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Investigation of the mission to the L1 libration point with the use Moon flyby and solar sails

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Abstract

This paper presents the results of analysis and design of various trajectories of a spacecraft transfer from a low Earth orbit to a quasi-periodic orbit in the area of the L1 libration point of the Earth-Sun system for the purpose of tracking solar activity. To observe solar wind, we need to obtain an orbit with the smallest possible amplitude of spacecraft motion with respect to Sun-Earth line. It is caused by requirements to register by spacecraft instruments those particles coming from the Sun which in further motion would reach the Earth. The L1 point is lying at 1.5 million kilometres from the Earth in Sun direction. To observe shock waves approach from the Sun as early as possible it is proposed to put spacecraft further from the Earth than L1. For this it is proposed to use solar sails mounted on spacecraft. In this work we investigate several ways of obtaining an orbit with a smaller amplitude compared with the amplitude of the orbit reached by direct transfer from an orbit around the Earth. Besides this orbit is shifted by solar radiation pressure in Sun direction. To put spacecraft onto described trajectory gravity assist manoeuvre near Moon is proposed which allows reaching required amplitude. In the paper the estimation is given for the mass of propellant one may save by applying mentioned technology. Following putting spacecraft onto nominal trajectory the trajectory correction manoeuvres are to be periodically fulfilled. As alternative method the use of controllable solar sails is considered. The GMAT (General Mission Analysis Tool) package, which allows numerical integration of the equations of motion of the spacecraft in a realistic force model, was used in this work to simulate the motion of the spacecraft. The results of this analysis are presented by trajectory plots and event timelines. The over roll scenario of mission with the use of described technologies is presented with appropriate characteristics of required manoeuvres.

Keywords: libration point, solar sails, solar activity.

Abbreviations

SC – spacecraft;

LEO - low Earth orbit;

GMAT - General Mission Analysis Tool

1. Introduction

This paper considers the problem of modeling the flight of a SC in the vicinity of the L1 libration point of the Earth-Sun system using solar sails for the purpose of tracking solar activity.

The collinear libration point L1, defined in the three-body circular problem, is located on the Sun-Earth segment at a distance of about 0.01 astronomical units (about 1.5 million km) from the Earth's center [1].

This work considers the possibility of placing at this point the spacecraft, which is an observatory for tracking solar activity in order to be able to predict the state of the Earth's magnetosphere, which reacts to anomalies in the emission of solar matter. The SC is planned to be similar to the Spectrum-RG.

The purpose of this work is to analyze and design various trajectories for the transition of the spacecraft from LEO to a quasi-periodic orbit around the L1 libration point of the Earth-Sun system in order to track solar activity.

Objectives:

1) To simulate the flight of a spacecraft from a LEO to an orbit around the L1 point of the Sun-Earth system.
2) To estimate the influence of the gravitational maneuver near the Moon on the resulting orbit amplitude.
3) Analyze the changes of the orbit of the spacecraft depending on the size of the sail.
4) Carry out the correction of the obtained orbit with the help of solar sails.

2. Modeling the flight to the L1 libration point

To simulate the motion of the spacecraft in this work we used the package GMAT, which allows numerically integrate the equations of motion of the spacecraft in a realistic model of forces using Runge-Kutta methods of various orders, Prince-Dormand, etc. In this study, the integration was performed by the Runge-Kutta method of order 8.

A low reference orbit with parameters was chosen as the reference orbit:

$a=6571$ km;
$e=0$;
$i=51{,}8°$;
$\Omega=0°$;
$\omega=0°$;
$\upsilon=120°$.

The choice of the value of the true anomaly was carried out by the enumeration method. The scripting language built into GMAT allows us to implement algorithms for calculating the value of the impulse required to fly to the libration point. The Δv value was corrected to obtain an orbit belonging to a stable variety of orbits around the point L1. In the course of the algorithm, the Δv value was obtained:

$\Delta v=3194.929$ m/s.

The orbit was integrated in the GMAT environment, using a gravity model that takes into account the influence of all planets of the Solar System.

The obtained orbit in the coordinate system associated with the libration point L1 is shown below in Figures 2.1-2.3.

