It is clear that, as the project is meant to use only low cost hardware, the system requires a lot of design effort. Despite the relatively low pointing accuracy, the low cost and power consumption justify the implementation of the system.

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Надійшла до редколегії 28.05.2012.

УДК 629.78

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DESIGN OF GROUND COMMUNICATION ANTENNA CONTROL SYSTEM FOR A NANOSATELLITE MISSION

Розглядається система програмного супроводження супутника наземною станцією. Наводиться алгоритм розрахунку параметрів супроводження, розрахунок лінії зв'язку, вибір антен і приводу стеження.

***Ключові слова*:** супутниковий зв'язок, наземна станція, програмний спосіб супроводження супутника, алгоритми керування супроводженням.

A system of program tracking of a satellite by a ground station is considered. Algorithms of calculating parameters of tracking, calculation of the communication line, choice of the antenna and the tracking drive motors are described.

***Key words*:** satellite communication, ground station, programmed way of tracking, algorithms of control of tracking.

Рассматривается система программного сопровождения спутника наземной станцией. Приводятся алгоритм расчета параметров сопровождения, расчет линии связи, выбор антенн и привода слежения.

Ключевые слова: спутниковая связь, наземная станция, программный способ сопровождения спутника, алгоритмы управления сопровождением.

Introduction

The present work shows the development of an antenna pointing control strategy for a satellite communication ground station. The station, situated at Dnepropetrovsk National University (DNU), aims to communicate with the university nanosatellite [11]. The satellite is being developed by different institutes of Ukraine for earth imaging missions. The role of a ground station is to communicate properly with a satellite in orbit [5]. Using an antenna, the station must receive information from the satellite and send commands to it. In this case, it will be used a parabolic antenna, which in general is directional.

Problem description

The satellite will fly in a sun-synchronous orbit, about 600 km of height from the surface. The ground station has a limited area of visibility. Given the orbit characteristics, the satellite has a few and short moments of communication per day. More about sun-synchronous orbit missions can be found in [2]. Considering that the gravitational force is the only one actuating the satellite, it is possible to predict where it will be after a period of time, if the initial condition is known. The satellite instantaneous position vector r, velocity vector v, and orbital path are defined by six orbital parameters, which are: specific angular momentum $\boldsymbol{h}$, inclination i, right ascension of the ascending node (RAAN) Ω, eccentricity e, argument of the perigee (AP) ω and true anomaly (TA) θ. These vectors and parameters are presented in figure 1, in the earth centered fixed frame of reference (ECFFF). The tracking algorithm will work in open-loop, with no measures correcting the estimation. This consideration allows the project to be simple and developed quickly, but unfortunately it also brings limitations. The satellite position may be lost if there are no updates measures in the estimation for a long time. Fortunately this problem can be disregarded, because the mission is for a short period of time. In order to compute the pointing angles, it is important to know the location of the ground station in the ECFFF. The tracking program must output the periods of observation and the sequence of angles so the controller can track the satellite.

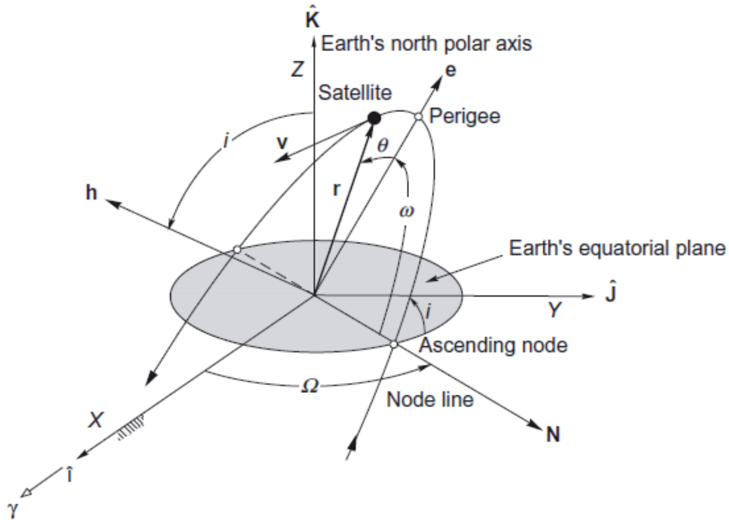

Fig. 1. Satellite orbital parameters (taken from [3])

