between Δt_2 radio signals on neighboring passes were 90, 96 (mostly), and 102 minutes. This allowed us to assume that this unknown small satellite belongs to satellites with the second type orbits. For numerical simulation were determined the ranges of small satellite orbital period T from 94 to 102 min with the step 1 s, the inclination i from 98 to 99° with the step of 0.01°, the argument of latitude u from 20 to 180° with the step of 1° and the longitude of ascending node Ω from 0 to 360° with the step of 1°.

IV. Orbit Determination Based on the Perturbed Circular Motion Model

Based on the perturbed circular motion model numerical simulation was carried out for the time of reception and the Doppler shift of radio telemetry at the 25 measuring points for the University ground station in the ranges of change of the orbital period ΔT, the orbital inclination Δi, the argument of latitude Δu and the longitude of ascending node ΔΩ.

The perturbed circular motion model of the small satellite took into account the secular perturbations of the longitude of ascending node Ω and the argument of latitude u due to the gravitational potential (J_2). The perturbed circular motion model geometry for the orbit determination is shown in Fig. 5.

The probability of success β_{el} of each set of orbital parameters (T, i, u, Ω) was calculated for the estimated time t_2 = 9:48:18 on 9.10.2019 (UTC) based on the analysis of only the small satellite elevation el above the University's ground station

$$\beta_{el} = (N_{el} / N_{total})\cdot 100\%,$$

where N_{el} is the number of calculated points with elevation $el > 0$ for a given set of orbital parameters (T, i, u, Ω), N_{total} = 25 is the total number of measurement points where numerical modeling was performed.

Similarly, the probability of success β_2 of each set of orbital parameters (T, i, u, Ω) was calculated based on the analysis of the small satellite elevation el and the Doppler shift of the frequency Δf_{calc} of the received radio telemetry signal over the University ground station.

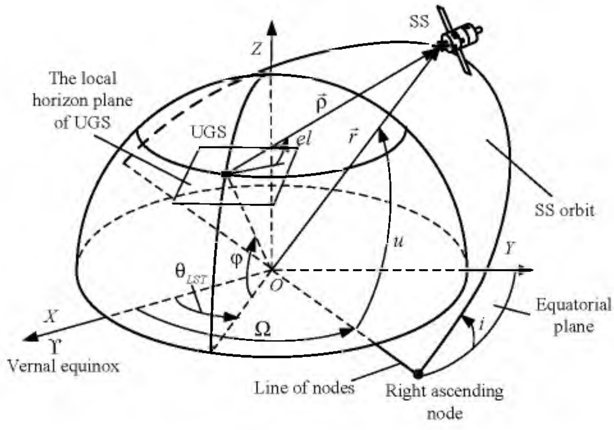


Fig. 5. The perturbed circular motion model geometry (UGS- the University Ground Station; SS - Small Satellite).

$$\beta_2 = (N_2 / N_{total})\cdot 100\%,$$

where N_2 is the number of calculated points with elevation $el > 0$ and Doppler frequency shift error of the received telemetry radio signal $|\Delta f - \Delta f_{calc}| < 200$ Hz for a given set of orbital parameters (T, i, u, Ω), N_{total} = 25 is the total number of measurement points where numerical modeling was performed..

V. Results and Discussion

In Fig.6 the dependence of the number of possible sets of orbital parameters (T, i, u, Ω) on the probability of success β_{el} and β_2 (with probability of success above 50%) of this set of orbital parameters is presented.