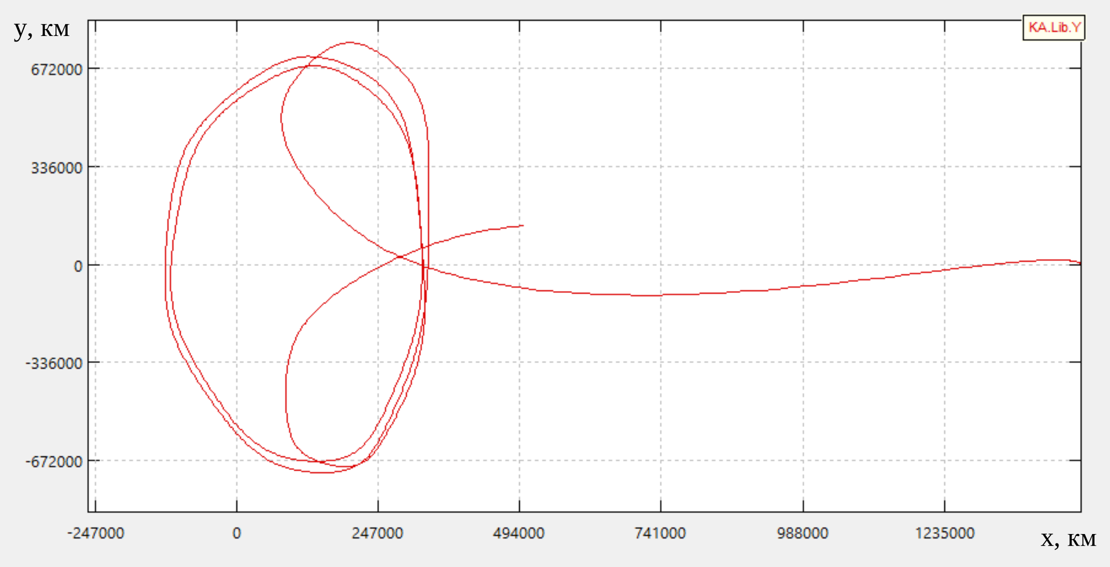

Fig. 2.1. Trajectory of the spacecraft

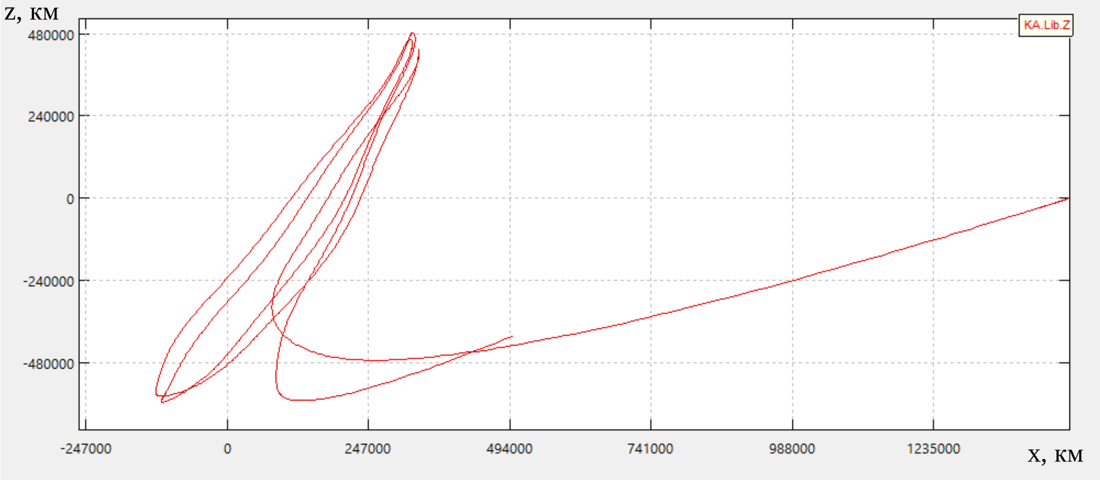

Fig. 2.2. Trajectory of the spacecraft

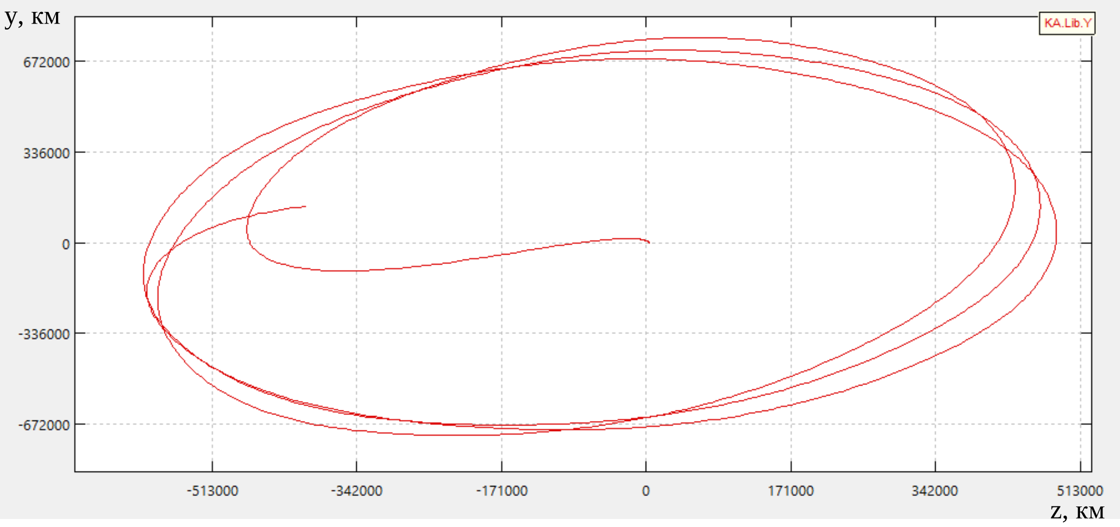

Fig. 2.3. Trajectory of the spacecraft

3. Decreasing the amplitude of the obtained quasi-periodic orbit

Having obtained an orbit in the vicinity of the libration point it is necessary to consider various options for reducing its amplitude. A smaller amplitude will make it possible to study the flux of particles emanating from the Sun, which has a direct effect on the Earth.

To reduce the amplitude it is necessary to give the vehicle a velocity pulse after it reaches the vicinity of the libration point L1. However, in order to save fuel, which in the future is planned to be used to solve the problems of orientation of the spacecraft and correction of errors in controlling its orbital motion, an alternative was considered, involving the use of a gravitational maneuver near the Moon.

3.1 Gravitational maneuver near the Moon

The use of gravity maneuvers near the Moon makes it possible to significantly expand the range of orbits attainable compared to a direct withdrawal. In addition to the possibility of reducing the amplitude of the orbit in relation to the Lagrange point, an important advantage of gravity maneuvers is the possibility of increasing the payload to be launched [4].

It is possible to achieve the required amplitude by a single-pulse transition from a near-Earth orbit, using a gravity maneuver near the Moon. For the first time such a launch scheme was proposed by Eismont et al. for the Relikt-2 project [2], [3]. In this work we will use a similar approach.

As a reference orbit for modeling a flight using the gravity maneuver near the Moon, an orbit similar to the reference orbit for a direct flight to the libration point was chosen. The values of the true anomaly and the required Δv were selected in the same way as in the previous calculation.

In the course of the algorithm, the necessary value of Δv for a flight to the Moon was obtained:

$\Delta v_1 = 3129$ m/s.

Then, at perigee, the spacecraft is given additional acceleration, which is necessary to reach the orbit in the vicinity of the libration point. The resulting value of necessary Δv is equal to:

$\Delta v_2 = 105$ m/s.

The resulting orbit in the coordinate system associated with the libration point L1 is shown below in Figures 3.1.1 – 3.1.2.

