MEASURES UNDERTAKEN BY THE RUSSIAN FEDERATION FOR MITIGATING ARTIFICIAL SPACE DEBRIS POLLUTION

V. Davidov[1], S.Kulik[1], M.Mikhailov[2], S.Chekalin[2], M.Yakovlev[2] Yu.Bulinin[3]

[1]Roskosmos 41, Pionerskaya Str., Moscow 129857, Russia
[2]Central Research Institute of Machine Building, 4, Pionerskaya Str., Korolev, Moscow Region, 141070 Russia
[3]Federal State Unitary Enterprise "Scientific and Production Association of Applied Mechanics" (NPO PM), 20, Molodezhnaya Str., Zheleznogorsk-2, Krasnoyarsk Region, 662990 Russia

ABSTRACT

The report briefly describes the study results of the near-earth space artificial debris population and measures the Russian Space Branch has been undertaking for the last decade for preventing the space debris population growth. In particular, the state-of-the-art of polluting the near-earth space with man-made debris has been reviewed with the analysis of space debris generation sources and debris distribution on orbits.

The causes and statistics of spent S/C and SLV stage fragmentations are scrutinized. The rules of using GEO, high circular and low earth orbits aimed at assuring environmental safety in terms of space debris are analyzed with the assessment of the degree they are being currently observed. The Report gives a forecast of near-earth space pollution with Russian rocket and space technology objects up-to 2015 and specifies definite measures to mitigate space debris population as per the IADC-elaborated governing strategy for preventing space debris generation growth [1].

NEAR-EARTH SPACE POLLUTION WITH MAN-MADE DEBRIS

The problem of polluting space with space debris fragments has acquired a global character. The risk of collision with orbital fragments is becoming a serious threat to the space flight safety.

The first officially registered space object collision occurred on July 24, 1996. French satellite #23606 (50 kg mass, 670 km orbit) collided with an Ariane SLV fragment. The collision velocity was 14 km per sec. The spacecraft failed hence jettisoning a large observable fragment of its gravity-stabilizing boom.

There occurred repeated dangerous approaches of large space debris fragments to the manned Orbital Stations. For instance, on November 8, 1992 a spent 500kg satellite flew by the MIR Station at the 300m distance at the relative to the Station speed of 12.7 km/sec. It was Kosmos-1508 satellite launched in 1983. On September 15, 1997 the MIR crew moved to the Soyuz recoverable module at the predicted time of its dangerous approach to American MSTI-2 satellite. Whereas on June 17, 1999 an uncontrolled spent stage of the Soyuz SLV came near ISS at the distance of less than 7 km. Therefore to solve the problem associated with man-made space debris pollution of near-earth space requires a substantial information support and effecting of necessary preventive measures.

Currently low earth orbits are populated by about 9000 trackable (cataloged) objects of artificial origin measuring 10-20cm or more and only 6% of the number is active spacecraft, while the rest are space debris fragments: spent spacecraft, SLV final stages, boosters, jettisoned structure elements like adapters, explosive bolts, fairing covers, etc. But the main sources of in-orbit space debris generation are S/C and SLV stage explosions which account for almost half of the cataloged objects and major amount of untrackable but dangerous in terms of collision small-size fragments: tens of thousands of space debris fragments measuring 1-10cm and hundreds of thousands of still smaller (< 1cm) artificial-origin fragments.

The highest concentration of space debris fragments is observed in LEOs within the 400 to 1600km altitudes (up-to 70%), i.e. just the zone the major part of unmanned spacecraft and space station fly in. GEO accounts for over 10% of cataloged objects (964 objects, out of which 323 objects are operating S/Cs), but the cataloged object dimensions are not more than 0.7-0.8m, because smaller objects can not be tracked by the ground observation facilities due to their performance characteristics.

SPACE OBJECT FRAGMENTATION CAUSES AND PREVENTION MEASURES

Analysis of the Space Object Fragmentations Catalog compiled by the Johnson Space Center (JSC) (USA) [2] shows that for the period of October 1957 to December 2003 there were 186 space object explosions. A large percentage of fragmentations accounted for by Russian space objects is conditioned by a great S/C launch number of the FSU and technological imperfection of SLV stages and spacecraft in terms of their in-flight fragmentations prevention in an unpowered flight, e.g. prevention of explosions of the SOZ engine blocks of the DM booster.

