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Research and educational network of ground stations for receiving and processing information from educational satellites

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Abstract. The research and educational network of ground stations for receiving and processing information from low-orbit educational spacecraft is considered in this paper. Ground stations are equipped with an orbit measurement and determination system with time synchronization. This network realizes receiving and processing telemetry of ultra-small satellites, performing measurements and determining their orbital parameters and teaching students of aerospace specialties. Software and hardware of stationary and mobile ground stations are considered. The ground station was tested in the modes of receiving data and measuring the ultra-small satellite orbit with different frequency of telemetry packets. The initial orbit determination by frequency and time measurements of a LUOJIA-1 01 nanosatellite telemetry signal on several orbits with a limited number of data on one pass was studied. The nanosatellite radio signal nominal frequency and initial orbital parameters were unknown. Close orbit determination using a ground station network for satellite constellation launch in the first week of flight was considered. The simulation results showed that if the mean anomalies of neighbouring satellites differ by 0.1°, the spacecraft can be identified in the constellation by the frequency and time measurements of the same radio signal at three synchronized ground stations.

1. Introduction

Many universities develop their own educational satellites as educational laboratories for training students of aerospace specialties, research and technology development [1–2]. Usually these are ultra-small satellite (USS) weighing up to 10 kg, developed according to the Cubesat standard [2–3]. Reliable and effective receiving of telemetry and forecasting future positions are important for control, tracking and radio communication with University ultra-small satellites. Due to budget constraints, a single ground control station (GCS) is used for control and receiving telemetry at the University USS, which is located within the city limits and has unsatisfactory reception conditions. In addition, the communication between the GCS and the low-orbit USS is limited to sessions of a few minutes 5–6 times a day. Sometimes the University GCS is connected to global international networks of USS ground stations. Satnogs is example of the international network of reception stations (more than 900 ground stations), which is used as a redundancy communication channel with the University nanosatellite BSU CubeBel-1, launched in October 2018.

The SGP4 model [4–5] with input orbital data in the TLE (two-line elements) format of the NORAD (the North American Aerospace Defense Command) is used to USS future passes prediction over the University ground station and processing information. Typically, TLEs are updated daily, and

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are available free of charge [6]. But in the long term, or in the event of military conflicts, the NORAD has the ability to rescind shared access to the orbital database. Less often, a navigation receiver is used onboard ultra-small satellite to determine the exact coordinates and velocity [7]. Another way to obtain initial orbital parameters for prediction models is orbit determination based on measurements of the received radio signal from USS [8]. The measured parameters for a low-cost ground station are the time and Doppler frequency shift of the received radio signal [8–9].

2. Ground station software and hardware. Measuring of telemetry radio signal parameters

The possibility of cooperative telemetry reception and USS orbit determination by a stationary University GCS and several mobile GS with time synchronization and spacing across the territory of the Republic of Belarus is considered in this paper. The telemetry receiving and processing on a stationary University GCS are performed using software and hardware of the communication system. 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 SDR receiver, YAESU G-5500 rotator with a control interface, 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; software for processing measurements; software for orbit determination and correction.

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 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 USS telemetry radio signal parameters for a mobile ground station is shown in figure 1. 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 (Figure 2). 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. 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 (Figure 2). 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.