A parabolic antenna will be used for the communication with the satellite, to send commands (X-band), to receive telemetry information (X-band) and the captured images (K-band). The nomenclature of the bands is according to the reference [7]. The antenna must be dimensioned so the channels can operate in 1 Mbps and 10 Mbps, respectively, when the satellite will emit 2 W. The link will be evaluated for the worst case of distance, which is when the satellite appears in the visibility zone for the first time. The representation of this moment can be seen in the figure 2, where *d* is the distance between the satellite and the ground station, *h* is the satellite altitude from the surface and R_e is the earth mean radius.

The antenna is rotated in two axes, azimuth and elevation. The range for elevation is between 0º and 90º, where the 0º points to the horizon and 90º to the zenith. The range for azimuth is between 0º and 360º, where the 0º points to the geographical north, 90º to the east, 180º to the south and so on. The rotator must be able to provide the angular position control with a good precision, considering the torque generated by the antenna weight and by wind forces. The necessary torque must be estimated so a commercial rotator can be selected. Given the provided torque, it must be evaluated the maximum wind velocity which the system can rotate. Finally, the whole pointing system must be simulated and evaluated.

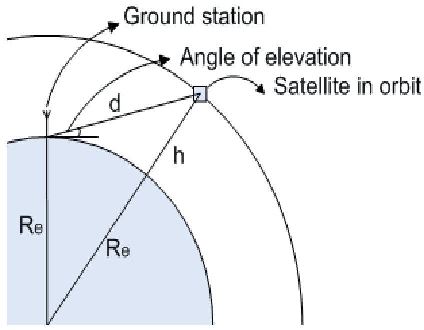

Fig. 2. Satellite first appearance representation

Mathematical formulation

There are different options for tracking algorithms, some of them are presented in [4], including the selected one. Just three of the six orbital parameters are considered to vary through time, the RAAN, the AP and the TA. The variation of the RAAN and of the AP are due to the earth oblateness. The oblateness is quantified by a constant called second zonal harmonic, and is represented by J_2. The variation of the three parameters are developed in details in the reference [4], and are presented here in equations 1, 2 and 3, where *a* is the semi-major axis of the orbit, μ is the standard gravitation parameters, R_E is the earth equatorial radius and h is the magnitude of vector ***h***.

$$\dot{\Omega} = -\left[\frac{3}{2}\frac{\sqrt{\mu}J_2 R_E{}^2}{\left(1-e^2\right)^2 a^{7/2}}\right]\cos i\,. \tag{1}$$

$$\dot{\omega} = \dot{\Omega}\frac{\left((5/2)\sin^2 i\right)-2}{\cos i}\,. \tag{2}$$

$$\dot{\theta} = \frac{\mu^2\left(1+e\cos\theta\right)^2}{h^3}\,. \tag{3}$$

Analyzing such equations, a discretization may be performed, so the parameters can be obtained interactively in time from the previous samples. The subindex *k* is used to represent the *k*-th sample of the constant. The time between the samples *k* and *k+1* is Δt. The discretized computations are presented in equations 4, 5 and 6.

$$\Omega_{k+1} = \left(-\left[\frac{3}{2}\frac{\sqrt{\mu}J_2 R_E{}^2}{\left(1-e^2\right)^2 a^{7/2}}\right]\cos i\right)\Delta t + \Omega_k\,. \tag{4}$$

$$\omega_{k+1} = \left(\left(-\left[\frac{3}{2} \frac{\sqrt{\mu} J_2 R_E{}^2}{\left(1-e^2\right)^2 a^{7/2}} \right] \right) \left(\left((5/2) \sin^2 i \right) - 2 \right) \right) \Delta t + \omega_k \,. \tag{5}$$

$$\theta_{k+1} = \left(\frac{\mu^2 \left(1 + e \cos\theta_k\right)^2}{h^3} \right) \Delta t + \theta_k \,. \tag{6}$$