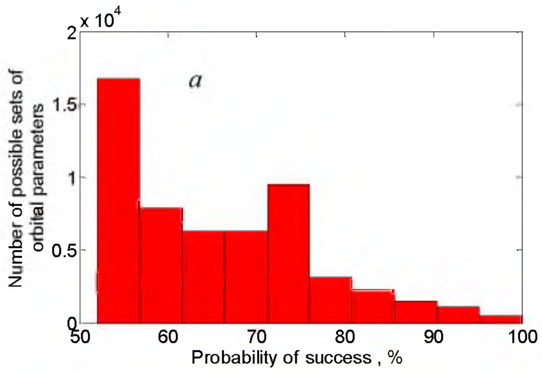
As shown in Fig. 6 (a) according to only elevation el estimation, there are 482 sets of orbital parameters (T, i, u, Ω) with the probability of success β_{el} = 100% and 55259 sets of orbital parameters with the probability of success β_{el} above 50%. At that time in Fig. 6 (b) it is shown that according to the elevation el and the Doppler frequency shift Δf_{calc} estimation, there is only one set of orbital parameters (T, i, u, Ω) = (5855 s, 97.98°, 115°, 359°) with the probability of success β_2 = 96% and only 23 sets of orbital parameters with the probability of success β_2 above 50%.

Based on unknown small satellite elevation and Doppler frequency shift probabilistic estimation at 25 measurement points, a set of orbital parameters (T, i, u, Ω) = (5855 s, 97.98°, 115°, 359°) was determined for the estimated time t_2 = 9:48:18 on 9.10.2019 (UTC).

Based on this set of orbital parameters and a circular perturbed motion model, 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 10.10.2019 (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 10:07:50 to 10:20:50 on 10.10.2019 (UTC). It was recognized small satellite LUOJIA-1 01 with NORAD database. The results were published on the Amateur radio site DK3WN SatBlog [17].

The accuracy of predicting the elevation el, azimuth az and Doppler frequency shift Δf_{calc} of radio telemetry signals was estimated at the interval of successful reception and decoding of telemetry packets of the small satellite LUOJIA-

1 01 (number 43485 in the NORAD system) in comparison with SGP4 prediction model. The elevation and azimuth prediction absolute errors did not exceed 3°, and the absolute error of Doppler frequency shift prediction did not exceed 160 Hz, which is sufficient for successful reception of telemetry radio signals and their decoding.



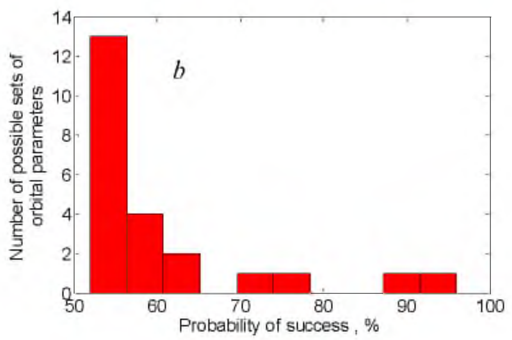


Fig. 6. The number of possible sets of orbital parameters (with probability of success β above 50%) versus the probability of success based on analysis of (a) elevation β_{el} and (b) elevation and the Doppler shift β_2.

At present the possibility of cooperative telemetry reception and small satellite orbit determination by a stationary Belarusian State University ground station and several mobile ground stations with time synchronization and spacing across the territory of the Republic of Belarus is investigated. The mobile ground station is also additionally equipped with an orbit measurement and determination system with time synchronization. The communication system software and hardware for the mobile ground station includes: 435-438 MHz band omni-directional quadrifilar helical antenna, the receiving system based on the SDR module, control industrial computer, satellite orbit and radio signal parameter prediction software, telemetry receiving and processing software. The orbit measurement and determination system with time synchronization for a mobile ground station consists of: GPS receiver, module for frequency and time measurements of the received radio signal, software for processing measurements; software for orbit determination and correction.

The orbit determination technology involved receiving and processing frequency measurements of the same satellite telemetry signal at several synchronized ground stations, and identifying the satellite using the NORAD orbital parameter database. The cooperative telemetry reception by a stationary Belarusian State University ground station and several mobile ground stations will allow using the resources of stations both for receiving satellite information and orbit determination. This will allow increasing the receiving geography, improving the quality of reception and independently obtaining orbital parameters and training students in practical technologies for receiving telemetry and orbit determination.

In conclusion, we have demonstrated the potential of Belarusian State University ground station for orbit determination of the unknown small satellite. Orbital parameters are theoretically investigated using NORAD TLE database and perturbed circular motion model. Finally, a good agreement with experimental Doppler frequency shift data was achieved.

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