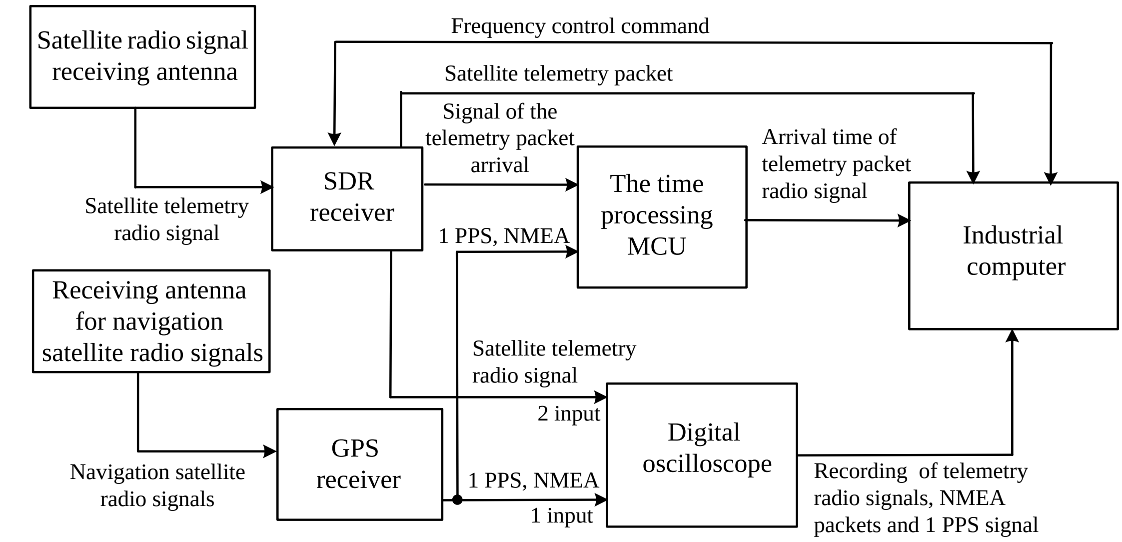

Figure 1. The block chart for measuring of USS telemetry radio signal parameters.

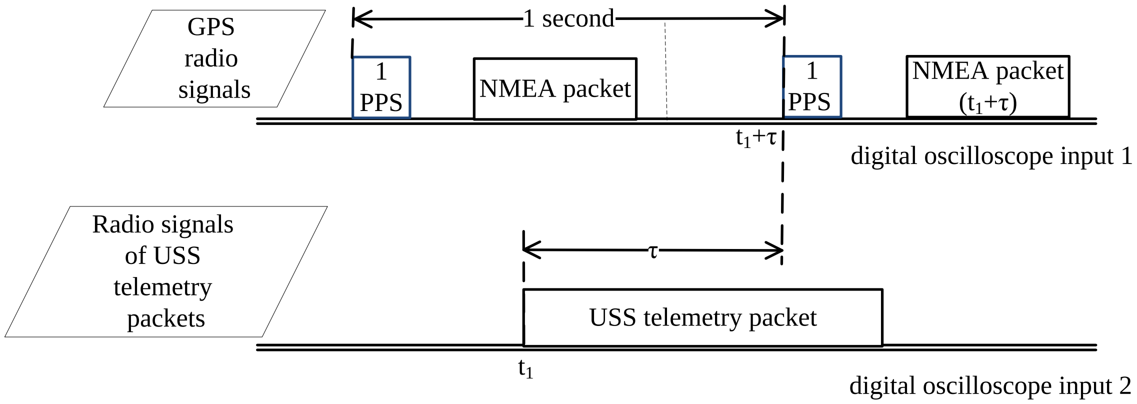

Figure 2. The radio signal time diagram for telemetry packets, NMEA packets and 1PPS signals.

3. The ground station operation modes, measurement and processing methods, mathematical models and algorithms

A satellite control session, a telemetry reception session, or an orbit measurement session can occur between USS and a ground station. A radio signal containing a control command packet or a measuring radio signal in a request measurement session is transmitted from the ground station to the satellite via the command link. A packet of response receipts or a measuring radio signal is sent back from the satellite to the ground station. A radio signal containing a telemetry packets or a measuring radio signal in an unsolicited measurement session is transmitted from the satellite to the ground station via the telemetry link.

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. 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 350 to 600 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 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). 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 correct them. The differential correction method of satellite orbit parameters using relative velocity data between satellite and the ground station is used. Relative velocity data is computed from the Doppler shift of received telemetry radio signal at the ground station.

The initial orbit determination is performed for the satellite measuring in the Omni-directional search mode. The target 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.

4. The ground station testing results for ultra-small satellite telemetry and orbit measuring

The developed mobile ground station was tested on receiving data and satellite orbit measurement with different transmission intervals between telemetry packets. The time and frequency of radio telemetry signals from nanosatellites CubeBel-1 (measurements on a single pass with transmission interval of 40 s) and LUOJIA-1 01 (measurements on several passes with transmission interval of 6 min) were measured. The frequency measurements of telemetry signals from these nanosatellites were compared with the simulation results based on the SGP4 prediction model with input data in TLE format. It is shown that the experimental data are in good agreement with the numerical simulation data. Errors in measuring the frequency of telemetry radio signals from nanosatellites relative to simulation data did not exceed 300 Hz.

