OPTIMIZATION OF MANEUVERING SCHEMES IN THE FRAMEWORK OF ADR MISSION IN LEO

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ABSTRACT

The paper focuses on the flyby issue involving large-size space debris (LSSD) objects in low Earth orbits. The data on overall sizes of the known upper-stages and last stages of launch-vehicles make it possible to emphasize five compact groups of such objects from the satellite catalogue in 600-2000 km altitude interval. Distinctive features of changes in mutual distribution of orbital planes of LSSD within a group are shown on the RAAN deviations' evolution portrait. In case of the first three groups (inclinations 71°, 74° and 81°), the lines describing the relative orientation of orbital planes are quasi-parallel. Such configuration allows easy identification of the flyby order within a group, and calculation of the mission duration and the required total ΔV. In case of the 4th and the 5th groups (inclinations 83° and 97-100°) the RAAN deviations' evolution portrait represents a conjunction of lines chaotically intersecting. The article compares two world-wide known schemes applicable to LSSD objects' de-orbiting.

1 COMPACT LSSD GROUPS

The analysis of Satellite Catalogue shows that is possible to mark out groups [1] of LSSD objects taking into account the criteria mentioned below:

- cross-section square is more than 5 m^2;
- orbital inclination deviations between LSSD objects in a group should map to zero;
- perigee altitude is more than 600 km;
- apogee altitude is less than 2000 km.

According to mentioned criteria more than 280 objects can be distinguished from the Satellite Catalogue and approximately 250 of them can be classified into 5 different groups (Table 1). The orbital inclinations within each group should be the same. The authors also limited the eccentricity to be no more than 0.01 so finally 150 LSSD objects were obtained in LEO region. The semi-major axes interval in case of first four groups does not exceed 50-80 km. The significant deviations in the Right Ascension of the Ascending Node (RAAN) between the orbital planes of the objects in each mentioned group are the general feature in this task.

Table 1. LSSD groups in LEO

Group number	Orbital inclination, deg	Semi-major axes interval, km	Eccentricity interval	Quantity of objects in a group
1	71	7193-7281	0.0002-0.0036	23
2	74	7122-7152	0.0006-0.0092	11
3	81	7211-7262	0.0031-0.0095	28
4	83	7318-7358	0.0008-0.0081	52
5	97-100	6973-7500	0.0003-0.0099	46

The first group (71°) is basically presented by 2nd stages of "Zenit-2". The second group (74°) consists of 2nd stages of "Cosmos-3M". The third group (81°) consists of 3rd stages of "Vostok-2M". The fourth group (83°) is mainly presented by 2nd stages of "Cosmos-3M" and several 3rd stages of "Tsyklon-3". The objects from group #5 are situated at Sun-synchronous orbits: "Long March -2, -4", "Zenit-2", PSLV, "Ariane" family and Thor Agena. The 2nd stage of "Zenit-2" is the largest and the heaviest object: 9000 kg of mass, 11.5m of length and 3.9m in diameter.

2 THE RAANs DEVIATIONS' EVOLUTION PORTRAIT

The orbits of objects in each group differ, though insignificantly, in semi-major axis (a), in eccentricity (e) and in inclination (i). The differences in orbital elements cause unequal precession velocities of the orbital planes. This results in orbital planes' relative position changes over a long time interval. It is necessary to choose a proper parameter characterizing the orbital plane's position, which would be suitable for describing these changes. Such parameter is proposed as follows: $\Delta\Omega_{ik}\in(-\pi;\ +\pi]$ – the deviation of the RAAN of the orbits of all i^{th} objects from the RAAN of the orbit of one specifically selected object with the fixed number $k \in \overline{1;m}$, where m is the quantity of objects in a group. With such approach, the lines $\Delta\Omega_{ik}(t)$ for orbits with similar parameters (groups #1-4 contain the majority of such orbits) will have a small angular coefficient, and the angular relative distance $\Delta\Omega_{ik}$ will be slowly changing with time.

