Calculating electric power generated by 3U CubeSat’s photoconverters depending the orbit and orientation parameters

V N Gorev¹,³, V Yu Prokopiev¹, Yu M Prokopiev¹, L D Sinitsina¹,² and A A Sidorchuk¹,²
¹ Novosibirsk State University, 630090, Pirogova str., 2, Novosibirsk, Russia
² OKB Fifth Generation Ltd., 630090, Nikolaeva str., 11, Novosibirsk, Russia
³ E-mail: vasily.gorev@gmail.com

Abstract. The paper describes a computational program developed in MatLab Simulink, that performs calculation of electric power generated by photoconverters for various missions of nanosatellites in low Earth orbit (LEO). Electric power generated by nanosatellite’s solar panels was estimated for polar LEO of 450 km altitude for two versions of the satellite’s static orientation. The results show how orientation maneuver at the Earth’s surface point affects power generated by the satellite’s solar panels.

1. Introduction
Nowadays CubeSat class of nanosatellites has become widespread [1, 2]. Such satellites have limited resources on board, in particular, the electric power available is one of the factors limiting the onboard equipment operation.

Information about the solar panels’ electric power is necessary to develop overall layout of a satellite, its onboard systems and payload. Insolation and, accordingly, the generated electric power depends on the satellite’s orbit and orientation, that is, information on the power available on board is also needed when developing a particular orbital mission.

The satellite generates electric power using photoelectric converters mounted on its body and folding panels. Photoelectric converters located on different sides of the satellite are illuminated differently. As the satellite moves in orbit, the angles of illumination change, and solar panels are shaded partially or fully by the satellite’s structures. These factors should be taken into account to construct a realistic model for calculating the electric power generated by a satellite.

Today, there are several software packages for calculating the insolation of a satellite depending on the mission parameters [3–5]. They are highly specialized, and not every program can calculate the total electric power generated by the photoelectric converters. Commercial software is quite expensive and often is not flexible enough to be fully integrated into the development routine.

On the other hand, there are such universal software packages as MatLab, Octave, SciLab and others. These are programming environments that include libraries of functions for numerical solution of various differential equations, empirical physical models etc., which can be applied to develop the software to calculate the ballistics of the satellite’s mission, its insolation and the electric power generated by solar panels.
This paper describes a program that calculates electric power generated by solar panels depending on parameters of the satellite’s mission, its geometry and photoelectric converters characteristics. The paper gives results of the calculation of power generated by solar panels for some orbits and orientation for 3U CubeSat with folding solar panels developed in Novosibirsk State University.

2. Methodology

2.1. Ballistics and orientation
The calculation software is developed in MatLab Simulink. Standard equations for six degrees of freedom of motion in Earth-centered Earth-fixed (ECEF) coordinates are used to calculate ballistics. The EGM2008 gravity model is applied. The interface to visualize orbital motion (figure 1, a), orientation and insolation of a satellite has been developed (figure 1, b) for ease of use and debugging of motion calculation algorithms.

Initial coordinates, velocity vector and time when the motion starts are set as initial data. The program implements the position of the Earth and its illumination by the Sun, depending on the UTS time [6]. For simplicity, the calculation is made for the vernal equinox (figure 1, a).

The initial satellite orientation angles and its angular velocity components are set equal to zero (or random) since the module that rotates the satellite is included into the program. The module at each step of time calculation based on the specified pointing parameters, current satellite pointing and its angular velocity calculates the torque, which is transmitted to the motion equations block that calculates the new satellite orientation angles at the next time step.

The satellite’s solar panels are not isotropically distributed over an angle, and there is a preferential direction — the normal to the plane of solar panels maximum projection. Therefore, the satellite orientation affects the electric power generated by solar panels, and the calculation requires the specified satellite orientation.