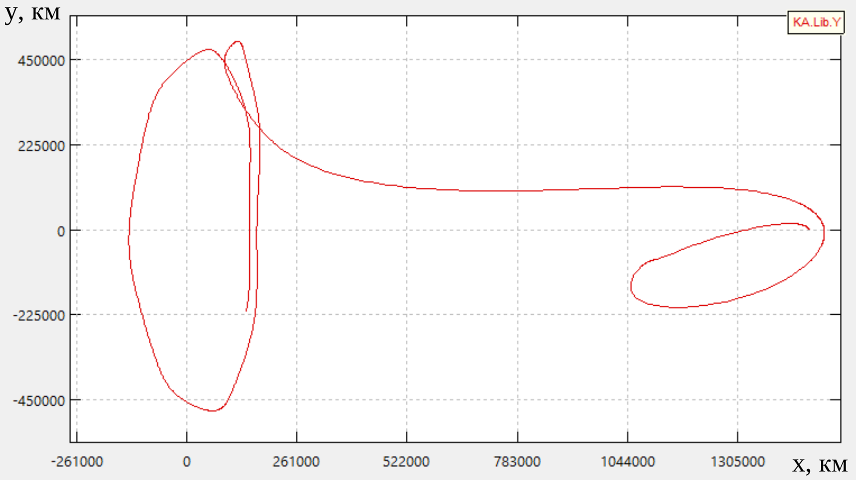

Fig. 3.1.1. Trajectory of the spacecraft

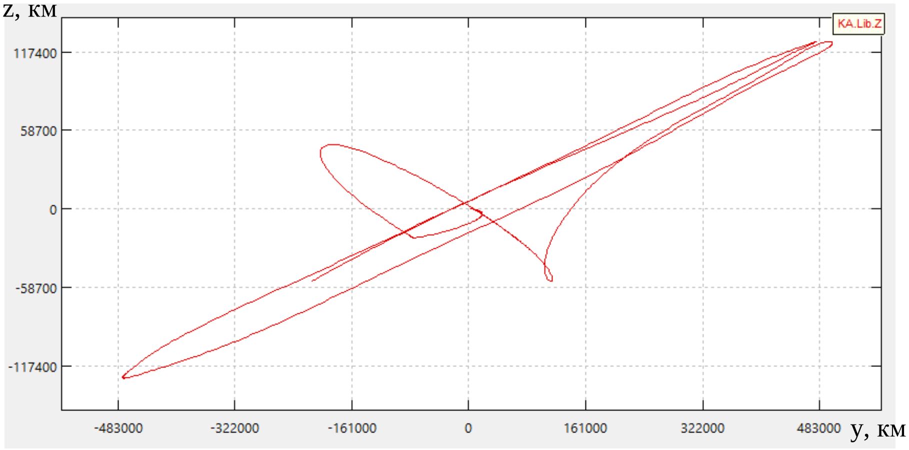

Fig. 3.1.2. Trajectory of the spacecraft

Comparing the trajectories in Figures 3.1.1 and 2.1 we can see that the amplitude of the orbit due to the gravitational maneuver of the Moon decreased from 672000 km to 477917 km.

3.2 Orbital maneuvers

Orbital maneuvers are necessary to reduce the amplitude of the orbit, especially its component along the Y axis, as was done in the Planck project.

Minimum corrective pulses allow both to parry external perturbations and maintain the trajectory in the vicinity of the L1 libration point, and to reduce the amplitude of the quasi-periodic orbit along the Y axis.

The total value of Δv required for this maneuver is:

$\Delta v_2 = 65$ m/s.

The value of Δv required for direct flight from LEO to an orbit in the vicinity of the libration point is:

$\Delta v_1 = 3194{,}93$ м/с.

The resulting orbit in the coordinate system associated with the libration point L1 is shown below in Figures 3.2.1 – 3.2.3:

