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# NANOSATELLITE MOTION SIMULATION FOR TESTING THE SUN SENSOR

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# NANOSATELLITE MOTION SIMULATION FOR TESTING THE SUN SENSOR

**Abstract:** Nanosatellite (NS) began to perform complex missions that require high orientation. In this research, we developed a mathematical model of solar sensors to determine the orientation of a NS. Various moments of obtaining the angle of the sun's rays when they hit the solar sensors were presented. The test results of the solar sensors used to simulate various orbit scenarios are described in detail, and graphs of the solar sensor readings are plotted based on the results obtained.

The article deals with modeling the motion of a NS in orbit. The NS is equipped with 6 solar panels. The VTS software was used to simulate the motion of the NS. Also, in the study of determining the orientation, two different problems were considered, that is, when the satellite is in the shadow part of the earth and when it is in the solar part of the earth. For these tasks, a mathematical model for determining the orientation was built. This method is very relevant for the study of small spacecraft.

**Keywords:** NS, solar panel, orbit, orientation, vector.

**Introduction:** In this paper, we consider a nano-satellite (NS), which makes a flight around the Earth's orbit. The device is equipped with solar panels, rigidly fixed in the coordinate system associated with the spacecraft (x, -x, y,- y, z, - z) to determine the orientation of the NS.

Solar panels on the NS can be used to optimize the production of solar energy and perform certain tasks, in this case, to determine the orientation of the NS. Many articles on the first application have been published, in which new configurations of solar panels have been developed and the use of solar energy has been studied [1-4]. For the latter application, in one of the mission examples, the strong atmospheric resistances in orbits below 500 km were modified to achieve satellite orientation stability [5-6].

Simulations and calculations are performed at the following approximation. It is believed that the motion of the planet is Keplerian, i.e. no perturbations affect the body, the motion of the NS is affected by the perturbation from the planet's orbit. Three coordinate systems are considered:

OXYZ – geocentric. The origin is placed at the center of mass of the Earth. The system is inertial.

OXYZ-orbital. The origin is placed in the center of mass NS, the axis OZ is directed along the radius vector connecting the centers of mass of the Earth and NS, the axis OX is perpendicular to the axis OY and lies in the plane passing through the radius vector and the velocity vector of the center of mass NS. The system is non-inertial.

Oijk-related. The origin of the coordinates is also placed in the center of mass of the NS. The axes are directed along the main axes of inertia of the body. The system is non-inertial.

Their relative positions are shown in Figure 1.

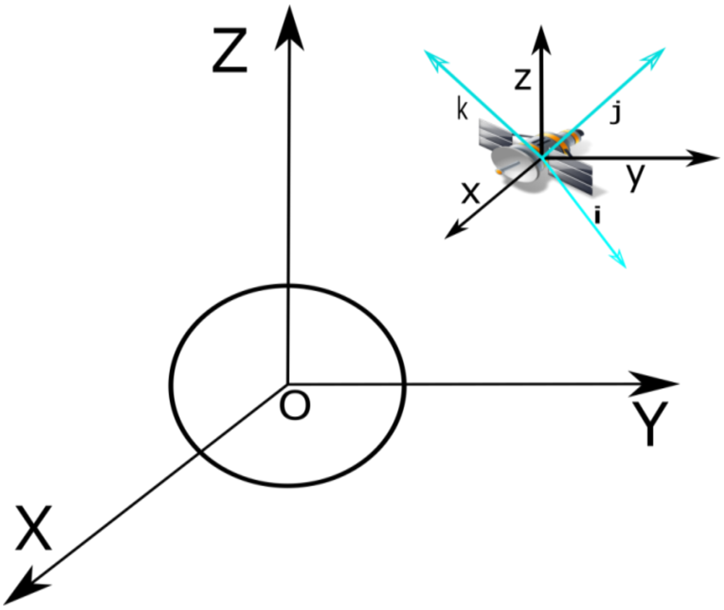


Figure 1 -Coordinate systems

I Angular motion of the NS

A satellite is a solid body moving in a circumcircular orbit around the Earth. The SDP4 model is used to describe the Earth's gravitational field. To rotate the NS around the center of mass, quaternions are used. A quaternion is a hypercomplex number with four parts, used in three-dimensional rotations and orientations of the NS. All rotations in space can be described by the axis of rotation and the angle about that axis. The advantage of quaternions over rotation matrices is that the axis and angle of rotation are easy to interpret. Using the following quaternion formula (1), we obtain the NS rotation data.

$$q = \begin{matrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{matrix} \qquad (1)$$

where q0 - is the scalar component,

q1-q3 - are the components of the vector.