The RAAN deviations' evolution portrait of group #2

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calculated for 10 years is presented on fig. 1a. The value of “zero” at the abscissa axis corresponds to orbital planes’ configuration on 21 November 2013. As it can be seen from fig. 1a, the straight lines of $\Delta\Omega_{ik}(t)$ (solid lines) do not intersect. In the LSSD groups #4 and #5, there are objects, whose orbits have differences in semi-major axis and inclination. These differences are enough to create the situation when the straight lines of the RAAN deviations $\Delta\Omega_{ik}(t)$ have many casual intersections (fig. 1b).

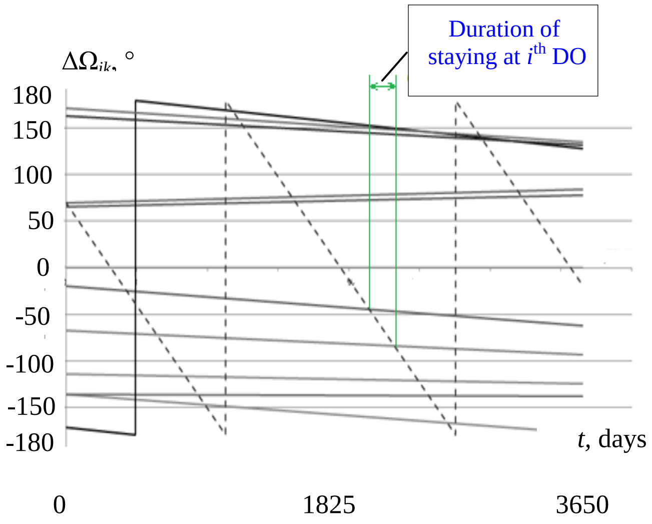

Figure 1a. The RAAN deviations' evolution portrait of LSSD group №2 (typical for groups #1-3).

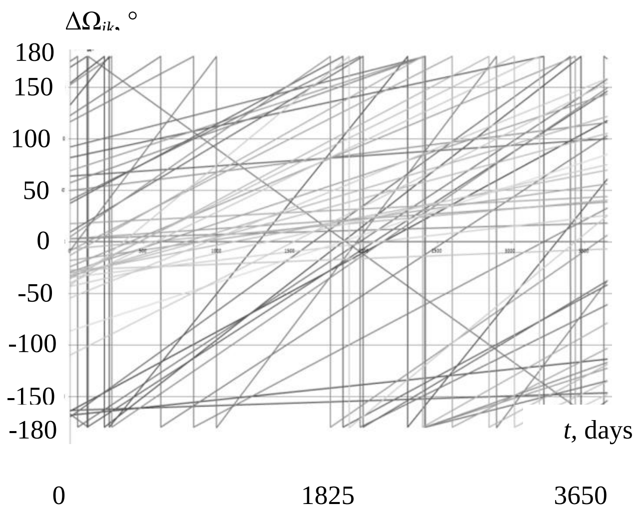

Figure 1b. The RAAN deviations' evolution portrait of LSSD group №5 (typical for groups #4-5).

To date, there are two de-orbiting schemes for LSSD objects in LEO which are under consideration. The first one [2, 3] suggests that a maneuvering space vehicle (SV) equipped with special small SVs, thruster de-orbiting kits (TDK), executes flights between LSSD objects. TDKs are to be inserted into the nozzles of LSSD objects. The kits have autonomous control and a stock of fuel to produce a braking impulse sufficient for object’s transition to the disposal orbit (DO). The second scheme [3, 4] suggests the usage of a single SV that executes flights between the objects and using its own propulsion system sequentially transfers the objects to the DO.