51.5% of spacecraft and 48.5% of SLV stages were subjected to fragmentation including 15% of the SOZ engines. Table 1 depicts the main causes of explosions and their specific contribution to space object fragmentations.

Table 1

Space object fragmentation causes	Number of explosions	% of total number of explosions
Propulsion systems	58	31
Chemical batteries	8	4.5
Intended fragmentations	54	29
Aerodynamic fragmentations	14	7.5
Collisions with space debris	1	0.5
Unknown reasons	51	27.5

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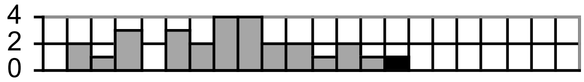
Analysis of the space object explosion change graphs over years and in their numbers with reference to the launch years shows that the space object explosion rate still remains at the previous level (4-5 explosions a year), but this rate is conditioned mainly by the explosions of previously launched objects.

Relying on the analysis of Russian space object fragmentations it is possible to state the following causes as typical ones:

1. Explosion of a pressurized container enclosing buffer chemical batteries due to the failed charger and depressurization of the batteries (Ekran-2, Kosmos-1275, Kosmos-1823 and other S/Cs).
2. Explosion of the liquid-propellant propulsion system containing unused hypergolic propellant components under long-term space environment effects (SOZ engine for the DM booster during launches of Astron S/Cs, spacecraft of the Gorizont and Kosmos series).
3. Modifications of the design without scrutinizing their consequences. As an example, the vent pipeline mounted in the tail section of the Zenit 2nd stage brought about rotation of the stage's separated part in orbit. The remaining oxygen poured over the oxidizer tank safety valve; as a result the valve was "frozen up" and when the pressure grew the tank exploded (Zenit 2nd stage during launches of Kosmos-2227 and Kosmos-2237 spacecraft).
4. Intended explosions of spacecraft in an emergency or explosions for destroying classified information carriers. Made as a rule in LEO with generation of short-lived fragments (emergency and defense-oriented spacecraft).
5. Proceeding from the analogous reasons and with the aim of preventing space object fragmentations after their active service life end all the onboard
6. sources of accumulated energy as well as remaining propellant components, batteries, pressure cylinders, self-destruction appliances, fly wheels and gyroscopes must be passivated, i.e. their energy should be spent and they themselves be in put in a safety state.
7. For the last 8-9 years the Russian Rocket and Space Corporations have been undertaking measures to minimize the number of explosions and mitigate their danger in terms of space pollution with artificial fragments. In 1995 intended S/C fragmentations were replaced by aerodynamic methods of getting rid of space objects. Since April 1996 jettisoning of both SOZ engines of the DM booster during GTO commercial launches has been banned with obligatory and complete use of their fuel in the "negative stabilization" mode or otherwise when launching spacecraft in LEO the booster with its DOZ engines splashes down. In 2003 an updated DM-03 booster version was designed excluding jettisoning and explosion of the SOZ engine blocks during federal S/C injection directly in GEO. Reduction of the total number of launches due to prolongation of the spacecraft lifetime contributes to reduction of the Russian spacecraft explosions number.
8. Fig.1 shows the graphs of changes of SOZ engine explosions number over years with reference to their launch years. It follows from the graphs, that the explosions of SOZ engine blocks since 1996 refer to the blocks launched before that time being operated by the old technology except the block exploded in 1999 (the given block was launched in 1996 with a federal spacecraft, but was operated by the old technology as well).