After obtaining the quaternion data for the rotation of the NS, you can find out which panels are illuminated by the sun, and analyze how the sun looks at the surface of the NS. The faces of the cube have six surfaces forming the body of the satellite. The coordinate vectors are orthogonal to each side of the cube. So there can be two solutions for each vector:

- the positive direction of the vector that was identified as the front side of the NS;
- the negative direction of the vector, which was identified as the back (reverse) side of the NS.

To calculate the position of the Sun relative to the satellite for any given location at a given time, you need to perform three steps[7]:

- Calculate the position of the Sun in the ecliptic coordinate system;
- Convert the result of step 1 to the coordinate system at the center of the Earth;

- Convert the result from step 2 to the coordinates of the NS body.

To get the position of the Sun relative to the satellite, use the following function in the Aerospace Toolbox MATLAB simulation program.

Planet Ephemeris (juliandate (2021,04,8), ‘Earth’, ‘Sun’)

This function implements the position of the target object relative to the specified central object for the specified Julian date ephemeris. By default, the function implements the position based on the DE405 ephemeris in units of kilometers.

After the rotation of the vector, we get data on the angle of incidence of the Earth-Sun vector on the face of the cube, with which we can find out which panels of the NS are illuminated at a given time (Figure 2).

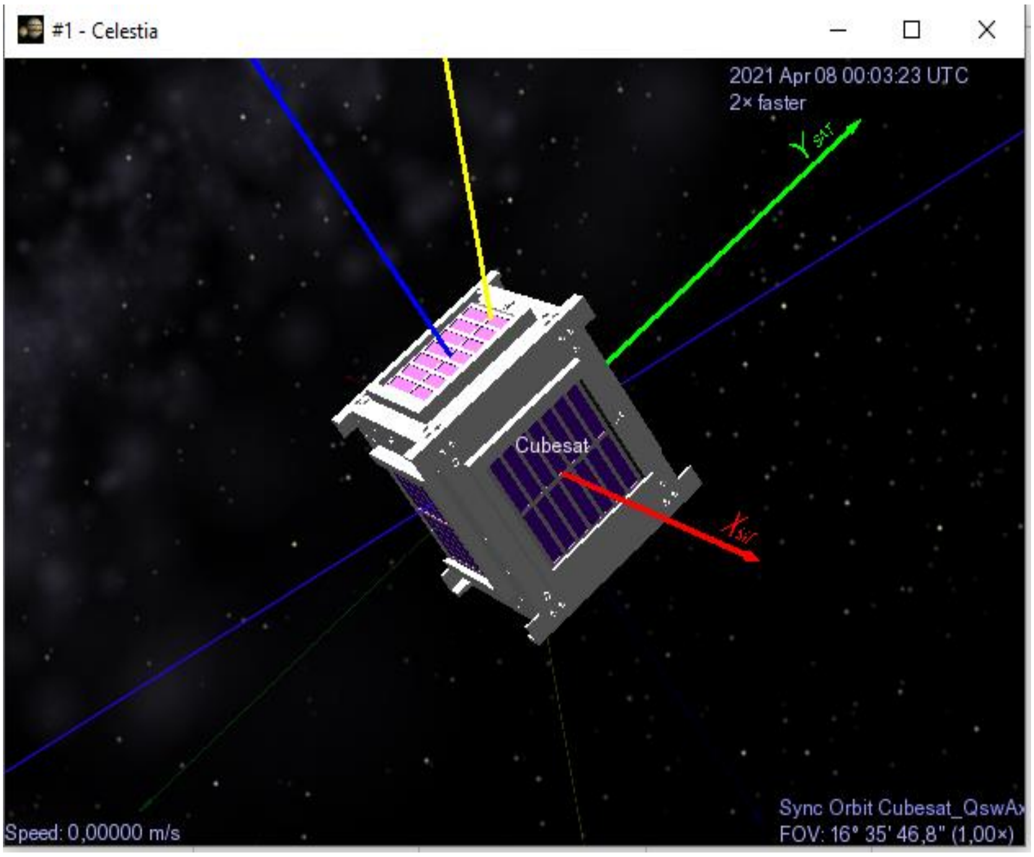


Figure 2 - Model of rotation at the moment of illumination of the NS face

II Plotting the NS 's orbit.