3 OBJECTS' FLYBY USING FIRST DE-ORBITING SCHEME

The quasi-parallel mutual distribution of $\Delta\Omega_{ik}(t)$ lines at the RAAN deviations' evolution portrait means that the orbital planes are stable in their relative angular motion. The scheme of simple, successive objects' flyby is optimal, herewith the objects should be beforehand arranged according to the initial RAAN values of their orbits. The rotation direction of the orbital plane should be chosen the same as the direction of the RAAN's natural precession [5]. It is necessary to perform the following sequence of actions to execute a flight between three LSSD objects (fig. 2a). After one TDK is fixed on the object No. 1, the maneuvering SV-collector performs a transfer to object No. 2. For this purpose the application of impulse $\overline{\Delta V_1}$ provides the active SV with a transition from the orbit of object No. 1 to the drift orbit (by the impulse here are meant, as a rule, two propulsion activations located at one revolution). As soon as the required orientation of the drift orbit’s plane and required phase angle are reached, impulse $\overline{\Delta V_2}$ is to be applied, so the active SV is transferred to the specified point at the orbit of object No. 2, to provide a TDK with an opportunity to be inserted into the nozzle of object No. 2. Further, the described actions are repeated in the form of impulses $\overline{\Delta V_3}$ and $\overline{\Delta V_4}$ to reach the object No. 3, etc. This order of actions was applied to the first three distinguished LSSD groups; the results of calculations are given in [1].

Multiple intersections of straight lines $\Delta\Omega_{ik}(t)$ at the RAAN deviations' evolution portrait may be used to propose another approach while creating the plan of flyby mission [6]. The intersection point of two lines $\Delta\Omega_{ik}(t)$ and $\Delta\Omega_{jk}(t)$ on fig. 2b corresponds with a time when the orbital planes of i^{th} and j^{th} LSSD objects have the same RAAN value. It will be enough to apply only two impulses (shown as ΔV_1 on Fig. 2b) at the revolution on which this intersection takes place and at previous revolutions to execute the transition from i^{th} object's orbit to the surroundings of the j^{th} object. So, if a line $\Delta\Omega_{ik}(t)$ intersects two another such lines then this line also represents itself the drift orbit which was specially formed before (in the first case shown above) to attain the required precession velocity. This circumstance accompanied with high intensity of intersections (LSSD group №4 and №5) allows supposing that several branches of LSSD objects could be determined so that these branches would permit to collect significant amount of the objects in a concrete group using only the involved objects' orbits themselves. The parts of the lines $\Delta\Omega_{ik}(t)$ which form the mentioned branches will be called "diagonals" below. As it was already mentioned while flying from i^{th} object to j^{th} object using a diagonal solutions one needs twice less propulsion activation; at the same time the required ΔV also decreases dramatically as soon as the most expensive RAAN correction is not being realized. The described approach was implemented in [6, 7] to calculate flyby maneuvers in groups №5 and №4.

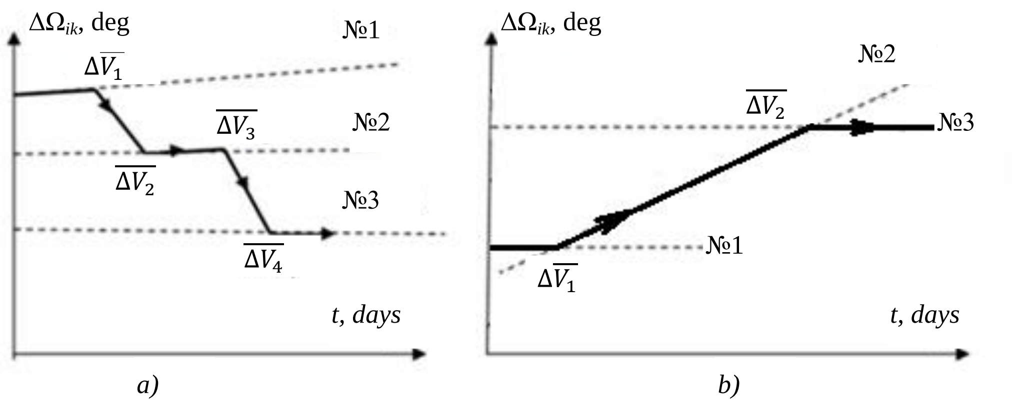

Figure 2. Possible versions of relative position of straight lines at the RAAN deviations' evolution portrait: a) orbital parameters of LSSD objects in a group have small mutual deviations of Δa, Δe and Δi; b) orbital parameters of LSSD objects in a group have considerable mutual deviations of Δa, Δe and Δi

