DOI: 10.13009/EUCASS2017-47

Service Spacecraft Control During the Space Debris Removal from the GEO Protection Region by the Ion Shepherd Method

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Abstract

The problem of service spacecraft (SSC) control was studied as applied to the space debris object (SDO) removal from the protected GEO region by the Ion Shepherd method. That study was made by numerical modeling for the dynamics of motion of a cluster consisting of two objects, one of which being an uncooperative object of space debris and another one - SSC with the ion gun on board. The motion of the latter is controlled by an electric propulsion system (EPS) with controllable thrust vector. Possibility to control a cluster of two objects using the proposed control algorithms is shown. Conditions are defined, under which the control by the proposed algorithms is stable.

1. Introduction

One of the least understood problems related to the implementation of the Ion Shepherd method, namely to the space debris removal from the certain region of geostationary orbit (GEO) with the use of a service spacecraft equipped with the electric propulsion system and an ion beam source designed to influence SDO (hereinafter referred to as the Ion Gun (IG)), is the problem of the SSC control at the stage of the SDO removal. It is a rather complicated problem, as the SDO mass is comparable to the SSC mass or even exceeds it, while the SDO reaction to the ion beam influence is variable and depends on the uncontrollable and unpredictable motion of the SDO around its center of mass [1, 2]. Main subject of this paper is the investigation by numerical modeling for a problem that might be formulated in the following way: control for a virtual (without the mechanical links) cluster of two objects, one of which being an uncooperative SDO and another one - SSC with the ion gun on board, the motion of which is controlled by EPS under the conditions of varying SDO response to the ion beam influence. Our investigation was mainly aimed at the assessment of stability of such cluster control process. Equations of motion in the inertial reference system were considered as the motion model. We neglected the disturbances caused by the asphericity of Earth, as well as by the factors of higher orders.

An elliptic orbit with the low value of eccentricity is considered as the SDO initial orbit. It is assumed that nominally at the starting time moment the SSC is moving along the same orbit as the SDO does, but it is behind the SDO and the distance between them allows starting the process of SDO removal. While modeling, we took into account that the real initial position of the SSC would differ from the nominal one by some low values. We shall analyze hereinafter the application of ion gun with a wedge-shaped ion beam [3], for which there is an inverse linear dependence of the force of beam action on the SDO on distance. It is shown in [3, 4] that it is possible to form a wedge-shaped beam with a half-angle of divergence in one direction within 2-4 deg by the IG slotted ion extraction system.

Consideration of the SDO response to the ion beam action is one of the complicated problems of modeling the process of the two-object cluster control. Calculations for the components of forces and momentums originating with the wedge-shaped beam action on SDO of certain configuration are presented in [3, 4]; according to them there are side components of the force of beam action on SDO at any relative orientation of SDO and SSC. The force value in the beam direction can decrease down to the values corresponding to 40-60% of the maximum value depending on the SDO orientation. It is in the nature of things to suppose that during the process of SDO transfer to the disposal orbit the SDO will rotate around the center of mass, and this is verified by observations [5]. As a result, the side projections of the force of beam action on the SDO, as well as the force value in the direction of the relative distance vector will be of oscillatory nature. It is obvious that it is impossible to develop a general numerical model for the space debris objects of different types. In our work, for the analysis of the cluster control process the model of beam interaction with SDO is specified in the form of two components: nominal force as a result of beam action on some

DOI: 10.13009/EUCASS2017-47

dummy object in the form of a circle with fixed effective radius and a variable force representing harmonic oscillations in the direction of the relative distance vector, as well as in the lateral directions. By varying the effective radius, as well as the oscillation amplitude and frequency of the alternating force component, it is possible to assess feasibility for the process of controlling a cluster of objects for different types of SDO, and moreover to assess stability of control process and formulate requirements to the control algorithms. A propulsion system comprising two thrusters of SPT-70 type [6] was considered as the EPS. SSC design is presented in Figure 1.

2. Coordinate System

The following coordinate systems were used for the modeling purposes: geocentric inertial coordinate system related to the SSC, orbital coordinate system, and the SSC-centric system.

The SSC structure diagram and directions of the SSC-centric coordinate system axes $OX_SY_SZ_S$ are shown in Figure 1.

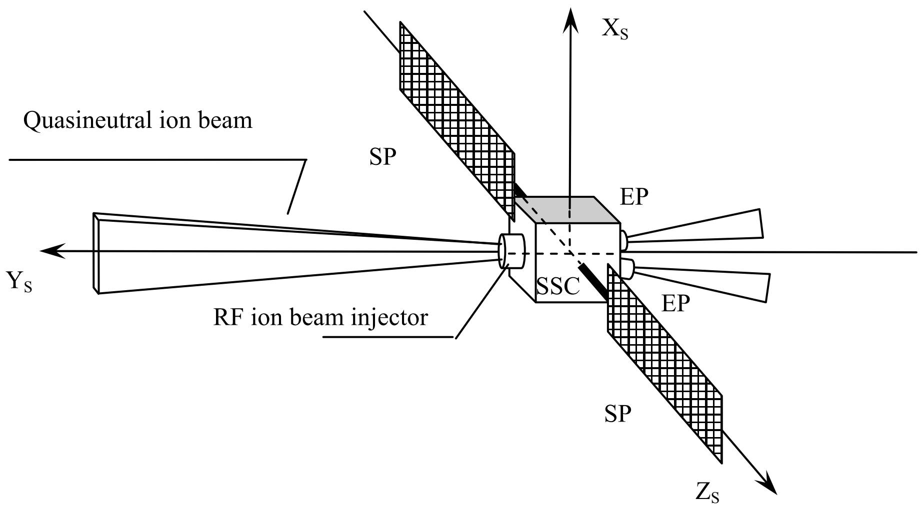

Figure 1: SSC structure diagram and the SSC-centric coordinate system axes

The ion gun of Figure 1 is rigidly fixed to the SSC body, and the direction of ion beam injection is orthogonal to the axis of rotation of solar panels (SP).The thrust is generated by two EPS thrusters in the direction being opposite to the beam direction. The axis Y_S coincides with the SSC longitudinal axis and is directed in the same direction as that of the EPS thrust vector. The axis Z_S is parallel to the SP rotational axis. The axis X_S supplements coordinate system up to the right-hand one.