The next step is to get the elements of the orbit on which the satellite is located. The data format that it will use to send this information to the ground station will be the TLE (two-line element) format. This type of message refers, as the name suggests, to two lines of text that include elements of the orbit of an object orbiting the Earth for a given point in time, called an epoch. In addition, there is another first line (called line 0), which gives the designation of the object. Even though it is optional, it is almost always enabled.

The choice of orbit may vary depending on the altitude, their orientation, and their rotation relative to the Earth. From the point of view of the Kepler elements, the position of the spacecraft can be easily determined. The six parameters are convenient for determining the orbit in space in an inertial system defined by its three axes X, Y, and Z. However, it can also be useful to express the position of a moving body in other parameters, such as the Cartesian or polar axes[ 8].

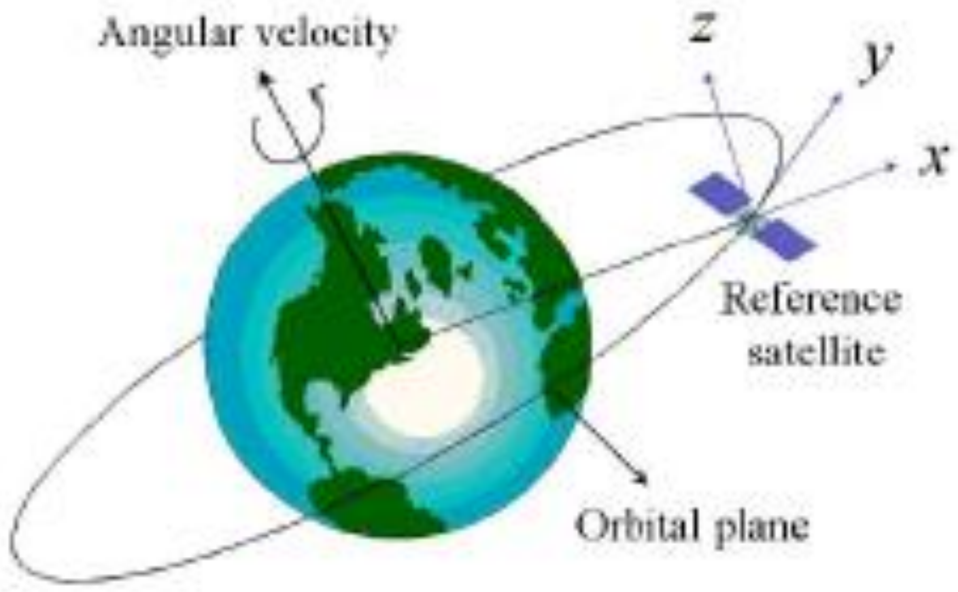


Figure 3 - Satellite orbit reference system [9]

Circular orbits are predicted by matching the centripetal acceleration with the force of gravity. To model the satellite motion scenario, we use the matlab function"Satellite-Centric". Then the initial vectors of the satellite's position and velocity are obtained using the TLE format. The TLE format contains all the necessary information for orbit propagation. This format will be used in the SDP4 orbital propogator. The advantage of the propogator is that it is more accurate than other progators.

To construct the orbit, we consider the calculation of the position of the STARLINK-64 spacecraft (the orbit parameters are shown in Table 1) at 00: 19: 51.670 UTC on April 8, 2021 [12].