The diagonal solution of LSSD objects flyby within a group can be obtained using the elements of graph theory. It is necessary to compose $\mathbf{T}_{i,j}$ – the matrix of $\Delta\Omega_{ik}(t)$ lines' intersections which is an analogue of classical adjacency matrix. The matrix $\mathbf{T}_{i,j}$ describes the moments of time when the orbital planes of i-th objects coincide with the orbital planes of j-th objects in terms of the RAAN. The matrix **T** is symmetrical and its main diagonal consists of «∞» symbols which describe the coincidence of lines $\Delta\Omega_{ik}(t)$. If the intersection point of two lines $\Delta\Omega_{ik}(t)$and $\Delta\Omega_{jk}(t)$exists then it's temporal coordinate t is to be put as a value of $t_{i,j}$ matrix element. If there are no intersection points (or this intersection takes place when $t \to \infty$), then there is a '–' symbol instead of the element. The search of diagonal solutions is being executed using the iteration algorithm which permits to run through the graph's nodes. The solutions selected from variety of the detected branches should be in accord with the following criteria:

- graph's nodes must be situated in interval of values $\Delta\Omega_{ik} \in (-\pi; +\pi]$;
- the direction of growth of the branch must be the same as the direction of growth of t;
- each straight line $\Delta\Omega_{ik}(t)$ can be used only once;
- while comparing two branches the longest one is given a higher priority;
- if two branches have the same length the priority is given to that which is characterized by the smallest value of sum of angular coefficients of the $\Delta\Omega_{ik}(t)$ lines involved.

The flight duration to the next LSSD object in case of the diagonal solutions is entirely fixed by the distance between intersection points of the lines $\Delta\Omega_{ik}(t)$ at the RAAN deviations' evolution portrait.

4 OBJECTS' FLYBY USING SECOND DE-ORBITING SCHEME

The following sequence of operations is to be performed while executing a flight between two LSSD objects using the second de-orbiting scheme. As soon as an SV-collector is launched into the surroundings of the object #1, approach and capture operations take place. Then, with one or two braking transversal velocity impulses, the transfer of the coupling “SV-collector + LSSD object” is carried out from the orbit of object #1 to the elliptical or circular DO of object #1. The calculation of such impulses does not involve difficulties. After the DO is formed, object #1 is separated from an SV-collector, which also stays at this DO#1 for a while waiting for the orbital plane of this DO and the orbital plane of the next object to become congruent by the value of the RAAN. At the moment when the values of the RAAN are approximately equal, an SV-collector executes series of maneuvers to reach the surroundings of the object #2. Afterwards the described actions are repeated. The orbital planes' congruence in terms of the RAAN corresponds to the intersection between the lines of $\Delta\Omega_{ik}(t)$ and the line of $\Delta\Omega_{i-1,k}^{DO}(t)$ representing relative dynamics of the DO of the previous object on the RAAN deviations' evolution portrait. Having the functions (close to linear) of $\Delta\Omega_{ik}(t)$ for each object's orbit in a group and functions $\Delta\Omega_{ik}^{DO}(t)$ for all DOs [8], it is possible to determine the duration of a collecting SV's staying at each DO in t – $\Delta\Omega$ coordinates (on fig. 1a it will be time intervals between the intersections of solid lines and the dotted line, corresponding to the concrete DO).