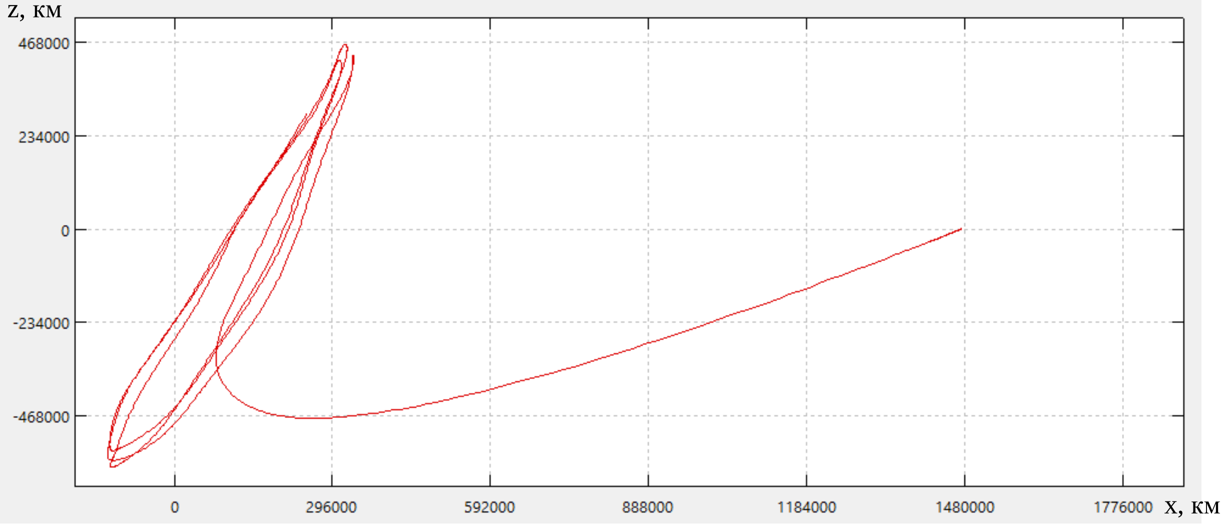

Fig. 3.2.1. Trajectory of the spacecraft

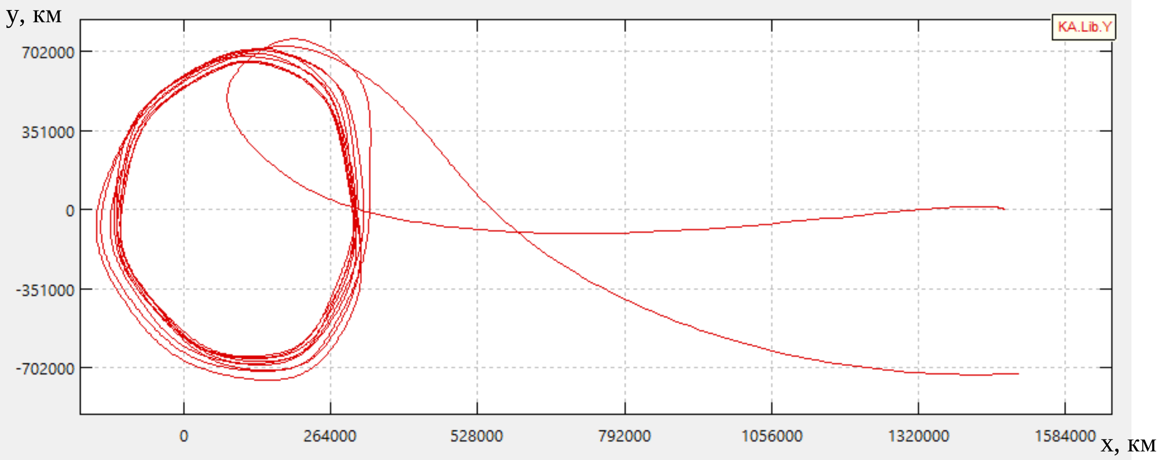

Fig. 3.2.2. Trajectory of the spacecraft

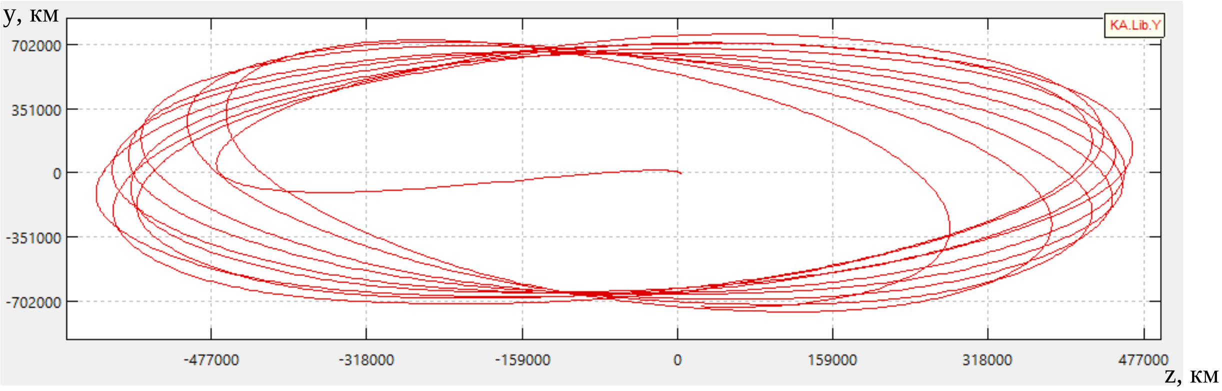

Fig. 3.2.3. Trajectory of the spacecraft

Looking at Figure 2.2.2 we can see that the amplitude of the orbit decreases by 50 thousand km.

Comparing these methods on the total momentum expended: 3234 m/s when using the gravitational maneuver near the Moon and 3260 m/s when using orbital maneuvers, we can draw the following conclusions:

- Less Δv, and therefore less fuel, is needed when using the gravity maneuver near the Moon. The fuel saved could be used in the future to maintain the orbit or to further modify it.

- The orbit obtained as a result of the gravitational maneuver near the Moon has a much smaller amplitude, which is better suited for the tasks solved by the spacecraft under development.

- The use of corrective pulses allows us to minimize the risks of the launch [8].

3. Using solar sails to "shift" the libration point

In order to obtain information about solar flares as early as possible it is proposed to place the spacecraft farther from the Earth than L1. For this purpose, it is proposed to use solar sails mounted on the spacecraft.

In this paper, a thin foil coated with a liquid crystal layer is considered as a solar sail. Under the influence of electricity, the liquid crystal layer can change its polarization, becoming either completely transparent or completely darkened. By changing the polarization of this layer it is possible to control the sail [5].