The following orientation designations are used: \( AbCd \) where \( A \) and \( C \) are vector of directions to objects in the surrounding space (to the Sun, nadir, ground antenna, etc.), \( b \) and \( d \) are vectors of specific spacecraft directions (unit vectors of axes of the body fixed coordinate system, vector of the solar panels maximum insolation, the camera’s optical axis etc.). In this case, the \( A \) and \( b \) vectors are fully aligned (priority 1), and the \( C \) and \( d \) vectors, are aligned if possible (priority 2). For example, \( NxSp \) means the following: the satellite \( x \)-axis (\( x \)) is aligned with the nadir vector (\( N \)); the vector of the solar panels maximum insolation (\( p \)), whenever possible, is aligned with the Sun vector (\( S \)).

2.2. Insolation calculation
The simplified 3D model consisting of one body is considered to be the initial data for calculating the satellite’s insolation. The model should reproduce the basic volumetric contours of the satellite, location, number and size of its photoconverters. Such a model is specially drawn in CAD (for example, SolidWorks) and exported in one of the standard formats (*.step or *.iges). Then the file is imported into the program for building computational mesh: Salome, AnSys Mesh, or others. The photoconverters and, if necessary, the remaining elements of the satellite’s structure are assigned unique names in the program. That allows grouping the elements of the corresponding structures in the calculation program. Then a mesh is constructed with a set specification consisting of triangular cells (figure 1, b). As a rule, the minimum required specification is used, since calculating of lighting is a resource-intensive computational task. The model’s geometry and the grid are saved in the standard *.msh format in the mesher software.
Then the grid file is loaded into the calculation program using the function given in [7]. In the program, the satellite grid model, as a set of vectors, is rotated within the selected coordinate system by the rotation matrix (DCM) synchronously with the satellite orientation calculation. The lighting of each (triangular) surface element is calculated depending on the satellite pointing and position in space corresponding to the Earth and the Sun, considering the surface element shading by neighboring satellite structures (figure 1, b).

In the visible area of a spectrum which is interesting from the point of view of solar panels performance, the surface element is illuminated by two sources — direct solar radiation and sunlight reflected by the Earth’s surface (Albedo) [8].

The intensity of solar radiation on the Earth’s orbit varies within 6.9% annually due to the change in the distance from the Earth to the Sun. The average annual solar constant varies slightly depending on the activity of the Sun within 1365-1367 W/m² [9]. In the calculation, the intensity of the solar radiation in the Earth’s orbit assumed 1367 W/m².

To calculate Albedo, the Earth grid model, similar to the satellite grid model, is loaded into the calculation program. For each element of the satellite surface, the radiation from all elements of the Earth grid model visible from the satellite is calculated. After calculating the radiation to the satellite’s surface element using the Fresnel equations and absorption and refraction coefficients (in the visible area of the spectrum) of the surface material, the power absorbed by the surface element is calculated. Also, considering the shading, the total power absorbed by the photoconverter is calculated.

2.3. Electric power calculation
Photoconverters are semiconductors for converting solar energy into electric power which can be classified due to the material they are made of: semiconductors and semiconductor compounds of Si, GaAs, InP, CdTe, etc., organic materials [10, 11]. According to the structure, photoconverters can be divided into crystalline or amorphous, unijunction and heterojunction. Today, heterojunction photoconverters have the highest efficiency (up to 45%) due to the fact that serial junctions with different absorption bands in the solar spectrum absorb a significant part of the spectrum jointly [12]. This paper considers a three-junction photoconverter produced JSC «Saturn» (Russia) with an efficiency of 28%.

The current-voltage characteristic of a photoconverter is the characteristic of three diodes combined in series (three photoconverter junctions). It depends on the total power of the absorbed radiation and
almost does not depend on the uniformity of a photoconverter illumination. With a constant light spectrum, the number of charge carriers formed in a photoconverter is proportional to the number of absorbed photons. Thus, with a constant spectrum of incoming radiation, the short-circuit current is proportional to the absorbed radiation power. That is, as the total (across the photoconverter surface) power of the radiation absorbed by the photoconverter increases, the current-voltage characteristic shifts upward by $I_{sc}$. With zero illumination $I_{sc} = 0$ (figure 2, a).

![Figure 2](image)

**Figure 2.** Current-voltage characteristics of a photoconverter at different irradiation (a), the dependence of the solar panels’ electric power on the output voltage (b).

