ORBITAL STABILITY AND OTHER CONSIDERATIONS FOR U.S. GOVERNMENT GUIDELINES ON POST-MISSION DISPOSAL OF SPACE STRUCTURES

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ABSTRACT

During 1997, the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD), in coordination with other United States Government agencies, developed draft guidelines for debris minimization. This paper reviews the guidelines for post-mission disposal of space structures in the regimes of low Earth orbit (LEO), semisynchronous orbit (SSO), and geostationary Earth orbit (GEO) as well as the special cases of Molniya and geotransfer orbits (GTO). The cost-effectiveness of reentry and disposal orbit strategies is discussed in terms of propellant requirements, and the long-term stability of identified disposal zones is analyzed. In particular, disposal orbits near SSO are found to exhibit instabilities that could cause disposed structures to penetrate operational altitudes within 20 years of disposal. Requirements for SSO disposal orbits are proposed in light of the stability analysis. Studies of GEO disposal orbits are included for completeness.

1. INTRODUCTION

The *Interagency Report on Orbital Debris* (November 1995) [1], published under the auspices of the United States National Science and Technology Council, Committee on Transportation Research and Development, included a recommendation for the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) to build on the initial NASA work in documenting and defining specific design measures for use in spacecraft and launch vehicle development that could be applied to minimize or eliminate the generation of orbital debris. A joint set of debris mitigation guidelines or standard practices was accordingly developed by NASA and DoD in conjunction with other U.S. Government agencies. In January 1998, a workshop was held with U.S. aerospace industry representatives to discuss the guidelines [2] and the possibility of their adoption as voluntary debris mitigation measures for both government and industry. The intent of this paper is to review the guidance provided in the standard and examine the cost-effectiveness of reentry and disposal orbit strategies as well as the long-term stability of orbits in the identified disposal zones.

2. SCOPE OF MITIGATION PRACTICES

The U.S. Government mitigation standard practices cite three methods for post-mission disposal: atmospheric reentry, maneuvering to a storage orbit, and direct retrieval. The practice for atmospheric reentry is to leave the space structure in an orbit for which atmospheric drag will limit the lifetime to no longer than 25 years after mission completion. Storage regimes are defined between low and medium Earth orbits (LEO and MEO), between MEO and geosynchronous Earth orbit (GEO), above GEO, and heliocentric or Earth escape. Earth escape and direct retrieval will not be further addressed due to the greater implementation difficulty for most satellites.

The U.S. Air Force Space and Missile Systems Center Office of Development Plans (SMC/XR) sponsored three studies of end-of-life disposal guidelines published by NASA in 1995 [3]. The first study encompassed disposal orbit stability and strategy for GEO [4]. The second study was for atmospheric reentry [5], and the third for disposal orbit stability and direct reentry strategy for orbits below GEO and above LEO [6].

A mission planner is faced with choices on reentry or disposal in a storage orbit, and it is important to have technically sound guidance for selecting the means for conducting the end of mission, both in terms of cost effectiveness and assurance that end-of-life (EOL) maneuvers result in the planner’s desired outcome. Thus, in addition to analysis of the options for disposal, this paper will also provide strategies to guide the mission planner as well as requirements for EOL spacecraft disposal maneuvers.

The U.S. Government and NASA guidelines are sufficiently similar that the results of the studies apply equally well. The differences in the two sets of

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a LEO disposal region above 2000 km while the NASA guidelines set the perigee altitude for disposal orbits as above 2500 km. NASA also permits storage orbits with perigee above 2500 km and apogee below GEO by 500 km. The U.S. Government practices break disposal orbits into those below and above the semisynchronous (circular 12-hour) orbits (SSO) in order to establish a protected region for operations of missions such as that of the Global Positioning System (GPS). Another difference in treatment of the SSO region is that the NASA guidelines envision a 600 km protected altitude band (limiting perigees to 300 km below and apogees to 300 km above the SSO altitude), but the U.S. Government guidelines limit perigees to 500 km below and apogees to 500 km above the same altitude. For GEO, NASA guidelines state that the perigee of the storage orbit should be above GEO altitude by at least 300 km plus a factor of 1000 times the spacecraft area to mass ratio in m^2/kg (to account for perturbations) while the U.S. standard practices require maneuver to an orbit with perigee altitude above 36,100 km (cited as approximately 300 km above synchronous altitude).