Once the orbital parameters are predicted, the position and velocity vectors may be predicted as well. The computation of these vectors in the ECFFF is shown in equation 7.

$$\begin{cases} r_{k+1} = Q_{k+1} \cdot \left\{ \dfrac{h^2}{\mu} \dfrac{1}{1 + e\cos\theta_{k+1}} \begin{bmatrix} \cos\theta_{k+1} \\ \sin\theta_{k+1} \\ 0 \end{bmatrix} \right\} \\ v_{k+1} = Q_{k+1} \cdot \left\{ \dfrac{\mu}{h} \begin{bmatrix} -\sin\theta_{k+1} \\ e + \cos\theta_{k+1} \\ 0 \end{bmatrix} \right\} \end{cases}, \tag{7}$$

where

$$Q_{k+1} = \begin{bmatrix} -\sin\Omega_{k+1}\cos i \sin\omega_{k+1} + \cos\Omega_{k+1}\cos\omega_{k+1} & -\sin\Omega_{k+1}\cos i\sin\omega_{k+1} - \cos\Omega_{k+1}\sin\omega_{k+1} & \sin\Omega_{k+1}\sin i \\ \cos\Omega_{k+1}\cos i\sin\omega_{k+1} + \sin\Omega_{k+1}\cos\omega_{k+1} & \cos\Omega_{k+1}\cos i\cos\omega_{k+1} - \sin\Omega_{k+1}\sin\omega_{k+1} & -\cos\Omega_{k+1}\sin i \\ \sin i\sin\omega_{k+1} & \sin i\cos\omega_{k+1} & \cos i \end{bmatrix}.$$

The satellite position is known, but it is also needed to know the ground station position at the same frame of reference at that instant. The ground station altitude H, latitude ϕ and sidereal time s are used for such computation. The algorithm for determining the sidereal time of the ground station at the current date and time and the position R are also presented in the reference [4]. The position of the ground station R in the ECFFF is presented in equation 8, where f is earth flattening.

$$R = \left[\frac{R_e}{\sqrt{1 - \left(2f - f^2\right)\sin^2\varphi}} + H \right] \begin{bmatrix} \cos\varphi\cos s \\ \cos\varphi\sin s \\ \sin\varphi \end{bmatrix}. \tag{8}$$

The difference between the vectors of the satellite position and the ground station position is the observation ρ. This resulting vector is represented in the ECFFF and needs to be transformed to the ground station frame of reference. Such frame of reference has the x-axis pointing to east, y-axis pointing to north and z-axis pointing to the zenith of the ground station. The transformation is presented in equation 9. The resulting vector ρ_G represents the line of sight from the ground station to the satellite. The direction of the vector is represented by the angles of elevation and azimuth.

$$\rho_G = \begin{bmatrix} -\sin s & \cos s & 0 \\ -\sin\varphi\cos s & -\sin\varphi\sin s & \cos\varphi \\ \cos\varphi\cos s & \cos\varphi\sin s & \sin\varphi \end{bmatrix} \rho \,. \tag{9}$$

The satellite link calculation is presented in details in the reference [1]. The equation 10 presents P_R, the power received by the ground station in dB, where λ is the carrier wave length, P_T is the emitted power by the satellite in dB and G_R is the receiver antenna gain in dB. The equation 11 presents the parabolic antenna gain, where D_A is the antenna diameter and η_A is the antenna aperture efficiency.

$$P_R = P_T + G_R - 20\log\left(\frac{4\cdot\pi\cdot d}{\lambda}\right). \tag{10}$$

$$G_R = 10\log\left[\left(\frac{\pi \cdot D_A}{\lambda}\right)^2 \eta_A\right]. \tag{11}$$