5 SELECTION OF THE DISPOSAL ORBITS

According to IADC guidelines, an SV should stay at a low DO for no more than 25 years. It is possible to classify two main types of DOs. In the first case an SV executes a braking velocity impulse in apocentre and forms an elliptical orbit with its pericentre situated in the upper atmosphere. The second case includes an application of two braking impulses in apocentre and in pericentre to form a circular orbit entirely situated in the upper atmosphere. The first type of DO requires less fuel compared to the second one. However, the DO's apogee remains in the functioning area of other SVs for a period of time. The usage of a circular DO immediately ensures the object's removal out of the functioning area of active SVs. The altitude of a circular DO is higher than the pericentre's altitude of an elliptical DO.

A special software “TRACE” was used to determine the parameters of DOs for all the LSSD groups in this article. The software is based on the numerical-analytical theory of orbital dynamics THEONA developed in Keldysh Institute of Applied Mathematics of RAS [9]. A "25 years" criterion was used to find the parameters of DOs.

Table 2 contains the values of radii of circular DO for each group (**R**, km) and semi-major axes and eccentricities for elliptical DOs. These data were obtained by considering an LSSD object with an average value of the ballistic coefficient equal to 0.045. This value is typical for the last stages of launch-vehicles. The initial date of propagation was 01 December 2013. The parameters *Min* **a** and *Min* **ecc** from Table 2 are the values of semi-major axis and eccentricity of the disposal orbit which should be selected for the initial orbit with minimal value of semi-major axis within a group. The parameters *Max* **a** and *Max* **ecc** correspond to the initial orbit with maximal value of semi-major axis within a group. For example: in the group #1 the semi-major axes interval is 7193-7281 km. Therefore, the left value is 7193 km. The elliptical DO will have the following parameters: *Min* **a**=7000.3 km and *Min* **ecc**=0.02760. The right value is equal to 7281 km, and therefore the elliptical DO will have the following parameters: *Max* **a**=7040.3 km and *Max* **ecc**=0.03420. Parameters of other DOs of the objects whose semi-major axes are located inside 7193-7281 km interval can be obtained using linear interpolation.

Table 2. Main DO's parameters for LSSD groups in LEO

i, °	**a**, km	**R**, km	*Min* **a**, km	*Min* **ecc**	*Max* **a**, km	*Max* **ecc**
71	7193-7281	6912.7	7000.3	0.02760	7040.3	0.03420
74	7122-7152	6912.8	6969.6	0.02194	6981.9	0.02436
81	7211-7262	6913.1	7007.5	0.02911	7030.5	0.03292
83	7318-7358	6913.5	7056.7	0.03709	7075.6	0.03991
97-100	6973-7500	6915.4	6937.6	0.02434	7090.4	0.03316

6 THE COMPARISON OF TWO DE-ORBITING SCHEMES

The main results of the flyby maneuver calculation for all five LSSD groups using the second scheme are given in Table 3. The same Table also contains data for the flyby missions using the first de-orbiting scheme. The second column describes the number of objects which constitute the concrete group. The columns 3 and 4 represent ΔV and time required to cover the group; the first value in each column corresponds to the flyby using the I scheme, the second value – to the flyby using the II scheme.

The flyby missions for the emphasized LSSD groups using both schemes were previously studied in papers [1, 6, 7 and 8]. There was a prototype SV executing flights between LSSD objects and carrying detachable de-orbiting units (TDK) onboard, described as an example in [2]. The characteristic properties of the vehicle was 2000 m/sec velocity reserve and 7 detachable units onboard. It was assumed to launch special warehouses with the same parameters for re-supply operations.

While carrying out flyby missions using the second scheme and elliptical DO, the total ΔV will be 2.4 and 1.5 times bigger than the result of using the first scheme for LSSD groups #1 and #3, respectively. As for the group #2 the ΔV is approximately the same for both de-orbiting schemes. The flyby time for group #1 is 2.8 times less for the second scheme; the mission durations for groups #2 and #3 are pretty the same while using both schemes.