3. GEO DISPOSAL [4]

In order to understand the long-term orbit perturbations and stability of super-synchronous orbits at 250 to 350 km above synchronous altitude, analysis and numerical integration techniques were employed to study eccentricity variations. Perturbations included sun/moon gravitational attractions and solar radiation pressure. Both the analytic and numerical techniques showed that the long-term eccentricity variations are well behaved (sinusoidal) with no secular change. The amplitude of the sinusoidal variation was found to be proportional to initial eccentricity and to have some dependence on initial argument of perigee. Very long-term (10 to 11 years) eccentricity variations resulted from sun/moon attractions, and the amplitude of annual variations due to solar radiation pressure depended on spacecraft area to mass ratio. Recommendations for GEO disposal strategy were to raise the mean orbit altitude by 350 km with initial eccentricity less than 0.001. For spacecraft with large area to mass ratios, additional altitude is needed to compensate for eccentricity variations due to solar radiation pressure. A reserve ΔV budget of 13 m/sec for disposal maneuvers was cited. This strategy will keep the disposed GEO debris at least 300 km above geosynchronous altitude to allow adequate clearance for longitude changes of operational GEO spacecraft. Early studies on GEO debris disposal may be found in [7 and 8].

4. ATMOSPHERIC REENTRY [5]

The U.S. Government standard practice for atmospheric reentry was analyzed under four different options for bringing spacecraft in within 25 years of end of mission: 1) chemical propulsion maneuvers, 2) low-thrust propulsion transfer, 3) balloon (drag enhancement device) deployment, and 4) the combination of chemical propulsion and balloon deployment. Spacecraft of various ballistic coefficient values and orbital altitudes of up to 2000 km were studied to determine the required fuel or drag enhancement device needed for deorbit within 25 years; using realistic values for specific impulse I_{sp} and balloon material density, the additional weight required for deorbit was found. The risk of collisions with other space objects during the 25-year reentry was also addressed. The program LIFETIME [9] was used to establish that the disposal orbits led to reentry within 25 years; initial and disposal orbits were all taken as circular. Epoch for start of the 25-year orbit was 1 January 2000. Spacecraft dry mass of 1000 kg was assumed, excluding propellant or balloon. The spacecraft drag coefficient was taken as 2.2. Table 1 gives representative ballistic coefficients and maximum initial altitudes for reentry within 25 years without disposal efforts.

Table 1. Maximum initial altitude values that ensure a 25-year orbital lifetime

Ballistic coefficient, m^2/kg	Maximum initial altitude, km
0.01	640
0.02	696
0.04	756
0.08	820

The evaluation of the four options for disposal found that low-thrust transfers (I_{sp} = 3000 sec) required about a tenth of the additional fuel of chemical propulsion (I_{sp} = 300 sec) for deorbit within 25 years. For example, from an initial altitude of 1400 km, the additional fuel for deorbit of a spacecraft with ballistic coefficient of 0.08 m^2/kg was about 10 kg for low-thrust maneuvering while the chemical propulsion system required 100 kg of additional fuel. Additional deorbit weight for balloon deployment, assuming a balloon material density of 0.132 kg/m^2 and neglecting the mass of the balloon deployment device, was found to be roughly quadratic with initial altitude. Balloon deployment was studied only for initial orbit altitudes up to 1000 km since the size and mass of the balloon becomes too large for practical applications at higher altitudes. Typical balloon weights for deorbit of spacecraft with ballistic coefficient of 0.08 m^2/kg were 5 kg for 850 km initial altitude and 85 kg for 1000 km. The option combining chemical propulsion with balloon deployment uses an approach with chemical maneuvers to reduce the initial altitude to 800 km (the altitude with the largest weight savings for the balloon option in comparison to the chemical propulsion option) followed by balloon deployment. Weight savings (relative to chemical propulsion alone) of about 20 kg over the altitude range of 800 to 2000 km were found for spacecraft of ballistic coefficient 0.01 m^2/kg while weight savings were minimal for spacecraft of ballistic coefficient of 0.08 m^2/kg.

Collision risks during the 25-year reentry orbit were also assessed for the four options. The U.S. Space Command catalog of 14 January 1998 was used with an assumed uniform growth rate of 250 satellites per year. The risk was found to be small for most of the deorbit options, on the order of 1 collision per 1000 deorbit events; however, the largest balloon deployed (from an initial altitude of 1000 km) had a collision rate of about 1 collision per 50 deorbits. Smaller debris impacts over 25 years led to the recommendation that for the balloon option to be feasible, the balloon material should be designed to survive an impact with a 1 mm diameter particle.