In the reference [8], the author shows the *Shannon Relation*, which is the maximum bit rate capacity for a communication channel. Such relation is presented in equation 12, and shows that for a given band width W, noise temperature T and received power $P_{R[W]}$ (in watts), the channel bit rate R_b must not exceed the channel capacity C, where k is the Boltzmann's constant.

$$R_b \le C = W \log_2\left(1 + \frac{P_{R[W]}}{W \cdot k \cdot T}\right). \tag{12}$$

The task of dimensioning the rotator must take into account the physical characteristics of the antenna. The first characteristic is the torque generated by the antenna weight. Another important calculation which depends on the antenna physical characteristics is the torque generated by wind forces. The force F_W is applied by the wind with velocity V_W is presented in equation 13, where ρ_W is the wind density, c_W is the coefficient drag, α_W is the angle between the wind and the axis of the antenna and A_A is the area of contact with the antenna. The area of contact generally depends on the direction of the wind.

$$F_W = 0.5 \cdot \rho_W \cdot c_W \cdot V_W{}^2 \cdot A_A. \tag{13}$$

The torque generated by the wind is presented in equation 14, where β is the angle between the wind direction and the radial axis of the antenna. The worst case of this calculation is when the β is about 45º, because of the trade-off between the contact area of the wind and the direction which the force is being applied.

$$T_W = F_W \cdot d_A \cdot \sin\beta. \tag{14}$$

Considering the antenna a point mass attached to the end of the rod rotated by the motor, the torque to rotate the antenna at a angular velocity rate $\dot{\omega}$ is given by equation 15.

$$\tau_A = m_A \cdot d_A{}^2 \cdot \dot{\omega}. \tag{15}$$

Results

The satellite tracking algorithm was tested for a satellite in an orbit similar to the one to be launched, and the ground station located at DNU. The simulation had the initial orbital parameters presented in the table 1, and the time interval between computations, Δt, is 5 seconds. In the table, the angles are computed in degrees and the specific angular momentum is in km²/s. The evaluation was performed for the period of 24 hours, starting at 09h00m00s of 02/04/2012.

Table 1

Initial orbital parameters for the simulation

h	i	Ω	e	ω	θ
$5{,}28 \cdot 10^4$	98º	0º	$1 \cdot 10^{-6}$	0º	0º

In figure 3, it can be seen the theoretical elevation angles to observe the satellite along the time. For obvious reasons, it is impossible for the ground station to observe the satellite when it has an observation angle below 0º. The satellite may become visible for angles above 0º, but the ambient is usually crowded with buildings and trees, so a threshold angle must be set. For the simulation it was used 7º, marked with a horizontal line in the graph. This threshold is an usual value set for the satellite observation.

The Table 2 presents the observation periods computed in the simulation. For the first observation period, the sequence of angles for elevation and azimuth can be seen in figure 4. The table shows clearly the need of a good communication link. For 24 hours, the satellite remains in the visibility zone for less than 30 minutes. This time must be enough for receiving all the images, the telemetry information and send commands to the satellite.

Table 2

Tracking output

Initial instant	Initial elevation	Initial azimuth	Final instant	Duration
02/04/12 09h09m20s	9,66º	204,72º	02/04/12 09h16m 10s	06min50s
02/04/12 20h51m55s	9,43º	115,75º	02/04/12 21h03m25s	11min30s
02/04/12 22h27m35s	7,81º	145,63º	02/04/12 22h37m10s	09min35s
03/04/12 07h52m40s	9,98º	151,13º	03/04/12 08h00m35s	07min55s

The antenna dimensioning and link evaluation for the worst case are summarized in table 3. It was used 500 K for the temperature noise and 0,65 for the aperture efficiency. Satisfying the requirements for the data channel, the other channel can be considered satisfied as well. The minimum rotating torque needed to rotate the antenna is about 75 Nm. The rotator must be able to rotate the antenna in velocities about 1,5 deg/s.