The bound coordinate system orientation is controlled by the SSC onboard attitude control system. Its primary task is to keep the IG axis in the direction towards SDO, from one side, and from another side – to provide SP orientation to Sun. Here we shall discuss such SP axis orientation, with which the SP axis is located in the local horizontal plane.

Figure 2 shows the relative distance vector and its projection onto the axes of the orbital coordinate system.

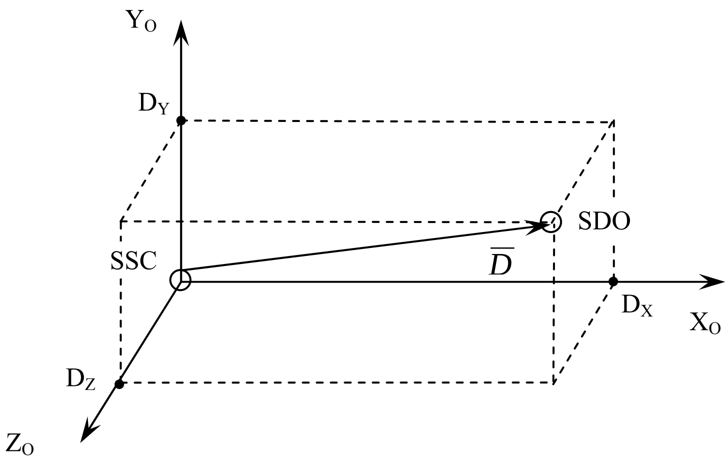

Figure 2: Relative distance in the orbital coordinate system

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The SDO location in the orbital coordinate system is shown in Figure 2 also. Projections of the vector of relative distance between SDO and SSC onto the axes of the orbital coordinate system are designated as D_X, D_Y, D_Z.

3. The model of ion beam interaction with SDO

While calculating the beam action on SDO, we used its simulation model that takes the following assumptions into account:

- SDO represents some conventional object in a form of a circle with the radius R_T;
- Ion beam generated by IG has a rectangular cross-section and is characterized by the divergence angle β_I over the larger side of the rectangle (a wedge-shaped beam);
- Real force of the beam action differs from the nominal one by the value of disturbance implying here the harmonic oscillations of the beam action force in the direction of relative distance and in the plane being orthogonal to such direction. Oscillatory component of the beam-SDO interaction force indirectly accounts for the SDO rotation relative to its center of mass during the removal process.

For a wedge-shaped beam, expression for the nominal thrust has the following form:

$$P_{TN} = \begin{cases} P_I, & \text{if } R_T \le L \times tg(\beta_I) \\ \dfrac{P_I \times R_T}{L \times tg(\beta_I)}, & \text{if } R_T > L \times tg(\beta_I) \end{cases}.$$

The nominal force component acts in the direction of relative distance. The oscillatory component of the beam-SDO interaction force is calculated in the coordinate system bound to SSC. The resultant force P_{TVi} of the beam-SDO interaction at the time moment t has the following form:

$$P_{TVX} = P_{TN} \times k_{VX} \times \sin(\varphi_{VX} + \frac{2\pi}{T_{VX}} \times t),$$

$$P_{TVY} = P_{TN}(1 - k_{VY}) + P_{TN} \times k_{VY} \times \sin(\varphi_{VY} + \frac{2\pi}{T_{VY}} \times t),$$

$$P_{TVZ} = P_{TN} \times k_{VZ} \times \sin(\varphi_{VZ} + \frac{2\pi}{T_{VZ}} \times t),$$

Here k_{Vi} is the ratio of the oscillatory component amplitude to the nominal force of the beam-SDO interaction; φ_{Vi}, T_{Vi} are the phase shift and period of the oscillatory component of the beam-SDO interaction force.

4. Motion equation integrating

The system of differential equations for the motion of SSC and SDO was solved by the Runge-Kutta method of the 4 degree with the constant integration step. Integration step has been chosen experimentally; it was 10 s, while integration duration was less than 10 days. The SDO initial location was given in the form of parameters of the elliptic orbit: major semiaxis 42157 km, eccentricity 0.0005, inclination 0 deg. It was assumed that SSC traveled in the orbit coinciding with the SDO orbit. The SSC standing behind the SDO in the orbit was 40 m, the SSC deflection from the vertical was 5 m, The SSC declination from the orbit plane was 5 m. Mass characteristics of the cluster: SDO mass 2000 kg, SSC mass 1500 kg. The IG and EPS performance: thrust produced by IG - 50 mN, number of EPS thrusters - 2, thrust of a single thruster - 40 mN.

While modeling, the following situations were considered:

- uncontrolled relative motion of SSC and SDO at the fixed initial conditions;
- relative motion of SSC and SDO at the uncontrolled EPS thrust, SSC being oriented so, that the beam would be always directed towards the conditional center of mass of the SDO;
- the use of the relay law to control the SSC lateral motion;
- application of regulator to control the SSC lateral motion;
- analysis for the EPS thrust influence on the control process;
- control with the account for oscillatory component of the force of beam action on the SDO.