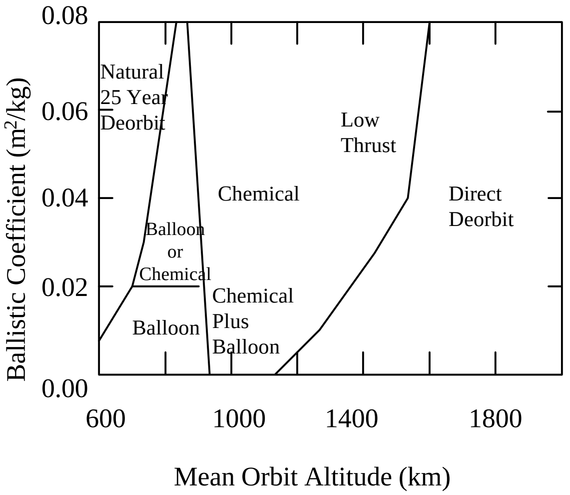

Fig. 1. Regions where explored disposal methods were the most weight efficient.

Figure 1 shows the general trends and conclusions from the study of disposal options. The boundaries separating the different disposal methods are notional in that costs and spacecraft operational capabilities for reentry must be considered for each mission. The low-thrust option offers significant reduction in additional weight, and as indicated in Fig. 1, may be the only viable option for high initial altitudes and large ballistic coefficients. However, low-thrust transfer occurs over much longer times than chemical transfer and requires an operational attitude control system during the entire transfer. At the highest altitudes, a direct deorbit (within half an orbital period) is more mass efficient than transfer to a circular orbit with a 25-year lifetime. At the lowest altitudes, the 25-year lifetime is satisfied without need for further action.

4. MEO DISPOSAL [6]

The study of MEO disposal addressed the orbit stability of two regions, one between 2000 and 4000 km as a potential storage region for missions at high LEO or low MEO and the other as storage zones for GPS, Molniya satellites and geosynchronous transfer orbit (GTO) stages. Long-term variations in semi-major axis and eccentricity were examined through analytical expansions and approximations. Then numerical and semi-analytic orbit propagators were used to study the disposal orbits for up to 200 years. While possible solar radiation induced resonances were noted for disposal orbits at 2500 and 3000 km, orbits selected to avoid resonances were stable. Long-term (100-year) numerical integration to determine proper orbit selection (altitude and inclination not close to one of the resonance conditions) is recommended, particularly for spacecraft with large solar panels. For LEO missions with mean orbit altitude less than 1500 km, direct reentry or deorbit within 25 years is recommended. For missions with mean altitude greater than 1500 km, the recommendation is for disposal in an orbit with minimum perigee of 2500 km.

Investigation of GPS disposal orbits above SSO used a doubly averaged equation in eccentricity that revealed a term in the expansion leading to large growth in eccentricity. The term is the sine of an angle of twice the argument of perigee plus right ascension of the ascending node $(2\omega + \Omega)$. For initial eccentricity of the disposal orbit of 0.02 and the angle term equal to 270 degrees, eccentricity grew to 0.5 in 140 years. Recommendations for GPS disposal were that the orbit should be raised by at least 500 km with eccentricity no greater than 0.005 and initial argument of perigee inside the windows determined for each of the six GPS planes [10]. Estimated ΔV is 50 to 70 m/sec.

Molniya disposal orbits demonstrated long-period eccentricity variations with large amplitude. To preserve a minimum perigee of 2000 km, the initial perigee of the disposal orbit should be raised to 3000 km. The apogee of a Molniya disposal orbit need not be lowered to 500 km below GEO since the inactive satellite will not come close to the geosynchronous region due to its high declination near apogee if the argument of perigee remains close to 270 degrees. GTO disposal orbits (perigee 2500 km, apogee 35,000 km, inclination 28.5 degrees) were found to be very stable with no large variations in eccentricity and inclination.

Direct reentry was also investigated under a strategy of performing single or multiple burns to ensure a controlled reentry with impact in a broad ocean area. Figure 2 shows the ΔV requirements for single-burn direct reentry and transfer to a 2500 km disposal orbit.