Number of explosions over years



- with reference to their launch years

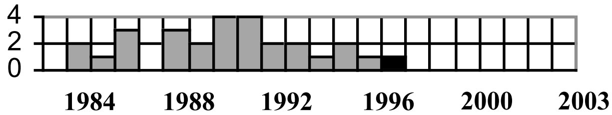


Fig. 1 Change of SOZ engine explosion number

MEASURES FOR ASSURING GEO SAFETY USE

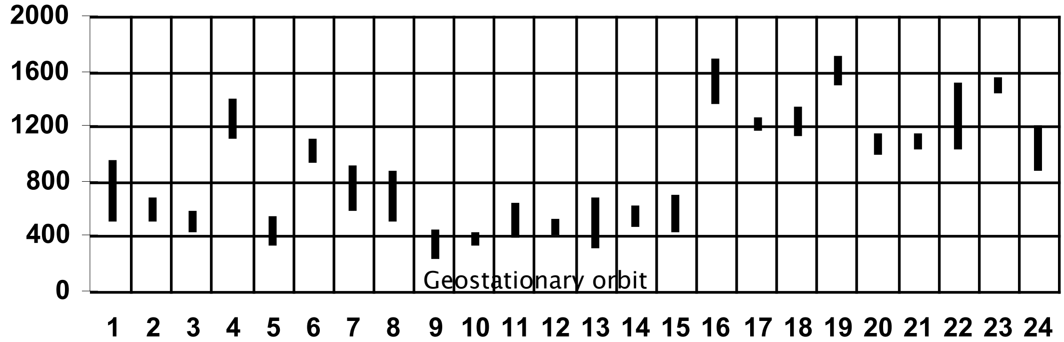
Though officially the 2 explosions of GEO space objects (Ekran-2 – June 1978 and Titan IIIC SLV stage – February 1992) have been registered, it is possible to suppose by analogy with the LEO fragmentations statistics having no observation data on space debris measuring < 0.7-0.8m that the virtual number of GEO fragmentations is substantially higher.

The Institute of Astronomy of the Russian Academy of Science made an attempt (turned out to be rather efficient) to detect spontaneous disturbances in the orbit elements of GEO spent spacecraft which could be interpreted as an explosion or collision with another object. It may be indirectly confirmed by several registered events of GEO spacecraft depressurizations (one of the reasons mentioned – spacecraft collision with a space debris fragment). For this reason there may be a great number of small space debris fragments populating GEO.

A priority mission of tackling the problem of GEO space debris is to remove spent S/Cs to a burial zone at the altitude of more than 235km, the latter to be found by the IADC-deduced formula, with their consequent passivation for reducing the number of potential space debris generation sources in the GEO operation zone. This Recommendation was agreed upon with the International Telecommunications Union (ITU), but practically the Recommendation is being followed unsatisfactorily by many countries to include Russia.

Earlier the Russian GEO spacecraft were removed from the orbit using the remaining propulsive mass. So far twenty four GEO spacecraft have been disposed of and in some cases the remaining fuel was enough to remove a spacecraft above GEO by 1400-1600 km (Fig.2). At the same time 60 spent and passivated DM boosters fly out of the orbit operation zone due to implementation of the adopted S/C GEO injection patterns.

The reason why many Russian spacecraft haven't been removed from GEO since the mid-90ies is that the orbital constellations have not been replenished with new spacecraft timely. Due to this the spacecraft have been operated for two and more periods of guarantee. Operation of a spacecraft is not terminated by an operator's decision. Instead, the operation ends when a



List of spacecraft (international number) transferred from GEO

1. _ 82113_	7. _ 87040_	13. _ 82020_	19. _ 85024_
2. _ 83088_	8. _ 88028_	14. _ 83066_	20. _ 86038_
3. _ 86082_	9. _ 89004_	15. _ 83118_	21. _ 87073_
4. _ 87028_	10. _ 91046_	16. _ 83016_	22. _ 87109_
5. _ 89048_	11. _ 91074_	17. _ 84028_	23. _ 88036_
6. _ 86090_	12. _ 80049_	18. _ 84090_	24. _ 88108_

Fig.2 Positions of GEO spacecraft removed from GEO (as per data of October 2004)

spacecraft is lost because of the complete failure of its telemetry system or because of the spacecraft irrevocable twist and similar reasons. Besides that due to ill-timed injections of new spacecraft in orbital positions declared by Russia the task of transferring "old" spacecraft to other longitudes became acute. Therefore most likely there are no any fuel reserves for removal of many still operating spacecraft. But this reason is temporary.

Fuel reserves onboard future GEO spacecraft of the SEASAT, Express-A, Yamal-200 have been provided for their removal when the spacecraft are spent. However, as the practice of operating GEO spacecraft shows the accuracy of determining the remaining propulsive mass of the engine still presents a problem. The matter is that that the engine propulsive mass reserves needed for transferring a spacecraft up-to 235 km (1.3-1.5% of the total reserve) are commensurate with the error of remaining fuel determination (± 1%).

ANALYSYS OF INTERACTION OF SATELLITE NAVIGATION SYSTEMS OF GLONASS AND GPS TYPES

Lately the IADC Committee launched within its framework discussions of the issues of probable interaction of the multi-satellite GLONASS (Russia) and GPS (USA) navigation systems brought about by evolution of their high circular orbits (Hcr 19140km and Hcr 20100 km accordingly) [ ].