Table 1-Orbit parameters

| Element | Symbol | Value in the TLE file | Numeric value |
|---|---|---|---|
| Time of the epoch | $t_0$ | 21123.38100113 | 16: 30:21.171 UTC April 8, 2021 |
| Inclination | $i$ | 52.9869 | 52.9869 |
| Longitude of the ascending node | $\alpha_{\Omega 0}$ | 99.7162 | 99.7162 |
| Eccentricity | e | 0000598 | 0000598 |
| Argument of periapsis | $\omega_0$ | 7.2492 | 7.2492 |
| True anomaly | $M_0$ | 117.2796 | 117.2796 |
| Frequency of access | n | 15.88178410 | 15.88178410 turns/solar day |

III Modeling of the orbital day/night alternation.

After constructing the orbit, it becomes known at what point in time the sun's ray falls on the NS.

Having received the vector of the Sun, we will study the Earth's satellite. The Earth and the Sun are almost spherical bodies, and the Sun is about 100 times larger than the Earth. Therefore, the shadow of the Earth is a cone with the centers of the Sun and the Earth.

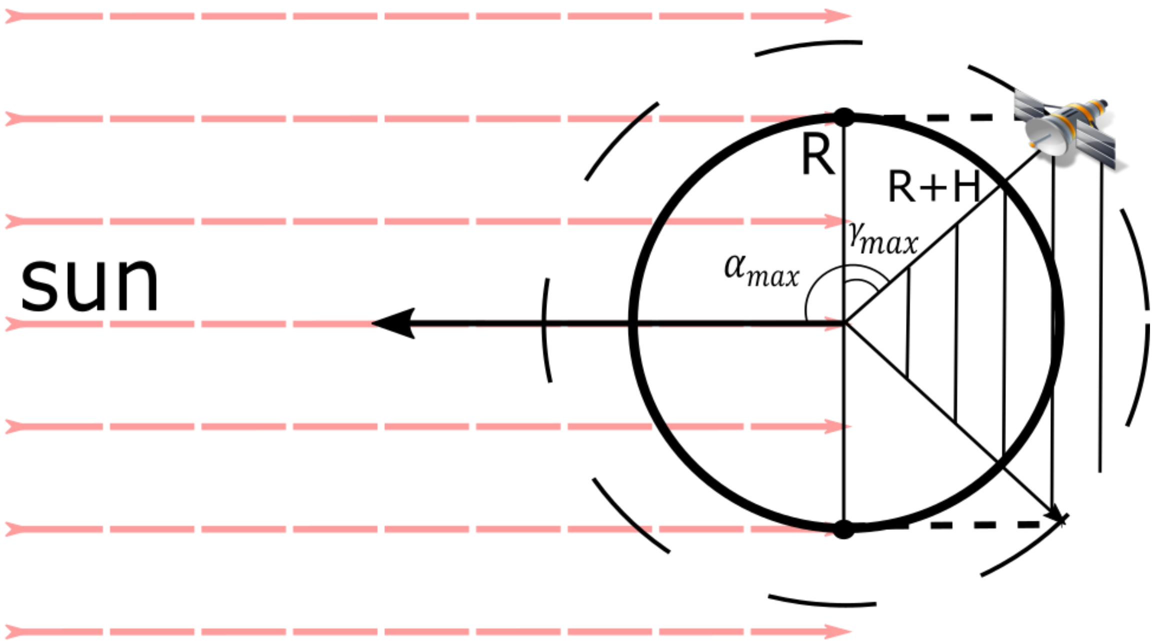


Figure 4 - Geometry of NS conditions in the earth's shadow

Homocentric beams have a common center, as well as three types of beams: convergent, divergent, and parallel [10]. In this case, we show that the focus of the Sun is at infinity, that is, the wave front will be flat, and the homocentric beams of rays will be parallel (Figure 4).

If the satellite's position is known at the specified time, we can use trigonometry to find out whether the satellite is in the shadow part of the Earth relative to the Sun.

To begin with, we find the angle between the vector of the NS positions and the positions of the Earth-Sun vector (2):

$$cos\alpha = \frac{r \cdot r_s}{\|r\| \cdot \|r_s\|}, \tag{2}$$

where, r - is the position of the satellite vector, which was obtained in the SDP4 orbital propogator.

$r_s$ - the position of the sun vector, which was obtained using the Earth-Sun ephemeris.