Solar sails unfolded on the spacecraft located at the libration point L1 will reduce the acceleration given to the spacecraft due to the gravitational forces of the Sun. Due to this equilibrium point (libration point) will be shifted closer to the Sun [5]. To place the spacecraft at a distance d from the Earth, the acceleration caused by solar radiation pressure must act on it:

$$W_r = \omega^2(a - d),$$

$a -$ the radius of the Earth's orbit around the Sun;

$\omega -$ angular velocity of the Earth rotation.

On the spacecraft, located on the line Sun-Earth, will act acceleration caused by the gravitational field of the Earth, equal to:

$$W_E = -\frac{\mu_E}{d^2},$$

acceleration from the gravitational field of the Sun:

$$W_S = \frac{\mu_S}{(a-d)^2},$$

$\mu_E, \mu_S -$ gravitational constants of the Earth and the Sun.

Then the necessary acceleration, which should be created by the solar sails, to keep the spacecraft in the vicinity of a given point:

$$W_P = -F\frac{S}{m},$$

F – sunlight pressure;

S – solar sail area;

m – spacecraft mass.

Then the equilibrium equation:

$$\omega^2(a-d) = \frac{\mu_S}{(a-d)^2} - \frac{\mu_E}{d^2} - F\frac{S}{m}.$$

Using the known data: $\mu_S = 132712517 \cdot 10^3\ km^3/s^2$, $\mu_S = 398.6 \cdot 10^3\ km^3/s^2$, a $= 149597.81$ thsd. km. – we can make a formula to find the necessary photon pressure force (under the condition of complete absorption of photons by the solar sail):

$$F = 4.5 \cdot 10^{-6}\left(\frac{a}{a-d}\right)^2 \frac{N}{m^2}.$$

Using this formula we can make a table 3.1 of the dependence of the necessary acceleration caused by the pressure of sunlight, the ratio of the mass of the spacecraft to the area of the solar sails on the distance d.

Table 3.1. Dependence of parameters of solar sails on the distance to the spacecraft

d, thsd. km.	$W_P, m/s^2$	$m/S, kg/m^2$
1500	0	-
2000	-0.0001333	0.03468
2500	-0.0002306	0.02018
3000	-0.0003118	0.01502
4000	-0.0004560	0.01042

Based on these data, three relations were considered m/S:

1) 0.0513;

2) 0.0682;

3) 0.115.

For each relation, a trajectory of flight from LEO was simulated using the gravitational maneuver near the Moon. Also for the relation $m/S = 0.0682$ was built trajectory without the use of gravitational maneuver to visualize its influence. The trajectories are shown in the figures below.