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5. Uncontrolled relative motion of SSC and SDO

Figure 3 shows time variations for projections of relative distance between SDO and SSC onto the orbital coordinate system for the case of the SSC uncontrolled motion. In addition, variation of the SDO altitude relative to the initial one is indicated in black. Projection of the relative distance onto the axis X_O is shown in blue, its projection onto the axis Y_O – in green, and onto the axis Z_O - in red. It is obvious from Figure 3 that the projection of relative distance along the motion trajectory onto the axis X_O increases monotonically, and at the end of the third day it becomes as long as 325 m. Oscillations are stipulated by the orbit ellipticity. Variation of the relative distance projections onto the axes Y_O , Z_O have the form of harmonic oscillations, while projection onto the axis Z_O oscillates near zero with the amplitude being equal to the initial SSC displacement of 5 m relative to the nominal position. Projection onto the axis Y_O oscillates near the value of -10 m with the amplitude of 5 m. Negative values are explained by the fact that SSC is located above SDO.

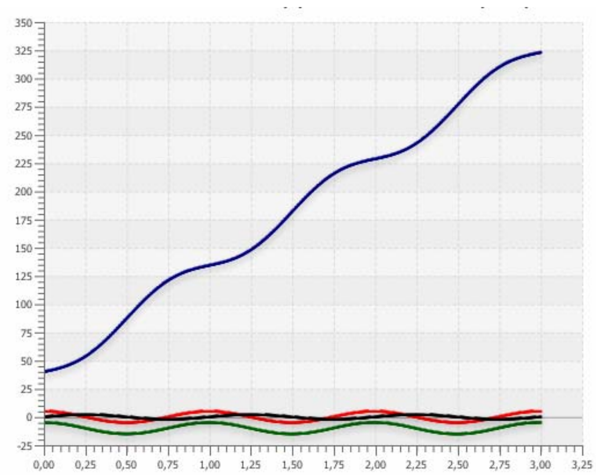

Figure 3: Projections of relative distance, uncontrolled motion

Variation of the SDO altitude relative to the initial value is of fluctuating nature with the amplitude of about 2 m and corresponds to the laws of motion in the elliptic orbit.

6. Relative motion of SSC and SDO at the uncontrolled EPS thrust

Relative motion of SSC and SDO at the uncontrolled EPS thrust was considered providing that the beam was directed to the SDO center of mass. SDO radius was assumed to be equal to 1.5 m and the beam divergence angle – to 4 deg. The constant component of the force of beam action on SDO was taken into account only. Projections of the relative distance onto the axes of the orbital coordinate system and variation of the altitude are shown in Figure 4 in the same colors as above. Relative distance is presented in Figure 5.

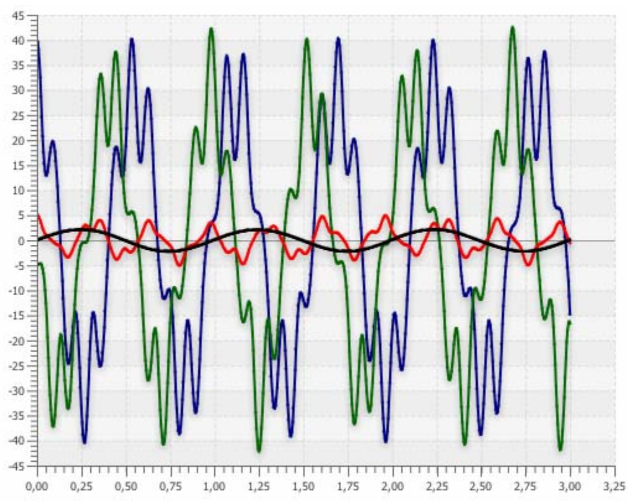

Figure 4: Projections of relative distance for the case of uncontrolled thrust

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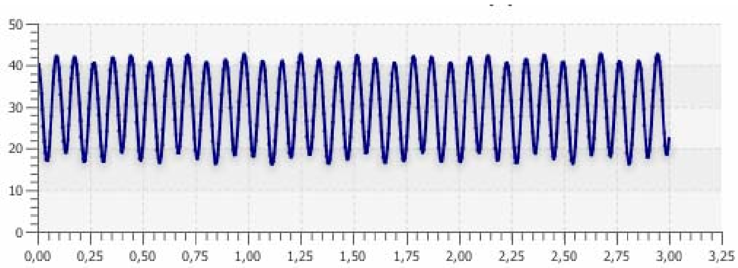

Figure 5: Relative distance for the case of uncontrolled thrust

It is obvious from Figures 4, 5 that during the beam action on SDO the service spacecraft and SDO are located close to each other, SDO being at intervals before or behind the SSC. The value of relative distance fluctuates relative to some average value with practically constant amplitude. Average value of relative distance is about 30 m. The relative distance is within 16-44 m. The SDO appears to be behind SSC 12 times during a day. Variation of SDO altitude departure from the initial value is of oscillatory nature near zero; it is mainly stipulated by the orbit ellipticity.

Thus, under the beam action the SSC-SDO cluster appears to be stable in relative distance with the practically unchanging flight altitude. With the aim to raise the SDO altitude, the control should be organized in such a way, that the SDO would be always located before the SSC. This could be reached if by rotating the EPS thrusters the SSC would be displaced so, that projections of relative distance onto the axes Y_O and Z_O would be reduced to zero. It is necessary to introduce control for the SSC lateral motion in order to raise orbit altitude.

