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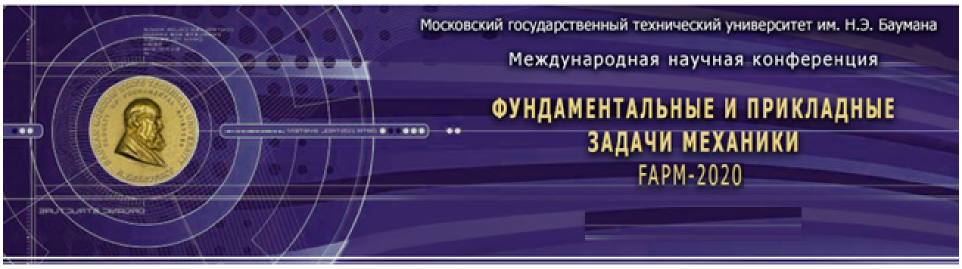
Составители: П.М. Шкапов, М.И. Дьяченко



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THE MATERIALS OF THE CONFERENCE

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End-of-life disposal in inclined geosynchronous orbits

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Abstract. Significantly Inclined Geosynchronous Orbits (IGO) are currently considered for various applications, like satellite navigation systems, intelligence and telecommunications. In the light of these developments, the aim of this report is to review the current definition of the Geosynchronous Protected Region, assessing if it would need an extension. Special attention is paid to the end-of-life disposal, in order to check the potential weaknesses of the current IADC formula and re-orbiting recommendations, focusing on the consequences of having operational orbits characterized by medium or high inclinations.

Keywords: *inclined geosynchronous orbits (IGO), end-of-life (EoL) disposal, space debris, geosynchronous protected region, IADC formula.*

The first version (2002) of the Mitigation Guidelines issued by the Inter-Agency Space Debris Coordination Committee (IADC) defined a toroidal Geosynchronous Protected Region, extending 200 km below and above the geosynchronous altitude of 35 786 km, and spanning latitudes in between −15° and +15° with respect to the Earth equator. A formula was also proposed (slightly amended in 2007) for the appropriate end-of-life disposal of spacecraft, in order to guarantee no further interference with the protected region over the long-term.

These definitions were elaborated when the nearly exclusive utilization of the geosynchronous region consisted of geostationary satellites placed and maintained, during their operational lifetime, close to the Earth equator. When finally abandoned, due to the concurring action of geopotential and luni-solar perturbations, such objects displayed a characteristic periodic orbit plane evolution, with a period of about 54 years and a maximum inclination of about 15°.

However, significantly Inclined Geosynchronous Orbits (IGO) are currently considered for various applications, like satellite navigation systems, intelligence and telecommunications. In the light of these developments, the aim of this presentation is to review the current definition of the

Geosynchronous Protected Region, assessing if it would need an extension. Special attention was paid to the end-of-life disposal, in order to check the potential weaknesses of the current IADC formula and re-orbiting recommendations, focusing on the consequences of having operational orbits characterized by medium or high inclinations.

The original IADC guideline for the end-of-life re-orbiting of spacecraft and orbital stages above the geosynchronous altitude, with $h_0 = 235$ km, was devised for objects close to the geostationary ring and resulted strictly valid, irrespective of the orbital and celestial initial conditions, for $i_0 \leq 2°$, and applicable in most cases for $i_0 \leq 10°$.

The potential growing use of geosynchronous orbits with higher inclinations has raised the problem of what strategy to adopt at the end-of-life for these new classes of objects. For $i_0 \leq 30°$, it was shown that an effective extension of the IADC formula would be possible by just increasing the value of h_0 as a function of i_0, with a maximum of 550 km for $i_0 = 30°$. This possibility arises from the fact that, despite the complexity of the perturbations acting on such orbits, the eccentricity would remain bounded to sufficiently low values for at least 200 years, irrespective of the orbital and celestial initial conditions. With $i_0 = 30°$ and $h_0 = 550$ km, no crossing of the geosynchronous protected region would occur, over 200 years, even in the less favourable combinations of orbital (Ω_0 and ω_0) and celestial (Sun and Moon position) initial conditions. It should be however pointed out that very often it would be possible to avoid any further long-term interference with the protected region adopting significantly lower values of h_0, being those found just the values able to guarantee the fulfilment of the guideline goal even with the worst initial conditions.

The cost of implementing the extended IADC formula, in terms of additional ΔV to be delivered by the propulsion system and mission impact, would not be negligible, but affordable. With $i_0 = 30°$, the maximum additional ΔV penalty would be 11.5 m/s, approximately doubling the cost currently incurred to apply the original IADC formula to nearly geostationary satellites.

This approach will not be instead generally applicable for $i_0 > 30°$. Reducing the initial inclination and/or changing the initial right ascension of the ascending node of the disposal orbit would be of course too much expensive and unfeasible, not to mention the Moon and Sun positions. Even choosing appropriate launch times, provided it were feasible from a mission point of view, might not be so beneficial, being quite tricky the accurate prediction of end-of-life epochs several years in advance.

The problem should be therefore addressed on a case by case basis, strongly dependent as it is from the initial orbital and celestial conditions. In certain cases, it should be possible to constrain the eccentricity growth from several decades to a few centuries, in others the eccentricity would grow to values so large to cause orbital decay in several decades. For very high inclinations and appropriate initial conditions, the interaction between the Lidov — Kozai effect and the other perturbations might lead to the emergence of a dynamical protection mechanism of the geosynchronous protected region, effective at least for several decades.

As a consequence of this situation, no easy to apply, general and cost-effective end-of-life disposal solution can be recommended for the re-orbiting of near circular geosynchronous objects with $i_0 > 30°$. Nevertheless, if the total number of these objects will not grow by more than two orders of magnitude in the next century, even simply abandoning them at the end of their missions would not lead to a significant increase of the collision probability in the geostationary ring and in the geosynchronous protected region, because they would be spread in a huge volume of space by the perturbations, spending only occasional and relatively short periods of time in the most populated geosynchronous belt. However, in order to further reduce the average long-term collision probability with objects residing in the geosynchronous protected region, an end-of-life re-orbiting above the geosynchronous altitude of a few hundred km might be in any case beneficial, even with an unbounded eccentricity.

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Особенности эволюции орбит разгонных блоков в окрестности рабочих высот глобальных навигационных систем

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Аннотация. В настоящее время российские и международные стандарты регламентируют параметры орбит захоронения только в двух защищаемых зонах околоземного пространства: на низких орбитах (высоты до 2000 км) и в окрестности геостационарной орбиты. В данном докладе рассматриваются особенности долговременной эволюции орбит разгонных блоков, которые ранее обеспечили формирование/восполнение систем глобального позиционирования Глонасс, GPS, Beidou (MEO) и Galileo. После выполнения своих функций эти объекты были переведены на специальные орбиты захоронения, параметры которых отличаются для каждой из указанных спутниковых систем. Возмущения, действующие на отработавшие разгонные блоки в течение длительного времени (десятки лет), могут приводить к потере устойчивости их орбит. В результате эти крупные объекты космического мусора начинают пересекать орбиты функционирующих навигационных спутников, что создает риск возможных столкновений.

Ключевые слова: *глобальные навигационные системы, разгонные блоки, космический мусор, эволюция орбиты, орбита захоронения, устойчивость орбиты*.