As a result of a long-term prediction it was established that the GLONASS orbit could intersect that of GPS. It may take place due to the eccentricity growth. Therefore though the GLONASS circular orbit altitude is 1000 km lower than that of GPS the GLONASS spacecraft apogee may turn out to be higher than the GPS orbit. They reviewed the possibility of changing the GLONASS orbit inclination plane by a few degrees thus enabling to prevent the stated effects.

The above-mentioned analysis demonstrated that for 40 years the GLONASS orbit apogee would grow up to the GPS orbit altitude with the original eccentricity of no less than 0.01. This is a maximally tolerable eccentricity of the GLONASS orbit. The virtual eccentricity is lower by an order of magnitude and the GLONASS spacecraft apogee would reach the GPS orbits not earlier than in 300 years. At the same time a change of the GLONASS orbit inclination during SLV launches is hampered because these launches are tied to the agreed SLV jettisoned parts fall areas. In case the inclination is altered during the spacecraft removal from the transfer to the target orbit the transfer pattern is complicated and the launched payload mass is reduced. If the inclination is changed by 5 degrees the payload mass loss will be 50-60 kg.

At the same time the comparative analysis of the orbit parameters of GLONASS and GPS active spacecraft (the spacecraft enumeration is given in accordance with Table 2) shows that the GLONASS S/C altitudes are substantially lower (by more than 900 km) than the nominal altitude of the GPS circular orbit. And the perigee altitudes of some GPS spacecraft are two times closer (approximately 450 km) to the GLONASS S/C orbit zone.

Evolution of the perigee altitude of GPS S/C 78047A, inactive now and having in 2004 the eccentricity of 0.03 shows that by 2008 the perigee altitude of the given S/C would reach the GLONASS orbit altitude.

With the years passing the trend to approach would be mutual. But the lower is the eccentricity a spacecraft has by the end of its active life the slower this tendency would be building up. According to the tentative evaluation if a spacecraft ends its active lifetime with its eccentricity at the level of 0.001-0.005 it would enable to exclude the possibility of mutual approach for a period of 200-400 years.

In association with the above-stated considerations it would be more expedient not to alter the orbit plane inclination, but to keep the orbit eccentricity of the GLONASS and GPS spacecraft for their operation term at the level of <0.005. The given requirement is met as concerns the GLONASS spacecraft.

Table 2

GLONASS S/C		GPS S/C					
_	International number	_	International number	_	International number	_	___________. ______
30	98077_	1	89044_	12	93007_	23	97067_
31	98077_	2	89097_	13	93017_	24	99055_
32	00063_	3	90068_	14	93032_	25	00025_
33	00063_	4	90088_	15	93042_	26	00040_
34	00063_	5	90103_	16	93054_	27	00071_
35	01053_	6	91047_	17	93068_	28	01004_
36	01053_	7	92009_	18	94016_		
37	01053_	8	92039_	19	96019_		
38	02060_	9	92058_	20	96041_		
39	02060_	10	92079_	21	96056_		
40	02060_	11	92089_	22	97035_		

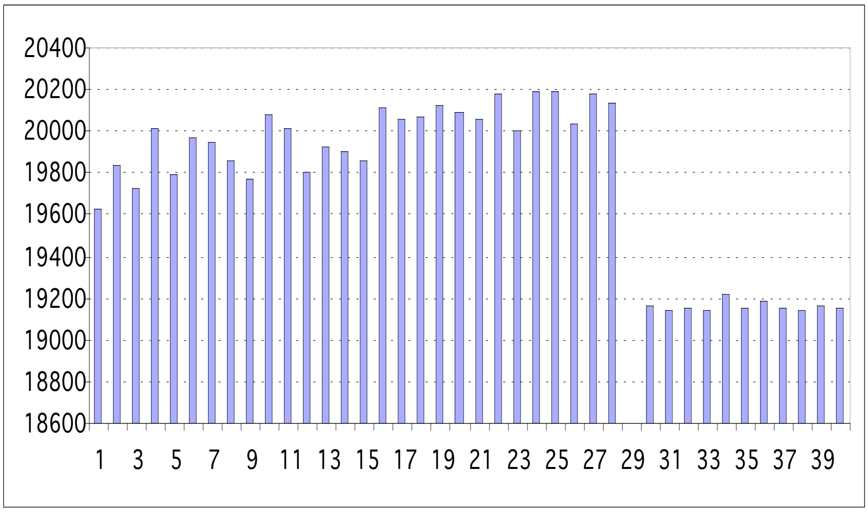


Fig.3 Perigee altitudes of GPS S/C (S/C 1 through28) and GLONASS S/C (S/C 30 through 40)