7. Relay control for the SSC lateral motion

The relay law is considered as one of the most simple algorithms of control for the SSC lateral motion. Requirements to SSC control accelerations were formed in the orbital coordinate system, and after that the angles of EPS thrusters deflection were calculated. With the SDO radius of 1.5 m and the beam divergence angle of 4°, the relay law parameter characterizing maximum deviation in the roll angle was assumed to be equal to 5°. Figure 6 shows the variation of relative distance projections and of the flight altitude. It is obvious that the use of relay law for controlling the lateral motion makes the process of SDO removal stable.

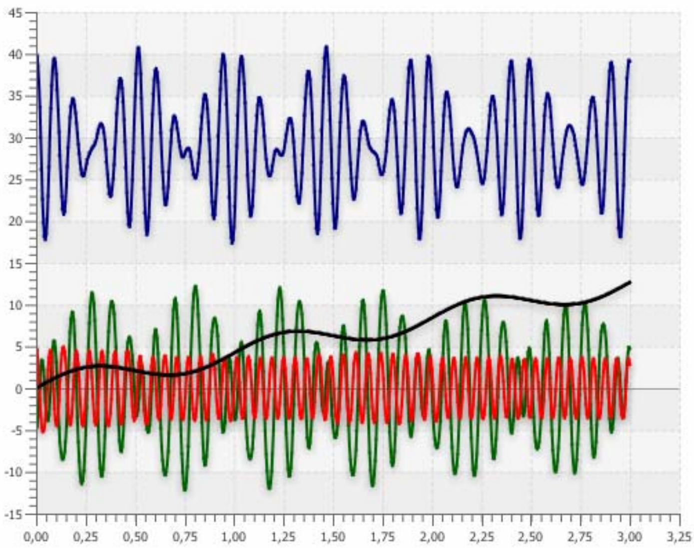

Figure 6: The relative distance projection, relay law

Variation of the relative distance projection onto the axis X_O of the orbital coordinate system in the tangential direction is shown in blue in the upper part of the figure. The projection value is positive always and fluctuates relative to the average value being approximately equal to 28 m within the limits of 17-41 m. The black line shows variation of the SDO altitude relative to its initial value. It is obvious from the plot that the altitude grows, and by the end of the 3rd day of flight it reaches 130 km, while during 10 days of flight the altitude increment can be over 430 km. Projections of relative distance in lateral directions fluctuate relative to zero. Amplitude of the relative distance

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projection fluctuation relative to the axis Z_O is about 5 m, the amplitude of fluctuations relative to the axis Y_O is varying: from 5 m to 12 m. Fluctuation frequency for the relative distance projections is about 12 fluctuations per a flight day.
Disadvantages of the relay control law include the absence of damping in the control law and thus the essentially oscillatory process of the relative motion of SSC and SDO.

8. Application of regulator to control the SSC lateral motion

With the aim to improve the control quality, we considered control law that accounts for the first and second derivates of the variation the relative distance projections onto the orbital coordinate system. We shall call it as the regulator for the relative motion control. We considered control along the axes Y_O and Z_O. Projections of the relative distance onto the axes of the orbital coordinate system and variation of the SDO altitude relative to the initial value are shown in Fig, 7 for the initial distance of 40 m. Variation of the SDO altitude is shown in black. By the end of the third day it reaches the value of about 140 km. In relation to other parameters of control process it may be noted that the angles of thruster deflection do not exceed 1.5°, and the SSC control acceleration being projected onto the relative distance direction is 0.02 mm/s^2.

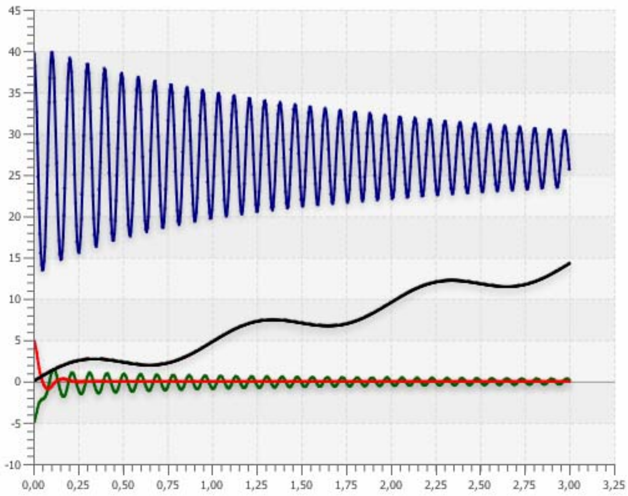

Figure 7: The relative distance projections, application of regulator

The SDO acceleration variation is shown in Figure 8.

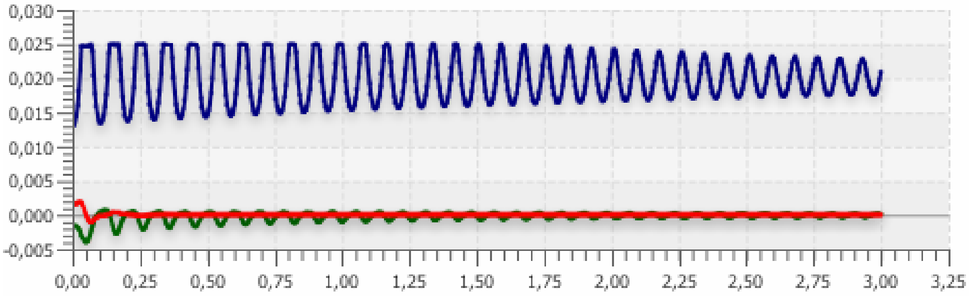

Figure 8: SDO acceleration, application of regulator

Time variation of the SDO acceleration projection onto the axis X_O (shown in blue) has a nature of a decaying oscillation relative to some average value of about 0.02 mm/s^2. Projections of the SDO acceleration during the lateral motion have low values not exceeding 0.003 mm/s^2 and become zero virtually instantaneously.
Figure 9 shows time variation of the relative distance projections onto the axes of the orbital coordinate system, and the SDO altitude variation relative to the initial value for the case of the SSC standing behind the SDO for 30 m.