The initial orbit determination for LUOJIA-1 01 nanosatellite was performed, provided that its nominal frequency of the radio signal and the initial orbital parameters are unknown. Based on the perturbed circular motion model was processed frequency measurements of the LUOJIA-1 01 nanosatellite on several passes. To justify nanosatellite motion model, the orbital parameters of low orbit satellites (altitude up to 2000 km) were analyzed using the NORAD system database (on data of 07.10.2019). The analysis showed that more than 90 % of these satellites have an almost circular orbit (with a small eccentricity value $e \ll 1$).

For satellites developed according to the Cubesat standard, an additional analysis of the orbital parameters and dynamics of their changes during the week of flight was performed. The results of the analysis show that there are two types of Cubesat orbits. The first type of orbit is associated with satellites launched from the International Space Station. They have inclination of about 51.6°, an orbital period of 90 to 94 min, and altitude of 330 km to 430 km. The second type of orbit is associated with satellites launched into a solar-synchronous orbit as secondary payloads. These Cubesats have inclination from 98 to 99°, an orbital period from 94 to 102 minutes, and altitude from 500 km to 800 km. The Doppler frequency shift of the telemetry radio signal these satellites in the radio visibility zone over the University ground station Minsk (latitude φ = 53°54'27" North, longitude λ = 27°33'52" East, altitude H = 0.23 km) varied in the range from −10.4 kHz to +10.4 kHz (for a nominal frequency from 435 to 438 MHz).

The nanosatellite orbit determination was made using 20 measurements of the reception time t_i and telemetry signal frequency f_i (i = 1–20) on several orbits over the University ground station for the period from 07.10.2019 to 09.10.2019 (UTC). The average reception frequency f_m = 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 as $\Delta f_i = f_i - f_m$. 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 satellite orbit belongs to the second type orbits.

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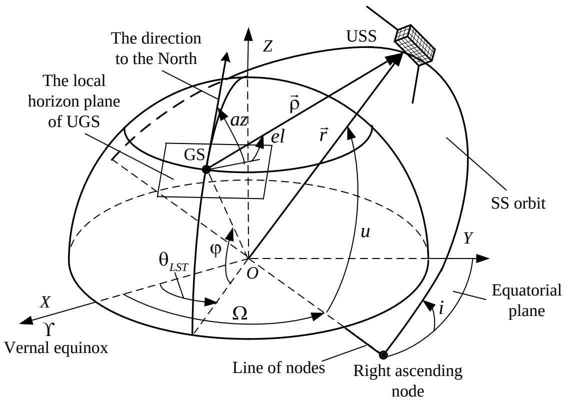

Figure 3. The perturbed circular motion model geometry (UGS – the University Ground Station; SS – Small Satellite).

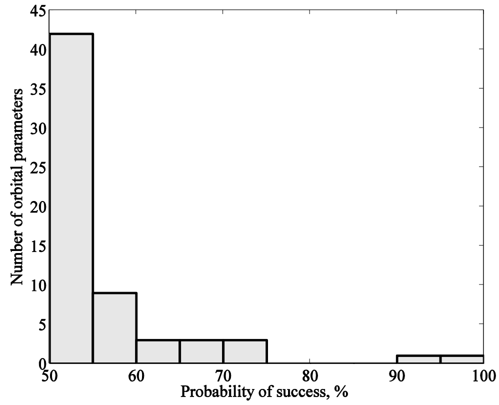

Figure 4. The number of possible sets of orbital parameters versus the probability of success β.