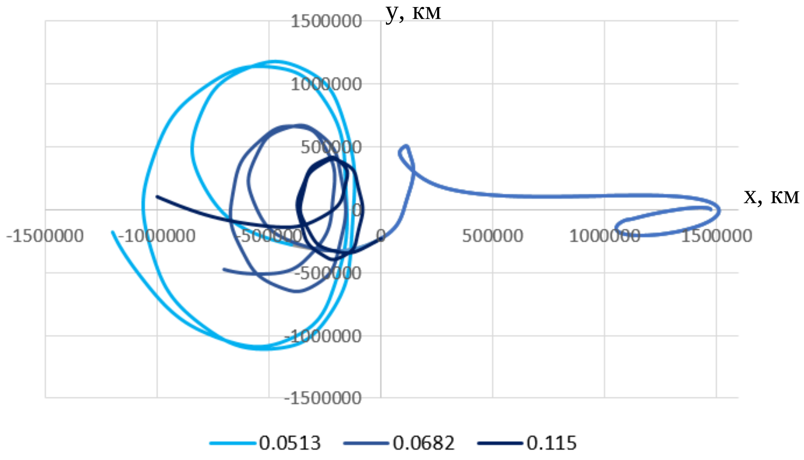

Fig. 3.1. Trajectories for different values of the m/S ratio

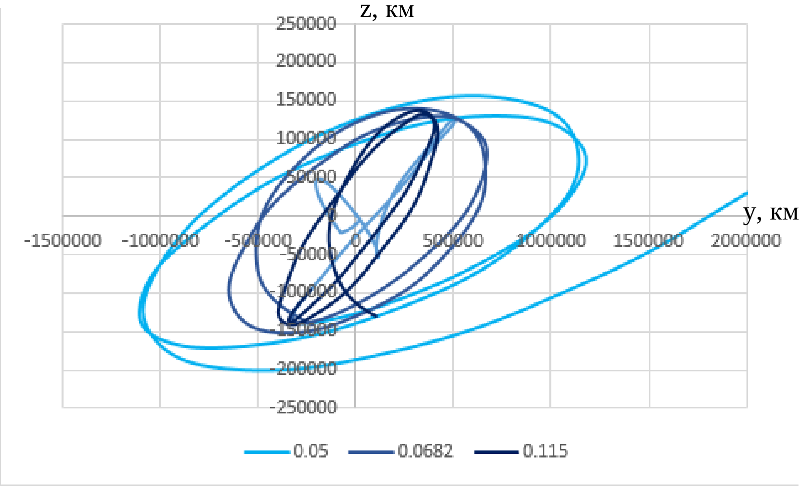

Fig. 3.2. Trajectories for different values of the m/S ratio

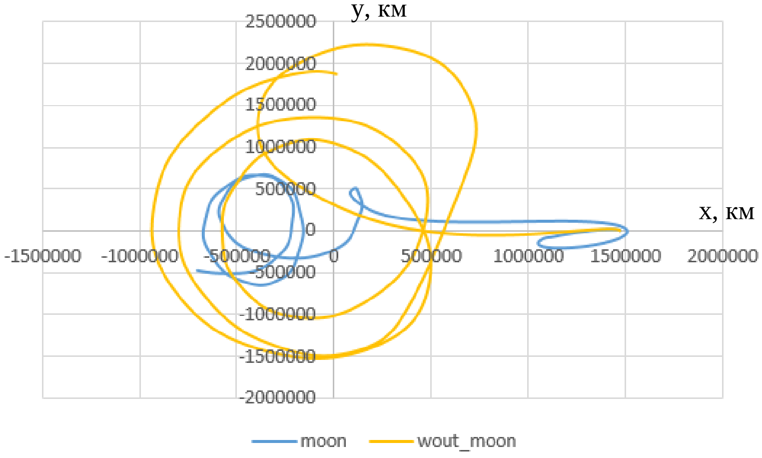

Fig. 3.3. Trajectories with and without the gravitational maneuver for $m/S = 0.0682$

Figure 3.3 confirms the decrease in the amplitude of the orbit under the influence of the gravitational maneuver near the Moon.

Figures 3.1, 3.2 shows that by increasing the sail area (decreasing the m/S ratio), the point of relative equilibrium shifts closer to the Sun, but this increases the amplitude of the orbit, which is not beneficial for us. Therefore, when choosing the final trajectory of the flight, it is necessary to find the optimal m/S ratio, corresponding to its necessary parameters.

4. Orbit correction using solar sails

It should be noted that, in practice, the one-pulse transition is usually not realized ideally, since additional corrective maneuvers are required. The number of such corrective maneuvers depends on the accuracy of ΔV pulses and the accuracy of determining the trajectory of the vehicle [6].

Consider the final orbits obtained by the transition from LEO and the gravity maneuver near the Moon, shown in Figure 4.1. We can notice that the spacecraft will make only 1.5 full orbital rotations before it descends from the orbit. To prevent the spacecraft from descending, it is necessary to maintain the orbit by corrective pulses.

To save fuel, instead of correcting impulses, it is proposed to use a solar sail. By changing its parameters (its reflectivity), it is possible to correct the orbit, increasing the lifetime of the satellite.

Consider the orbit corresponding to the ratio m/S = 0.0513 in Figure 4.1.

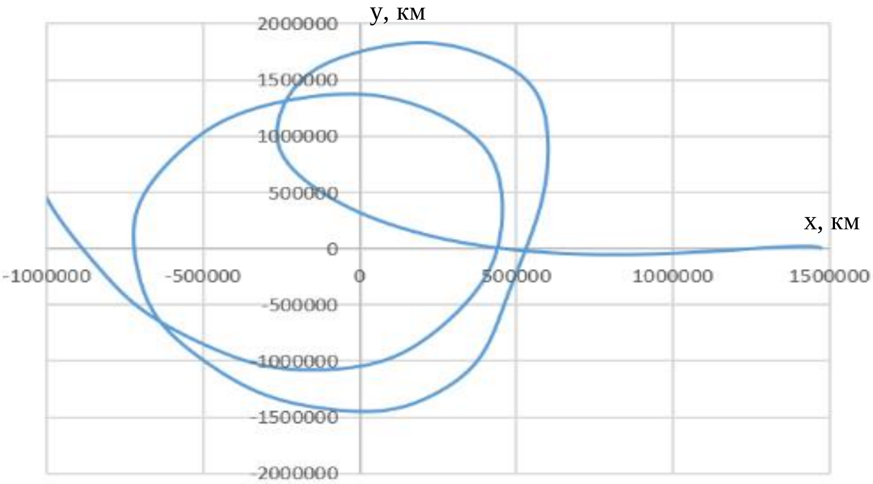

Fig. 4.1. Trajectory of the spacecraft

After the correction we obtain the trajectories shown in Figures 4.2, 4.3.