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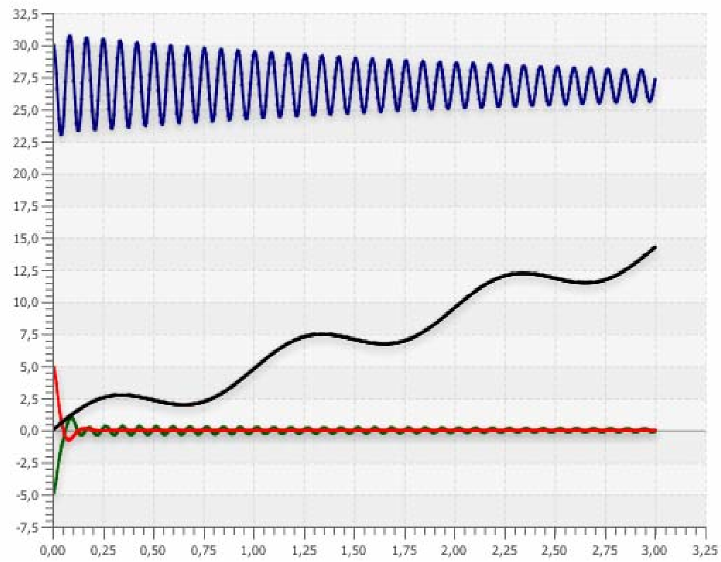

Figure 9: The relative distance projections, application of regulator

When comparing Figure 7 and Figure 9, it becomes obvious that at the initial standing behind of 30 m the amplitude of the relative distance oscillation relative to the average value is about 2 times less than in the case of the standing behind of 40 m. Average value of distance is the same for both cases and equals to 28 m. Variation of the SDO altitude is 140 m in both cases. It is important to note that the SDO altitude variation is defined by acceleration produced by the SSC, and it has weak dependence on the nature of SDO motion relative to the SSC. The higher is the EPS thrust, the higher is the final altitude. The stability of control process is very important in this case, because the SDO should not be found behind the SSC and the relative distance projections onto the axes Y_O and Z_O of the orbital coordinate system should not have high values. Analysis for the modeling results for the dynamics of the process of control for the SDO removal out of the GEO region under protection in view of the constant component of the beam - SDO interaction force revealed the following peculiarities:

- With the stable control process, the relative distance value oscillates relative to its average value that is defined by the condition of equality of the SDO and SSC accelerations in the direction of relative distance.
- Intensity of the relative distance oscillations around such average value is higher, the larger is the difference between initial relative distance and its average value.
- Average value of relative distance depends of the beam divergence angle.
- The SDO altitude increment does not depend on the beam divergence angle and is practically completely defined by the EPS thrust (at the IG fixed thrust). The altitude increment during the SDO removal from GEO is not influenced essentially by the nature of the relative distance variation process. But in this case it is important that the SDO should be in front of the SSC and that projections of relative distance onto the axes Y_O and Z_O should not have high values.

Above peculiarities make it possible to obtain some analytic expressions for the parameters of the SDO removal process.

9. EPS thrust limitation

For the given values of the SDO effective radius and of the beam divergence angle there is some threshold distance:

$$L^* = \frac{R_T}{tg(\beta_I)}$$

It is such that for the distance being less than this value ($L \le L^*$) the SDO acceleration is constant:

$$a_{SDO} = \frac{P_I}{m_{SDO}}$$

The values of threshold distance for different values of the SDO effective radius and different beam divergence angles are presented in Table 1.

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Table 1: Threshold distance for different values of the SDO effective radius and different beam divergence angles.

Effective radius, m	Threshold distance (m) for a beam with the divergence angle of:		
	2°	4°	6°
0.5	14.3	7.2	4.8
1.0	28.6	14.3	9.5
1.5	43.0	21.5	14.3
2.0	57.3	28.6	19.0

The SSC acceleration is defined as:

$$a_{SSC} = \frac{P_E - P_I}{m_{SSC}}$$

For the control process to be stable, it is necessary that the acceleration produced by SSC at the distance $L \le L^*$ would be less than the SDO acceleration produced by the beam: $a_{SSC} < a_{SDO}$. Otherwise, the SSC would come closer the SDO, reducing the relative distance to zero. If this condition is met, the SDO will move away with constant acceleration; and as soon as the condition $L > L^*$ is met, the SDO acceleration will start to decline. It is clear that for a stable control process the average distance should be longer than the threshold distance ($L_{aver} > L^*$). Limitation for the SSC acceleration will lead to the requirement to limit the EPS thrust:

$$P_E < P_I\left(1 + \frac{m_{SSC}}{m_{SDO}}\right)$$

Maximum SDO acceleration for the IG thrust of 50 mN and mass of 2000 kg is 0.025 mm/s^2. Maximum EPS thrust for the SSC mass of 1500 kg is 87.5 mN.