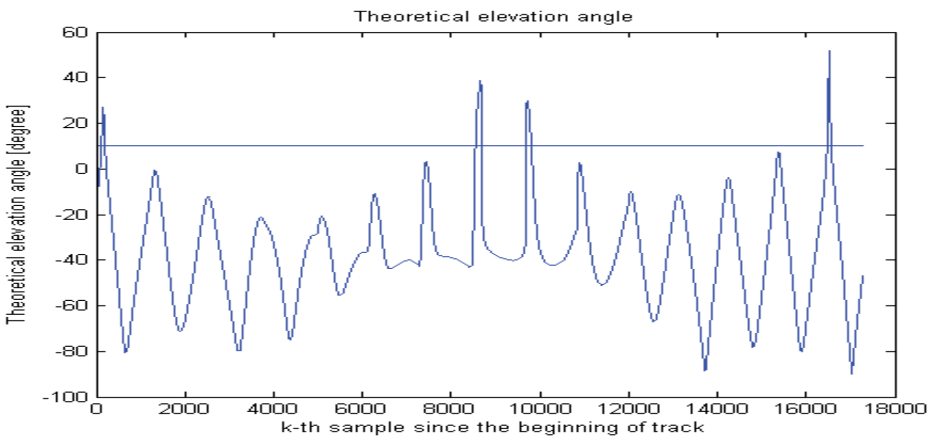

Fig. 3. Required angles of observation obtained in the simulation

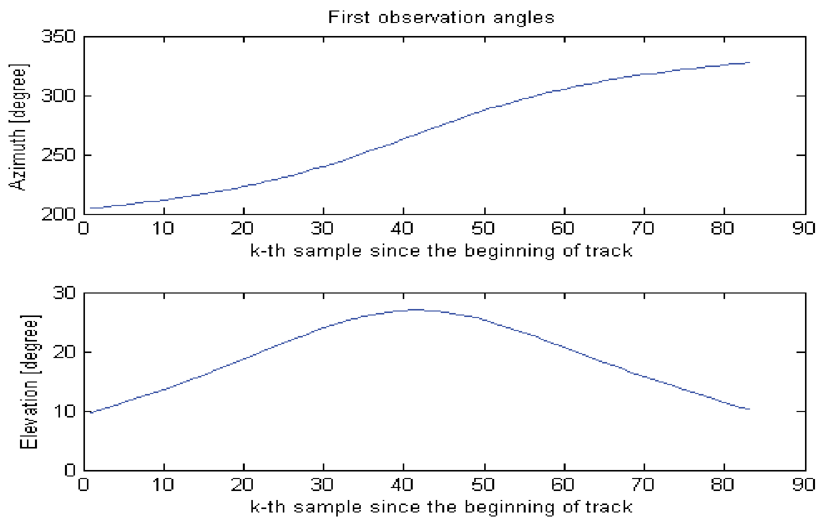

Fig. 4. Sequences of angles for the first observation of the satellite

Table 3

Link evaluation

Characteristic	Data channel
Received power [dB]	–132.757
Antenna gain [dB]	35
Antenna diameter [m]	2,6

A scheme of the control procedures is presented in figure 5. The implemented computer software will predict the satellite periods of visibility, as well the duration and the required pointing angles according to the rotator step precision. All this information will be stored in the computer memory. The reference of the antenna will be set to the initial angles of observation. When the time of the visibility period comes, the controller reference will be updated during the observation by RS-232 protocol. When that period of visibility is over, the next one is computed and the process is repeated.