The radius of the Earth drawn at the point of contact of the parallel ray of the Sun is perpendicular to the tangent. Knowing the radius of the earth and the height of the orbit of the NS, we determine the angle $\cos\gamma_{max}$ by the formula 3:

$$\gamma_{max} = \frac{R_E}{R_{E+H}}, \tag{3}$$

where, $R_E$ is the radius of the Earth, H - is the height of the NS orbit.

$$\alpha_{max} = \gamma_{max} + 90° \tag{4}$$

So, from the above, we can calculate that the satellite will be completely obscured by the Earth under condition (5):

$$\alpha \leq \alpha_{max} \geq \alpha \tag{5}$$

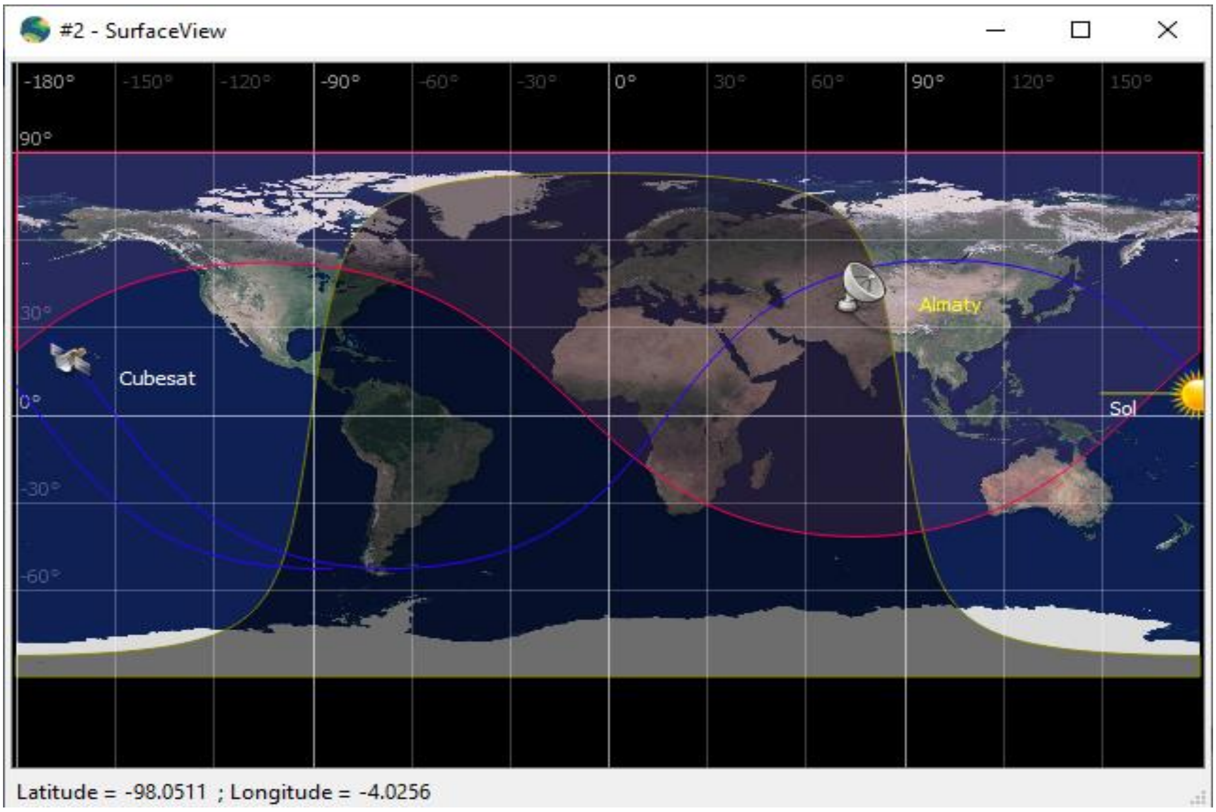
To calculate the Earth's shadow, one of the initial tasks is to determine the Sun's vector ($r_s$), already performed in the equation using the ephemeris function. Once the Sun's vector is determined, equation (5) is used to check whether the Sun is in the Earth's shadow, based on the figure. Note that the shadow, as expected, has a cylindrical shape. That is, if the angle $\alpha \leq \alpha_{max}$, then the NS is in the shadow of the Earth. In other cases, when the orbit rotates, the NS is illuminated by the Sun.