For orbit determination algorithm were set the ranges of the circular orbit parameters: period T from 94 to 102 min c step 1 c, the inclination i from 97 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°. The perturbed circular motion model (Figure 3) of the satellite took into account the secular perturbations of the right ascension of the ascending node Ω due to the gravitational potential. The probability of success β of each set of orbital parameters (T, i, u, Ω) was calculated for the estimated time t_2 = 9:48:18 on 09.10.2019 (UTC) based on the analysis of the calculated elevation el and the Doppler shift of the frequency Δf_{calc} of the received radio signal over the ground station:

$$\beta = \frac{N}{N_{total}} 100\,\%\,, \tag{1}$$

where N, N_{total} = 20 is the number of calculated points and the total number of measurement points where numerical simulations were performed with elevation $el > 0$ and error $|\Delta f - \Delta f_{calc}| < 300$ Hz of the measured Doppler frequency shift Δf relative to the calculated Δf_{calc} for each set of orbital parameters (T, i, u, Ω).

In figure 4 the dependence of the number of possible sets of orbital parameters versus the probability of success is presented. Our results showed that for the time t_2 with probability of success β above 50% the ranges of the orbital parameters were: period T from 5852 to 5859 s, inclination i from 97.97 to 97.99°, argument of latitude u from 114 to 117° and the right ascension of the ascending node Ω from 356 to 4°. There is only one set of orbital parameters (T, i, u, Ω) = (5855 c, 97.98°, 115°, 359°) with the probability of success β = 100%, one set (T, i, u, Ω) = (5855 c, 97.98°, 115°, 360°) with β = 95%, and 60 sets of orbital parameters with β from 50% to 75%.

Based on set of orbital parameters (T, i, u, Ω) = (5855 c, 97.98°, 115°, 359°) and the perturbed circular motion model, the elevation el, azimuth az and Doppler frequency shift of 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 nanosatellite LUOJIA-1 01 at the pass interval from 10:07:50 s to 10:20:50 on 10.10.2019 (UTC). The accuracy of predicting the elevation, azimuth and Doppler frequency shift of radio signals was estimated at the interval of successful receiving and decoding telemetry 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 receiving and decoding telemetry.

A simulation of the cooperative operation of a network of three spaced University ground stations (Minsk, Brest, and Mogilev) for orbit determination the Starlink-1143 satellite in the first week of flight was performed. This satellite was launched on February 17, 2020 in a constellation launch of 60

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satellites of the Global Internet System. In the first week of the flight, the satellites in the constellation had similar orbital parameters. The orbit determination technology involved receiving and processing frequency measurements of the same satellite telemetry signal at three synchronized ground stations, and identifying the satellite using the NORAD orbital parameter database.

The Doppler shift Δf_{exp} of the received frequency of the telemetry radio signal (with the addition of 100 Hz noise) of the Starlink-1143 satellite was simulated for two time points t_1 and t_2 using TLE input data and SGP 4 models. Using NORAD database for constellation launch on February 17, 2020 was calculated the pass parameters over ground stations (elevation el_i,, azimuth az_i,, range ρ_i, relative velocity between satellite and the ground station $d\rho_i/dt$) and the Doppler shift of the telemetry signal frequency $\Delta f_{calc.\, i}$ for time point t_i (i =1.2). Satellite identification was performed with the conditions $el_i > 0$ and $|\Delta f_{calc.\, i} - \Delta f_{exp.\, i}| < 300$ Hz.

The simulation results showed that if the mean anomalies of neighboring satellites differ by 0.1^o, the satellite can be identified in the constellation by the frequency and time measurements of the same radio signal at three synchronized ground stations. The simulation results showed that the cooperative telemetry reception by a stationary University GCS and several mobile GS with time synchronization and spacing across the territory of the Republic of Belarus 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.

5. Conclusion

In summary, we have demonstrated the research and educational network of ground stations for receiving and processing information from low-orbit educational spacecraft. The ground station was tested in the modes of receiving data and measuring the ultra-small satellite orbit with different frequency of telemetry packets. It was shown, that errors in the frequency measurements of received telemetry radio signals for CubeBel-1 and LUOJIA-1 01 nanosatellites relative to the calculated SGP 4 model with initial data in TLE format did not exceed 300 Hz. Finally, the initial orbit determination by 20 frequency and time measurements of a LUOJIA-1 01 nanosatellite telemetry signal on several orbits with a limited number of data on one pass was studied.

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