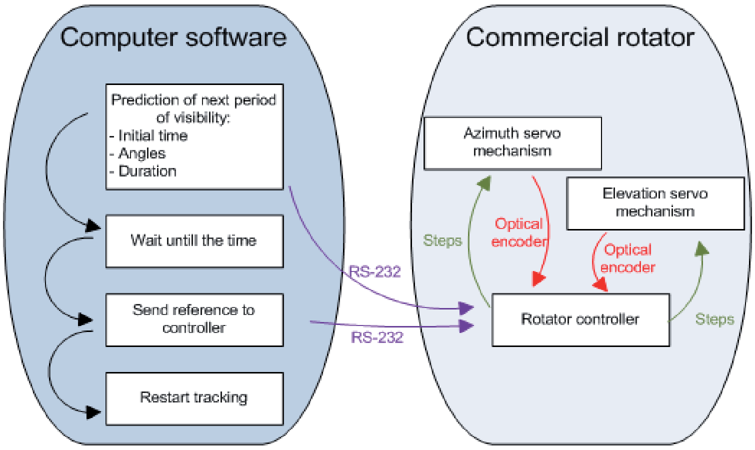

Fig. 5. Controller schematics

A final simulation was performed to evaluate the link signal. In this simulation, it is considered additive random noise in the received power and in the angular position of the servo mechanism. The result of the simulation of the signal received by both antennas for the first observation are presented in figure 6. The horizontal line traced marks the minimum signal needed for the connection.

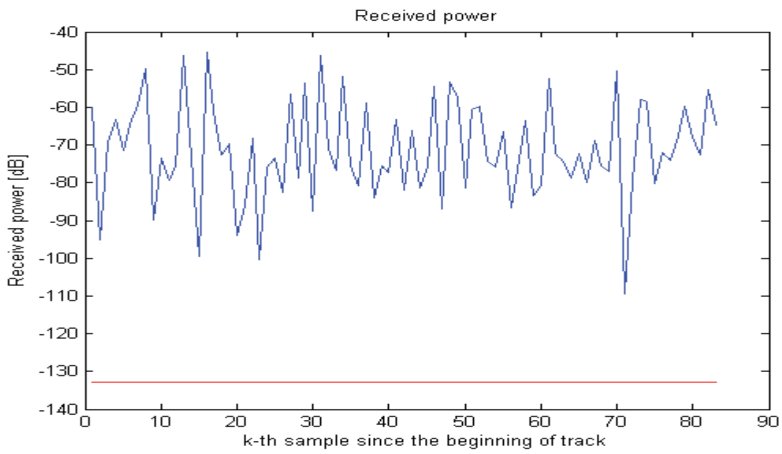

Fig. 6. Signal simulation results for the first observation period

Conclusions and future work

The tracking precision obtained with the selected open-loop technique is good enough for short missions as the one performed by the satellite. After a long period, the estimation of the satellite position will diverge, and it would be lost. To extend the validity of the tracking, it is important to update the estimation with a position measurement. The position can be updated with external information about the satellite. As future work for this ground station, some information about the satellite position can be inferred from the received signal using techniques like the ones presented in [6]. To merge such information with the prediction, it can be used a stochastic filter, preferable non linear, like *Extended Kalman Filter* or *Unscented Kalman Filter* [9]. In that way, the ground station can be used for different missions.

The link evaluation was satisfactory for the communication demands. Even with the added random noise, the link could receive information in the required connection bit rate. Some work is necessary to be done in the field of signal processing for the received signal by the ground station and for the emitted to the satellite as well.

The commercial rotator, shown in figure 8, can rotate with angular velocities up to 6 deg/s for azimuth and 2,25 deg/s for elevation. The admissible rotating torque is about 150 Nm, allowing the antenna to rotate even in presence of winds of 10 m/s. The brake maximum torque is 1580 Nm, holding the antenna position even in winds with speed higher than 20 m/s. The rotator is suitable for the project, because according to [10], the average wind speed in Dnepropetrovsk usually up to 4 m/s, rarely exciding 8 m/s. A classic problem faced by ground station is the observation of satellites passing in positions near the zenith. When such event happens, the angular velocity in the azimuth angles varies very quickly, disabling the rotator to follow the reference. Some work can be done in the reference signal to minimize this problem, as the one presented in reference [3].

Fig. 7. Commercial rotator

The strategy presented is suitable for the satellite mission requirements. The requisites for satellite tracking and communication were defined and satisfied, keeping the project simple. Some improvements for future work were presented as well, so the ground station can cover different missions.

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Надійшла до редколегії 28.05.2012.