IV Visualization of the mission.

We use the VTS program (software from the CNES company) as a tool for visualization of the NS [11].

The VTS application is used for visualization of: 3D models, satellite geometry, mobile parts, data sources for determining position, orientation, rotation angle, etc. The tool can be used as a graphical verification method, as an educational tool, and even as a communication support for the exchange of information between space experts.

The VTS graphical user interface is designed to simulate a satellite orbiting the Earth in three dimensions. Figure 5 shows the ground track of the NS projected on a two-dimensional map of the world in one day.



Latitude = -98.0511 ; Longitude = -4.0256

Figure 5 - Track in one day

The graph "visibilitySun" shows the time when the sun illuminates the NS.

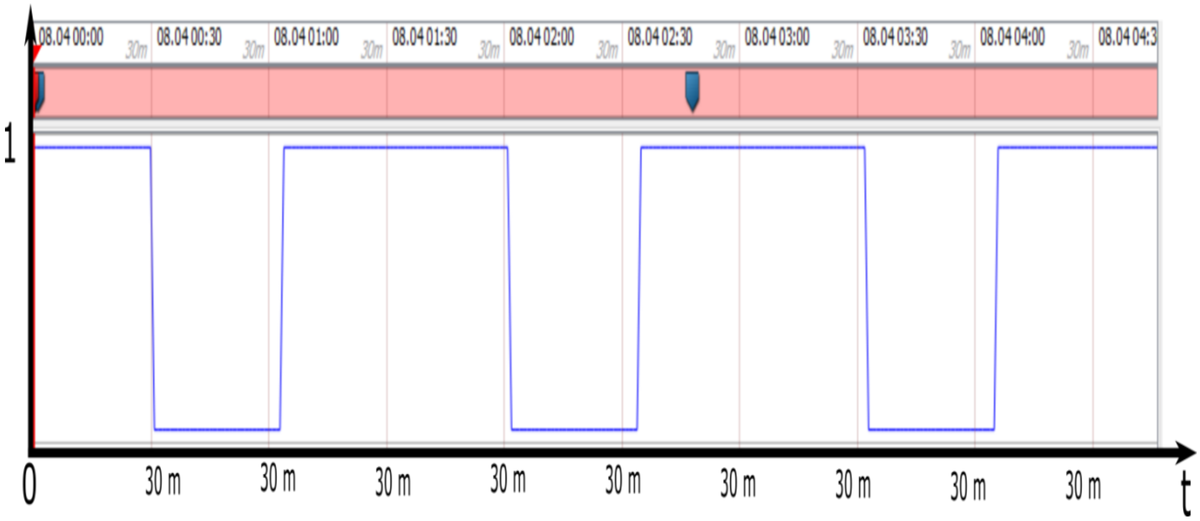


Figure 6 - Graph of the illumination of the NS during the orbit movement

The determination of the total illumination on each side of the NS is shown in Figure 8. The gap in the middle of graph is the result of an eclipse of the Earth. And also here you can see on which panels the sun's ray falls at the moment of rotation of the satellite in the constructed orbit.