10. Average value of relative distance

Average value of relative distance is defined based on the condition of SSC and SDO accelerations equality. At $L > L^*$ and a wedge-shaped beam, the SDO acceleration has the following form:

$$a_{SDO} = \frac{P_I \times R_T}{m_{SDO} \times (L \times tg(\beta_I))}$$

In view of the expression for SSC and SDO accelerations, the average distance can be defined as:

$$L = \frac{1}{tg(\beta_I)} \times \frac{P_I \times R_T}{P_E - P_I} \times \frac{m_{SSC}}{m_{SDO}}$$

Similar calculations were made for a conical beam in view of the inverse square dependence of the momentum density reduction on the distance between the objects. The average distance values are presented in Table 2 for various beam types, EPS thrust values and divergence angles.

11. The SDO altitude increment

For the transfer with low transversal thrust, the altitude increment and characteristic velocity are interrelated via the difference in circular velocities in the initial and final orbits:

$$\Delta V_{char} = \sqrt{\frac{\mu}{r_{GEO}}} - \sqrt{\frac{\mu}{r_{GEO} + \Delta h}}$$

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The values of altitude increment as a function of EPS thrust during 10 days of flight are presented in Table 2 for the same calculation variants.

Table 2: Altitude increments during 10 days and average distance as the functions of the EPS thrust and IG beam type

Thrust, mN	SSC acceleration, mm/s	Characteristic velocity, m/s	Altitude increment, km	Average distance (m) for a conical beam with the divergence angle of:			Average distance (m) for a wedge-shaped beam with the divergence angle of:		
				2°	4°	6°	2°	4°	6°
52	0.0013	1.15	31.61	186.0	92.9	61.8	805.4	402.2	267.6
54	0.0027	2.30	63.25	131.5	65.7	43.7	402.7	201.1	133.8
56	0.0040	3.46	94.92	107.4	53.6	35.7	268.5	134.1	89.2
58	0.0053	4.61	126.64	93.0	46.4	30.9	201.4	100.6	66.9
60	0.0067	5.76	158.38	83.2	41.5	27.6	161.1	80.4	53.5
62	0.0080	6.91	190.17	75.9	37.9	25.2	134.2	67.0	44.6
64	0.0093	8.06	221.99	70.3	35.1	23.4	115.1	57.5	38.2
66	0.0107	9.22	253.84	65.8	32.8	21.9	100.7	50.3	33.5
68	0.0120	10.37	285.73	62.0	31.0	20.6	89.5	44.7	29.7
70	0.0133	11.52	317.66	58.8	29.4	19.5	80.5	40.2	26.7
72	0.0147	12.67	349.62	56.1	28.0	18.6	73.2	36.6	24.3
74	0.0160	13.82	381.62	53.7	26.8	17.8	67.1	33.5	22.3
76	0.0173	14.98	413.66	51.6	25.8	17.1	62.0	30.9	20.6
78	0.0187	16.13	445.73	49.7	24.8	16.5	57.5	28.7	19.1
80	0.0200	17.28	477.84	48.0	24.0	16.0	53.7	26.8	17.8
82	0.0213	18.43	509.98	46.5	23.2	15.5	50.3	25.1	16.7
84	0.0227	19.58	542.17	45.1	22.5	15.0	47.4	23.7	15.7
86	0.0240	20.74	574.38	43.8	21.9	14.6	44.7	22.3	14.9
87.5	0.0250	21.60	598.57	43.0	21.5	14.3	43.0	21.5	14.3

The above values of average distance correspond to the SDO effective radius of 1.5 m. In the bottom line of the Table the values of average distance coincide with the threshold values of relative distance. The line corresponding to the EPS thrust of 80 mN that was used for modeling is shown in blue and the lines corresponding to the altitude increment of less than 200 km are marked by grey color. Values of average distance for other values of SDO effective radius can be obtained similarly.

12. The control process modeling in view of the oscillatory component of the force of IG beam action on SDO

The force of beam action on SDO may differ substantially from the nominal force. According to calculations [3], the value of force in the beam direction may decrease depending on the SDO orientation down to the values of 40-60% of the maximum value. It was assumed in calculations that the amplitude of the oscillatory component of the force of beam action on SDO in the plane being orthogonal to the direction of relative distance is 10% of the nominal force. The minimum value of the action force in the relative distance direction was considered to be 40% of the nominal force.

At the level of threshold distance the limits of SDO acceleration variation will have the following values in view of the oscillatory component:

– In the plane being orthogonal to the relative distance direction: from 0.0025 mm/s^2 to -0.0025 mm/s^2;
– In the direction of relative distance the value of SDO acceleration can vary from 0.025 mm/s^2 to 0.010 mm/s^2.

It is necessary to note that with the SDO acceleration of 0.010 mm/s^2, for the removal process stability the SSC acceleration should not exceed this value, that should not be higher than 0.010 mm/s^2. The EPS thrust of 65 mN corresponds to such value, while the EPS thrust of 72.5 mN corresponds to the average value of SDO acceleration. Thus, the following conclusion may be made: for the stability of SDO removal process under certain conditions

DOI: 10.13009/EUCASS2017-47

either lower EPS thrust or the use of EPS with the thrust throttling may be required. The cut-off of the EPS thrusters or of one of them at least, can be one of the variants of thrust throttling.
Variation of relative distance and of its projections for the period of oscillatory component of the force of beam action on SDO of 10 minutes is shown in Figure 10 and Figure 11.