The power produced by a photoconverter (figure 2, b) is calculated by the formula:

$$P_{el}(u) = u \cdot [I_{cvo}(u) + \alpha \cdot P_{sorb}],$$

where $P_{el}(u)$ – electric power produced by the photoconverter depending on the output voltage, $I_{cvo}(u)$ – photoconverter’s current-voltage characteristic at zero irradiation, $P_{sorb}$ – radiation power absorbed by the photoconverter, $\alpha = 0.1244$ A/W – size factor calculated from the photoconverter technical data sheet.

At each time step calculation, for each photoconverter, based on its absorbed radiation power, the dependence $P_{el}(u)$ is calculated. The maximum of this dependence is taken as the power generated by photoconverter. The total power generated on board is calculated as the sum of power output of all photoconverters, at its own maximum power points.

The calculated power is the maximum possible power that can be available to onboard equipment and payload. It does not take into account the efficiency of the power supply system, which set up the photoconverters’s maximum power regime [13, 14] and switches the photoconverters modules to obtain the necessary voltage for the onboard equipment and battery charging. Approximately, the efficiency of converters and switches will be equal to 0.8. Also, the paper does not take into account the efficiency of battery charging/discharging.

3. Calculation Results and Discussion

The satellite flight in a circular orbit of 450 km altitude is considered; for simplicity, the orbit is polar. The calculation made for several angles between the orbit and the direction to the Sun: $\beta$ takes values from 0° to 90° with a step of 22.5°. Different variants for the satellite orientation are considered.

Air resistance has a significant effect for satellites which operate in LEO. The lifetime of a satellite is approximately proportional to the ratio of its mass to the area of its frontal projection (normal to the motion direction). Therefore, it is expedient to set orientation the satellite minimum projection normal
to the velocity vector. The following combination is taken as priority 1: the velocity vector of the orbital motion and the $z$ axis of the body fixed coordinate system are set parallel (figure 1, b).

It should be noted that mechanization of solar panels to rotate relative to satellite chassis is excessively complex for CubeSat, so the tasks to obtain maximum power and point the satellite contradict each other and require analysis for developing the mission.

As a pair of priority vectors 2, let’s compare two cases (figure 3, a):

- Direction to the Sun and the normal to projection of maximum insolation will be denoted as $V_{zSp}$;
- Direction to the nadir and the $Y$ axis of the satellite (normal to the lateral surface) will be denoted as $V_{zNy}$.

In the first case, the solar power generation will be greatest among other orientation sets satisfying priority 1. The second case is implemented if it is required to steer the payload (for example, a camera) at the Earth. Due to the CubeSat design features [1], it is more convenient to install a camera for shooting the underlying surface normal to the satellite’s surface.

The results of the calculation of the electric power produced by the photoconverter, depending on the motion time on its orbit, are shown in figure 3, b. The average electric power generated for $V_{zNy}$ in the $\beta$ range of angles from $0^\circ$ to $90^\circ$ is 10.1 W; in the $V_{zSp}$ case, the average output power in the specified angle range is 13.3 W, which is one-third higher. In the range of angles $\beta$ from $0^\circ$ to $-90^\circ$ for $V_{zNy}$, it will be symmetrical if the satellite turns $180^\circ$ around nadir vector by going through the point $\beta = 0^\circ$, that is, the orientation satellite by velocity vector becomes $V_{zSp}$, which does not contradict $N_{zNy}$. If the orientation by velocity vector still $V_{zNy}$, the power generated will decrease due to the non-optimal orientation of the folding solar panels to the Sun.

Let’s consider the situation when the payload is not to be aim to the nadir but to the specific point on the Earth’s surface. Let the axis of the payload be directed along the satellite $z$ axis. For example, a camera with a lens longer than 100 mm is applied. To develop the satellites modes of operation during orientation maneuver, it is useful to have data on the available power.

Let the satellite move in the polar orbit of 450 km altitude and fly over Novosibirsk at noon. The following cases of the satellite pointing are presented (figure 4, a):

1. The $z$-axis is directed at the $A$ surface point (antenna) (priority 1) in continuous mode; in priority 2, the $p$ vector is oriented towards the Sun, $AzSp$. 