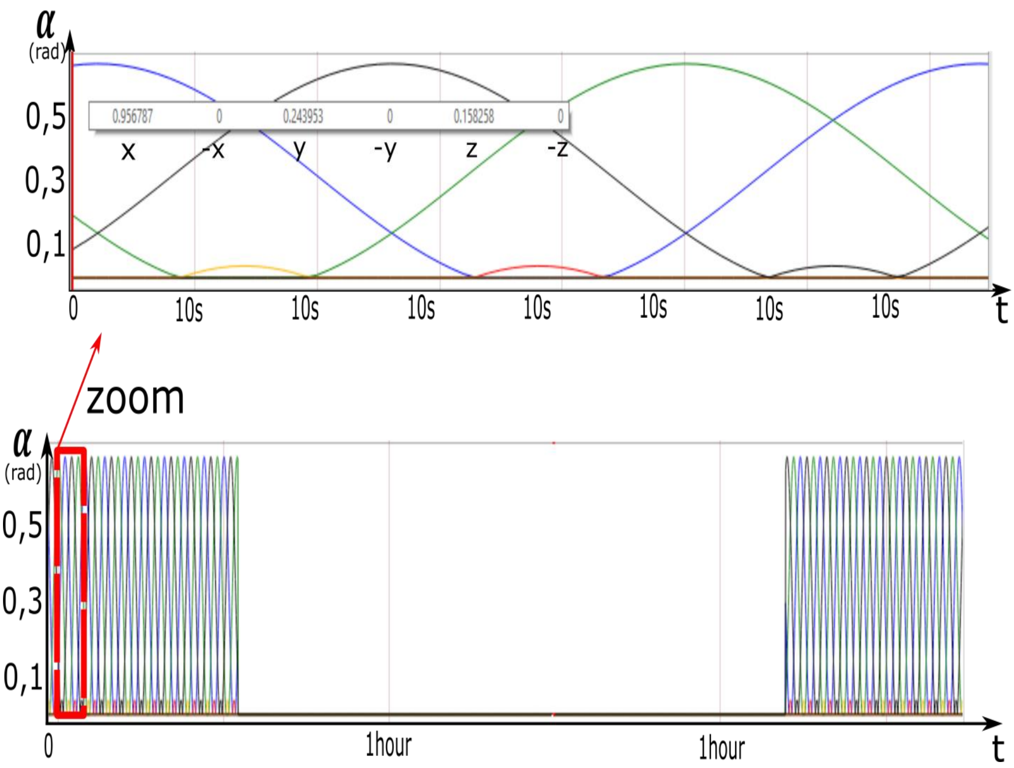


Figure 7 - This graph shows which panels the sun's ray falls on at a given time

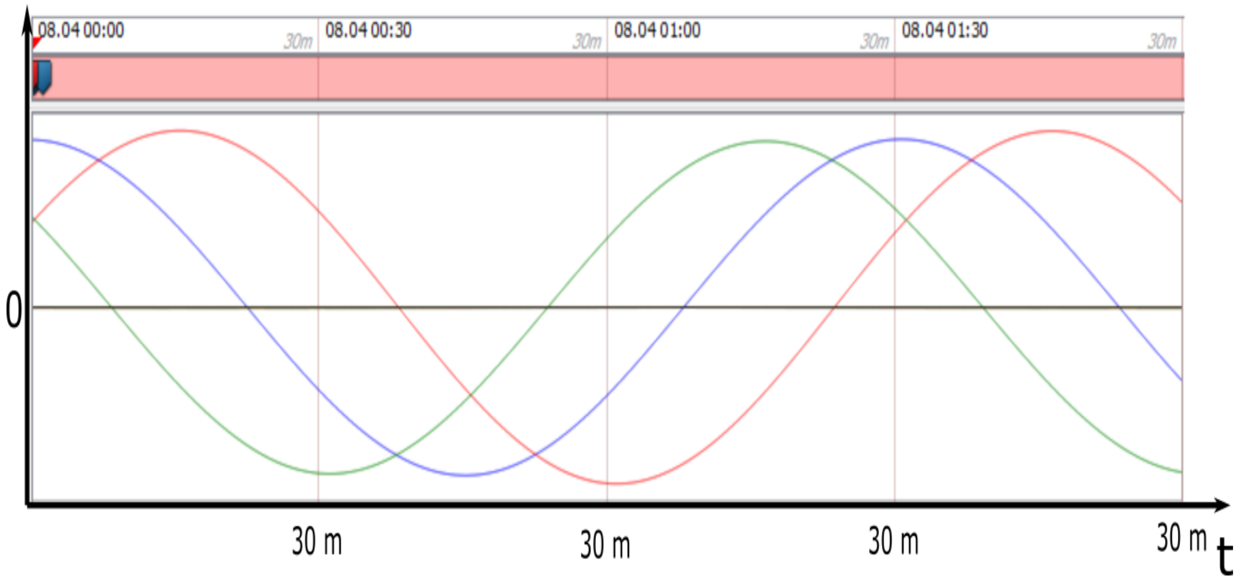


Figure 8 - Graph of the position and velocity of the NS

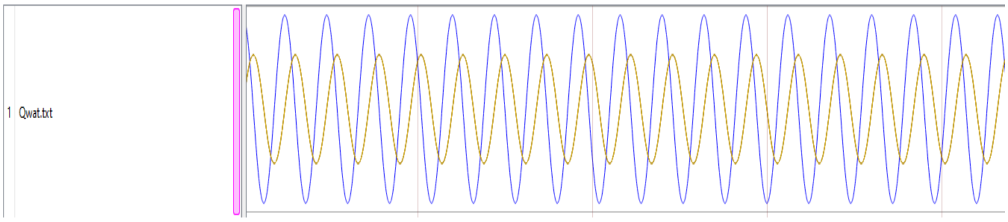


Figure 9 - Graph of the rotation of the NS around its axis

**Conclusion:** In conclusion, in this article, a mathematical model of the sun sensor was developed. When developing this model, we considered three cases of the sun's ray falling on the edge, as well as the case in the shadow part relative to the sun. For each case, a different mathematical model was developed. The principle of operation of this method is to determine the position of the satellite relative to the incident beam of the sun, which allows you to orient the satellite in orbit using solar sensors. To test the mathematical model of the solar sensors, we simulated the movement of the satellite in orbit. The model showed data on the angle of incidence of the sun's beam on the face of the NS and tested the orientation sensors. In the darkened side, respectively, all sensor readings were zero. These readings were used to determine the orientation of the NS at a time. In the process, we used tools like Matlab and VTS. This method is very relevant in the development of small satellites, since the orientation of the satellite has an important role in scientific research.

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## МОДЕЛИРОВАНИЕ ДВИЖЕНИЯ НАНОСПУТНИКА ДЛЯ ИСПЫТАНИЯ ДАТЧИКА СОЛНЦА

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**Аннотация:** Наноспутник (НС) начал выполнять сложные задачи, требующие высокой ориентации. В этом исследовании мы разработали математическую модель солнечных датчиков для определения ориентации НС. Были представлены различные моменты получения угла падения солнечных лучей при попадании на солнечные датчики. Подробно описаны результаты испытаний солнечных датчиков, используемых для моделирования различных сценариев орбиты, и построены графики показаний солнечных датчиков на основе полученных результатов.