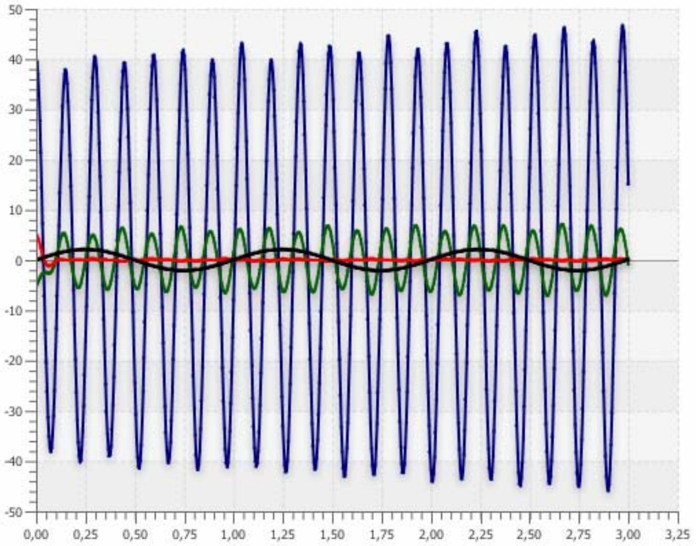

Figure 10: Projections of relative distance. Disturbance period 10 min, thrust 80 mN.

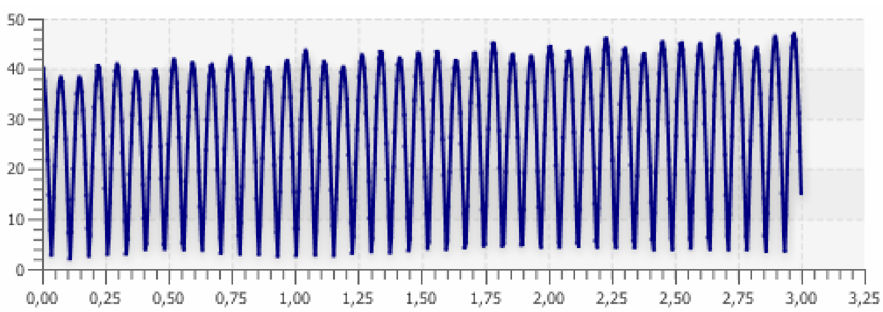

Figure 11: Relative distance. Disturbance period 10 min, thrust 80 mN

It is obvious from Figure 10 and Figure 11 that at the presence of harmonic oscillations of the force of beam action on SDO along three axes of the bound coordinate system the control process is unstable. As was mentioned above, this is related to the fact that the average value of SDO acceleration is substantially less than the acceleration corresponding to the nominal interaction force.
Variation of the relative distance projection, of SDO altitude and of the SDO acceleration at the EPS thrust of 62 mN is shown in Figures 12 – 17 for different periods of oscillatory component of the force of beam action on SDO.

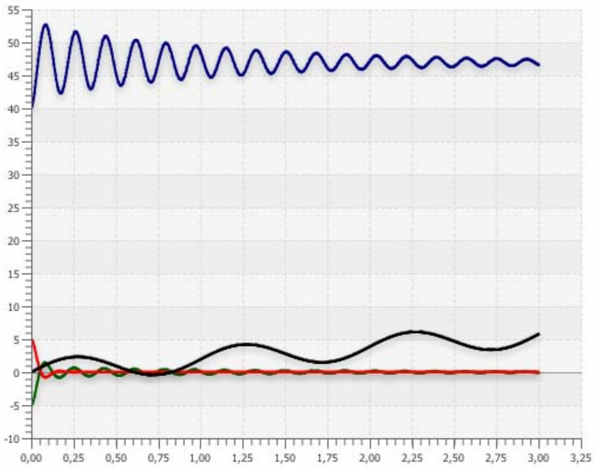

Figure 12: Projections of relative distance. Disturbance period 10 min, thrust 62 mN

DOI: 10.13009/EUCASS2017-47

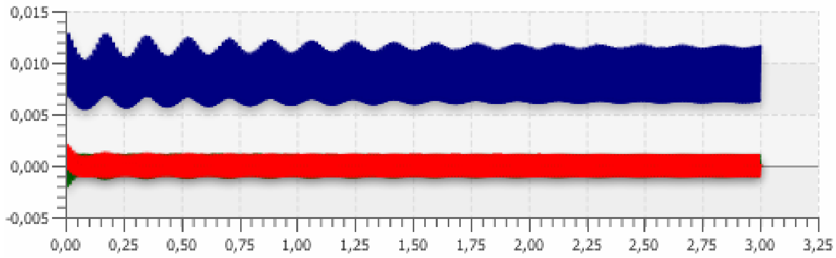

Figure 13: SDO acceleration. Disturbance period 10 min, thrust 62 mN

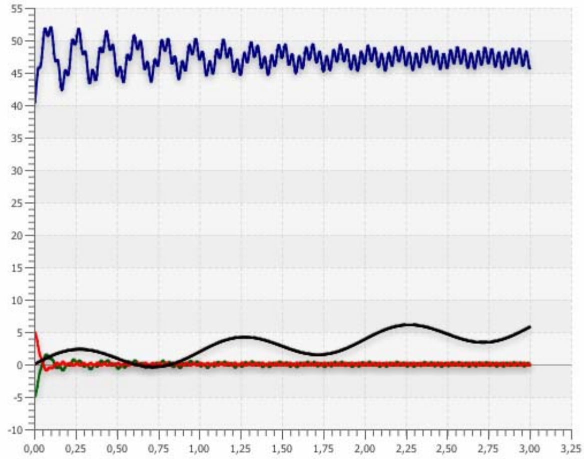

Figure 14: Projections of relative distance. Disturbance period 1 hour, thrust 62 mN