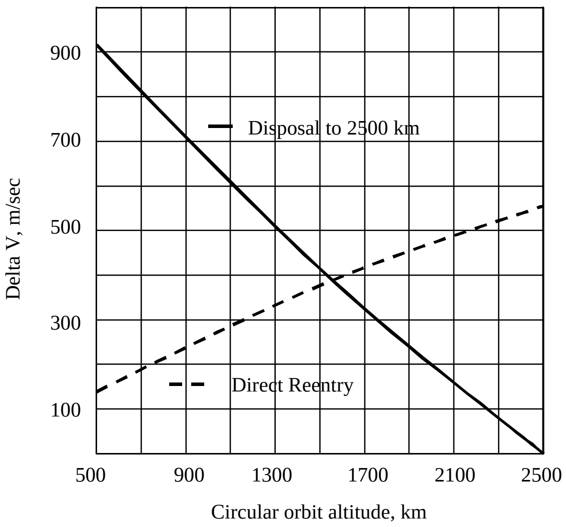

Fig. 2. ΔV requirements for direct reentry and disposal.

For Molniya satellites, direct reentry requires less ΔV than placement in a disposal orbit if EOL eccentricity is greater than 0.7. Direct reentry for eccentricity of 0.72 would require a ΔV of about 95 m/sec compared to just over 160 m/sec for disposal. For a typical GTO, direct reentry requires about 40 m/sec but 200 m/sec to place the stage in a disposal orbit. Other than potential ΔV savings, direct reentry options for Molniya and GTO objects should be favored over disposal orbits due to the relatively high population density near the two inclinations, 28.5 and 63.4 degrees, and the collision hazards these highly elliptical orbits pose to SSO missions as well as their own active and disposal orbits.

5. SUMMARY

U.S. Government standard practices for debris mitigation are generally supported by the analysis described here but should be reviewed to account for orbital variations in identified disposal regions. For GEO disposal, the standard practice's reference to only an initial perigee altitude above synchronous altitude does not acknowledge eccentricity variations or the influence of spacecraft area to mass ratio. Both the NASA guidelines and those under development by the Inter-Agency Space Debris Coordination (IADC) Committee explicitly include spacecraft area to mass ratio as a factor for increasing perigee of the disposal change is 235 km plus a factor of 1000 times the spacecraft reflectivity coefficient times the area to mass ratio. The need to minimize initial eccentricity should also be introduced into the U.S. Government practices, NASA and international guidelines.

Atmospheric reentry standard practices appear feasible based on the study of a range of options. Chemical propulsion has wider applicability due to the more frequent availability of on-board thrusters. The additional wet mass for chemical propulsion deorbit may be 10 to 20% or more of the spacecraft dry mass. While wet mass is not as strong a cost driver as dry mass, cost may be the determining factor in selecting a disposal method. Simplicity, reliability and launch vehicle weight margin are other factors that could drive the selection. Low-thrust transfers offer significant reduction in deorbit mass but require the spacecraft attitude control system to be operational long after end of mission. Balloons or other drag enhancement devices can provide weight savings over chemical maneuvers and should be relatively simple to implement, but do present a larger cross-sectional area for collisions and impacts from smaller debris. There has been little operational experience with balloon systems so the simplicity of this option may be overestimated. Combining chemical maneuvers with a balloon can result in weight savings, but at the cost of increased complexity.

The risk of human casualties from atmospheric reentries is to be limited to less than 1 in 10,000 for each reentry. The casualty exposure is directly related to the inclination of the orbiting object in that a random reentry can occur anywhere within the North and South latitudes equal to the inclination value. An effect of requiring reentry within 25 years of end-of-mission is that the number and rate of reentries will increase, and casualty exposure will also increase relative to the "do-nothing" case of simply abandoning spacecraft on orbit at end of mission.

The direct reentry technique provides controlled disposal, typically into an ocean area, with ΔV savings for lower LEO spacecraft, Molniya satellites and GTO stages. However, application of the technique requires accurate tracking of spacecraft to support calculations for designing the retro-burn, to maintain collision avoidance assurance for manned space systems, and intensive analysis of break-up and debris impact footprints. Effective employment of the direct reentry technique also requires good ground station coverage during apogee burn(s). Thus, this technique may not be universally applicable.

MEO disposal orbits, including those near 2000 to 2500 km, should be selected to avoid resonance regions. A general recommendation is that the initial eccentricity of the disposal be limited to nearly circular. The U.S. Government standard practice of disposal at least 500 km above SSO is strongly supported.

6. REFERENCES

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