![Figure 3. The satellite orientation $V_{zSp}$ and $V_{zNy}$ (a). Dependences of the electric power generated by the solar panels on the time of orbital turn for different angles $\beta$ (b), the orbital average electric power depending on the angle $\beta$.](image-url)
2. Initially, the satellite has a basic \( VzSp \) orientation, the \( z \)-axis is directed to the antenna (\( AzSp \)) by priority 1, so that the satellite should be already pointed at the moment of climbing the horizon at the aim point. When set over the horizon, the satellite returns to \( VzSp \).

3. For comparison, the \( VzSp \) case is given at \( \beta = 0^\circ \), without pointing at the object.

4. Basic \( SpVz \) pointing: by priority 1, the satellite is pointed by the \( p \) vector to the Sun, by priority 2 - to the \( z \)-axis along the velocity vector. An antenna pointing maneuver is performed as in case 2 - the \( AzSp \) orientation is set.

5. For comparison, the \( SpVz \) case is given at \( \beta = 0^\circ \), without aiming at the object.

Figure 2 shows the dependences of the generated power on the time of orbital motion corresponding to these orientation variants (figure 4, b).

![Figure 4](image)

**Figure 4.** Satellite orientation at the point on the surface (a). Effect of the satellite aiming at the point on the Earth’s surface on the electric power generated by photoconverters.

In the case of the \( VzSp \) initial orientation, the aiming maneuver (case 2) increases the average power generated during the maneuver (\( \tau = 714 \) s) by 7.1% compared to case 3 (figure 4b), respectively, and the average power produced for the period (\( T = 5603 \) s) slightly increases.

With the basic \( SpVz \) orientation, the generated power for a given orbit is maximally possible and amounts to 20.9 W when irradiating and 13 W on average per turn. In this case, the aiming maneuver during the flight over the aim point reduces the average power by 64%, which decrease the average power generated per turn by 8.7% (figure 4, b).

In the case of \( AzSp \) constant antenna pointing (case 1), the average power generated per turn is almost equal to the average power generated in case (case 2).

Both the pointing and mission tasks (the onboard payload) for which the maneuver is performed require power. In the event of a shortage of power produced by photoelectric converters during pointing, the deficiency will be compensated by accumulator batteries but the aiming maneuver (communication sessions) may be performed on two or three consecutive turns, and the accumulator power may not be enough. In this case, it may be necessary to apply, as a basic option, the orientation at the Sun (case 4).

The basic orientation at the Sun (case 4) for a given orbit has an average per turn generated power 1.6 times higher than with a basic orientation along the velocity vector (case 2) (figure 4, b).

Thus, to accomplish the task, the satellite may need to carry out a complex sequence of aiming (orientation) maneuvers and related actions of other satellite subsystems — a scenario that needs to be planned and optimized in advance as a whole, or constructed automatically on some “planning depth” into the future based on formalized problem statement.

It should be noted that for a given orbit (\( \beta = 0^\circ \), a flight over the place of pointing), the effect that the orientation maneuver will have on the power generated by the solar panels will depend on the latitude of the aim point. Since almost a full 180° turn is made when flying over aim point, the average power generated during the maneuver will be approximately the same for any latitude. Therefore, a orientation
maneuver to the place in the upper latitudes will increase the average power per turn as compared to the case when the maneuver is not performed. When the satellite is aiming at the point near the equator, the average power per turn will be reduced.

4. Conclusion
The calculation software and methodology developed in MatLab Simulink that allows calculating the electric power generated by photoconverters for various missions of satellites operating in LEO are described. The method to formalize the formulation of a satellite pointing problem is touched upon.

With the help of the developed software, the influence of orientation maneuvers (nadir orientation or aiming at the surface point) on the electric power generated by the solar panels of the satellite operating in LEO of 450 km was calculated. Using the example of the satellite aiming at the surface point, it is shown that complex sequences of orientation operations are possible — the scenarios that need to be planned and optimized as a whole.

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