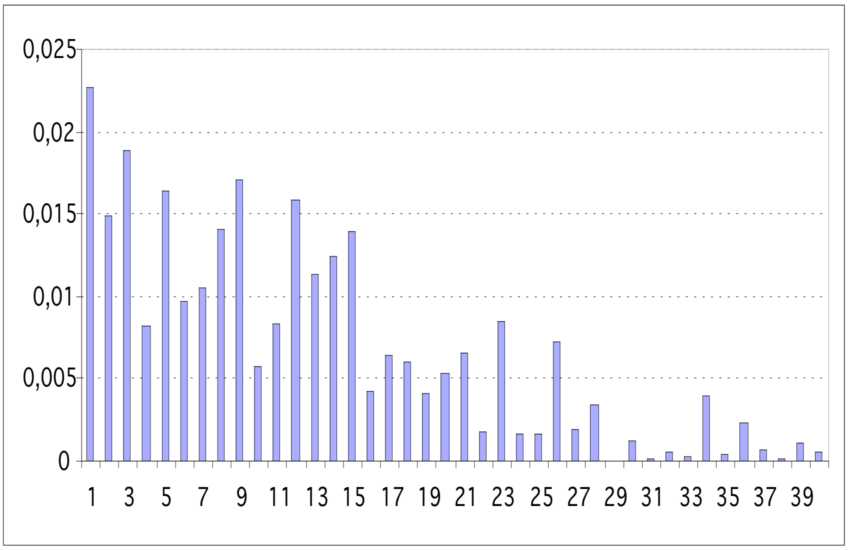


Fig.4 Orbit eccentricities of GPS S/C (S/C 1 through 28) and GLONASS S/C (S/C 30 through 40)

MEASURES TO MITIGATE LEO SPACE DEBRIS POLLUTION

The long-term forecast of LEO pollution with space debris fragments measuring >10cm (up-to 2100) relying on the foreign models [ ] demonstrates that if the present rates of space debris grows remain as they are now (on condition no measures to mitigate are not undertaken), then the number of LEO space debris fragments would increase by 5-8 times, while the number of collisions with them would grow up-to 40-60 events. According to this forecast termination of explosions and removal of spent spacecraft and boosters from their orbits would substantially diminish the space debris population and the number of collisions in LEO.

It is possible with due regard for the experience of applying the Russian space debris model to comment the obtained modeling product as follows.

The measures of transferring spent S/C and boosters from their operation orbits to orbits of the 25 year lifetime are beyond any doubt in terms of LEO space debris mitigation.

As for stabilization of the collisions number, there is no full clarity in the given problem. By our estimations currently collisions of object of different sizes make a considerable contribution to LEO pollution with small-size fragments (measuring <0.5cm). With the time passing the role of this pollution source would grow. This pollution source was not taken into account when the above-said modeling was performed (its role is underestimated).

Another remark concerns the summary evaluation of the collisions number of space debris fragments measuring >10cm for a 100 year forecast period. According to the Russian modeling product on condition the mitigation measures were not undertaken, this number is two times less than the averaged number of collisions found applying the foreign models.

So, the foreign models have a substantial “deviation” in assessments of the collisions number: the contribution of large object collisions is overestimated, while the contribution of space debris fragments of different sizes among the small-size fragments population is underestimated.

In all cases the transfer of spacecraft and boosters to the 25-year lifetime orbits (perigee lowering with passivation) if to compare this procedure with their recovery to the Earth results in the buildup of objects concentration at the manned flight altitudes. Judging by the modeling data this buildup would be insignificant for the coming 20 years, but in 100 years the objects concentration would grow by 2-3 times. These assessments need to be specified, but one can agree with the Recommendation that utilization of the Control System data and procedures for preventing collisions would diminish the said collision risk for manned space missions.