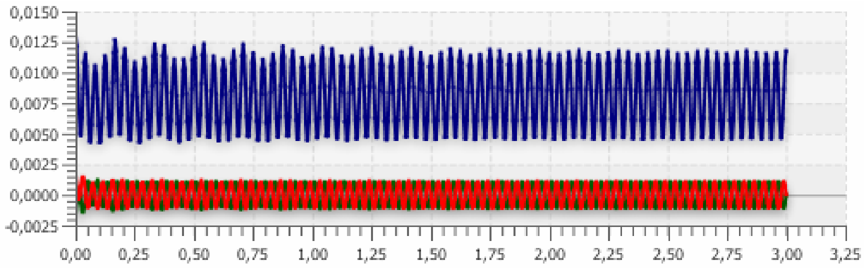

Figure 15: SDO acceleration. Disturbance period 1 hour, thrust 62 mN

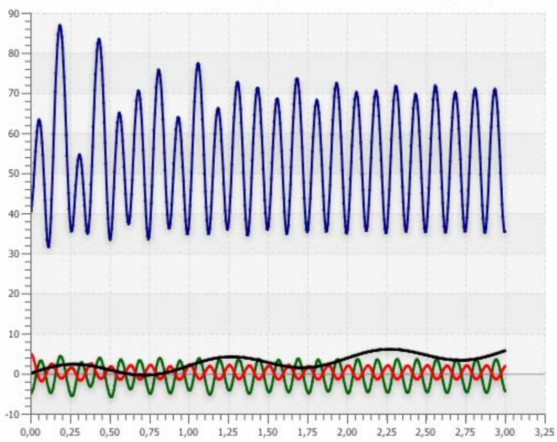

Figure 16: Projections of relative distance. Disturbance period 3 hours, thrust 62 mN

DOI: 10.13009/EUCASS2017-47

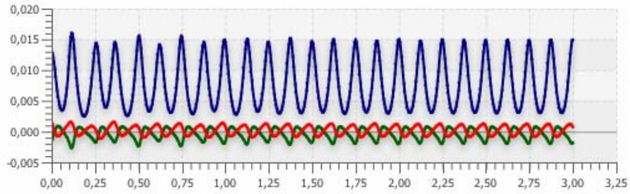

Figure 17: SDO acceleration. Disturbance period 3 hours, thrust 62 mN

It is obvious from Figures 12 – 17 that with the EPS thrust reduction down to 62 mN the control process becomes stable at the presence of oscillatory component of the force of beam action on SDO. However, the stability degree decreases with the elongation of the force oscillatory component period. So, at the oscillation period of 10 minutes the relative distance fluctuations near some average value of about 44 m are small. In fact, the process of relative distance variation in the case of the oscillation period of 10 min corresponds to the process of relative distance variation without regard for the oscillatory force component with smaller effective radius of SDO. Increase in the period of oscillatory component of the force of beam action on SDO leads to the growth of amplitude of the relative distance fluctuation relative to its average value, and finally this can cause the control process instability. From the physical point of view, this can be explained by the fact that with the elongation of period of the force oscillatory component the period of time, during which the SDO faces the beam with its side, at which the beam action force is minimum, grows also. If with this the relative distance is short and the SSC acceleration is higher than that of the SDO, the SDO appears to be behind the SSC.

The SDO acceleration value fluctuates near the average value of 0.008 mm/s^2 that is defined by the SSC acceleration with the frequency of oscillatory component of the force of IG beam action on SDO. The SDO altitude increment at the EPS thrust of 62 mN is substantially lower than at the thrust of 62 mN, and during 3 days it comprised 60 km, that when calculated for 10 days will be about 200 km. Taking into account that situation corresponding to the nominal component of the force of beam action on SDO is the particular case of the control process, it may be noted that for the implementation of stable process of SDO removal from GEO the EPS should be capable of producing thrust of various values. The EPS thrust throttling will contribute to the increase in the SDO altitude increment.

The procedure proposed for modeling the beam-SDO interaction, the nominal and oscillatory components including, allows for assessing potentialities of the implementation of the process of controlling a cluster of two objects, promotes selection of algorithms for controlling the SSC EPS thrust vector, and makes it possible to assess control process stability as applied to a cluster of objects.

Conclusions

1. The discussed mathematical model for a motion of a cluster comprising two objects includes equations of motion for the centers of mass of SSC and SDO, algorithms of control for the SSC lateral displacement, and the model of the IG beam force action on SDO
2. Two algorithms are proposed for controlling the lateral motion: a) the one responding to the sign of the relative distance projection with the account for the dead zone, and b) the one accounting for both the sign of the relative distance projection and the first, as well as the second derivatives of the relative distance projection variations. So, in concrete calculation it turned out that at thrust of IG of 50 mN at oscillatory reduction of force of impact on the target to 40% of nominal rate stability of traffic control of two objects is reached at the size of EP thrust of EP 60-70 mN
3. With the use of the developed simulation model of the beam force action on SDO that includes two components of force: nominal and oscillatory, the parameters of the SDO removal process were obtained. So, according to calculation it appears that with the IG thrust of 50 mN and the oscillatory component of force of up to 10% of the nominal value, the stability of control for a motion of a cluster of objects is reached at the EPS thrust of 60-70 mN.
4. All in all, our studies resulted in the determination of conditions, under which the proposed control algorithms are stable and efficient.

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