Статья посвящена моделированию движения НС по орбите. НС оснащен 6 солнечными батареями. Программное обеспечение VTS использовалось для моделирования движения НС. Также при исследовании определения ориентации были рассмотрены две разные задачи, то есть когда спутник находится в теневой части Земли и когда он находится в солнечной части Земли. Для этих задач была построена математическая модель определения ориентации. Этот метод очень актуален для исследования малых космических аппаратов.

**Ключевые слова:** Наноспутник (НС), солнечная батарея, орбита, ориентация, вектор.

## НАНОСПУТНИКТІҢ КҮН СЕНСОРЫН СЫНАУҒА АРНАЛҒАН ҚОЗҒАЛЫС СИМУЛЯЦИЯСЫ

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**Андатпа:** Наноспутник (НС) жоғары бағдарлауды қажет ететін күрделі миссияларды орындай бастады. Бұл зерттеуде біз НС бағдарын анықтау үшін күн датчиктерінің математикалық моделін жасадық. Күн датчиктеріне түскен кезде күн сәулесінің бұрышын алудың әр түрлі сәттері ұсынылды. Әр түрлі орбиталық сценарийлерді имитациялау үшін қолданылатын күн датчиктерінің сынақ нәтижелері егжей -тегжейлі сипатталған, алынған нәтижелерге сүйене отырып, күн датчигінің көрсеткіштерінің графигі салынады.

Мақалада НС орбитадағы қозғалысын модельдеу қарастырылады. НС 6 күн батареясымен жабдықталған. VTS бағдарламалық қамтамасыз ету НС қозғалысын модельдеу үшін пайдаланылды. Сондай -ақ, бағдарды анықтауды зерттеуде екі түрлі мәселе қарастырылды, яғни жер серігі жердің көлеңкелі бөлігінде болғанда және жердің күн бөлігінде болғанда. Бұл тапсырмалар үшін бағдарды анықтауға арналған математикалық модель құрастырылды. Бұл әдіс шағын ғарыш аппараттарын зерттеу үшін өте өзекті.

**Түйінді сөздер:** NS, күн панелі, орбита, бағдар, вектор.