In case of the 5th group the flyby mission realization using the I scheme requires 1.5 times less ΔV in comparison with the II scheme, but three single SV-collectors will be involved. The operation time for each SV is at least half less than the time required to cover the 5th group using the II de-orbiting scheme.

In case of the 4th group the flyby mission realization using the I scheme requires half less ΔV in comparison with the II scheme, but again three single SV-collectors will be involved. The operation time for each SV is comparable with the time required to cover the 4th group using the II de-orbiting scheme.

Table 3. Comparative characteristics of the I and the II de-orbiting schemes

Group number	Quantity of objects	Total ΔV, m/sec	Flyby duration, days	Required SV for the I scheme
1	*2*	*3*	*4*	*5*
1	23	2233 / 5207	3318 / 1206	1 SV+2 (1) Refuel
2	11	1540 / 1834	1570 / 1718	1 SV+1 (0)
3	28	4213 / 6291	3744 / 3179	1 SV+3 (1) Refuel
4	12	540	3148	1 SV+1 (0) Refuel
	10	358	3522	1 SV
	30	7218	2180	1 SV+3 (2) Refuel
4_Σ	52	8116 / 14834	8850 / 2928	3SV+4 (2) Refuel
5	18	1891	2942	1 SV+2 (1) Refuel
	12	767	3476	1 SV+1 (0) Refuel
	16	4450	1723	1 SV+1 (0) Refuel
5_Σ	46	7108 / 11194	8141 / 7970	3SV+4 (1) Refuel
Σ	160	23210 / 39360	25623 / 17001	9 SV+14 (5) Refuel

7 CONCLUSIONS CONCERNED WITH FLYBY OF ALL THE FIVE LSSD GROUPS

1. Five compact LSSD groups were emphasized in LEO. These groups are constituted by the objects whose orbits have approximate inclinations.
2. The RAAN deviations' evolution portrait built for the specific LSSD group represents an effective tool while carrying out the analysis of mutual distribution of objects' orbital planes within a group. Identifying the optimal flyby sequence has also proved useful.
3. The tendency to design a platform with 25 and more TDK onboard within the framework of the development of the I scheme is in correct as it is impossible to cover this number of objects using a single charge of fuel and TDK. On the other hand, the quantity of TDK which was suggested in the article [2], 6-7 units onboard the single SV-collector or warehouse, is evidently not enough. If the quantity of TDK is increased up to 11-12 units, the required number of warehouses to cover all groups will be decreased from14 to 5 (data in brackets taken from the last column of the Table 3).
4. In case of the first three LSSD groups, the short mission duration is the only advantage of the II scheme (except group #2) whereas this scheme is inferior to the I scheme in terms of ΔV and the required number of resupplies.
5. The II scheme can be realized to complete the flyby mission for the group #2 as optimization of the de-orbiting technology because both de-orbiting schemes are equivalent for this group in terms of required SV-collectors, energetic and temporal costs.
6. The significant flyby duration (close to 10-12 years) is the only disadvantage of diagonal solutions (1st scheme) applicable to groups №4-№5 [6]. This happens because of relatively small difference in the precession velocities of involved orbital planes within the framework of the concrete group.
7. In case of group #5, the I scheme gains 1.5 more in the required ΔV and twice in mission duration. Speaking about the group #4, the I scheme has an advantage (double) only in terms of ΔV.
8. It is enough to use 9 SV-collectors and additionally 5 resupplies described in [2] to cover all the five LSSD groups (160 objects) in case of using the I scheme.
9. A minimum of two SV-collectors functioning at the same time in LEO are required to ensure the recommended de-orbiting rate of LSSD objects.
10. The clean-up problem for LEO should be solved comprehensively: SV-collectors should operate simultaneously inside several LSSD groups.

8 ACKNOWLEDGEMENTS

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