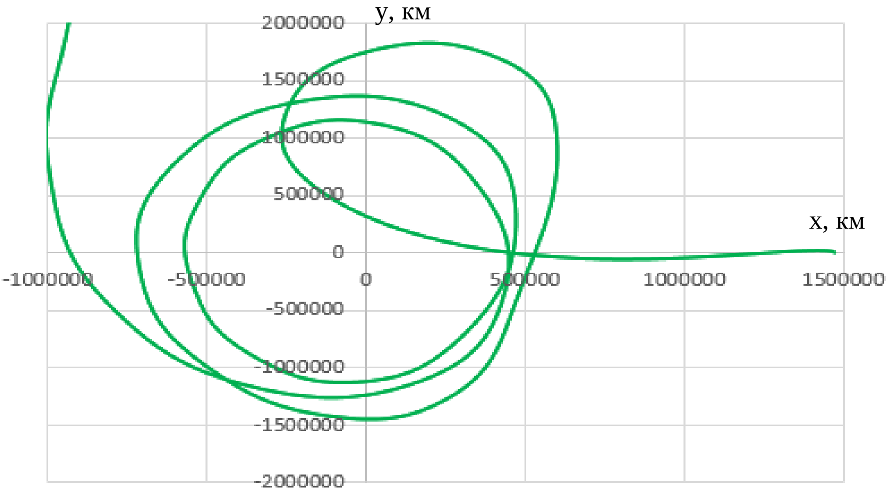

Fig. 4.2. Trajectory of the spacecraft

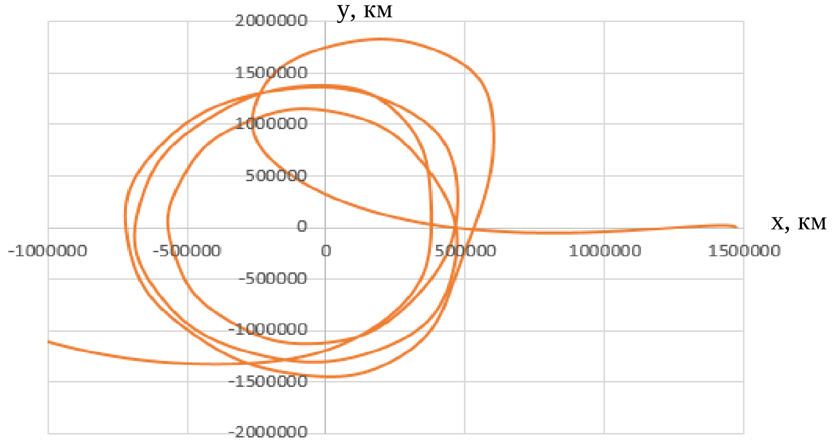

Fig. 4.3. Trajectory of the spacecraft

If necessary, further trajectory correction is possible, but this requires clarification of the coordinates of the spacecraft.

Conclusion

The main conclusions on the results of this work:

- A spacecraft flight to the L1 libration point to study the Sun from LEO was simulated using a single-pulse transition.

- The effect of the gravitational maneuver near the Moon was investigated. The orbit resulting from its use has a much smaller amplitude (decreasing from 672000 km to 477917 km), which is better suited to the tasks of the spacecraft.

- When using the gravity maneuver, less momentum is needed than when using corrective pulses, and therefore less fuel. The saved fuel can be used in the future to maintain the orbit or to further modify it.

- The effect of the sail size on the resulting orbit parameters was analyzed: as the sail area increases (m/S ratio decreases), the point of relative equilibrium shifts closer to the Sun, but the orbit amplitude increases.

- The orbit was corrected with the help of solar sails: the satellite's orbital lifetime was increased from 1.5 to 3.5 revolutions in the vicinity of the libration point.

Thus, in this work, various trajectories for the transition of a spacecraft from a LEO to a quasi-periodic orbit around the L1 libration point of the Earth-Sun system using solar sails were designed and investigated.

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