Transfer operations are to be carried out taking into account the capabilities available and require specific modifications of spacecraft and boosters. For instance, to transfer a spacecraft of the Gonets type flying in the 1500 km circular orbit to a parking orbit for a time of 25 years or less ($H\pi/H_=350/1500$km) would require a deceleration impulse $_\bar{V}x=286$m/s thus consuming an extra propulsive mass reserve exceeding many times the reserves provided in the spacecraft design. Naturally realization of such a transfer procedure is applicable only to a modified spacecraft. Therefore to meet the requirements for a spent spacecraft transfer to a parking orbit it would be necessary to specify trade-off approaches both in terms of lowering the maximum removal altitudes and tolerable times of launching this operation as applied to specific objects.

SPACECRAFT AND SLV LAUNCHES PREDICTION UP TO 2015 AND MITIGATION MEASURES

The S/C launches prediction under the Federal Programs of Russia for the period of up to 2015 (Table 3) shows that the expected average annual number of S/C in-orbit injections runs to about 33 objects, while the average annual number of SLV launches is within 26 launches. In this case according to the prediction the distribution of Russian spacecraft launches in orbits is as follows: 68% - LEO ($H \leq 1500$ km); 18.5% - high elliptical and high circular orbits; ~ 12% - GEO and 1.5% - departure trajectories.

Table 4 gives the measures for mitigating the near-earth space pollution with Russian rocket and space technology objects. The preliminary assessment of the efficiency of the measures undertaken in comparison with the old technology of operating spacecraft and launch capabilities shows that these measures would reduce more than twice the population of spent rocket stages and S/C in orbits and actually would prevent their explosions in space.

The first-priority countermeasures already being undertaken in this direction by many nations including the Russian Federation have enabled to somehow slow down the growth of space pollution with man-made fragments. But this is an insignificant advance in solving this global problem. We are facing a long-term, multi-task work to be done before the new technologies of environmentally safe operation of rocket and space assets are fully realized.

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PREDICTION OF RUSSIAN S/C AND SLV LAUNCHES UNDER FEDERAL PROGRAMS FOR THE PERIOD OF UP TO 2015

Table 3

Orbit type	Number of launched S/C (SLV launches)					
	2004-2005	2006-2010	2011-2015	∑ КА (РН)	∑ КА+РН	~%
Low circular H≤600km	30(28[x])	72(68[x])	66(60[x])	168(156[x])	324	45,4
600km<H≤1000km	7(7)	16(14[x])	17(15[x])	40(36[x])	76	10,6
1000km<H≤1500km	12(4[x])	21(7[x])	30(10[x])	63(21[x])	84	11,8
	49(39[x])	109(89[x])	113(85[x])	271(213[x])	484	67,8
High elliptical 600-1600km/39000-40000km	6(6)	17(17)	12(12)	35(35)	70	9,8
500-2000km/80000-200000km	-	3(3)	2(2)	5(5)	10	1,4
	6(6)	20(20)	14(14)	40(40)	80	11,2
High circular H=19100km	6(2[x])	20(9[x])	10(5[x])-	36(16–)	52	7,3
GEO	9(9)	26(18[x])	14(12[x])	49(39[x])	88	12,3
Departure, injection in libration points L4, L5	-	3(3)	2(2)	5(5)	10	1,4
∑	70(56[x])	178(139[x])	153(118[x])	401(313[x])	714	100

* – piggyback launches included

MEASURES FOR MITIGATING SPACE POLLUTION WITH RUSSIAN ROCKET AND SPACE TECHNOLOGY OBJECTS

Table 4

Orbit type	Space object launch prediction, %	Measures*
Low circular	67,8	Self-cleaning under atmosphere effect Removal from operation orbit directly into upper atmosphere or transfer to parking orbit (<25 years) applying LPE deceleration impulse and passive deceleration system
High elliptical	11,2	Lowering of spent boosters and S/C orbit perigee altitude by LPE deceleration impulse Change over to modified DM-03 booster without SOZ engine jettisoning and explosion
High circular	7,3	Obligatory study of man-made fragments pollution of high circular orbits and rules of their use within the IADC framework
GEO	12,3	Disposal of spent GEO S/Cs in burial zone applying correction thrusters To transfer spent boosters to burial zone or orbit below GEO zone
Departure	1,4	Same measures as mentioned in the graph “Low circular orbits” concern SLV final stages (after booster separation)

*In-orbit jettisoning of functional elements of all spacecraft is excluded and they are to be passivated, if their stay in space is expected to be long.